
Plasma Science: Enabling Technology, Sustainability, Security, and Exploration

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Plasma Science: Enabling Technology, Sustainability, Security, and Exploration

Committee on a Decadal Assessment of Plasma Science

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

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Preface

Plasma science, the investigation of ionized gases and their interactions with materials, is a discipline absolutely critical to the U.S. economy, national security and protection of our planet from space weather events, while also being one of the major and fundamental areas of physical science. The extraordinary reach of plasma science can be gleaned from the range of plasma enabled technologies that the past decades have enjoyed. These span microelectronics fabrication (plasma science underpins the $1 trillion information technology industry), health care, lighting and displays, water purification and materials synthesis. Moreover, plasma science offers unparalleled opportunities to address outstanding and critical societal problems. Not the least of these contributions is making a major impact on society's ability to address climate change and energy sustainability through the development of fusion generated, carbon free electricity. In addition, plasma science is the basis of stewardship of our nuclear deterrent. Control of intense lasers interacting with plasmas is enabling a new generation of particle accelerators that could revolutionize X-ray imaging from medicine to industry and enable investigation of new quantum phenomena. Plasma science as a scientific discipline in its own right is remarkable in spanning a huge range of physics, contributing to and drawing from disciplines as diverse as space physics and astrophysics, materials science and engineering, atomic, molecular and optical physics, chemistry, biology, medicine and agriculture.

The importance of plasma science to the nation is reflected by its support from a variety of federal agencies in developing decadal assessments to measure the impact, accomplishments, future research directions and the role of plasma science to the United States. This report, *Plasma Science: Technology, Sustainability, Security, and Exploration*, (hereafter "*Plasma 2020*"), is the third in the series of decadal studies providing this assessment. The *Plasma 2020* report was requested and funded by the National Science Foundation, the Department of Energy, the Office of Naval Research, and the Air Force Office of Scientific Research. The committee's statement of task authored by these agencies appears in Appendix A.

By any measure, plasma science and plasma enabled technologies have revolutionized modern society and enabled our understanding of the fundamental processes that govern stars and galaxies, the magnetic fields of planets, the atmosphere, interaction of intense electromagnetic fields with matter, and how energy self-organizes in response to its environment. Besides the fundamental and exciting nature of plasma science in exploring nature, we indeed live our everyday lives surrounded by the extraordinary fruits of applying plasma science to any number of applied problems. Technologies ranging from cell phones to solar cells rely on plasmas for their economic fabrication. The lesson to be drawn from these examples of plasma science in our lives is that there is enormous potential for plasma science to make equal and greater contributions to society moving forward. The recognition of this potential led to a partial focus by the committee to identify in the findings and recommendations of *Plasma 2020* the means to make these potential contributions a reality.

There is, however, a possible impediment to achieving that potential, and that is the manner in which federal funding for plasma science is structured in the United States. Unfortunately, plasma science funding, because of its wide-ranging utility to so many applications and sciences, tends to be distributed across multiple agencies and there is a lack of cohesive strategic goals. This has a limiting effect on plasma science as a whole, but of greater concern is that it leaves opportunities untaken and in some cases threatens the leadership of the nation in multiple areas of plasma science and engineering. Although our comments on this topic are specific to plasma science, the committee expects that our recommendations may apply to other fields of science and technology as well.

Plasma science and engineering is intrinsically interdisciplinary. The basic science of the field is in its own right a unique discipline and fundamental plasma science is in large part supported by the federal agencies that sponsored this report. However, the majority of the applications and technologies enabled by plasma science are within the realm of other federal agencies (or other offices or programs in the sponsoring agencies). These administrative separations of the fundamental science and the society benefiting applications is an impediment to performing translational research that produces the technologies that empower society. Compartmentalization even occurs within and between agencies that primarily support fundamental plasma science. There are many reasons for this compartmentalization, ranging from interpretation of guidelines that discourage duplication to narrow definitions of missions. This compartmentalization is not in the best interest of furthering the science of plasmas, and in particular, is not in the best interest of the nation, which would benefit from more coordinated fundamental and translational research, while also addressing the science needs of industry. A major theme of *Plasma 2020* is partnerships between federal agencies that can mitigate this compartmentalization. In this regard, the findings and recommendations of *Plasma 2020* extend far beyond the agencies that sponsored this report.

During review and final preparation of *Plasma 2020*, we are in the midst of the Covid-19 pandemic (March to May 2020). The areas of plasma medicine and plasma biotechnology encompass the use of plasmas for sterilization of materials and living tissue such as skin, and address the need to physically kill pathogens without risking antimicrobial resistance. Plasma medicine and plasma biotechnology are examples of interdisciplinary fields that have fallen between the cracks of the perceived responsibilities of individual funding agencies. Plasma focused agencies are reluctant to sponsor projects that involve biological systems and biologically focused agencies are reluctant to sponsor projects that have a focus on plasma physics. As a result, we may have missed an opportunity to have another tool at our disposal to aid in the current health crisis.

During the development of *Plasma 2020*, the DOE Office of Fusion Energy Sciences (FES), in response to a Congressional request, began a strategic planning process. The Fusion Energy Scientific Advisory Committee (FESAC) will provide FES with a proposed strategic plan after *Plasma 2020* is issued. The plan will be based on a community planning process requested by FESAC and initiated by the American Physical Society Division of Plasma Physics through establishment of an oversight committee. That community planning process was conducted while *Plasma 2020* was being developed. Although the FES strategic planning process applies only to FES and its operational goals moving forward, FES does sponsor a considerable fraction of the plasma science that is conducted in the United States, and so there will be some overlap between the *Plasma 2020* and the FES report in terms of science challenges. The purview of *Plasma 2020* however extends beyond FES to all federal agencies that sponsor fundamental research in plasma or benefit from plasma technologies. Having said that, synergies between the reports emphasize the importance of those topics.

During the development of the *Plasma 2020* report, the National Academies of Sciences, Engineering, and Medicine's *Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research* was issued. This report discussed a path forward for the United States to perform the research and develop the technologies needed to produce magnetic fusion generated electrical power. Magnetic fusion energy is also a topic of the *Plasma 2020* report. As with the FES strategic planning process, the synergies between the recommendations of the burning plasma report and *Plasma 2020* are some indication of their importance.

Given the extreme breadth of plasma science and engineering that is the purview of this report, the *Plasma 2020* committee did not make specific recommendations on prioritizing, for example, the recommendations of the burning plasma report over those of developing laser-plasma based particle accelerators or vice-versa. The intent of *Plasma 2020* is to present the scientific science challenges, prioritize *within* the sub-fields of plasma science and propose structural changes to how plasma science is coordinated to address those science challenges and the translational research that produces societal benefit.

Finally, the committee thanks the national and international plasma science and engineering communities for providing input and their perspectives. These communities were engaged through solicitation and their submission of white papers; participation in a series of town hall meetings at universities, national laboratories, conferences and workshops; and through presentations made to the committee in closed and open sessions. The committee reached out to numerous members of the community for specific contributions and input where we felt additional insight and expertise was needed. The committee also thanks the reviewers for their candid and helpful comments, the National Academies staff and, in particular, Dr. Chris Jones and Dr. James Lancaster for guiding the committee through this process.

Mark J. Kushner and Gary P. Zank, *Co-Chairs*
Committee on the Decadal Assessment of Plasma Science

Acknowledgment of Reviewers

This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following individuals for their review of this report:

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Toshiki Tajima, University of California, Irvine.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they see the final draft before its release. The review of this report was overseen by Richard A. Gottscho, NAE, LAM Research Inc., and T. Kenneth Fowler, NAS, University of California, Berkeley. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

Contents

Summary

PLASMA SCIENCE: ENABLING TECHNOLOGY, SUSTAINABILITY, SECURITY, AND EXPLORATION

Plasma science and engineering (PSE) is a technological and scientific success story. Advances in plasma science have enabled critical technologies and processes that benefit society, from materials processing and healthcare to forecasting space weather. That record of translating of advances in fundamental science to technologies is continuing to address out nation's most critical needs.

Plasmas, often called the fourth state of matter, are ionized gases and perhaps the most abundant form of matter, making up nearly 99.9 percent of the observable universe. Today, plasma dynamics informs our understanding of the most fundamental processes in the Sun and stars, planetary ionospheres and magnetospheres, interstellar space, and in accretion disks surrounding black holes. Many technologies defining modern society rely on the chemical activation of atoms and molecules that plasmas enable. Plasma-based technologies have enabled efficient lighting, new materials, welding, internal combustion and jet engines, medical implants, and water purification. Plasmas—which enable microelectronics fabrication through the etching and deposition of materials—have been indispensable to the information technology revolution. Translating basic research in plasma science and engineering has the potential to produce new society altering technologies, including: clean energy and energy independence through controlled fusion, a new paradigm for chemical processing, compact particle accelerators for science, medicine and industry, forecasting of extreme space weather events, agricultural and medical advances, all while expanding our knowledge of extreme states of matter that govern astrophysical phenomena. From magnetic fields generated throughout the universe to the earthly creation of states of matter that exist only in the center of stars, to exploring whether life can exist on exoplanets—all are enabled by plasma science through theory, computations, observations, and experiments.

Plasma research is primarily funded as a science discipline by the Department of Energy (DOE), National Science Foundation (NSF), Department of Defense (DoD), and National Aeronautics and Space Administration (NASA). Several other agencies fund activities that are critical to plasma science by providing essential fundamental data required for plasma studies. However, the science and technologies enabled by plasmas are critical to almost all U.S. federal agencies and departments. The interdisciplinary impact of PSE cuts across many current and proposed federal initiatives. For instance, nanoscience, advances in artificial intelligence, machine learning, accelerators, and quantum-based computing are made possible by plasma materials processing of microelectronics devices. Similarly, exploration of the solar system is propelled by plasma-fueled electric propulsion. NNSA's (National Nuclear Security Administration) stockpile stewardship depends on high energy-density plasmas, and space weather is a Sun-Earth plasma system.

The National Academies of Science, Engineering, and Medicine was tasked to assess progress and achievements in plasma science over the past decade and to identify major science challenges and opportunities for the next decade. This assessment evaluates plasma science's contributions to the nation and how the discipline supports the U.S. economy and national security. This report also makes recommendations to ensure the health of the plasma science field, covering workforce development, the role of the United States in international collaborations, and the optimum deployment of resources to meet the science challenges. The report summarizes progress in the field since the Plasma 2010 Decadal Study.

Of special note is the emergence of Laser Plasma Interactions (LPI) as a frontier field in advancing the fundamentals of plasma science, high field science, quantum physics and translational research towards applications. This emergence was recognized by the 2018 Nobel Prize in Physics.

GRAND CHALLENGES OF PLASMA SCIENCE AND ENGINEERING

PSE transforms fundamental scientific research into powerful societal applications. This outstanding strength of PSE is captured in the following "PSE Grand Challenges"—high-level goals, presented without ranking, in which mastery of the complexities of plasma science benefits society:

- *Understanding the behavior of plasmas under extreme conditions* will enable predictive and efficient controllable energy conversion by plasmas, addressing the challenges of sustainability, economic competitiveness, and national security, while expanding our knowledge of the most fundamental processes in the universe.
- *Mastering the interactions of the world's most powerful lasers and particle beams* with plasmas will enable precision x-ray imaging for medical science, advances in national security, compact particle accelerators, advanced materials and sustainable energy sources, while opening new regimes for high-energy and quantum physics.
- *Developing fusion-generated electricity will tap the virtually unlimited fuel in seawater*, to bring the benefits of energy independence and carbon-neutral power to the nation, through economical, deployable, and sustainable fusion systems enabled by advances in experimental and computational plasma physics.
- *Demonstrating that lasers and pulsed-power devices can produce inertially confined fusion ignition* by producing plasma-based extreme states of matter that will support stockpile stewardship, further the goal of sustainable energy, energy independence, and expand our knowledge of high energy density physics.
- *Electrification of the chemical industry*—that is, driving chemical processing by electrical means facilitated by plasmas, by controlling the flow of power through low-temperature plasmas (LTPs) to produce predictable chemical transformations in gases, solids, and liquids, on scales capable of economically establishing a future based on renewable and sustainable electricity, and addressing pandemic threats to our health through plasma sterilization of surfaces and tissue.
- *Developing timely and actionable space-weather forecasting and nowcasting* will enable us to mitigate the potentially damaging effects of extreme solar plasma storms on spacecraft, humans, power grids, and infrastructure.

REPORT RECOMMENDATIONS

The PSE community in the United States has seen many changes since the publication of the *Plasma 2010 Decadal Report*, with landmark contributions to the science of plasmas, national security, space exploration and economic competitiveness. These advancements confirm the value and need for both discipline-centric fundamental research and interdisciplinary research that translates science to applications.

The interdisciplinary reach of PSE is a strength and testament of its value to the nation; however, the often highly mission-driven support of PSE also leads to fragmentation of the field, lack of an identifiable home agency, and a reduced ability to exploit interdisciplinary opportunities. While acknowledging that there are common scientific challenges that cross the field, this report is structured around the subfields of PSE to enable federal agencies to best receive the findings and recommendations most relevant to their missions. Nonetheless, the committee's recommendations propose actions to mitigate fragmentation of the field, encourage a more cohesive discipline that embraces a diverse and inclusive community, enable greater plasma-related collaboration between programs and agencies, and support joint initiatives between plasma-focused agencies and those benefiting from plasma science and technology.

The following sections include at their end the most high level recommendations for this report. (These high-level recommendations, as well as more specific recommendations developed in the individual chapters, are collected in Appendix B.)

Stewardship and Advancement of Interdisciplinary Research

Fundamental research in PSE can and does rapidly translate to societally relevant technologies, the benefits of which cut across the missions of many federal agencies. The support for fundamental research in plasma science by several federal agencies, and particularly by the NSF/DOE Partnership in Basic Plasma Science and Engineering, is critical to addressing the grand challenges described above. While the underlying science has common intellectual threads, this inherently interdisciplinary community is organized into sometimes isolated subdisciplines. This isolation results in part from the diversity of applications that motivates the fundamental research and is reinforced by mission-driven support at the federal level that may not take full advantage of synergies between fundamental research in the subdisciplines and applications.

In many areas of PSE, such as plasma materials processing, application-focused development is the primary mission of a program rather than that the funding of fundamental plasma research. As a result, the interdisciplinary and multidisciplinary strengths of PSE are not being fully utilized, to the detriment of the fundamental plasma research and to the detriment of the intended applications. For example, there is enormous potential for PSE to contribute to one of society's greatest challenges—sustainability—while also contributing to economic competitiveness. At NSF, this research would best be performed in the Engineering Directorate (EngD) while other areas of plasma science would find their homes in the Directorate for Mathematical and Physical Sciences and the Directorate for Geosciences. Historical support for PSE in the EngD has been inconsistent, and particularly so since the Plasma 2010 report, in large part due to the changing priorities of individual EngD programs. This has made it difficult to develop long-term PSE strategies to address critically important challenges such as sustainability.

The challenges towards leveraging public-private partnerships for economic and national security benefits are large; however, the potential benefits outweigh these challenges. At the small-business end of the innovation chain, the resources and know-how required to make breakthroughs in translational research can fit poorly within traditional Small Business Innovation Research / Small Business Technology Transfer (SBIR/STTR) models. At the large-business end of the innovation chain, there are extreme pressures from international competition, in large part resulting from strong foreign government support for fundamental and translational research in key industries.

Recommendation: Federal agencies directly supporting plasma science and engineering (PSE) and those federal agencies benefiting (or potentially benefiting) from PSE should better coordinate their activities extending into offices and directorates within larger federal agencies

Recommendation: Federal agencies and programs within federal agencies that are separately focused on fundamental plasma research, and those that are focused on science and technologies that utilize plasmas, should jointly coordinate and support initiatives with new funding opportunities.

Recommendation: The Engineering Directorate (EngD) of the National Science Foundation (NSF) should, as a minimum, consistently list PSE in descriptions of its

relevant programs and consistently participate in the NSF/Department of Energy (DOE) Plasma partnership.

Recommendation: More strategically, NSF should establish a plasma-focused program in the EngD. that would advance engineering priorities across the board, including advance agricultural systems, energy and environment, chemical transformation, advanced manufacturing, electronics and quantum systems.

Recommendation: Federal agencies focused on plasma research, and DOE in particular, should develop new models that support the translation of fundamental research to industry. Programs that support vital industries depending on plasma science and engineering (PSE) should be developed through relevant interagency collaborations.

Education and Workforce Development

There are great opportunities for new university faculty in PSE to address sustainability, investigate laser-plasma produced quantum effects, make space weather predictions, and explore exotic states of matter. However, the current trends in PSE demographics and hiring practices are eroding the ability of the field to meet these challenges and national priorities. A multidisciplinary approach has been at the heart of the success of the field of plasma science, while simultaneously working against its long-term vitality in academia. Plasma physics is a minority discipline in nearly every university department containing plasma-focused faculty while many physics departments contain no plasma physics faculty. As a result, maintaining faculty expertise is becoming progressively more challenging. Many universities do not require or offer plasma physics classes for undergraduates in science and engineering. Plasma-specific educational and research programs that also provide opportunities to diverse and less advantaged populations are needed to ensure a critically populated PSE workforce. Increased emphasis on PSE undergraduate research and internships, particularly at principally undergraduate institutions (PUIs), will also improve awareness of our field among all undergraduates, and women and underrepresented students in particular, thus enabling a fuller, more diverse pipeline and hence a more diverse discipline.

The demographics of the PSE workforce indicate that the next decade will likely see significant turnover, making it critical to take deliberate actions to renew the PSE workforce. Diversity, equity, and inclusion (DEI) broadens a discipline to the betterment of that discipline and to the betterment of the society the discipline serves. Regrettably, PSE is among the least diverse of the science, technology, engineering, and mathematics (STEM) fields. Rectifying this requires a diverse student pipeline and a commitment to welcome, support and retain members of under-represented groups. A professional workforce cannot reflect society if the student pipeline entering PSE is not diverse. The number and diversity of students entering the pipeline can be increased by increasing the numbers of undergraduate students exposed to PSE through research experiences. PSE research programs in PUIs could have a disproportionately large influence in both filling and diversifying the PSE pipeline.

Recommendation: Federal agencies—for example, Department of Energy (DOE), National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), and Department of Defense (DoD)—should structure funding programs to provide leadership opportunities to university researchers in plasma science and engineering (PSE) areas and to directly stimulate the hiring of university faculty.

Recommendation: Funding agencies (e.g., NSF, DOE, NASA, DoD) should structure funding to support undergraduate and graduate educational, training, and research opportunities—including faculty—and encourage and enable access to plasmas physics for diverse populations.

The Competitive International Research Enterprise in Plasma Science and Engineering

The research enterprise in PSE has had broad impact over the past decade; however, this progress has also been made in an environment of tremendous international investments across the spectrum of PSE that challenge and may potentially usurp U.S. leadership. International investments in large fusion devices, powerful lasers, and research networks over the past decade have generally exceeded that made by the United States; just two examples being the EU investment in the Extreme Light Infrastructure and the Wendelstein 7-X stellerator. Given these strong international investments, incremental progress in facilities in the United States is insufficient to maintain leadership. Computational plasma science and engineering (CPSE) has become essential across PSE for experiment and mission design and diagnosis, idea exploration, and prediction. For computations to continue to progress in PSE, the next generation of researchers needs to be better educated through the development of plasma-focused computational textbooks and courses, and through participation in funded computational research projects.

Recommendation: Federal agencies (e.g., NSF, DOE, NASA DoD) should support a spectrum of facility scales that reflect the requirements for addressing a wide range of problems at the frontiers of PSE.

Recommendation: Federal agencies whose core missions include plasma science and engineering (PSE)—for example, Department of Energy (DOE), National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), and Department of Defense (DoD)—should provide recurring and increased support for the continued development, upgrading, and operations of experimental facilities, and for fundamental and translational research in plasma science. A spectrum of facility scales should be supported, reflecting the requirements for addressing different problems at the frontiers of PSE.

Recommendation: Federal agencies should support research into the development of computational algorithms for plasma science and applications for the heterogeneous device computing platforms of today and upcoming platforms (e.g., quantum computers), while also encouraging mechanisms to make advanced computational methods, physics-based algorithms, machine learning, and artificial intelligence broadly available.

Better Serving the Community

Following the recommendations of the *Plasma 2010* report, the DOE Office of Fusion Energy Science (FES) broadened the scope of its programs to better serve the plasma science community. The title of the FES office does not now accurately reflect its broader mission, and may actually hamper collaboration within DOE and with other federal agencies on nonfusion research.

Recommendation 4: Consistent with our recommendations to broaden the impact of plasma science, the Department of Energy (DOE) Office of Fusion Energy Science (FES) should be renamed to more accurately reflect its broader mission, and so maximize its ability to collaborate with other agencies and to garner nonfusion plasma support. A possible title is *Office of Fusion Energy and Plasma Sciences*.

Organization of the Report

In this report, outstanding contributions to scientific knowledge, economic vitality, and national security over the last decade in several fields of PSE are discussed. An initial overview chapter discusses the key findings and recommendations, while introducing a theme of fundamental research supporting translational research and the benefit of coordination and collaboration between federal agencies. The following 6 chapters each address a sub-field of PSE. Each chapter presents exciting future research directions, the national benefits that will occur with the translation of scientific advances to applications, and develops individual chapter-level findings and recommendations. Although cross cutting themes and challenges are discussed, particularly in Chapter 2, the committee elected to make vertical cuts through the discipline since this better maps onto the current support infrastructure of the federal agencies. If the recommendations of this report are adopted, the next plasma decadal study will be positioned to organize the report using horizontal disciplinary cuts. Synopses of the Chapters follow.

Chapter 2: Fundamental Plasma Science

A recurrent theme of the report is linking basic plasma science research and translational research. We cannot over-emphasize the importance of maintaining strong support for research in fundamental and basic areas of the discipline—both for the intrinsic value of that research and in producing the necessary foundational knowledge that underlies all translational and applied research. Research in basic plasma science is essential to PSE, and there have been major advances in understanding the underlying, unifying principles that transcend plasma science: magnetic reconnection, waves and shocks, turbulence, particle acceleration, and self-organization. With the focus of basic plasma research being on understanding fundamental principles, the immediate applications are not always clear. However, this work provides the foundation for the entire field.

Computational Plasma Science and Engineering (CPSE)

Computation and theory are critical for prediction, diagnosis, and experimental design in PSE, which will only be enhanced by artificial intelligence (AI) and machine learning (ML). Computational science is essential to PSE, expanding our understanding of fundamental science and helping develop technologies. Thus, the continued impact of CPSE will depend on making state-of-the-art computations accessible to researchers who are not computational experts

Chapter 3: High-Intensity Laser-Plasma Interactions

Expanding plasma-based capabilities in high-intensity ultrafast lasers, with increasing energies, repetition rates, and control, are opening new areas of high field plasma physics, including the investigation of quantum processes and the creation of matter from pure photon energy. Laser and particle-beam control of the most intense sustained electromagnetic fields in plasmas is opening new disciplines in plasma optics and particle acceleration. Plasma-driven electron and ion accelerators can achieve high particle energies in a smaller spatial region compared to conventional accelerators and are opening new regimes for high-energy particle physics colliders and high-performance compact x-ray sources. These new compact accelerators have important application to medicine, industry and national security.

Chapter 4: High Energy Density (HED) Plasmas and Inertial Confinement Fusion (ICF)

Understanding the dynamics of plasmas in the HED regime addresses fundamental questions in astrophysics and space physics, material science and quantum materials, nuclear physics and atomic physics, and is essential to stockpile stewardship. Major new facilities have had a great impact on the HED field, helping it to flourish over the past decade. HED physics encompasses inertial confinement fusion (ICF), the pursuit of controlled fusion in the laboratory by compressing matter to densities found at the center of stars. We stand at the brink of achieving the milestone of fusion ignition, sharing science, similar challenges, and the potential for societal benefit with magnetic fusion energy. While existing HED facilities will produce further scientific advances over the next decade, planning for successor ICF and HED facilities, both laser- and pulsed-power driven, is beginning.

Chapter 5: Low-Temperature Plasmas (LTPs)

The chemically reactive nature of LTPs has enabled society-wide transformations in our quality of life, ranging from materials synthesis, to water purification, to enabling the IT revolution through plasma-enabled fabrication of microelectronics. LTPs are partially ionized plasmas that produce chemically reactive environments in gases, on surfaces, and in liquids. Over the past decade, LTPs have greatly advanced atomic-layer etching and deposition of materials, control of electromagnetic waves, space propulsion, human healthcare, and agriculture, and protecting the food chain. LTP technologies are propelling the electrification of the chemical industry—that is, driving chemical processing by electrical means facilitated by plasmas.

Chapter 6: Magnetic Confinement Fusion Energy (MFE)

The societal benefit from MFE could be enormous, as fusion energy can provide a carbon-free source of electrical power from an essentially limitless source of fuel and enabling energy independence. Nuclear fusion, the process of fusing lighter elements to create heavier elements and release energy, powers stars. In the laboratory, strong magnetic fields can confine hot plasmas to produce star-like fusion—Magnetic Confinement Fusion Energy (MFE). The past decade has brought MFE to the brink of creating the first burning plasma in the ITER project, scheduled to come online by 2026, and to produce a burning plasma in 2036. A 2019 NASEM study endorsed U.S. participation in ITER as an essential step toward realizing commercial fusion power in the United States, and recommended using that knowledge to develop an economical compact fusion pilot power plant.

Chapter 7: Space and Astrophysical Plasmas (SAPs)

SAPs possess properties inaccessible to Earth-bound experiments, raising questions as varied as the origins of the universe and the habitability of exoplanets. Future Earth- and space-based observing platforms and space missions will address some of the most profound questions about the universe. The societal benefits of understanding SAPs extend from the practical to the inspirational. Notably, the past decade has brought us closer to understanding the origins and effects of space weather, enabling forecasting and nowcasting that will protect spacecraft, instruments, and humans in space, along with electrical power grids on Earth—all of which is essential to our national security. Startling recent advances include detection of a possible neutron star merger through the simultaneous excitation of gravitational waves, gamma ray bursts, x-ray and visible plasma emission, and the first images of a black hole, both extraordinarily exotic events that represent SAP research.

1

Plasma Science: Enabling Technology, Sustainability, Security, and Exploration

A SOCIETY WITH PLASMA SCIENCE

How does plasma science impact today's society?

- The internet, computers, cell-phones, jet turbines, medical implants, lighting, solar cells, nanomaterials, advanced batteries and spacecraft exploring our solar system are all enabled by plasmas.
- Stockpile stewardship, hypersonic flight, space weather, indeed our very national security, relies on our understanding and mastering the complexities of plasmas.
- From magnetic fields generated throughout the universe to the earthly creation of states of matter that exist only in the center of stars, to exploring whether life can exist on exoplanets—all are enabled by plasma science.

Perhaps our greatest present and future challenge is sustainability. How do we sustainably use the planet's resources while having ever more prosperous societies? How do we generate the power we need? How do we produce the essential chemicals and materials society needs? Plasma science can be a large part of addressing those challenges. We can envision a future in which plasma science, aggressively stewarded, can use its potential towards achieving a sustainable society by providing

- Nearly unlimited sources of carbon-free electricity;
- Compact particle accelerators for imaging and cancer treatment;
- New materials, green chemical production, new modalities for medicine and agriculture;
- Secure management of our Nation's most strategic weaponry; and
- Fundamental knowledge about the creation of the solar system and worlds beyond.

Enabling this vision of the future through the support of plasma science is the topic of this report.

Plasma is often called the 4th state of matter - gases, liquids, solids, and plasma. Plasmas are ionized gases in which electrons have been removed from neutral atoms to make a collection of negatively charged electrons, positively charged ions, sometimes including negative ions, and neutral atoms and molecules. Plasmas are perhaps the most abundant form of matter, accounting for 99.9%, of the visible universe. Stars are made of plasmas—the Sun is a plasma. Life on Earth may have started from amino acids formed by lightning, a plasma, in the primordial atmosphere. A huge array of technologies that define modern society relies on the chemical activation of atoms and molecules enabled by plasmas, from lighting to the fabrication of microelectronics devices. Plasmas are increasingly being used to benefit human health and well-being, from plasma-based medical devices for wound healing and cancer treatment to the use of plasmas to enhance the growth rate and yield of agriculturally important crops. Plasmas are the source of electromagnetic radiation and, when combined with intense lasers, could act as compact particle accelerators for medical and security imaging, and exploration of the frontiers of high-energy physics. Our national security relies on plasmas, from our strategic weapons to the high-energy-density experiments needed to steward our nuclear deterrent. Plasmas are the basis of one of the most ambitious experiments ever attempted: controlled thermonuclear fusion reactions that one day will provide sustainable electricity. Understanding the most fundamental processes in planetary ionospheres and magnetospheres, in interstellar space, and in the matter falling into black holes requires that we first understand the dynamics of plasmas. Spacecraft powered by plasma propulsion are now visiting asteroids and distant planets, and may propel astronauts to Mars. The existence of life and habitability on planets and moons in the solar system, and the much larger collection of exoplanets, will in large part be determined by space weather, a plasma phenomenon.

In many ways, plasmas are the technological and scientific success story of the 20th century, with the potential to completely redefine the 21st century. During the 20th century, plasma-based technologies enabled efficient lighting, new materials, welding, internal combustion and jet engines, medical implants, and water purification. Plasmas, through microelectronics fabrication by etching and deposition of materials, are singularly responsible for the information technology revolution. We came to understand the plasma processes that power the stars, how the dynamics of the Sun's surface affect our atmosphere, and how dusty plasmas in the laboratory can teach us about the atmospheres of comets.

In the 21st century, translating fundamental research in plasma science and engineering (PSE) into practice will produce controlled fusion, an entirely new paradigm for chemical processing, compact accelerators for medical and security imaging, warning systems for extreme space weather events, agricultural and medical advances, propulsion sending spacecraft and astronauts to the planets, an expansion of our knowledge of extreme states of matter that govern astrophysical phenomena, and experiments that reproduce those conditions for study on Earth.

The potential of fundamental research in PSE to translate to societal benefit is captured in the vision of a *Future Based on Renewable Electricity (FBRE)* where societies are powered by non-polluting, renewable, and sustainable electricity. [1] The source of that electricity will be largely plasma-enabled, from plasma fusion reactors to solar cells that are produced by plasma materials processing. That electricity will be stored in batteries made with plasma-synthesized materials. The electrical infrastructure will be protected by predictions of space weather events resulting from advanced understanding of the plasma processes connecting the Sun to the surface of our planet. Plasma-based processes will use the potential energy in that electricity to convert waste products to the chemicals upon which society depends, and to recover resources and protect public health by cleaning polluted water. Agriculture and the food cycle will become electricity based, through plasma-based production of fertilizer, enhancement of plant growth, and ensuring food safety. New modalities in healthcare will become electricity based by taking advantage of plasma-based patient-specific treatments and imaging.

Plasma science and engineering is perhaps the most interdisciplinary of the major fields of physics. With rare exceptions, there are no departments of plasma physics or plasma engineering in U.S. universities. However, some form of plasma science, from fundamental investigations to technological applications, is found in nearly every engineering, life science, and physical science department in colleges and universities. The impact of PSE is due to its interdisciplinary nature since fundamental advances in plasma science can rapidly transition to societal benefit. That impact is felt across U.S. federal agencies and departments. "Plasma" formally appears in the titles of research and technology programs at the DOE, NSF, DoD, and NASA. However, the technologies and science enabled by plasmas are critical to the NIH, EPA, NIST, USDA, FDA, NSA, DHS, and across the law enforcement agencies. As a result, the impact of the interdisciplinary nature of PSE can be found in how plasmas enable current and proposed federal initiatives. Advances in artificial intelligence, machine learning, and quantum-based computing are made possible by plasma materials processing of microelectronics devices. Exploration of

[1] "Science Challenges in Low Temperature Plasma Science and Engineering: Enabling a Future Based on Electricity through Non-Equilibrium Plasma Chemistry", http://arxiv.org/abs/1911.07076.

the solar system is propelled by plasma-fueled electric engines. NNSA's stockpile stewardship is singularly dependent on high energy-density plasmas.

This decadal study, *Plasma 2020*, reviews the scientific advances and societal benefits brought by PSE over the past decade; and discusses the scientific challenges that must be addressed to continue and expand upon those societal benefits.

AN INTELLECTUALLY DIVERSE FIELD UNITED BY SCIENCE CHALLENGES

PSE is perhaps one of the most intellectually diverse of the physical sciences. Plasmas exist over more than 10 orders of magnitude in pressure (or energy density) and more than 10 orders of magnitude in spatial scale. At one extreme of spatial scale are the micron-sized cathode-spot plasmas that sputter metals to place thin metal films on materials. At the other extreme are the plasma jets that emanate from galaxies and the diffuse plasmas permeating galactic clusters. Plasmas with temperatures rivaling and exceeding that of the center of the Sun are being investigated to sustain fusion in the laboratory, while plasmas gentle enough to touch human tissue are being investigated for biomedical therapies.

In spite of these vastly different spatial scales, pressures, power levels, and applications, common themes and scientific challenges do bring cohesiveness to the field. These common challenges may not apply universally to every subfield and application of PSE, but there is continuity throughout the field. Common scientific challenges that unite the field include:

- Complexity arising from multiple scales and phenomena.
- Controlling synergistic exchanges in plasma-surface interactions.
- Understanding and leveraging how complex phenomena can self-organize into coherent structures.
- Controlling the flow of power through plasmas as means of energy and chemical conversion.
- Developing ever more capable diagnostics, theories, and computations to characterize this complexity.

Even with these common themes, the intellectual diversity and breadth of applications in PSE is enormous. As a result, the subfields of PSE are supported by several federal agencies whose missions align with those subfields. In many ways, this diverse base of relevance and support among federal agencies is a strength and testament to the value of PSE to the nation. In other ways, this highly mission-driven support of PSE has led to fragmentation of the field, lack of an identifiable home agency, and reduced ability to capitalize on interdisciplinary opportunities. This is particularly the case in those areas of PSE that involve the life sciences and materials.

While acknowledging that there are common scientific challenges, this report is structured around the subfields of PSE. This choice was made to enable federal agencies to optimally receive the findings and recommendations that are most relevant to their missions. At the same time, our high-level recommendations propose actions to mediate that fragmentation of the field, to work towards a more cohesive discipline, to enable more plasma-related collaboration between agencies and between programs in single agencies, and to jointly support initiatives between plasma-focused agencies and those benefiting from plasma science and technology.

This proposed coordination and collaboration has great potential to advance both PSE as a discipline and to advance the missions of agencies. For example, dozens of low-temperature plasma projects at the various NASA Centers span many different areas important to NASA missions, ranging from plasma technologies for waste gasification, remediation and sterilization to devices such as plasma contactors and electric thrusters. These projects tend to be led by engineers and research scientists in different mission areas who are not necessarily plasma specialists, without significant leveraging of expertise from other plasma-focused projects within NASA and without the input of plasma experts in other federal agencies. The outcomes of these efforts would certainly benefit from improved coordination of plasma-focused activities within NASA, and from outreach by NASA to other agencies to provide plasma expertise to the projects. The likely outcome is a better end result and reduction in the time to deployment or flight.

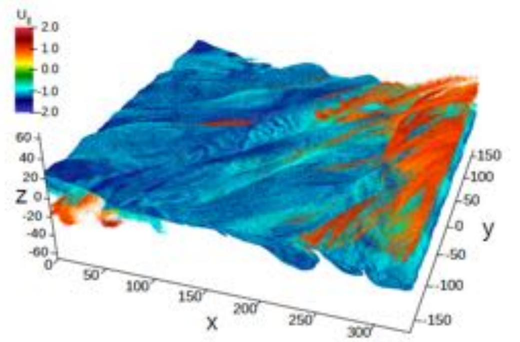


FIGURE 1.1 *Simulations of Reconnection*: Advanced computations are critical to the investigation of fundamental plasma properties. Here, results are shown of a 3-dimensional particle-in-cell simulation of electron and ion acceleration in a current sheet formed during magnetic reconnection. The particles are shown at their spatial location (*x,y,z*) with color indicating the particle velocity parallel to the background magnetic field. The simulation used state-of-the-art high performance computational techniques with nearly 115 billion computational plasma particles. The energetic particles appear to carry significant current. The rope-like structures are known as magnetic flux ropes and can confine energetic particles (red regions).
SOURCE: S. Byna et al., "Parallel I/O, analysis, and visualization of a trillion particle simulation," SC '12: Proceedings of the International Conference on High Performance Computing, Networking, Storage and Analysis, Salt Lake City, UT, 2012, pp. 1-12. https://ieeexplore.ieee.org/document/6468542.

PSE ACCOMPLISHMENTS AND OPPORTUNITIES

The advances in PSE during the past decade have been outstanding in their contributions to scientific knowledge, economic vitality, and national security. As discussed below and in the chapters, impressive progress has been made on several challenges highlighted in the Plasma 2010 report. For example, Plasma 2010 cited the inability “to place a satellite at the right place and time to study reconnection.” The 4 satellite Magnetospheric MultiScale mission (MMS), launched in 2015, has enabled just such measurements. Plasma 2010 cited opportunities to use HED to study astrophysical plasmas. Outstanding progress has occurred in laboratory astrophysics, an example being measurements of opacity of iron for studies of stellar interiors. Plasma 2010 recognized the importance of understanding "multiscale" processes in magnetized plasmas. Impressive insights into these processes have come from simulations and experiments—such as interactions between global MHD instabilities and microturbulence. The opportunities to control plasma-chemical processes were highlighted in Plasma 2010. Major advances have been made in our understanding and use of ns pulsed power to selectively produce reactive species for combustion and chemical conversion. Plasma 2010 cited the need for plasma accelerators, then a nascent field, to be scaled to much longer plasmas and achieve higher energies. This has been realized, with particle bunches close to 10 GeV and staging of plasma.

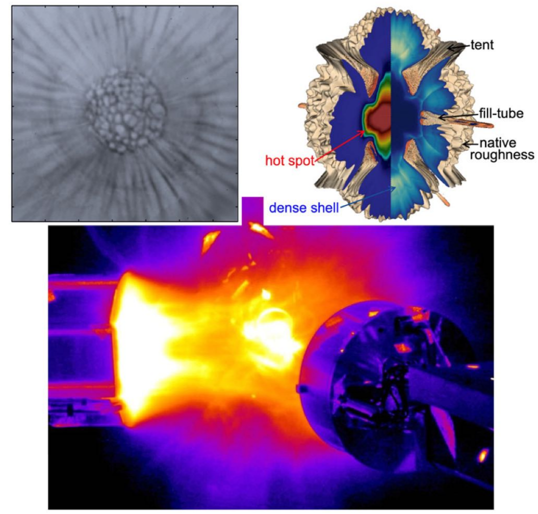


FIGURE 1.2 *The Most Intense Plasmas on Earth.* High energy density physics is flourishing at the start of the new decade. The major facilities (the Omega/Omega EP laser at the Laboratory for Laser Energetics, University of Rochester; the National Ignition Facility at Lawrence Livermore National Laboratory; the Linac Coherent Light Source (LCLS) at the SLAC National Accelerator Facility; and the Z-Machine at Sandia National Laboratory) are producing a wealth of exciting new data. These mature facilities are complemented by new capabilities in multi-dimensional computation and novel, transformative diagnostics. In this image, (top left) a proton radiograph of hydrodynamic instabilities in a plastic foil experiment on the Omega laser demonstrates progress in diagnostics, (top right) results from 3-dimensional calculations of an imploded capsule on the NIF demonstrate progress in simulations, and (bottom) a shot-time image of the center of the target chamber on the NIF demonstrates the state-of-the-art in facilities. SOURCE: Top left: L. Gao, Dissertation at LLE, University of Rochester; top right: Reproduced from D.S. Clark et al., Phys. Plasmas 23:056302, 2016, with permission of AIP Publishing, https://aip.scitation.org/doi/figure/10.1063/1.4943527; bottom: Lawrence Livermore National Laboratory, https://lasers.llnl.gov/media/photo-gallery?id=sgemp_shot.

Fundamental Plasma Science

Plasma processes occur in nature, laboratories and in industrial settings over a vast range of space and time scales. Despite this great diversity of plasmas, there are unifying themes and processes, such as magnetic reconnection, waves, turbulence, charged particle acceleration, and self-organized structures. The past decade has seen tremendous progress in understanding these underlying, unifying principles. This progress was enabled by results produced by controlled and reproducible laboratory experiments; observations of solar and astrophysical processes and missions to space; advanced computer simulations (see Figure 1.1); and by the development of theories that account for these observations and simulations while explaining regimes not yet accessible by either observations or simulations. Research and education in fundamental plasma science are essential to the entire PSE enterprise. In spite of its great importance, the link between basic plasma science and its many applications is not always appreciated. As a result, support for fundamental plasma research is sometimes deemed of secondary importance to supporting applications. Furthering discovery of fundamental plasma processes is in fact at the root of and essential to applications, and so can be transformational for PSE.

In the following the committee describes an extremely broad range of plasmas, which span an enormous range of plasma densities, temperatures, composition, and magnetic fields, and are vital to our economic competitiveness and national security. The opportunity, *the challenge*, for basic plasma science is to make new discoveries and breakthroughs that help unify the field so that advances in one subfield of plasma science benefits another, and that those fundamental advances translate quickly to applications and societal benefit.

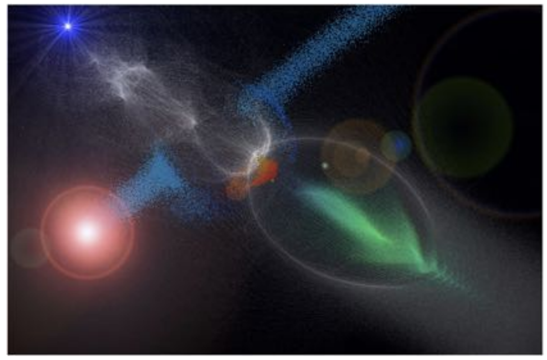


FIGURE 1.3 *Accelerating electrons using a Trojan Horse*—One of the challenges in plasma acceleration of electrons is having the seed electrons accelerated at the right place at the right time. In experiments at the Facility for Advanced Accelerator Experimental Tests (FACET), the seed electrons were released by photoionization of neutral atoms inside the plasma. This technique is called the Trojan Horse. In this image, a laser beam (red, at left) strips electrons (blue dots) off helium atoms - the photocathode. Some of the photo-electrons (red dots) are accelerated inside a plasma bubble (white elliptical shape) created by an electron beam (green). SOURCE: Courtesy of Bernhard Hidding.

High Energy Density (HED) Plasmas and Inertial Confinement Fusion (ICF)

High energy density (HED) plasma physics is the study of matter whose energy content exceeds any natural phenomenon on earth. HED physics often describes the behavior of space and astrophysical plasmas, and the systems on which the United States relies for national security. HED physics is a field with broad, cross-cutting applications in plasma physics. Understanding the dynamics of HED plasmas addresses many fundamental questions relevant to the broader plasma communities, including space science, material science and quantum materials, nuclear physics, atomic physics, and the generation and transport of hard radiation. Major new facilities have had a great impact on the HED field, helping it flourish over the past decade. These facilities include the LCLS (Linac Coherent Light Source at the SLAC National Accelerator Laboratory), NIF (National Ignition Facility at Lawrence Livermore National Laboratory), Z (the Z-pulsed power machine at Sandia National Laboratories), and Omega/Omega EP (lasers at the Laboratory for Laser Energetics at the University of Rochester). Experiments on NIF and Z, as demonstrated in Figure 1.2, have produced essential data for stockpile stewardship and national security. Experiments on LCLS and Omega, and supported by the fundamental science programs at NIF and Z, have enabled extraordinary improvements in our understanding of extreme states of matter.

HED physics encompasses inertial confinement fusion (ICF), which is the pursuit of controlled fusion in the laboratory by the compression of matter to the densities found at the center of stars. The ICF community is pursuing several options to achieve fusion, including magneto-inertial confinement, direct laser illumination to compress small pellets of deuterium and tritium (DT), and indirect laser drive. Ignition of a controlled fusion event in the laboratory is only one of the most visible challenges to HED plasma science. Significant new understanding of the plasma physics required for ignition and data essential to our national security have been gained on NIF even without ignition. While the existing major facilities are expected to continue to produce scientific advances for at least the next decade, planning for the next generation of ICF and HED facilities, both laser- and pulsed-power-driven, is beginning. LCLS II is under construction, and proposals to upgrade the MEC (Matter in Extreme Conditions) facility at SLAC are in progress. If the United States is to continue as the international leader in ICF, the next HED facility, intended for ignition must be designed and built.

High Intensity Laser-Plasma Interactions and Accelerators

Laser and particle-beam control of intense electromagnetic fields that can be sustained and organized in plasmas, far beyond the intensities accessible in ordinary matter, has produced new fields and capabilities in plasma optics and particle acceleration. Combining plasmas with laser and particle beams enables focusing, guiding, and amplification of those beams to unprecedented high intensities, as demonstrated in Figure 1.3. Electrons and positrons can be accelerated in plasmas by resonant plasma wakefields created by these lasers or particle beams with rates of acceleration that can be thousands of times those of conventional accelerators. These plasma-driven accelerators are maturing as a technology and will improve the performance of future high-energy particle physics (HEP) colliders and enable compact, short pulse and high intensity X-ray sources. The field is on the verge of creating precise low-dose X-ray imaging systems for medical science and national security in the next decade. Ultrafast, high-gradient acceleration by HILPI have produced ion beams in excess of 100 MeV, with potential applications ranging from medical therapy to probes of HED plasmas. These outcomes will be enabled by high average power, high repetition rate, shaped-pulse laser systems, and a new understanding of their interactions with plasma. The high-intensity electromagnetic fields produced in these systems are enabling, for the first time, experiments in nonlinear high-field Quantum ElectroDynamics (nQED), the fundamental theory of how light and matter interact. The electric fields being produced in plasmas are approaching the intensities capable of producing matter from the pure electro-magnetic energy of photons.

HILPI is strongly linked to other areas of plasma science in the underlying physics, in applications and enabling capabilities. With advances in laser technology, the coupling of lasers and plasma phenomena can be controlled, providing the ability to manipulate and measure states in plasmas with unprecedented accuracy. Understanding and controlling these new processes are pushing the frontiers of exascale computing while requiring new computational algorithms. Continued advances in HILPI supported by new facilities with higher precision and repetition rate has the potential to enable revolutionary new capabilities for society and to support fundamental studies across the field of plasma science.

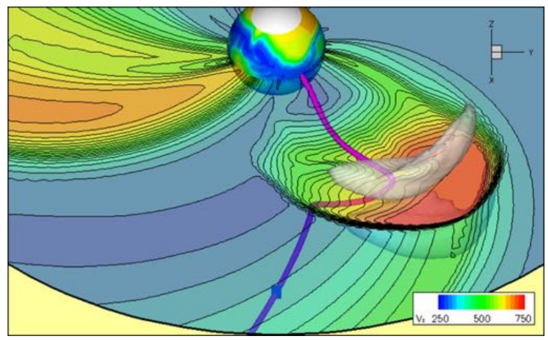


FIGURE 1.4 *Predicting the path of Coronal Mass Ejections.* Computer simulations are providing unprecedented insights, and predictions, of solar events such as coronal mass ejections - CMEs, where huge amounts of ionized gas are expelled towards the earth. Here are results of a 3-dimensional numerical simulation of a CME traveling from the outer corona of the Sun into the heliosphere—that region of space surrounding the Sun. This physics-based first-principles model gave us the first capability for predicting the plasma and magnetic-field properties of the space environment from 20 solar radii to Earth. Over the past decade, this and other physics-based codes have become increasingly powerful and realistic, transforming our ability to comprehend and forecast space weather effects throughout the heliosphere. SOURCE: Courtesy of Dusan Odstrcil, George Mason University; https://nsf.gov/news/mmg/mmg_disp.jsp?med_id=68959&from=.

Space and Astrophysical Plasmas (SAPs)

Space is perhaps the final frontier for plasmas. Space and astrophysical plasmas (SAPs) reach regimes inaccessible to Earthbound laboratory experiments, enabling deep insights into fundamental plasma processes. Some of these fundamental phenomena can be sampled directly by spacecraft, while others can only be studied by spectroscopy, imaging, polarimetry, and other remote sensing techniques. New observations by ground- and space-based instruments continually challenge theorists and computational scientists to decipher the underlying plasma physical processes, while increasingly sophisticated numerical simulations guide the requirements and choice of targets for the next generation of observing platforms and space missions (see Figure 1.4).

The societal benefits of understanding SAPs range from the practical to the inspirational. Over the past decade, research into the origins and effects of space weather—disturbances throughout the solar system, including Earth, driven by solar eruptions—has brought us ever closer to linking together the complex chain of phenomena that connect our Sun to Earth and beyond. However, we are far from being able to predict space weather events and impacts from start to finish—an ambitious grand challenge for PSE in the next decade. Deeper investigations into the adverse effects of space weather on spacecraft, instruments, and humans in space, as well as our electric power grids and other vulnerable infrastructure on Earth, are essential for both national security and protection of our upcoming robotic and human explorations of the Moon and Mars.

The pioneering detection of gravity waves from a neutron star merger was accompanied by observations of radio, X-ray and visible plasma emission that produced unprecedented insights into the nature of and conditions within this cosmic event. The future of gravitational wave astronomy is inextricably linked to improving our understanding of these exotic events through SAP research. The explosion of discoveries of planets orbiting distant stars (exoplanets) over the past decade has driven a parallel effort to apply our knowledge of plasma-produced space weather in our own solar system to those distant systems, in order to determine whether some exoplanets may be hospitable to life. SAP science therefore plays a key role in the formidable challenge of searching for extraterrestrial life.

SAPs are also fascinating and exotic—from solar flares to active galactic nuclei and black hole accretion disks—giving plasma physics high public visibility and recognition. The importance of the public appeal of SAPs cannot be overstated in motivating the study of science in general and plasma physics in particular. We are now experiencing the retirement of an entire generation of researchers who were inspired to pursue careers in science by our first ventures into space—Explorer, Mariner, Apollo. The images brought to us by the Hubble Space Telescope and the Solar Dynamics Observatory have been equally motivational. We can only expect that continuing and expanding our intellectual reach in SAPs will continue to bring new generations of researchers into science and plasma science in particular.

SAP studies rely heavily on other areas of plasma science, from laboratory experiments on magnetic reconnection and dynamos to atomic and nuclear calculations of opacities, involving HED physics, basic plasma science, particle acceleration physics, computational plasma physics, and radiative hydrodynamics. In turn, SAPs serve as unique windows into a vast range of plasma conditions that can test fundamental theories, motivate novel laboratory experiments, and answer critical questions about particle acceleration, atomic and molecular spectroscopy, and turbulence. Plasma engineering is essential for the design and construction of state-of-the-art instruments on spacecraft, capitalizing on the latest techniques and materials to obtain the spatial and spectral resolution and sensitivity needed to probe ever deeper into SAPs throughout the universe.

Magnetic Confinement Fusion Energy (MFE)

Nuclear fusion, the process whereby lighter elements fuse into heavier elements and release energy, is the power source of stars. In stars, self-gravity confines plasmas hot and dense enough to produce fusion reactions that are the source of their enormous power. In the laboratory, strong magnetic fields are used in lieu of gravity to confine hot plasmas to produce fusion - magnetic Confinement Fusion Energy (MFE), as demonstrated in Figure 1.5. The societal benefit of this research is clear and enormous—fusion energy can provide a carbon-free source of power for generating electricity, utilizing an abundant and essentially limitless source of fuel. The fusion reaction that most MFE research focuses on uses two isotopes of hydrogen: deuterium and tritium (D-T). Tritium is radioactive but can be produced from lithium. Both deuterium and lithium are abundant in sea water, ensuring there is a sufficient supply of both to use fusion power to provide the energy needs of our planet for many hundreds of thousands of years. (The amount of lithium that might be used in fusion reactors is a tiny fraction of that currently expended in batteries.) Newly investigated approaches to fusion power could directly produce highly energetic charged particles that can generate electrical current without also producing unwanted neutrons. However, their energy requirements for break-even (generating more energy than expended in making the reactions) are more stringent than for D-T processes.

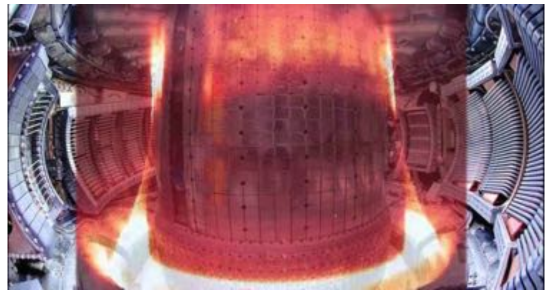


FIGURE 1.5 *Record pressure in a magnetically confined plasma*: In 2016, the Alcator C-Mod tokamak achieved a world record plasma pressure for magnetically confined plasmas. To achieve the record, MIT scientists employed over 4 megawatts of radio frequency heating, raising the plasma temperature to over 35 million degrees Celsius or approximately twice as hot as the center of the Sun. The C-Mod experiments reached a plasma pressure near the target value for future ITER experiments, which was enabled by new understanding of the stability properties of the boundary of the plasma. SOURCE: Courtesy of the MIT Plasma Science and Fusion Center.

Progress in fusion research over the past decade has placed MFE on the brink of creating the first burning plasma—a plasma where self-heating from fusion reactions dominates external heating. The goal of the international ITER project is to demonstrate a burning plasma. ITER is under construction and is on schedule to produce first plasma by 2026.. A recent National Academies study ("A Strategic Plan for U.S. Burning Plasma Research") endorsed U.S. participation in ITER, and made the case that knowledge gained from the burning plasma experiments to be conducted on ITER will be essential in realizing commercial fusion power in the United States. The study also recognized that while the ITER design is a low-risk route to a burning plasma, it is also a high-cost route to commercial fusion power. A fusion-based electrical power network using ITER concepts may be simply too expensive. The study recommended that U.S. researchers learn from ITER and apply that learning to the development of a compact fusion pilot power plant that would lead the way to more economical fusion power. To achieve this goal, the field must address challenges at the forefront of PSE and take advantage of advancements in technology (e.g., high-temperature superconducting magnets) that are only now beginning to mature.

Low-Temperature Plasmas (LTPs)

Low temperature plasmas are partially ionized plasmas that contain electrons energetic enough to collisionally break apart molecules to produce chemically reactive species while also keeping the overall gas temperature near ambient—low enough to contact living tissue. The ability of low temperature plasmas (LTPs) to produce chemically reactive environments in gases, on surfaces, and in liquids has already made society-wide transformations in our quality of life—from lighting, materials synthesis, and water purification to enabling the information technology revolution through plasma-enabled fabrication of microelectronics. Plasmas are now being used to remove harmful substances from water, such as perfluoroalkyl carboxylate, that have defied other economic means of remediation. Plasma methods that etch a single layer of atoms from semiconductor devices have enabled the microelectronics industry to make ever smaller and more capable devices. Clinical trials and practice are now using plasmas to treat human cancer and promote wound healing. There are many opportunities to advance these applications further, for example in the anticipated future growth of the integrated circuit industry associated with intelligent machines, autonomous vehicles, and other innovative technologies, and protecting the food chain, and addressing pandemic spread of bacteria and viruses through plasma sterilization of materials and tissues.

A strategic opportunity for LTP science is to assist in the electrification of the chemical industry—that is, to drive chemical processing by electrical means facilitated by plasmas. The key enabling science will be controlling the flow of energy through LTPs to produce predictable chemical transformations in gases, on solids, and in liquids (see Figure 1.6). The electrification of the chemical industry is a grand science and engineering challenge that will enable an economically viable and sustainable future based on renewable electricity.

To achieve this goal, we first need to deepen our understanding of how energy flows through plasmas, in order to produce more selective and efficient chemical transformations. This challenge will require investigations of kinetic and collisional processes, plasma self-organization, transport and plasma-surface interactions under highly non-equilibrium conditions. This new understanding will also augment plasma-aided technologies across the board, thereby benefiting nearly every sector of our society. Examples include controlling plasma-surface interactions at the atomic level to enable the next generation of materials for quantum computing, combating anti-microbial resistance, improving nitrogen fixation and food safety, creating new energy storage technologies, and developing plasma-based propulsion capable of taking humankind to Mars and beyond.

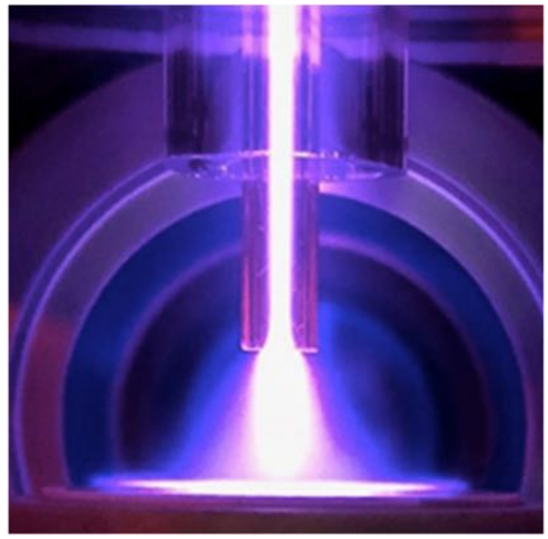


FIGURE 1.6 *Low temperature plasmas.* LTPs are a unique state of partially ionized matter composed of ions, electrons, atoms, molecules and reactive and excited species. Energetic electrons colliding with molecules can produce a non-equilibrium chemically reactive environment in gases and on surfaces at near ambient temperatures. Research is focused on how electrical energy is selectively and efficiently converted into chemical reactivity, and transporting that reactivity to the interface between plasmas and complex materials including liquids, biological and next generation semiconductor materials. The atmospheric pressure helium plasma jet in the image is impinging on a substrate as a method to treat surfaces, ranging from inorganic to living tissue. LTPs have had a transformative impact on society, from water purification to plasma-enabled fabrication of microelectronics. Emerging applications address grand societal challenges including combating anti-microbial resistance and cancer, enhancing food safety and nitrogen fixation and creating new sustainable chemical conversion and energy storage technologies. SOURCE: Courtesy of A.M. Lietz, E.V. Barnat, and M. Kushner.

Computational Plasma Science and Engineering (CPSE)

Computation is one of the four main methods of scientific investigation—the others being theoretical, experimental, and observational. However, computation merits special attention due to its growing number of uses, including prediction, diagnosis, and experimental design; the rapidly changing nature of the field, the emergence of artificial intelligence (AI) and machine learning (ML) as computational disciplines, and the opportunities for PSE to leverage computations to address its research challenges. Over the past decade, computational capabilities have increased by many orders of magnitude, in large part by increasing the number of central processing units (CPUs, also called cores) on a single microprocessor chip and by very efficiently linking together many microprocessors. These advances have taken computing from Gigascale (10^9 floating point operations [flops] per second) to Petascale (10^{15} flops/s), making use of 10s or 100s of thousands of CPU and Graphics Processing Unit (GPU) cores. In the next decade, computational capabilities will increase another 3 orders of magnitude to reach the Exascale (10^{18}

flops/s) level. The coming advances will impact every scale of computing. High-performance computing (HPC) will become affordable by small research groups, allowing them to tackle computational analyses several orders of magnitude larger than they could just a few years ago. Breakthroughs in computational capabilities make it possible not only to speed up large simulations, but also to discover new realms in the underlying science.

Specialized CPSE software capable of utilizing the emerging highly concurrent and heterogeneous hardware is under development for specific applications related to the research missions of federal agencies. However, these efforts are not affecting nor are they accessible to all areas of PSE. Indeed, even in areas of agency-supported research, critically accessible software is not available. For example, PSE does not have the range of software that is available in computational fluid dynamics (CFD) or structural mechanics, which includes both commercial codes and well-supported, more research-oriented, open-source codes. This situation is exacerbated by the increasing array of potential computational devices, including quantum based. The multi-scale, multi-physics and multi-applications nature of PSE makes it difficult to develop broadly applicable and accessible codes, a condition that is also exacerbated by segmentation of the field. Concerted effort is therefore needed to better unify computational efforts across the realm of PSE, particularly for implementing new computational approaches, such as AI and ML. To date, AI/ML has shown encouraging results in prediction through pattern recognition, but the possibilities for discovery in PSE using AI/ML, particularly in deriving underlying fundamental parameters, have not yet been fully developed.

Efforts that will enable the development of more broadly applicable, high performance, and easily implemented software for PSE, with the goal of achieving the robustness of CFD software, clearly deserve support. Major thrusts include education, to develop the next generation of computational PSE practitioners in both software development and scientific discovery, and ensuring that algorithm development continues in both the mathematical and computer sciences. Even within a single computation, PSE phenomena are often multi-scale and multi-physics, which makes it difficult to develop efficient algorithms for machines that require extremely high levels of concurrency. Ultimately, developing efficient computational platforms for PSE may require codes that take advantage of heterogeneity (computing across multiple devices of different architectures). This goal becomes even more challenging when it is also necessary to make these codes accessible to the broader community—non-computer experts should not need to become expert code developers to utilize computations. As new devices become available, such as quantum computers, plasma theorists and computer scientists should jointly develop new algorithms that account for the multi-physics nature of PSE from the start, as opposed to trying to make existing incompatible algorithms fit new architectures.

VALUE OF PSE TO THE NATION

Grand Challenges of Plasma Science and Engineering

Plasma science and engineering holds rich science challenges while being extremely relevant to the economic vitality and security of the nation. Addressing these challenges is part of the continuum of translational research that begins with fundamental scientific understanding and culminates in societal benefit. In most fields of PSE, it is not possible to investigate plasma science challenges in isolation without focusing on some aspect of the science that is motivated by, and whose findings will translate to, an application.

Underpinning these challenges is the need to develop a predictive understanding of plasmas over a vast range of accessible parameters: from weakly ionized, low temperature atmospheric pressure plasmas, through high temperature, high density plasmas, to the extreme plasma conditions that can only be accessed on earth by ultra-intense lasers. Plasmas are complex physical entities that can exist in states that range from weakly coupled to strongly coupled and from non-magnetized to magnetized states. Plasmas also exhibit a wide variety of self-organized behaviors. These rich scientific topics all motivate the study of plasmas as a distinct scientific discipline. Deep, predictive understanding of plasmas will provide the fundamental knowledge upon which future applications can be built. There should be continued investments in theoretical, computational, and experimental exploration of the fundamental processes of plasmas, not only to advance the science of the discipline, but also as a necessary prelude to applications.

The translational continuum from fundamental science to applications is an outstanding strength of PSE, and is captured in the following *PSE Grand Challenges*—high level goals in which mastery of the complexities of plasma science benefits society.

- *Understanding the behavior of plasmas under extreme conditions will enable energy conversion by plasmas to be predicted and efficiently controlled, to address the challenges of sustainability, economic competitiveness, and national security, and expand our knowledge of the most fundamental processes in the universe.*

  When astrophysical objects undergo disruptive events, such as the violent ejection of material from the Sun that influence space weather or the formation of relativistic jets of material from the black holes at the centers of galaxies, it is the violent reconnection of magnetic fields that produces massive plasma outflows and energetic particles. Inside plasma processing reactors, oscillating electric fields heat plasmas that produce new materials. Powerful lasers generate plasmas that compress matter to densities found in the center of stars. Mitigating disruptive events in fusion plasmas will be an important achievement in helping to realize the economical production of fusion power, satisfying the energy demands needed for national security. These are all examples of energy conversion from one form to another that occurs in plasmas. This conversion empowers societies with beneficial applications and is the basis of nearly all astrophysical and space plasma phenomena. Understanding the complexities of these plasma-enabled energy conversions will require new theoretical, computational, and experimental approaches. At one extreme, controlling and predicting these complexities will improve economic competitiveness and national security. At another extreme, increasing our knowledge of how our universe operates will enable us to answer fundamental questions about the birth and death of stars while protecting astronauts on their journeys to the planets.

- *Mastering the interactions of the world's most powerful lasers and particle beams with plasmas will enable precision x-ray imaging for medical science, advances in national security, compact particle accelerators, advanced materials and sustainable energy sources, while opening new regimes for high energy and quantum physics.*

  The coupling of intense, high repetition-rate lasers with plasmas will produce conditions that have never before existed on Earth, and the resulting physical phenomena will expand our knowledge of how matter behaves under intense electric fields. Mastery of that knowledge will enable creation of plasma optics that control light with unprecedented intensities, new compact particle accelerators, conditions approaching *nonlinear Quantum ElectroDynamics* (nQED), and opportunities for precision plasma physics and control of particle-wave interactions. With the development of petawatt-class (10^{15} W), high repetition-rate lasers, new technologies will emerge ranging from compact particle accelerators and coherent x-ray imaging to remote detectors for national security. These capabilities will provide transformational improvements in resolution and capability for medicine, biology, materials science, and the investigation of fundamental meso- and nanoscale physics. These next-generation lasers will extend the reach of high energy particle physics, and improve our understanding of the fundamental forces that shape the universe.

- *Accelerate the development of fusion generated electricity, tapping the virtually unlimited fuel in sea-water, to bring the benefits of carbon-neutral power to society, through economical, deployable, and sustainable fusion systems enabled by advances in experimental and computational plasma physics.*

Perhaps society's greatest challenge is sustainability—a vision that will in part be enabled by a transition to carbon-free and carbon-neutral sources of electricity. Having such sources provides for a *future based on renewable and sustainable electricity* (FBRE). Controlling fusion reactions will provide nearly limitless clean power by converting hydrogen into helium in star-like plasmas on Earth, and holds the promise of providing sustainable electricity. To meet that goal, science and technology challenges must be addressed using the most advanced computational and experimental techniques. The significant investments already made in main-line magnetic fusion energy (MFE) concepts should continue to determine how to create steady state, disruption-free fusion burning plasmas and how to engineer the plasma-facing materials to withstand the intense heat generated by fusion reactor plasmas. At the same time, alternative MFE concepts and innovative technologies must be explored and exploited to achieve economical fusion power that will help enable the FBRE. Pursuit of main-line and alternative concepts will require investments in and leveraging of computational and experimental investigations of the fundamental yet complex plasma transport occurring in MFE systems, while partnering internationally to develop the technologies and demonstration systems required to transition fusion power into a practical source of unlimited carbon-free electricity.

- *Demonstrate that lasers and pulsed-power devices can produce inertially confined fusion ignition by producing plasma-based extreme states of matter to support stockpile stewardship, further the goal of sustainable energy, and expand our understanding of high energy-density physics.*

The compression of matter by lasers and pulsed power will produce inertial confinement fusion (ICF), one of the most scientifically and technologically complex projects ever attempted. High energy-density physics, the basis of ICF, involves extreme states of matter that occur naturally only in astrophysical objects. Understanding these extreme states is absolutely essential to the stewardship of our nuclear stockpile and to understanding supernovae, some of the largest releases of energy in the universe. Advancing that stewardship and understanding cosmic phenomena require the most sophisticated computer simulations ever attempted, advanced pulsed-power facilities, ever more refined diagnostics, and support for new methods to produce and analyze the fundamental experimental and computational data produced by and required by these efforts. The states of matter produced by HED plasmas in pursuit of ICF have never before controllably existed on earth, have never before been directly studied, and have nearly defied being described computationally from first principles.

- *Enable electrification of the chemical industry by controlling the flow of power through low temperature plasmas to produce predictable chemical transformations in gases, on solids, and in liquids, on scales capable of economically establishing a future based on renewable and sustainable electricity (FBRE).*

The ability of low temperature plasmas (LTPs) to induce desired chemical transformations in gases, on surfaces, and in liquids has already been exploited to improve our quality of life—from lighting, materials synthesis and water purification, to enabling the information technology revolution through plasma-based fabrication of microelectronics. An improved ability to control chemical transformations through electricity-driven LTPs has tremendous potential to meet a wide range of current and future societal challenges, including the transformation of the chemical industry from fossil-fuel–driven to electricity-driven. This enhanced capability in LTPs will broadly benefit society by controlling plasma-surface interactions at the atomic level to create the next generation of materials for quantum computing, combating anti-microbial resistance, helping to prevent pandemic outbreaks of pathogens through plasma sterilization of materials and tissue, improving agricultural efficiencies and food safety, enabling new energy-storage technologies, and developing plasma-based propulsion capable of taking humankind to Mars and beyond.

- *With life, technology, and space travel at risk from damaging solar plasma activity, develop the capability for timely and actionable space-weather observations and predictions to mitigate the potential effects of extreme solar plasma storms on spacecraft, humans, power grids, and infrastructure.*

  Living with a star means enjoying its benefits and dealing with its disruptive behavior. The Sun, itself a plasma, steadily emits the solar wind while intermittently producing coronal mass ejections and flares in which intense electromagnetic radiation and massive clouds of magnetized plasma can be directed toward Earth. The high-speed plasmas and energetic particles produced by these extreme eruptions can collide with and potentially damage spacecraft and harm human passengers, and interact with Earth's magnetic field and atmosphere, producing electrical transients that affect communications, power grids, and infrastructure. Our aspirations to explore the Moon, Mars, and the rest of our solar system are also endangered by adverse space-weather. Although humankind cannot prevent extreme solar plasma eruptions from occurring, being able to predict those events many days in advance can provide the time to take protective measures. Achieving this predictive capability will require substantial advances in our theoretical and computational abilities to model solar eruptions, the acceleration of highly energetic particles, and the interaction of these energetic particles and magnetized plasmas with spacecraft and planetary magnetospheres. Achieving this capability will require a new generation of space-based constellations and ground-based observatories. The Space Weather Operations, Research, and Mitigation (SWORM) subcommittee of the National Science and Technology Council is leading a community-wide conversation on benchmarking of extreme space weather events based on studies, data acquisition, and research. Global efforts to develop metrics for model validation are underway under the aegis of the COSPAR (Committee on Space Research) International Space Weather Action Team program. Continued interagency and international cooperation will be key to meeting the grand challenge of accurate and timely space-weather prediction.

In addressing these Grand Challenges, the humanities and social sciences provide an important lens through which all scientific advances can be viewed. Because PSE is integral to so many of the technological developments of the last several decades, it is important for the field to be introspective about the impact of those technologies. Furthermore, because of the great potential for areas such as low temperature plasmas to impact important societal needs such as water purification and waste cleanup, it will be important to contemplate topics such as social justice in order to ensure that such critical societal needs can benefit all of society

Critical Support from Other Science Areas

PSE is an intellectually broad and interdisciplinary field that benefits nearly every other field of science and engineering. For example, the biotechnology and material disciplines have made and continue to make advances based on the ability of plasmas to synthesize, modify, and functionalize surfaces and materials. At the same time, PSE is exceedingly dependent on allied disciplines for the fundamental data utilized in analyzing experiments and needed for model development. As PSE focuses on translational research that involves plasma surface interactions, there are critical data needs for how plasma produced activation energy (energy electrons and ions, chemically species, UV/VUV radiation) interact with hard solids, liquids and soft and organic materials, including living tissue. These data are best produced by experts in those disciplines, in collaboration with PSE researchers as needed. We often find that generation of fundamental data that is used by other disciplines sometimes falls out of favor with funding agencies as that work is perceived as being a service. It is the committee's experience that these data needs are often at the leading edge of science challenges in allied disciplines; and so should be strongly and robustly supported.

This need for critical and robust support from allied sciences is nowhere more true than in the synergistic relationship of PSE with atomic, molecular, and optical physics (AMOP) and chemical physics (CP). The most basic processes in PSE involve electron and ion impact on atoms, molecules, and surfaces (solid and liquid) to produce excited states and new functionality, to generate electromagnetic radiation and energetic particles, and to catalyze chemical reactions between multiple phases. Describing and analyzing these processes require a wide range of fundamental data, including electron impact cross sections for excitation, dissociation, and ionization of atoms and molecules; optical absorption cross sections; oscillator strengths and opacities; charge exchange cross sections; and reaction probabilities of plasma-produced radicals, ions, and photons with gases, solids and liquids. The importance of these fundamental data cannot be overstated—they are essential to the health and advancement of PSE. Well supported programs in AMOP and CP not only advance the science of those disciplines but also enable advances in other disciplines, and PSE in particular.

Diversity, Equity, and Inclusion and the Plasma Science and Engineering Workforce

The principle of diversity, equity, and inclusion (DEI) broadens a discipline to the betterment of that discipline and to the betterment of the society the discipline serves. Regrettably, plasma science and engineering is among the least diverse STEM fields, for historical and current reasons. For example, data from the annual Survey of Earned Doctorates in 2013-2017 shows that the percentage of women annually earning doctorates in plasma physics averaged 14% (below the approximately 20% average for physics), while the percentages of PhDs obtained by Hispanic and African-American students fluctuated around 3% (with several years reporting zero). These data are consistent with statistics from the American Institute of Physics. Additionally, a 2017 assessment from the University Fusion Association has shown that the fusion community (which represents a large portion of the overall PSE community) is aging, with an average age of 56. At the same time, STEM fields that may utilize plasmas, such as chemical engineering and bioengineering, are significantly more diverse.

The committee notes that federal agencies funding research in PSE have greatly differing expectations for grantees to produce broader impacts in their research and conduct outreach activities. The committee endorses the premise that the primary focus of these agencies should be addressing the science and technology challenges in PSE that will lead to societal benefit. However, the committee also feels that a more consistent set of expectations among these agencies would deliver a stronger message of the importance of diversifying PSE.

A professional workforce cannot reflect society if the student pipeline entering PSE is not diverse. There are many causes for lack of diversity in the pipeline and many remedies being proposed to diversify the pipeline. Early exposure to plasma science (e.g., the APS-DPP Plasma Expo, science museum exhibits, and university outreach activities) is important for building an appreciation of plasma science on the part of students and the general public. A more direct method for increasing interest in PSE and in diversifying the pipeline is to increase the numbers of undergraduate students exposed to PSE through research experiences. Such research experiences are more readily available at universities with PhD programs in physics and engineering than at primarily undergraduate institutions (PUIs). Yet, the highest degree in more than two-thirds of physics departments in the United States is the bachelor's degree, and approximately half of all physics bachelor's degrees are awarded by departments that do not offer a PhD. Therefore, the majority of U.S. physics students and potential plasma physics graduate students are likely not exposed to plasma physics as undergraduates. A significant portion of the future PSE workforce relies on prospective graduate students encountering plasma research only in graduate school, and only if a plasma program exists at that institution.

PSE research programs in PUIs could have a disproportionately large influence in developing the PSE workforce by exposing undergraduates to plasma physics and engineering, thus increasing the pipeline of students entering graduate school with the goal of studying plasma physics. PUIs tend to be liberal-arts-focused institutions with broader curricula and more diverse student bodies. Their smaller student-to-faculty ratios enables closer mentoring of research experiences involving students who would not otherwise have research opportunities. Smaller colleges and institutions also have a history of serving underrepresented minorities and first-generation college students, thereby helping to introduce PSE to precisely the audience needed to diversify the pipeline.

The committee acknowledges and is concerned about the lack of diversity in the core areas of PSE. The goal of the PSE community should be to improve the diversity of PSE to reflect the society it serves by increasing the participation of women, ethnic and religious minorities, gender-preference and gender-identity minorities including members of the LGBTQ+ community, and persons with disabilities, while recognizing that this list may not be fully inclusive of all underrepresented communities in PSE. Addressing this persistent problem of underrepresentation should be a high priority in the PSE community. The committee strongly believes in the benefits that will result from improving that diversity, and strongly encourages community leaders throughout the PSE enterprise to carefully consider and assess the DEI practices within their own organizations. Even more critically, individual members of the PSE community should be involved in DEI activities at the most primary levels in their institutions.

The committee acknowledges and supports the DEI activities that have been initiated since the Plasma 2010 report, and the committee encourages continued community-wide discussions and actions that will produce a more diverse PSE discipline. Professional societies, universities, national academies, national laboratories, and federal agencies are now actively engaged in addressing DEI issues in STEM, and in PSE in particular. Given the demographics of the field, the next decade will likely see significant turnover in the PSE workforce, providing ample opportunities for improving the diversity of the field. Although the committee is not formally endorsing a particular organization's DEI activities, the committee strongly endorses the importance of and efforts of the field to diversify.

FINDINGS AND RECOMMENDATIONS

The Plasma Science and Engineering (PSE) community in the United States has had an enormous impact since publication of the Plasma 2010 report. Internationally leading research has been performed in all fields of PSE, with landmark contributions having been made to the advancement of the science of plasmas, national security, and economic competitiveness. These advances confirm the value and need for discipline-centric research on the basic plasma science challenges, the interdisciplinary research that will translate that learning to applications and support for that translational process. To expand upon that progress in the next decade, the discipline needs greater interdisciplinary coordination of federal agencies (and programs within agencies) in their approach to PSE, an activity that would be in their own benefit as well as that of the discipline. The committee notes that the NRC *Plasma Science Committee (PSC)* at one time helped to heighten awareness of these opportunities and be a spokes-group for the field. Unfortunately, the *PSC* has been inactive for several years. Expanding the impact of research in PSE also needs an ecosystem of facilities, diagnostics, computations, and, importantly, renewal of the PSE workforce through education and career enhancement programs. The high-level, findings and recommendations from this study are discussed below. These high-level recommendations, as well as more specific individual chapter-based recommendations, are collected in Appendix B.

Stewardship and Advancement of Interdisciplinary Research

Finding: Plasma science and engineering (PSE) is inherently an interdisciplinary field of research. While the underlying science has common intellectual threads, the community is organized into sometimes isolated sub-disciplines.

At the same time, examples of initiative-driven and long-term collaborations between federal agencies in PSE are rare. The recently enacted Space Weather Research and Forecasting Act that mandates joint activities by NASA, NOAA, NSF, DOD, and FAA, and the NSF/DOE Partnership in Basic Plasma Science and Engineering, are notable exceptions. This isolation is in part driven by the extreme diversity of applications that motivates the fundamental research. It is also occasionally reinforced by narrow, mission-driven support at the federal level.

Several program managers contacted by the committee were cautious about participating in interdisciplinary programs in PSE due to the risk of being perceived as duplicating research priorities of other agencies, a practice which has been historically discouraged. The committee and the PSE field have a different perspective.

During review and final preparation of Plasma 2020, we are in the midst of the Covid-19 pandemic (March to April 2020). The areas of plasma medicine and plasma biotechnology encompass the use of plasmas for sterilization of materials and living tissue such as skin, and address the need to physically kill pathogens without risking antimicrobial resistance. Plasma medicine and plasma biotechnology are examples of interdisciplinary fields that have fallen between the cracks of the perceived responsibilities of individual funding agencies. Plasma focused agencies are reluctant to sponsor projects that involve biological systems and biologically focused agencies are reluctant to sponsor projects that have a focus on plasma physics. As a result, we may have missed an opportunity to have another tool at our disposal to aid in the current health crisis.

Finding: What may be narrowly perceived as duplication is actually critically necessary collaboration needed to address the complex science challenges in PSE while rapidly translating results to society-benefiting outcomes.

Finding: Institutional barriers between sub-disciplines of PSE make mutually advantageous interactions difficult, yet interactions between sub-disciplines have led to important advances that would have been difficult to produce otherwise.

Finding: A more unified voice for the field would create opportunities for interdisciplinary and translational research, and initiate activities that exploit synergies among different subdisciplines of PSE.

Recommendation: Federal agencies directly supporting plasma science and engineering (PSE) and those federal agencies benefiting (or potentially benefiting) from PSE should better coordinate their activities extending into offices and directorates within larger federal agencies

One mechanism to facilitate this coordination is to establish an Interagency Working Group (IWG) with representatives from agencies that investigate plasmas as part of their mission (e.g., NSF [MPS, GEO, ENG], DOE [SC, NNSA, ARPA-E], NASA [SMD, HEOMD], DOE [FES, NNSA, HEP, BES, ARPA-E], NOAA, DoD [AFOSR, ONR, ARO, DTRA]) and those agencies that benefit from (or could benefit from) plasma applications (e.g., EPA, NIH, DHS, FDA, NSA, and USDA). The IWG would identify feasible areas of collaboration and build upon current programs that contribute to the missions of the agencies in basic and applied PSE areas. In this regard, those agencies performing research in basic plasma science (e.g., NSF, DOE, DoD) could reach out to agencies that benefit or could benefit from plasma applications (e.g., NIH, USDA, EPA), while mutually soliciting community input on possible areas of collaboration. Given the breadth of the IWG, this effort would best be coordinated by the National Science Foundation, perhaps in partnership with the National Science and Technology Council (NSTC) and the Office of Science and Technology Policy (OSTP). (NSTC/OSTP have experience in organizing such working groups, for example, in HED.) Several potential interagency collaborations on topics across the field of PSE are listed in Table 1.1. The collaborations listed in Table 1.1 are intended to be examples of potential partnerships that would meet many of the needs and priorities of the field and nation. The committee intends these suggestions as starting points for discussions.

Finding: Fundamental research in PSE can and does rapidly translate to the development of societally relevant technologies, the benefits of which cut across the missions of many federal agencies.

In fact, the majority of PSE research is motivated by the final application, from producing electricity using controlled fusion and protecting information technology assets from errant space weather, to plasma synthesis of new materials and medical diagnostics using table-top laser-accelerators. In some areas of PSE, such as MFE and ICF, the motivating application is contained within the same agency or program that funds the fundamental plasma research. In these situations, the translational research is well leveraged towards the intended application. In other areas of PSE, such as plasma materials processing, the motivating application is the primary mission of an agency or program other than that funding the fundamental plasma research. For example, plasma-based accelerators benefit broad interests outside the agencies principally responsible for their development. The *DOE High Energy Physics Accelerator Stewardship* is an example of such a program.

Finding: The interdisciplinary and multidisciplinary strengths of PSE are not being fully utilized. This situation is to the detriment of the fundamental plasma research and to the detriment of the intended applications.

Although inter-agency and intra-agency collaborations that jointly fund PSE activities exist, these efforts are largely ad-hoc and not in the form of proposal-driven initiatives. Notable exceptions include the recurring NSF/DOE *Partnership in Basic Plasma Science and Engineering*, an outcome of the 1995 Plasma Decadal Study, and the recently announced NSF/NASA *Next Generation Software for Data-driven Models of Space Weather with Quantified Uncertainties.* Another successful example is the 2007 *Interagency Task Force on High Energy Density Physics,* with membership from the DOE Office of Science (OS) and NNSA, NASA NIST, NSF and DoD, which had a significant impact on the high energy density field. A recent RFI (request for information) issued by the DOE OS to support research in advanced microelectronics, a component of which is plasma materials processing, involves multiple programs within the OS. Increased collaboration between agencies to support fundamental research, translational research, and applications-focused research in PSE would benefit all partners. The barriers to such collaboration should be reduced. Examples of beneficial cross-agency linkages are listed in Table 1.1.

Finding: Interagency (and inter-program) initiatives would fully exploit the interdisciplinary and multidisciplinary potential of plasma science and engineering (PSE) in both fundamental and translational research if properly stewarded.

Recommendation: Federal agencies and programs within federal agencies that are separately focused on fundamental plasma research, and those that are focused on science and technologies that utilize plasmas, should jointly coordinate and support initiatives with new funding opportunities.

There are extraordinary opportunities for such jointly sponsored initiatives in, for example, materials, biotechnology, medicine, agriculture, accelerators, energy, environment, propulsion, manufacturing, space weather, security, and computations. Some of these opportunities and potential agency partnerships are listed in Table 1.1. These initiatives will significantly advance fundamental plasma science while accelerating the translational outcomes of those advances. One of the goals of the recommended IWG would be to address the scope, feasibility, and possible implementation of these initiatives, an activity best organized by NSF. Within federal agencies whose programs are highly mission-driven, coordination of such initiatives may best come from higher levels—for example, at the level of the DOE Office of Science.

Finding: The potential is enormous for PSE to contribute to one of society's greatest challenges—sustainability. The contributions that PSE could make extend from fusion-based, carbon-free electrical power generation to electrification of the chemical industry.

As the needs for sustainability become clearer, the plasma science challenges will become more focused and more tied to the applications. Although the research will remain fundamental, the research will also become more translational. At NSF, this research would best be performed in the Engineering Directorate (EngD). However, support for PSE in the EngD has been inconsistent, and particularly so since the Plasma 2010 report. As the priorities of programs in the EngD change, PSE is added and removed from program descriptions. Programs in the EngD also choose to participate or not in the NSF/DOE Plasma Partnership depending on the changing priorities. With this inconsistent record of support for PSE in the Engineering Directorate, it is difficult to develop long term PSE strategies to address critically important challenges such as sustainability.

Finding: The translational nature of fundamental research in plasma science and engineering (PSE) needs to be formally recognized at NSF.

Recommendation: The Engineering Directorate (EngD) of the National Science Foundation (NSF) should, as a minimum, consistently list PSE in descriptions of its relevant programs and consistently participate in the NSF/Department of Energy (DOE) Plasma partnership.

Recommendation: More strategically, NSF should establish a plasma-focused program in the Engineering Directorate. that would advance engineering priorities across the board, including advance agricultural systems, energy and environment, chemical transformation, advanced manufacturing, electronics and quantum systems.

These efforts would complement the more fundamental plasma physics program in the Mathematical and Physical Sciences Directorate. The PSE program in EngD could follow the recommendations of the NSF workshop “Science Challenges in Low Temperature Plasma Science and Engineering: Enabling a Future Based on Electricity through Non-Equilibrium Plasma Chemistry” [arXiv preprint arXiv:1911.07076 (2019)].

Finding: Public-private partnerships (PPP) have long been a benefit to PSE, largely in the form of SBIR (Small Business Innovative Research) and STTR (Small Business Technology Transfer) programs.

SBIR/STTR programs have been highly successful in translating fundamental science towards commercialization. Although PSE industries have long funded fundamental research focused towards developing their own products, the emergence of venture-capital-funded fusion research and international competition in industries reliant on plasma science have significantly changed the landscape for PPPs. One recent development acknowledging the new landscape is the DOE Office of Science Innovation Network for Fusion Energy (INFUSE), whose goal is to accelerate fusion energy development in the private sector by opening resources at DOE laboratories and reducing barriers to collaboration. In another example, an increasing number of small companies that specialize in space-weather plasma data and models tailored primarily to aviation, aerospace, and defense needs have been responding to SBIR/STTR calls by several federal agencies, broadening the commercial space-weather sector.

There are challenges in leveraging PPP for economic and national security benefits for both small and large companies. The requirements to make breakthroughs in translational research and commercialization in multidisciplinary fields such as PSE may exceed the resources and know-how of many small businesses. These requirements then fit poorly within the traditional SBIR/STTR structure. For large businesses, there are extreme pressures from international competition, in large part resulting from strong foreign government support for fundamental and translational research in key plasma-based industries. For example, South Korea and China have aggressive national programs to address fundamental research vital to the plasma-based microelectronics industry.

Finding: With there being few U.S. governmental programs designed to translate industrially relevant fundamental science to practice, U.S. industries are at a competitive disadvantage internationally.

Recommendation: Federal agencies focused on plasma research, and DOE in particular, should develop new models that support the translation of fundamental research to industry. Programs that support vital industries depending on plasma science and engineering (PSE) should be developed through relevant interagency collaborations.

Examples of translational research that would benefit plasma enabled industries include development of diagnostics that could be used for real-time control of plasma processes, understanding and optimizing the production of plasma generation precursors used in materials processing and developing industrially relevant modeling platforms. The United States is well known for being a hotbed for entrepreneurship and it is unclear whether the PSE research infrastructure is well suited to meet entrepreneurial needs. For example, many biotechnology startups use plasma processes for biocompatible coatings, yet are more likely to seek support from NIH than FES. Are their needs met?

The committee acknowledges that this is a multifaceted recommendation with many avenues for implementation. Certainly, the PSE community could take advantage of existing resources to engage with the private sector, such as the National Academies Government-University-Industry Research Roundtable (GUIRR). One implementation could be encouraging or requiring more collaborative research between universities and small companies, both for commercialization and to meet the needs of national laboratories. In parallel, INFUSE-like programs could be extended through partnerships to support the science needs of industries and companies, large and small, in areas of national importance that depend on PSE. Another implementation would be to sponsor translational research to bring plasma-based capabilities to a level where private research and development can continue. A particularly valuable implementation would be to regularly convene an advisory board of technical leaders from industries that rely on or could utilize advanced PSE capabilities, to articulate the needs of industry in fundamental research. Such an advisory board would guide federal agencies in how best to support translational and multidisciplinary research, including selection of SBIR/STTR topics that have a high probability for industrial impact. This could be coordinated by the recommended IWG, with a more mission, outcomes focused agency, such as the DOE, leading the effort.

The Plasma Science and Engineering Community

Plasma science and engineering is a highly multidisciplinary field, a quality that is reflected by the large number of federal agencies with interests in plasmas, and the diverse array of university departments in which plasma faculty and researchers can be found. At any given university, one is likely to find plasma-focused faculty in physics, chemistry, geophysics, space sciences, astronomy and astrophysical sciences, climate sciences, and many engineering fields (e.g., aerospace, electrical, nuclear, chemical, biomedical, and mechanical).

Finding: The multidisciplinary approach has been at the heart of the success of the field, while simultaneously working against the long-term viability of the field in academia.

Since plasma physics is a minority discipline in nearly every department containing plasma-focused faculty, maintaining faculty expertise is becoming progressively more challenging. Universities provide thought leadership and drive innovation, while also training the workforce for the field, and that leadership and training requires a robust faculty in PSE.

Finding: Lack of a critical mass of faculty in PSE inevitably will lead to an erosion of U.S. capability in PSE. At the same time, the university leadership in PSE is rapidly aging and will need renewal in the coming decade.

There are great opportunities for new PSE university faculty to address sustainability, investigate laser-plasma produced quantum effects, make space weather predictions, and investigate exotic states of matter. However, the committee is gravely concerned that poor PSE demographics and current hiring practices are eroding the ability of the field to meet national priorities, from security to the economy. There are simply too few early-career faculty to renew the field. Opportunities for scientific leadership are also essential for healthy university programs. This is particularly true for those faculty members whose primary focus is investigating the fundamentals of plasma science as opposed to their applications.

Recommendation: Federal agencies—for example, Department of Energy (DOE), National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), and Department of Defense (DoD)—should structure funding programs to provide leadership opportunities to university researchers in plasma science and engineering (PSE) areas and to directly stimulate the hiring of university faculty.

These leadership opportunities are critical to all areas of PSE. Examples of implementing this recommendation include soliciting major new facilities or missions with leadership teams composed in part or wholly by university researchers. Major activities in the field could be organized around centers that are led by university researchers. Specific programs could be implemented to provide funds for the creation of faculty positions, following the model of the NSF Faculty Development Program in Space Sciences.

Finding: Plasma-specific educational and research programs that also provide opportunities to diverse and less advantaged populations are needed to ensure a critically populated PSE workforce.

As discussed earlier in this chapter, increased emphasis on PSE undergraduate research and internships, particularly at primarily undergraduate institutions (PUIs), will improve awareness of our field among all undergraduates, and women and underrepresented students in particular, thus enabling a more heavily populated and a more diverse discipline. Stronger links between PUIs and research institutions would also improve the pipeline.

Finding: Plasma-specific intern programs and summer schools are needed for undergraduate and graduate students, as are programs supporting students with incomplete preparation to progress in plasma physics, such as the American Physical Society *Bridge Program*.

The past DOE *National Undergraduate Fellowship* program in plasma physics, now a *Science Undergraduate Laboratory Internship* (SULI) program at Princeton Plasma Physics Laboratory, and the American Physical Society Division of Plasma Physics outreach events for students, are two successful examples. Physics curricula are traditionally sequential, with plasma physics typically covered towards the end of the sequence (if at all).

Finding: Requiring students to know early in their undergraduate years that plasma physics is a career goal has limited the number of students continuing in plasma physics in graduate school and has excluded less advantaged populations.

Finding: Support for junior faculty, for course development, and for curricula enhancement (e.g., inclusion of plasma physics in other courses) are necessary to enable students from a wide range of institutions to enter the field.

Federally funded programs to support undergraduate education, graduate fellowships, postdoctoral fellowships, and early-career awards have been essential in attracting and supporting a talented and diverse population of junior scientists to PSE. However, recent policy changes have eliminated many of these programs in important areas of PSE within the DOE Office of Science. While the policy changes were intended to prevent duplication of educational efforts across agencies, the programs that were eliminated have no equivalents in other agencies. Consequently, their loss has significantly affected the ability to attract and retain new talent and university faculty in PSE.

Finding: The committee regards multi-agency investment in education, whether through directly supporting undergraduate and graduate students or programs, or through faculty, and resource development, as being critical. The more "duplication" of effort in these areas can only further strengthen PSE.

Recommendation: Funding agencies (e.g., NSF, DOE, NASA, DoD) should structure funding to support undergraduate and graduate educational, training, and research opportunities—including faculty—and encourage and enable access to plasmas physics for diverse populations.

To implement this recommendation, federal agencies supporting PSE research could be allowed to establish domain-specific educational and outreach programs, reversing recent changes that were intended to reduce duplication in educational programs across the federal enterprise. New opportunities for undergraduate research in PSE at smaller PUIs would increase exposure of diverse populations to plasma physics and engineering, thus increasing both the population and the diversity of the pipeline into graduate school and the profession. This activity could be built on the model of the NSF program in Facilitating Research at Primarily Undergraduate Institutions. Stronger links between PUIs and research institutions could be established by postdoctoral or graduate fellowships for researchers to work at PUIs or jointly with larger plasma institutions, and by broadening REUs (Research Experiences for Undergraduates) beyond NSF.

The Research Enterprise in Plasma Science and Engineering

The research enterprise in PSE has had tremendous impact over the past decade. Plasma science has opened opportunities across a remarkably diverse range of areas, including semiconductor processing, new accelerators, understanding astrophysical and planetary states of matter, new energy sources, and enhancing national security. Although the progress has been impressive, it has also been made in an environment of tremendous competing international investments across the spectrum of PSE. These investments challenge and may potentially usurp U.S. leadership in PSE. International investments in large fusion devices, powerful lasers and research networks over the past decade have generally exceeded that of the United States.

Finding: Given these strong international investments, incremental progress in facilities in the United States is insufficient to maintain leadership.

Finding: A spectrum of facility scales is required by the sub-fields of PSE to address their science challenges and translational research.

Finding: Mid-scale facilities (e.g., in the $1 million to $40 million range, depending on agency) offer particularly good opportunities for broadening participation within academia.

Recommendation: Federal agencies (e.g., NSF, DOE, NASA DoD) should support a spectrum of facility scales that reflect the requirements for addressing a wide range of problems at the frontiers of PSE.

In some cases, advancing the state of the art requires significant investments in large facilities built over many years, while in other areas, better equipping the laboratories of single investigators with advanced diagnostics as part of a distributed network best serves the field. However, research facilities cannot function efficiently without the support of experienced scientific staff, and operations cannot proceed efficiently without the procurement of increasingly costly essential materials, such as liquid helium.

> **Finding:** Investment in facilities without the concurrent support of research and operations is not optimum
>
> **Recommendation: Federal agencies whose core missions include plasma science and engineering (PSE)—for example, Department of Energy (DOE), National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), and Department of Defense (DoD)—should provide recurring and increased support for the continued development, upgrading, and operations of experimental facilities, and for fundamental and translational research in plasma science. A spectrum of facility scales should be supported, reflecting the requirements for addressing different problems at the frontiers of PSE.**
>
> **Finding:** Computational Plasma Science and Engineering (CPSE) has become essential across PSE for experiment and mission design and diagnosis, idea exploration, probing of fundamental plasma physics processes, and prediction.

For computations to continue to progress in PSE, the next generation of researchers critically needs to be better educated through the development of plasma-focused computational textbooks and courses, and through participation in funded computational research projects. At the same time, the computational landscape is rapidly evolving, with increasing heterogeneity in devices, languages, and coding practices. GPU computing is just now under development, and new devices, such as quantum computers, are on the horizon. As a result, writing computational plasma software now requires mastery of multiple technologies, all of which are swiftly changing, leading to crises whereby small developer teams cannot build performant software. Simultaneously, new methodologies for prediction, including machine learning and artificial intelligence, are becoming increasingly possible with new, high-throughput computing devices.

> **Recommendation: Federal agencies should support research into the development of computational algorithms for plasma science and applications for the heterogeneous device computing platforms of today and upcoming platforms (e.g., quantum computers), while also encouraging mechanisms to make advanced computational methods, physics-based algorithms, machine learning, and artificial intelligence broadly available**.

Stronger cooperation between programs within NSF, DOE or DoD that support computer science, applied mathematics, and physical sciences and engineering is encouraged. Several possible partnerships are listed in Table 1.1. Proposals should be solicited and supported that include at least as a component, the development of plasma-focused computational educational materials, and in particular graduate-level texts.

Table 1.1 provides examples of interagency (and inter-program) collaborative initiatives on two levels. The first initiatives are between plasma-focused agencies and are designed to leverage the advances in fundamental plasma science that they support separately. The second initiatives are designed to maximize opportunities for translating fundamental plasma science advances to applications. These initiatives are between plasma-focused agencies that support fundamental plasma science, and non-plasma focused agencies supporting applications that benefit from plasma science. The table contains examples of such initiatives, not recommendations that each of these initiatives be implemented. These suggestions could serve as a starting point for the interagency discussions and collaborations. (Acronyms for these agencies can be found in Appendix C.)

Better Serving the Community

Following the recommendations of the Plasma 2010 report, the DOE Office of Fusion Energy Science (FES) broadened the scope of its programs to better serve the plasma science community. This broadened mission, contained primarily within the *Discovery Plasma Science* (DPS) program of FES, has increased its support of research on low temperature plasmas, basic plasma physics, and high energy-density plasmas. FES continues to be a vital member of the NSF/DOE Partnership in Basic Plasma Science and Engineering. The committee gratefully acknowledges the response of FES to the Plasma 2010 recommendations to broaden its mission.

> **Finding:** Although the majority of the FES budget is still devoted to supporting fusion science, the present office title does not now accurately reflect its broader mission. The present title may, in fact, impede the ability of FES to collaborate with other offices within DOE and with other federal agencies, including impeding its ability to garner support for non-fusion plasma research.

> **Finding:** The national interest as a whole would be better served by renaming the office to better reflect the broader mission of FES, maximize its ability to collaborate with other agencies and to garner non-fusion plasma support.

> **Recommendation: Consistent with our recommendations to broaden the impact of plasma science, the Department of Energy (DOE) Office of Fusion Energy Science (FES) should be renamed to more accurately reflect its broader mission, and so maximize its ability to collaborate with other agencies and to garner nonfusion plasma support. A possible title is *Office of Fusion Energy and Plasma Sciences*.**

TABLE 1.1 Examples of Interagency and Interoffice Collaborative Initiatives

This table lists examples of interagency (and inter-program) collaborative initiatives on two levels. The first initiatives are between plasma-focused agencies and are designed to leverage the advances in fundamental plasma science that they support separately. The second initiatives are designed to maximize opportunities for translating fundamental plasma science advances to applications. These initiatives are between plasma-focused agencies that support fundamental plasma science, and non-plasma focused agencies supporting applications that benefit from plasma science. The table contains examples of such initiatives—it is not specifically recommended that each of these initiatives be implemented. These suggestions are intended to serve as a starting point for interagency discussions and collaborations. (Acronyms for these agencies can be found in Appendix C.)

Agencies (Alphabetical. **Bold** is suggested lead(s).)	**Topic**	**Strategic Importance**
DOD-AFOSR, DOD-ONR, **DOE-FES**, DOE-NNSA, NASA, NSF-ENG, NSF-GEO, **NSF-MPS**,	Education and career enhancement programs	With a demographic turnover due to senior scientist and faculty retirements, the health of Plasma Science and Engineering is at a critical juncture. Deliberate programs to increase and diversify the pipeline into PSE, and career development of early-to-mid career professionals (academics in particular) are needed. The need for renewal of PSE faculty at universities and researchers at national laboratories is at nearly crisis levels.
DOD-AFOSR, DOD-ONR, **DOE-FES**, DOE-NNSA, NASA, NSF-GEO, **NSF-MPS**	Mid-scale facilities and networks of facilities for basic plasma science and translational research.	The development of mid-scale facilities and networks of facilities for plasma science is sporadic across agencies. Coordination and collaboration for development of new hardware for basic plasma science experiments and operational expenses would leverage the efforts of all agencies. Mission-driven agencies whose facilities focus applications partnering with or accommodating basic plasma experiments would speed translational research.
DOD-AFOSR, DOD-ONR, **DOE-FES**, DOE-HEP, DOE-NNSA, NASA, NSF-ENG, NSF-GEO, **NSF-MPS**	Multi-agency plasma science centers	Multi-agency plasma science centers would provide an ideal environment for interdisciplinary advances in fundamental concepts, while enabling rapid translation to technologies required by mission-focused agencies.
DOD-AFOSR, DOE-ASCR, **DOE-FES**, DOE-NNSA, NASA, **NSF-CISE**, NSF-ENG, NSF-GEO, NSF-MPS,	Computational plasma science	Support development of open source models and shared libraries for universities and federal centers to more effectively contribute to and benefit from agency specific missions.
DOE-FES, **NASA**, NSF-GEO, NSF-MPS	Fundamental research in space, heliophysics and astrophysical plasmas for advancing missions	Adding NASA as a partner to the NSF/DOE Partnership would advance fundamental science in space and astrophysical plasmas while also addressing the needs of heliophysics and astrophysics missions.

Agencies (Alphabetical. **Bold** is suggested lead(s).)	**Topic**	**Strategic Importance**
DOD-ONR, DOE-FES, NASA, **NSF-GEO, NSF-MPS**	Laboratory-heliophysics/astrophysics	A synergistic program would enable heliophysical and astrophysical plasma scientists to collaborate closely with laboratory experimental programs, to leverage their different needs and knowledge bases to advance both fields.
DOD-AFOSR, DOD-ONR, DOE-FES, NASA, NOAA, **NSF-GEO**	Geospace and ionospheric plasma science	Multi-agency approaches to investigating the local space environment, critical to national defense and environmental stewardship, will leverage more fundamental approaches with mission driven research. Capabilities in development of single and multi-satellite systems would be more efficiently shared. Multiagency collaboration would work towards establishing standards for sharing data between agencies that would greatly enhance basic research.
NASA-HEOMD, **NASA-SMD**, NSF-GEO, NSF-MPS	Charged dust phenomena in microgravity and on airless bodies	Management of spacecraft charging and dust is critical to developing next generation space systems (e.g., ISS, cubesats, moon/planetary landers). There are translational opportunities for collaborative investigation of plasma-dust interactions on the Moon, Mars, comets, and other airless bodies in the solar system for future human exploration and resource exploitation.
DOD-AFOSR, DOD-AFRL, DOD-DARPA, DOD-ONR AFRL, DOE-FES, **NASA,** NSF-ENG, NSF-MPS	Basic plasma physics for electric propulsion and translation to technologies	There is little coordination of electric propulsion (EP) programs across agencies. In some agencies, EP research is sporadic, and so knowledge can be lost. Translational opportunities would be greatly enhanced if fundamental research performed by more plasma focused agencies would be readily applied by more technology focused agencies.
DOD-AFOSR, DOE-FES, DOE-NNSA, **NASA**	Advanced Space Propulsion	Beyond electric propulsion, colonization and exploitation of the moons and planets will require massive propulsion systems for mass transfer and speed. Space propulsion based on fusion drives will become viable as ICF efforts advance.
DOD-AFOSR, DOD-ARO, DOD-DARPA, DOD-ONR, **DOE-FES**, **NIH**, NSF-BIO, NSF-ENG	NIBIB, NCI: Plasma cancer treatment and effects on the immune system; DNA damage; cellular response, migration and proliferation	There are tremendous opportunities for plasma focused agencies (e.g., DOE-FES, NSF, AFOSR, ONR) and agencies needing urgent battlefield treatment (e.g., DARPA, ARO) to collaborate with NIH many areas. The goal is to leverage the knowledge of how plasmas are produced, controlled, and interact with materials with the opportunities for plasma to disinfect, treat

Agencies (Alphabetical. **Bold** is suggested lead(s).)	**Topic**	**Strategic Importance**
	by plasma; effects of plasma activated liquid on biomolecules and cells; anti-microbial resistance (AMR) NBIB: Dose standardization in plasma medicine. NIBIB, NIGMS, NINDS: Plasma tissue and nerve regeneration , wound healing NCI: Positron and antimatter beams for cancer treatment. NIAMS, NIGMS: Plasma treatment of surgical infections, and antibiotic resistant infections. NIAMS: Plasma altering microbiome of the skin NIDCR, NIBIB, NIAMS: Plasma enhanced biomaterials	cancers, promote wound healing, affect DNA, produce immunogenic response and produce biocompatible materials, Atmospheric pressure plasmas have already shown therapeutic effects in immune responses, cancer treatment, and tissue regeneration through production of RONS (reactive oxygen and nitrogen species). However, the adoption of plasma-medical procedures has been slow because the connectivity between the plasmas sciences and health sciences is weak. Understanding plasma modification of biomolecules (e.g. amino acids) is key to the building blocks of plasma-medical sciences. Strategic matters of surgical infection and antimicrobial resistance (AMR) can be addressed directly by plasma treatment. Topical plasma application has potential for control of the skin microbiome and its composition, and treatment of inflammatory skin diseases. As plasma becomes more adopted into medical science, standards are required for what constitutes a "plasma dose", and tissue-specific outcomes that can be used to assess effectiveness across a spectrum of plasma devices must be defined. Plasma enhances the capabilities of current biomaterials used for surgical, dental, and wound healing application, but these uses are still at an early stage. Plasma materials processing has great potential for improving biocompatibility and antimicrobial properties of conventional wound dressings.
DOD-AFOSR, DOE-ARPA-E, **DOE-FES**, NSF-ENG, **USDA**-NIFA, EPA	Plasma agriculture and plasmas for food safety	Plasma-based technologies offer enormous potential for agriculture processes (e.g., liquid fertilizer production, nitrogen fixation, seed treatment, pesticides/herbicides, antimicrobial plant treatment) and food safety (decontamination, shelf-lifetime enhancement). The field has advanced based largely on empirical studies. Plasma-science–based studies will lead to translational advances for mission-driven agencies.
DOD-AFOSR**, DOE-ARPA-E**, DOE-EERE, DOE-FES, **NSF-ENG**, EPA, USDA-NIFA	Electrification of the Chemical Industry	Future societies will be powered in large part by renewable and sustainable electricity. Plasmas are the science and technology capable of using this electricity to provide for society's chemical needs by electrifying the chemical industry. Waste products can be converted to chemical feedstocks and polluted resources recovered. Plasmas can also play a role in decarbonizing chemical industry process heating.

Agencies (Alphabetical. **Bold** is suggested lead(s).)	**Topic**	**Strategic Importance**
DOD-AFOSR, DOD-ARO, DOD-DARPA, DOD-ONR, DOE-DOE-ARPA-E, **DOE-BES**, **DOE-FES**, FAA, NASA, **NSF-ENG, NSF-MPS**	Plasma-based materials processing and additive manufacturing	Plasma materials processing is at the root of nearly all advanced materials, from microelectronics fabrication, advanced energy storage materials, lightweight composites, and photonics, to super-plastic and super-hard and energetic materials for security applications. An interagency initiative and collaboration would leverage the fundamental processes in controlling plasmas for producing reactive species as materials precursors and functionalizing surfaces for development materials for mission-focused agencies.
DOD-AFOSR, DOD-DARPA,DOD-ONR DHS, DOE-BES, **DOE-FES**, **DOE-HEP**, **DOE-NNSA**, NIH-NCI, **NSF**	Accelerator science, development and applications; and stewardship	Compact plasma systems offer new capabilities across the broad space of accelerator applications. These include high energy sources in compact packages, miniature 'endoscopic' accelerators, high dose rates, high performance X-ray and neutron sources, and future particle colliders to extend the reach of our understanding of the universe. Advances in the fundamental science of laser and beam driven plasmas, coupled with technology development, are needed to enable transformational and translational capabilities across agencies.
DOD-AFOSR, DOD-DARPA, DOD-DTRA, DOD-ONR, DHS, DOE-BES, **DOE-FES**, DOE-HEP, **DOE-NNSA**, NIH-NCI, NSF-BIO, NSF-MPS, NSF-ENG	X-ray sources and radiography	Transformational x-ray sources enabling both higher resolution and lower dose in compact systems are emerging based on plasma accelerators, lasers and harmonics. Development is needed to enable application benefits across agencies. These range from enhanced screening for homeland security and nonproliferation, to compact coherent Free Electron Lasers for basic science, to nondestructive evaluation for industry and stockpile stewardship, to improved medical imaging and therapy.
DOD-AFOSR, DOD-DARPA, DOD-DTRA, DOD-ONR, DHS, DOE-BES, DOE-FES, **DOE-HEP**, **DOE-NNSA,** NSF-ENG, NSF-MPS, NIH-NCI, NSF	Ion accelerators, neutron sources, and plasma optics	New ion and neutron sources, together with plasma optics, are under development that could leverage high intensity lasers to generate new sources with applications including medical therapy, high energy density science, and security. Fundamental research is needed in plasma- based ion acceleration, neutron sources, and plasma optics in concert with mission- driven agencies that will use these capabilities.
DOD-AFOSR, DOD-DARPA, DOD-DTRA, DOD-ONR, DHS, DOE-BES, DOE-FES, DOE-HEP**, DOE-**	kHz Ultrafast laser development	Development of high average power ultra-fast lasers and their application to laser-plasma science and technology addresses mission needs across federal agencies including accelerators, sources and plasma optics. DOE-HEP currently has an accelerator stewardship program including kHz lasers to drive plasma accelerators. DoD develops high average power long pulse

Agencies (Alphabetical. **Bold** is suggested lead(s).)	**Topic**	**Strategic Importance**
NNSA, NIH-NCI, **NSF-ENG, NSF-MPS**		lasers. Extension of such programs is needed to meet application needs for plasma based sources, plasma optics, and HED science.
DOE-ARPA-E, **DOE-FES**	Fusion energy and the private sector	The private sector is well positioned to investigate high-risk alternate concepts on more rapid time scales than at federal and university facilities. Including the private sector in long-range planning and collaboratively apportioning the fusion risk-portfolio between the public and private sectors will speed progress.
DOE-ARPA-E**, DOE-BES**, **DOE-FES**, DOE-NNSA, NSF-DMR	Materials for fusion	Materials are required that can withstand high neutron fluences and high heat flux in fusion reactor environments, a need that transcends all fusion focused agencies. Materials informatics and synthesis techniques are more advanced in non-plasma centric agencies while the context and test of materials is best done by the plasma-centric agencies.
DOD-ONR, DOE-FES, **DOE-NNSA, NSF-MPS**	High Energy Density Physics Beyond Thermodynamic Equilibrium	Collaborative theoretical and computational research on atomic physics, radiation transport and magnetohydrodynamics is required to include kinetic effects. These developments are required to analyze and diagnose HED and ICF experiments, and extend current modeling capabilities to be truly predictive.
DOD-DARPA, DOD-ONR, DOD-DTRA, DOE-FES, **DOE-NNSA**, NSF-MPS	Intermediate pulsed power facilities	Midscale pulsed power facilities are critical to support basic science research in high energy-density experiments and computations. Fundamental research at mid-to-large scale will support concepts for next-generation pulsed power facilities (including the "ZNext" 60 MA accelerator), and high power microwave sources.
DOD-ONR**, DOE-NNSA**, NASA, NSF-MPS	Validation of HED, ICF and astrophysical computations	Advances in HED computations for investigating fundamental astrophysical plasma physics and ICF must be accompanied by coordinated inter-agency experiments for validation.

2

The Foundations of Plasma Science

PLASMA SCIENCE—THE ENABLING FUNDAMENTALS

Plasma is the most abundant state of visible matter in the Universe. Plasma processes occur in nature, laboratories and in industrial settings over a vast range of space and time scales. Many of these plasmas are permeated by magnetic fields, which add further richness and complexity to the underlying dynamics. Despite the great diversity of plasmas, there are underlying unifying phenomena. For example, eruptive dynamics, where a quiescent plasma undergoes a sudden change in its configuration and releases large amounts of energy, is seen in disruptions of plasmas in fusion reactors (when a growing instability can destroy the ability to confine a plasma), space storms in planetary magnetospheres, solar and stellar flares, and in astrophysical explosive events like flares from the Crab Nebula, and Gamma Ray Bursts (GRBs). The time-scales for these phenomena can vary from milliseconds to several hours, and the energy liberated exhibits an enormous range, from approximately 10^7 Joules for a fusion plasma disruption to 10^{44} Joules for a GRB. (As a point of comparison, the average U.S. household uses about 10^8 Joules of energy per day.) These eruptive phenomena are at the leading edge of plasma science and under intense study. It is widely believed that the dynamics of magnetic fields embedded in these plasmas play a crucial role in their behavior.

The basic processes that underlie a wide range of plasma phenomena, and provide cohesiveness to the field, are the subject of this chapter. This report discusses some of the foundational concepts of plasma science that cut across the subfields, and where advances in our understanding of their complexities can lead to transformational change across multiple applications spanning the entire range of plasma science and engineering (PSE), from microelectronics to health care. It is this interdisciplinary aspect of plasma science that has been a powerful attractor of talented scientists and engineers who are engaged in a rich spectrum of activity in academia, industry, and national laboratories. The quest to understand the fundamental aspects of plasma phenomena and to develop applications for societal benefit based on that understanding is a unifying theme of this diverse community.

In many fields of science, there is a tension between curiosity driven research and application-inspired research. PSE is not devoid of that tension. Having said that, the extreme intellectual diversity of PSE has produced a field that embraces addressing the most critical fundamental science challenges, and translating that fundamental understanding into technologies that benefit society. The continuum spans researchers who primarily address fundamental plasma science concepts to researchers who are focused on plasma-enabled technologies. The committee cannot stress in strong enough terms the importance of jointly and holistically supporting the continuum of research from the fundamental to the applied. These are not separate activities—they are part of the continuum that leads to societal benefit.

While the frontiers of fundamental plasma science continue to be strongly driven by experiments—small, medium, and large, as well as major international facilities and space missions—computer simulations are playing an increasingly important role and form the "third leg" of discovery (in addition to experiment and theory). These simulations make use of novel algorithms and software developed by applied mathematicians and computer scientists in collaboration with physical scientists and engineers using state-of-the-art computing platforms.

Research in basic plasma science is now supported by and spread across multiple federal agencies—the DoD, DOE, NSF, NASA, and NNSA. This breadth of support reflects the intellectual breadth and the interdisciplinary nature of the enterprise. However, there is a danger that in the drive to develop new plasma-based applications, the connection to and support of the underlying science will weaken. The field should keep in mind the *Pasteur Quadrant* (Stokes, 1997), a guiding principle that describes the symbiotic relationship between basic and applied research. One of the objectives of this report is to identify such issues and make recommendations for collaboration that span multiple funding agencies. (See Table 1.1 in Chapter 1.)

The committee identifies four cross-cutting strategic challenges in basic plasma science, followed by more detailed discussions of areas within PSE that address these challenges. These are not the only basic plasma sciences challenges that span the field, but exemplify unifying challenges. *Computational Plasma Physics*, which underlies all of PSE, is discussed first and followed by *Magnetic Reconnection* and *Waves, Turbulence and the Dynamo Effect*—plasma processes that are ubiquitous in plasmas in the laboratory and nature. This is followed by a discussion of fundamental processes in the context of *Dusty Plasmas*, *Non-Neutral and One-Component Plasmas* and fundamental aspects of *Low-Temperature Plasmas*. These specific examples illustrate how cross cutting challenges impact diverse areas of PSE. This is not an exhaustive list of examples. For example, some aspects of the fundamentals of plasma shock physics are discussed in Chapter 7.

STRATEGIC CHALLENGES IN FOUNDATIONAL PLASMA SCIENCE

Strategic Challenges in fundamental plasma science are cross-cutting themes that apply across the field of PSE. Although each challenge may not apply to every sub-field of PSE, these challenges unify the field.

1. ***Understand and predict plasma behavior under extreme conditions that challenge our present models.***

"Extreme conditions" in plasmas can be realized in many ways. Some of these plasmas are created with such high densities and temperatures that their thermodynamic properties cannot be addressed by current theories and computational models. In other plasmas, extreme is measured by the ratio of electrostatic energy to thermal energy—referred to as the coupling constant Γ—being much larger than unity, making them behave more like soft or solid condensed matter than a gas. For these plasmas, the traditional methods of kinetic theory, valid for values Γ much smaller than unity, break down. Other plasmas, such as planetary magnetospheres or the interplanetary medium, have mean-free-paths between collisions that are comparable to or even much larger than the system size, and are virtually collisionless. The optimum form of the fluid equations that are needed to predict their large-scale dynamics during space weather events remains an open question. Finally, in many astrophysical objects the plasma is relativistic (in realms where Einstein's theories of special and general relativity are needed), magnetically dominated (so that magnetic field, rather than pressure forces, controls the overall dynamics), and strongly affected by radiative and quantum effects like electron-positron pair creation.

2. ***Quantify and, in the laboratory control, how plasma processes direct the conversion of energy from one form to another, the transfer of energy across a vast range of scales, and the transport of energy in the laboratory and nature.***

Fundamental plasma processes such as magnetic reconnection, shocks, turbulence, and the dynamo effect control the conversion of energy from one form of to another—from magnetic energy to kinetic energy, from flow energy to magnetic energy, or from gravitational energy to kinetic energy and radiation. The nature and structure of turbulence in weakly collisional or collisionless plasmas, systems in which energy from large scales is transferred to small kinetic scales where it is then dissipated, is a subject of intense research. These systems are found in nature (e.g., the flow of energy from the Sun through the solar wind) and the laboratory (e.g., high energy density experiments). These processes are examples of where investigation of fundamental plasma phenomena will rapidly translate to applications in the form, for example, of efficient energy conversion in magnetically confined fusion reactors or plasma processing of new materials.

3. ***Predict self-organization of plasmas and, where needed, control that self-organization.***

Plasmas permeated by electric and magnetic fields can spontaneously self-organize in spatial coordinates (3-dimensions). They can also self-organize in an expanded space, called phase space (6-dimensions), defined by three spatial and three momentum coordinates, producing coherent structures in space and organizing how particles move with respect to them. (See Figure 2.1.) Examples of self-organization in coordinate space (3D) include the dynamo effect, whereby large-scale and slowly varying magnetic fields emerge from magnetic and velocity turbulent fluctuations on much smaller spatial scales and much shorter time scales. Examples of self-organization in phase space (6D) include solitary electrostatic waves in space or laboratory experiments. Self-organization can also involve extreme states of matter, where the fundamental research challenge is to understand how the redistribution of energy, momentum, and angular momentum in physical or phase space gives rise to coherent plasma structures at all scales. Understanding these self-organized structures is critical to developing applications in which these phenomena occur, either beneficially or detrimentally—plasma propulsion, magnetrons used for plasma production of thin films, plasma-liquid interactions in health care and agriculture and beam-plasma interactions.

FIGURE 2.1 Seeking *Minimum Energy*. This image shows self-organization of a toroidal fusion plasma which spontaneously forms a helically deformed minimum-energy state. This occurs when the device is operated at high current (exceeding 1 Mega-Amperes). This particular device is a Reversed Field Pinch Experiment (RFX) at Padova, Italy. The colored nested surfaces represent magnetic surfaces reconstructed from actual laboratory measurements. The helical deformations are much stronger at the plasma core than at the edge . SOURCE: Nature Physics 5, 570, 2009).

4. ***Control and predict interactions between plasmas and solids, liquids and neutral gases.***

Low-temperature plasmas (LTPs), which involve complex interactions between plasmas and solids, liquids, and gases, have revolutionized the microelectronics industry and enabled the production of high-efficiency lighting, low-cost solar cells, and bio-compatible human implants. The beneficial applications of LTPs continue to grow rapidly, stimulating research into multi-phase plasma systems—plasmas which simultaneous interact with more than one phase. The plasma-material interactions in fusion plasmas, which can involve either plasma-solid or plasma-liquid interactions, are another example of multi-phase plasmas, which have critical implications for the performance and economic competitiveness of fusion reactors. Understanding the fundamental processing of plasmas sustained in or crossing multiple phases advances fundamental plasma science and is at the heart of translational research leading to technologies.

COMPUTATIONAL PLASMA PHYSICS

Computations have become as essential to plasma physics as experiments. Computations enable researchers to ask, “What if?”, and provide quantitative answers. At the heart of computation is theory, which produces the fundamental relationships (*the equations*) describing the plasma dynamics that are ultimately implemented in computations, and for suggesting directions of investigation. Our fundamental understanding of plasmas first emerges in these dynamical equations. However, these equations are typically not analytically solvable (particularly in multiple dimensions). Computation is the method for extending fundamental investigations beyond that which is analytically tractable and to test the predictions of analytic theory, which must often rely on approximations to the original equations. This extension of theory then seamlessly feeds the translational research that produces society-benefiting outcomes, through the use of these same computer models to, for example, optimize magnetic configurations for fusion reactors, chart coronal mass ejections from the Sun to Earth, or design plasma materials processing reactors. Experiments are the ultimate test of theory and computer simulations. However, experiments to be performed today are limited to the facilities that now exist. For example, at the time of this writing, it is not possible to carry out an experiment using a 100 Petawatt laser for a laser-plasma interaction, as such lasers do not now exist. However, it is possible to use computations to describe the dynamics of these laser-plasma interactions. The outcomes of those computations improve our intrinsic understanding of these phenomena and, from a very practical perspective, help us design a better laser and better experiments.

Computation: Impact on Experimental Design and Diagnostics

Computation is a critical step in experimental design. Usually, no large experiment is built without some prior guidance from computation. At the very least, engineering design involves significant computation, which must be performed to ensure that the experiment will operate safely. More relevant to plasma physics, the dynamics of the system are computationally investigated within the range of known models and the wisdom of the experimental design can be evaluated. For example, will a newly designed plasma thruster achieve the desired impulse given our current understanding of the turbulent transport of momentum? Will a laser illuminated pellet achieve a desired fusion gain given our current theories of preheating? In the best of cases, computation can be predictive, providing confidence that certain physical outcomes will be experimentally observed, and predict a range of outcomes. Computations also provide a yardstick with which experimental results can be compared and enable us to determine whether the physics underlying the experimental results is understood. If the results of computations do not agree with experiments, one possible reason is that the underlying physics may not be understood well enough to predict an experimental outcome. The degree and manner of disagreement then guide further investigations.

Another area of increasing importance is the use of computations for diagnosing experiments. Plasmas are notoriously difficult to diagnose, given that they are hot, radiating environments, in which physical probes may not be able to survive and diagnostic lasers may not be able to penetrate. In other instances, diagnostics may not be available due to short time scales or small sizes, or because the plasma is inaccessible—for example, space and astrophysical plasmas. In the study of laser-plasma acceleration of particles, the time scale of the essential interaction, involving laser pulse profile evolution, electron trapping and electron acceleration, occur over micrometers of space in less than picoseconds of time, which is extremely challenging for diagnostics. Computations can be the surrogates for diagnostics in these inaccessible regimes.

Computations are used across all of plasma science, and opportunities to leverage computations are expanding. Cloud computing, first developed for commercial use, is putting enormous computational power into the hands of researchers without their having to make the commensurate capital investment. These resources are enabling development of new state-of-the-art codes, improving the capabilities of the underlying theoretical models, integrating across physical domains, and enabling models to address large ranges in space and time.

The Computational Revolution: Where Is It Now?

Consider a full numerical solution of the plasma in a reactor of the type used for etching and deposition for microelectronics fabrication. The reactor would have a volume of 10,000 cm^3 and a particle density (both positive and neutral) of 10^{15} cm^{-3}. The simulation would have 10^{19} particles each with 6 coordinates or 48 bytes of computer storage, for a total of 6×10^{19} degrees of freedom requiring 5×10^{8} Terabytes of memory for its representation. Performing one integration time step on such a system would require resources three orders of magnitude greater than available in an exascale computer (an exascale computer can perform 10^{18} calculations per second), and that would still be short of a useful simulation that would require millions of time steps. While the revolution in computing has brought us high fidelity simulations, it is far from being able to compute any system with exact fidelity. (In fact, the largest problems being computed today have of order 10^{11} degrees of freedom, smaller by 8 orders of magnitude.) Nevertheless, computations do strongly impact technology development. (See Figure 2.2.)

Although computations at the outset might sound, in principle, straight forward, considerable complications are present. In practice, computations first require (like analytic calculations) a step in identifying the appropriate, approximate equations that can be represented with fidelity on existing computer hardware and that will result in calculations that can be completed in a reasonable time. A kinetic approach is used when the dynamics involves detailed changes of the particle velocity distribution function. (Kinetics refers to theoretical or computational approaches that include the distribution of the velocities.) When such detailed knowledge is not needed, or the magnitude of the calculation is too large, fluid approaches are used. In these methods, an average over the velocity distribution produces equations for mass, momentum, and energy conservation. Certain assumptions must be made to reduce the number of fluid moments to a manageable (less than infinity) number in order to make the problem tractable. These assumptions can introduce significant departures from the physical description provided by the original kinetic model. For example, the damping of certain waves can be very different from one type of fluid model to another. Nonetheless, the fluid equations, regardless of the simplifying assumptions, are typically easier to implement on very large computers and so are often the method of choice for analyzing plasmas.

Computational approaches are as varied as experiments. For example, at the kinetic level, there are particle-in-cell (PIC) and continuum approaches. In the PIC approach, the plasma is treated as a statistical ensemble of particles moving under the influence of external and self-generated electromagnetic forces. In the latter approach, the system is modeled by partial differential equations (PDEs) for particle distribution functions which move under the influence of exactly the same forces. The PIC approach may require less computer memory, but the continuum approach has less numerical noise. Noise can be reduced in particle approaches by simply using more particles or using "δf" methods which track the perturbation in the distribution of particles from a known solution. When the magnetic field in the plasma is strong, one can use the gyrokinetic approach, which assumes that the time scale of variations is long compared with the cyclotron period for charged particles orbiting around magnetic field lines, and so only the time average motion of the particle is tracked. In the case of strong magnetic fields and low-frequency dynamics one can use magnetohydrodynamics

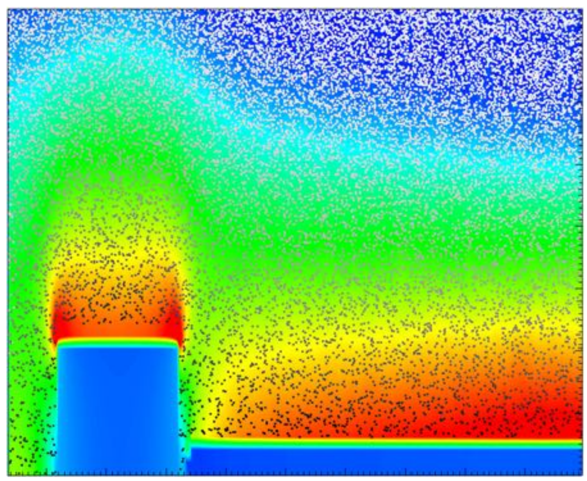


FIGURE 2.2 Simulation of plasma etching reactor near a semiconductor wafer using particle in cell (PIC) techniques. The wafer is in blue at the lower right. The blue rectangle on the bottom left is the focus ring, which is used to make the etching more uniform towards the wafer edge. The electric field strength is shown by the color contours, near zero where it is dark blue, then increasing, shown in red, as the plasma sheath is entered near the wafer. The ions are shown as gray particles, with darker gray indicating a greater speed in the downward vertical (impacting direction). The ions are pulled out of the plasma and gain downward velocity before hitting the wafer. SOURCE: Courtesy of Daniel Main, Tech-X.

(MHD) or multi-fluid equations. (In MHD, continuum equations describe the dynamics of a conducting fluid under the influence of electric and magnetic fields; and the consequences of the resulting conductivity and currents on those fields.) For fluid dynamics, one can choose an algorithm that can represent thin shock waves in supersonic (or near sonic) flows. For solving systems on time scales long compared with those of the basic oscillations in the system, implicit methods are useful.

Subscale Processes and Infrastructure

Plasma physics computations rely heavily on subscale physics processes. An example of a subscale process in a magnetized plasma is the gyrokinetics approximation, which allows one to ignore time scales smaller than the ion cyclotron period and which are not important to turbulence and transport. At another level, models have been developed that provide the fluxes of particles, momentum, and energy as a function of *local* parameters, like density and temperature gradients. Such reduced models have continued to be developed and refined in the last decade. Significant progress has also been made in developing subscale infrastructure that involves atomic and molecular ionization. For example, electric field ionization is important for plasma generation by laser interaction and has become increasingly important with the growth of the sub-field of plasma acceleration.

Development of Novel Algorithms—Theory Based

For continuum approaches (both for traditional fluid and continuum phase-space models), there have been many developments in improving algorithms and formulations such as least-squares Finite Elements and Discontinuous Galerkin. There have also been advances in multi-fluid higher fidelity models (5-moment, 10-moment, 13-moment) and shock capturing methods, which are critical to understanding collisionless plasmas.

For particle PIC approaches, there have been advances in implicit methods. These methods avoid numerical instabilities that occur when the physical spacing between grid points, exceeds the Debye length. (The Debye length is the characteristic distance over which a plasma exhibits charge separation effects and does not satisfy charge neutrality.) This resolution requirement can be prohibitive for simulating practical plasmas. There have been many advances in modeling that more faithfully capture the dispersion of electromagnetic waves, providing a better model of wave-particle interactions. This particular advance is especially important for accurate modeling of plasma processes such as particle acceleration, reconnection and shocks.

Development of Novel Algorithms—Computing Based

Parallel and now massively parallel computers have become the norm for advanced computations. Computations on parallel computers simultaneously use hundreds of thousands of individual processors (or cores) to increase the size of the problem that can be addressed. Message-passing based, distributed memory methods to use these many cores became common in the past decade, and algorithms were adapted to the new computing hardware. For example, computations were rewritten to maximize computational speed while considering the time required for data to be passed between cores, and algorithms were developed for load balancing to enable efficient use of large numbers of cores. Most software was written in a fashion of asynchronous, autonomous applications on each processor, each performing its own computations, passing information to other processors and waiting on data from other processors before continuing.

In the last decade, the need to structure data and code became even more important, with the advent of Advanced Vector Instructions and Graphical Process Unit (GPU) computing. With large processor core counts, the use of threads, which is a way for a computer program to divide itself into two or more tasks, has become more important. With GPU computing, the role of asynchronous paradigms has attracted great interest. To make proper use of such devices, one must manage thousands of separate threads of computation. This is an evolving area, and many different computing paradigms are currently being investigated.

Code Availability

In plasma physics, state-of-the-art computation is available to a relatively small group of researchers. This is perhaps best illustrated by way of contrast. Those wishing to make use of Computational Fluid Dynamics (CFD) simulations have any number of ways to engage, such as using one of the many commercial codes available, using an open-source code, or using an in-house developed code. This relatively easy accessibility to CFD codes enables a large group of users to make use of high-performance computation. Commercial codes cater to those needing ease of use, extensive documentation, and robustness. In-house development of codes is usually undertaken only by the most expert, as they must develop the most appropriate algorithms for a class of physical problems that maps well onto the available computing hardware. This must be done in a manner that produces the desired scientific and engineering results. Well-maintained, open-source codes provide a middle ground. They do not typically come with the level of documentation or support provided by commercial codes, but they do provide a resource that a person with the time to invest in learning can make use of without getting into the intricacies of code development. However, in PSE there are relatively few commercial plasma codes that provide an easy point of entry to simulations (and these come at a price). Companies are beginning to provide such software, but none have reached the level of ease of use and broad applicability as found in CFD or in the areas of stress analysis, or electromagnetics of structures, each of which are provided by large companies and have large markets. There are projects underway to provide some broad, open-source solutions for PSE. However, the breadth and applicability of these offerings varies widely.

Computation: Training the Workforce

Computational plasma education needs to cover the many methods used in plasma physics—fluid (in particular, MHD or multi-fluid) approaches and kinetic approaches (both continuum and PIC). For the fluid approaches, there are a wide variety of textbooks, largely due to the use of CFD across many fields. However, for the kinetic approach there are few modern textbooks. For the particle approach there are some venerable texts, but it is difficult to find textbooks that address continuum approaches to modeling plasma dynamics. This makes it difficult to introduce students to the field, especially as there have been many discoveries since the older classic texts were originally published. Indeed, the entire fields of gyrokinetics simulations, distributed memory computing algorithms, and analysis of large data sets are missing from the existing texts.

There is little motivation for writing advanced graduate textbooks. It is difficult for researchers to find the time to write textbooks when they face demands to write research papers and obtain grant funding. These barriers could be addressed by educational funding that is specific to textbook writing. There is also a need for education about how to use numerical software. As codes become more widely used and the users are no longer the developers, the users no longer have an intimate understanding of the relevant algorithms and methods. What those users need is only a high-level understanding, but enough to know what to look for to indicate that a simulation might not being giving the proper results. In particular they need to learn about the process of code verification and validation—how to determine whether a code is working by testing it.

In part, the problem of computational plasma education reflects the broader problem of not having a dedicated plasma reviews journal in the same way that, for example, Annual Reviews of Astronomy and Astrophysics serves astronomy and astrophysics. A dedicated plasma review journal that publishes 15 to 20 major review articles annually, thus collecting the major findings in a consolidated and comprehensive format, would serve the community well, from students to seasoned researchers alike. A useful side benefit is that the authors of these articles often use them as the basis for a monograph.

The Computational Revolution: What Is to Be Done?

Subscale Methods and Data Infrastructure

Subscale methods are needed for computation in nearly every area of PSE. How can kinetic effects be represented in global simulations of large systems based on extended fluid equations (such as in the vicinity of black holes, neutron stars and planetary magnetospheres, or in fusion plasmas)? How does one characterize viscous effects at the boundaries of plasma thrusters? Can one develop models that account for the change in the velocity distribution functions in low-temperature plasmas? While analytical closure models continue to be subjects of interest, there is significant interest in developing new models based on deep learning methods.

Although significant progress has been made in developing infrastructure for data, much remains to be done. For example, the development of LxCAT, a web-based, open-access platform for data needed to model LTPs, has led to greater availability of critically needed data for the LTP community. This community-driven effort is volunteer supported and, by any measure, has been successful. However, the experience has also emphasized the need for ease of accessibility to software libraries for interpolation and implementation, standards for assessing the goodness and consistency of the data, and long-term support that does not depend on the goodwill of volunteers.

Development of Algorithms—Math Based

A continuing challenge in computation is the need to resolve systems not for physics reasons but for numerical stability and convergence reasons. For example, one must resolve the plasma frequency in PIC simulations even though the evolution of the system to the steady state occurs on much longer time scales. One must resolve the Debye length in PIC simulations to avoid grid instability even in regions where the plasma varies on much larger spatial scales. A common remedy is to use implicit methods. However, implicit methods can be problematic. Implicit methods typically require solving large matrices, which is time consuming and, in general, such solutions over an entire domain are difficult for distributed memory computation. Research oriented towards improving this situation would be welcomed and would have substantial impact on fluid as well as kinetic approaches. Are there explicit algorithms that eliminate these instabilities? More generally, algorithms that work well in the emerging world of heterogeneous computing would be an advance.

Development of Algorithms—Computing Based

Device-based computing is the development of algorithms that are specialized or can only be used on specific architectures of types of devices. For example, computations on GPU simply need different numerical approaches than used for conventional CPUs (central processing units). The challenge of mapping algorithms onto device specific architectures will become even more important as quantum computers become available. The advent of device-based computing and computing on huge numbers of distributed cores has led to experimentation with new data structures. How does one deal with very large datasets, especially when memory is actively managed, as memory allocation and release of large amounts data remains costly.

The challenge of device-based computing has been the focus of the DOE Exascale Computing Project (ECP). While the ECP has been very successful and has been strongly endorsed by the recent National Academies Report on a Strategic Plan for Burning Plasma Research (2018), the coverage of ECP does not include the broad reach of PSE disciplines. Optimizing device-based computing requires a much more specialized approach in matching the details of the algorithm to the computing architecture. This unfortunately works against broadly applicable codes that may use different algorithms (e.g., fluid at high pressure, kinetic at low pressure). The lack of a broader ECP-like initiative places the PSE community in a challenging situation. Computations supported by the ECP address specific targeted applications while areas not supported by the ECP may not have the resources to develop state-of-the-art device-based algorithms. Work is required at both ends of the spectrum—device-based algorithms that are more generally applicable and more resources devoted to fostering the development of device-based algorithms across the PSE community. The future promises even greater complications. To date, GPU computing has been largely performed using the CUDA framework, which works for only NVidia hardware. Standardization of GPU frameworks would lower the barrier of entry for users and suppliers.

Legacy codes refer to well established, often extremely complex, computer models that have served the community well, but often do not have state-of-the-art algorithms. A major challenge is bringing legacy plasma codes up to the state-of-the-art in computational standards while not compromising their physics robustness. This will require deliberate and careful selection. One criterion might be whether the code to be upgraded will be readily available and widely used. Public-private partnerships could leverage the expertise in the private sector where, for example, in exchange for making codes widely available, commercial plasma code developers could be funded to make their codes more performant. With the increasing complexity of computation, it is increasingly difficult for small teams to have the expertise and personnel needed to write or adapt codes for the wide range of available architectures. This implies that research codes will remain confined to small teams, which will not have the resources to port them to multiple devices.

With quantum computing on the horizon, device-based computing becomes a more important strategic discussion. How can such computing devices be used in computational plasma physics? The Fusion Energy Sciences Roundtable on Quantum Information Science (QIS) has identified two Priority Research Opportunities: "using QIS to do plasma science" and "using plasma science to advance QIS." Following this report, DOE-FES has solicited proposals and made awards that make a promising beginning. There is significant enthusiasm and excitement in the plasma science community about participating in the quantum computing frontier, which will have an impact across all computational sciences.

Verification and Validation, and Uncertainty Quantification

Verification and Validation (V&V) are a critical part of computation, as they provide confidence in the computational results. (Verification refers to making certain that the computations solving the equations properly. Validation refers to the computations accurately modeling the physics.) In PSE, as in other fields, standard problems with established results exist against which codes can be compared. In plasma physics, some successful computational examples are the Geospace Environmental Modeling (GEM) reconnection challenge, and the Cyclone Base Case that is a standard set of tokamak conditions intended to compare computations of micro-turbulence. Validation studies tend to be more selective since they depend greatly on the availability of time on experimental facilities and the required coordination and interaction with teams of modelers. The adoption of computations for complex plasma systems would be aided greatly by a more extensive set of validation cases with sufficient (and accurate enough) diagnostics data to provide stringent tests of codes. With experimental costs in some areas of PSE significantly increasing, accurate validation of computational models is especially needed so that computer simulations can be more reliable in their predictive capabilities.

As computations address frontier areas where fundamental data (e.g., opacities, cross sections, materials properties) and validating experimental data may not be available, uncertainty quantification becomes more important. How do needed assumptions or estimates of fundamental data, or methods propagate through a full simulation? There is not a vigorous culture of making such uncertainty quantification in PSE computations, particularly for large simulations for which a limited number of runs can be made. Developing strategies for uncertainty quantification in general, and for large codes in particular, would benefit the field.

MAGNETIC RECONNECTION: TAPPING THE ENERGY OF MAGNETIC FIELDS

Magnetic reconnection is a fundamental process whereby magnetic fields reconfigure topologically (sometimes viewed as “breaking” and “reconnecting) and in the process release energy. Magnetic reconnection underlies many explosive and disruptive plasma phenomena over a wide variety of plasmas in both nature and in the laboratory and plays a pivotal role in electron and ion heating, non-thermal particle acceleration to high energies, and magnetic flux and energy transport.

In heliophysics, magnetic reconnection plays a key role in a wide range of phenomena, including solar flares, coronal mass ejections, coronal heating, solar wind dissipation, interaction of interplanetary plasma with Earth and other planetary magnetospheres, dynamics of planetary magnetospheres such as storms and substorms, and the interaction of the heliospheric boundaries with the interstellar medium. Magnetic reconnection is critical to solar and planetary dynamo processes. Without magnetic reconnection, magnetic fields advected by the plasma will become horribly tangled up and no large-scale order can emerge. In astrophysics, the importance of magnetic reconnection has been recognized for star formation in molecular clouds, stellar flares, explosive phenomena in magnetars and pulsars, and cosmic-ray acceleration. Magnetic reconnection is thought to occur in both coronae and interiors of magnetized accretion disks in proto-stellar systems and X-ray binaries, as well as in interstellar medium turbulence. Magnetic reconnection is believed to occur in the centers of Active Galactic Nuclei (AGN), where matter is accreted onto supermassive black holes. On even larger scales, magnetic reconnection may be important in extragalactic radio jets and lobes as they propagate and relax, and even in galaxy clusters. In laboratory fusion plasmas, magnetic reconnection occurs during the sawtooth oscillations in the temperature profile seen in the tokamak core, the growth of nonlinear instabilities that cause disruptions, and self-organization phenomena in reversed-field pinches and compact tori.

While magnetic reconnection is a fundamental process in plasma physics that is worth understanding in its own right, such understanding has very practical implications and is critical to our ability to control thermonuclear plasmas for producing fusion energy and predicting space weather, to name two examples. In magnetic confinement devices such as tokamaks, major disruptions can occur due to the nonlinear interaction of reconnecting instabilities, which need to be controlled and mitigated. Extreme space weather events producing storms and substorms are thought to be powered, at least in part, by magnetic reconnection. These events can disrupt or damage the electrical power grid, can cause major interference with communication networks, damage spacecraft and be a danger to astronauts. Space weather is discussed further in detail in Chapter 7.

Achievements of the Last Decade in Magnetic Reconnection

During the last decade, thanks to space missions, laboratory experiments, analytical theory and sophisticated computer simulations, our understanding of magnetic connection has advanced greatly. These accomplishments include:

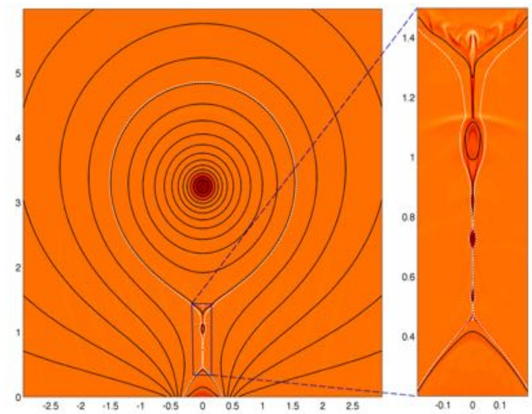


FIGURE 2.3 High-resolution MHD simulation of the standard model of a coronal mass ejection (CME) from the Sun in which a large mass of material escapes from the Sun. The figure represents an intermediate stage in CME dynamics, exhibiting the formation of plasmoids due to the instability of a thin current sheet that spontaneously forms. The plasmoids are constantly ejected by the reconnection outflow, and new plasmoids are generated in the current sheet until the sheet disrupts, releasing the large balloon-like lobe that breaks away as a CME. SOURCE: Courtesy of Yi-Min Huang, Princeton University.

- An improved theoretical understanding of the plasmoid instability (an instability of thin current sheets) has been achieved, and has led to the prediction of a new regime of fast reconnection in which the reconnection rate deviates from the classical Sweet-Parker theory and becomes independent of the resistivity of the plasma when the resistivity is below a critical threshold. (See Figure 2.3.)
- The instruments aboard the multi-satellite mission MMS (Magnetosphere Multiscale Mission) have produced data of unprecedented spatial and temporal resolution of the reconnection layer in the magnetosphere around Earth down to electron micro-scale (skin depth). These datasets, while confirming several theories of laminar reconnection, are producing new challenges on the interplay between reconnection and turbulence. The Fermi Gamma-ray Space Telescope, which observes the entire sky, has provided remarkable data on gamma-ray spectra from solar flares, which provides insights into the energetics of magnetic reconnection.
- The use of sophisticated diagnostic tools (e.g., electron cyclotron emission (ECE)) on tokamaks such as KSTAR, have provided deeper understanding of sawtooth reconnection events, bringing into question our past understanding, and posing new challenges for theory and simulation.
- High-energy-density plasma experiments at high-power laser facilities such as Omega at the Laboratory for Laser Energetics (LLE) at the University of Rochester and the National Ignition Facility at the Lawrence Livermore Laboratory (LLNL) have provided new data for testing the predictions of theory and simulations of magnetic reconnection, often co-existing with shocks and turbulence. These data have been extended to include magnetized plasmas, having self-generated Biermann magnetic fields as well as externally imposed magnetic fields.
- New laboratory experiments at the Facility for Laboratory Reconnection Experiments (FLARE) at the Princeton Plasma Physics Laboratory (PPPL) and the Terrestrial Reconnection Experiment (TREX) at the University of Wisconsin-Madison have exceeded the capabilities of earlier experiments such as the Magnetic Reconnection Experiment (MRX) at PPPL and the Versatile Toroidal Facility (VTF) at MIT in size and scope. These new facilities provide an excellent complement to space missions by enabling the exploration of new regimes of reconnection through reproducible experiments and detailed diagnostics.

Current and Future Science Challenges and Opportunities

In spite of significant progress in the science of magnetic reconnection, major scientific challenges remain to be resolved. These challenges are discussed these challenges in the context of the strategic challenges posed here.

Challenge 1: Understand and predict plasma behavior under extreme conditions that challenge our present models.

While our theoretical understanding of reconnection in collisional non-relativistic laminar plasmas is reasonably mature, there are significant gaps in our understanding of reconnection in weakly collisional and collisionless plasmas, both non-relativistic and relativistic. For collisionless plasmas, there are many numerical simulation results. However, analytical theory for such systems is much less developed, which has made it difficult to infer scaling laws for a broad range of realistic plasma parameters and system sizes. This also applies to the role of collisionless reconnection in compact astrophysical objects where electrons and positrons are formed and constitute a plasma (also called *pair-plasma*). Experiments in high-power laser facilities have the potential to address relativistic, radiative, and pair-plasma regimes.

Extreme-scale computing will be a valuable tool for addressing the high-Lundquist-number (S) regime where plasmas have a very high conductivity. However, the computational cost to resolve the thin layers (boundary layers) and follow the system evolution on the Alfven time (i.e., the system size divided by Alfven wave speed) increases as $S^{3/2}$ for 3-dimensional explicit simulations. For $S\sim10^6$, these requirements can quickly surpass the capabilities of a petascale computer. These limitations require a strategic approach to produce reliable scalings in the high-S regime, which can then be used to better extrapolate to conditions of interest to astrophysics. In weakly collisional or collisionless regimes, the structure of reconnection layers involves both ion and electron kinetic scales. As summarized in Figure 2.4, the space and time scales associated with both electrons and ions impose a daunting level of scale separation both in space and time that is difficult to address in computations.

Challenge 2: Quantify and, in the laboratory control, how plasma processes direct the conversion of energy from one form to another, the transfer of energy across a vast range of scales, and the transport of energy in the laboratory and nature.

Magnetic reconnection controls the conversion of magnetic energy to the energy of particles in the form of plasma flows and heating or accelerating particles to very high energies. The rates at which such conversions occur can be large. Reconnection involves coupling between the largest scale size of the system down to the orders of magnitude smaller kinetic ion and electron dissipation scales. Recent results suggest that plasmoid dynamics may couple these multiple scales efficiently. (A plasmoid is a structure that looks like a cat's eyes within which magnetic fields lie on nested surfaces, as seen in Figure 2.3.) Key questions include how the number and size of plasmoids scale with the system-size and plasma parameters, and how the reconnection process responds to turbulent fluctuations which span an enormous range of spatial scales. Two-fluid effects and kinetic transport physics are thought to speed reconnection while the effects of micro-turbulence on reconnection are not well understood. (In the two-fluid model, one uses separate fluid equations for electrons and ions.) The latter effect is a particularly important area to investigate as space observations suggest that that reconnection occurs in a bath of turbulence.

Determining the mechanisms for acceleration of particles to high energies and the apportionment of energy between different species are among the most important challenges in space and astrophysical plasmas. Magnetic reconnection, shocks, and turbulence are widely discussed as possible mechanisms. In planetary magnetospheres, energetic particles in the radiation belts (observed, for example, by the Van Allen Probe mission) have a significant impact on space weather. In our Milky Way galaxy, cosmic rays represent only one-billionth of the interstellar particles but carry as much energy as the galaxy's thermal plasma for reasons that are not fully understood.

Challenge 3: Predict self-organization of plasmas and, where needed, control that self-organization.

Magnetic reconnection releases energy that was formerly trapped in magnetic field lines, converting that energy to other forms, such as the flow of a plasma or highly energetic charged particles. These other forms of energy can be degraded by collisions and turbulence, resulting in states of lower energy, heating, and increased entropy. In this process, self-organization can occur. The classic Taylor theory of plasma relaxation is based on a non-ideal plasma containing multiple reconnecting instabilities. These instabilities relax to a unique final state of minimum energy subject to global constraints that are approximately preserved by the dynamics. This process is thought to occur in laboratory and astrophysical plasmas, but the Taylor state is not always realized. What are the constraints that prevent systems from doing so?

Advances in computational plasma physics have enabled understanding of coherent, self-organized structures in both configuration space in fluid simulations as well as structures such as "phase-space holes" predicted by fully kinetic simulations. In the latter case, there is not yet an underlying theoretical framework that accounts for the simulation results. Observational tests of theories have produced interesting results, but much more work is needed to provide a truly predictive capability for magnetic reconnection.

WAVES, TURBULENCE, AND THE DYNAMO EFFECT

The rich variety of waves exhibited by plasmas is fundamental to a wide range of phenomena in laboratory, space and astrophysical settings. Plasma waves can transport energy and momentum, produce heating of electrons and ions, and energize and scatter particles. Plasmas are often far from thermal equilibrium and instabilities can arise as a result, converting plasma energy into waves. Turbulence, often

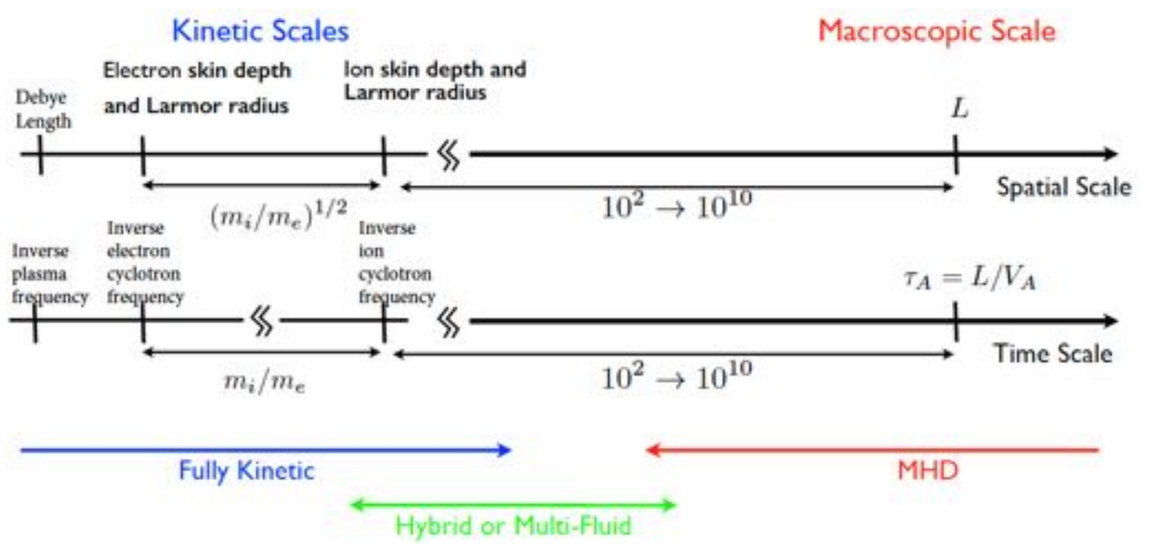


FIGURE 2.4 Spatial and temporal scales in collisionless reconnection. The shortest timescale is the inverse of the plasma frequency followed by the inverse of the electron cyclotron frequency. Electron spatial scales include the Debye length, the electron inertial length, and the electron Larmor radius. Mass is denoted by m with subscript i (e) representing ion (electron). SOURCE: Courtesy of William Daughton, Los Alamos National Laboratory.

driven by unstable waves, is ubiquitous in plasmas and is widely cited as the dominant mechanism for heating and transport of particles, energy and momentum in many settings. Instabilities, waves and turbulence also play a role in the plasma dynamo, processes by which magnetic fields are generated and amplified both on small and large spatial scales with lifetimes that can vary widely depending on the plasma medium.

Relevance and Benefits

Waves and instabilities are the first type of dynamics that nearly all forms of collisionless or weakly collisional plasmas experience. Such collective dynamics result from nearly all ways of describing plasmas—at the 3D macroscopic level by fluid equations (MHD and multi-fluid), and at the 6D microscopic level by the kinetic equations. Thanks to decades of close collaboration in PSE between theory and experiment, our understanding of linear (or small-amplitude) waves and wave-particle interactions is quite mature. As waves and instabilities grow in amplitude and interact with each other and with particles, nonlinear effects become very important. These non-linear processes can produce turbulence, dissipation, heating, and particle acceleration, and a variety of coherent structures. Nonlinear effects in nature are wide-ranging—momentum transport in accretion disks around compact astrophysical objects such as black holes and neutron stars; heating of the solar and stellar atmospheres and of the stellar winds (consisting of high-speed particles) that flow out from the Sun and other stars; particle acceleration that produce the Northern lights during substorms in Earth's (or other planetary) magnetospheres; energetic cosmic rays that pervade the Universe; and the rich spectrum of waves that accelerate and expel energetic particles from the Van Allen radiation belts. These nonlinear effects can also dominate in laboratory plasmas—laser-induced plasma waves that can accelerate particle beams, expelling energetic particles from fusion plasmas; and wave-driven currents that offer the potential benefit of enabling a fusion plasma to operate in steady state. The possibilities are nearly endless.

Studies of the dynamo effect address the question of why our Universe is magnetized? There are two classes of dynamos. "Small-scale" dynamos amplify magnetic energy but produce negligible magnetic flux because the averaging of fluctuations over space and time leads to near-perfect cancellations. "Large-scale" dynamos produce large-scale magnetic field structures with non-zero magnetic flux. Beautiful in its regularity, the Sun's magnetic field and its 11-year cycle is an example of large-scale dynamo. (See Figure 2.5.) The spontaneous emergence of large-scale magnetic fields from

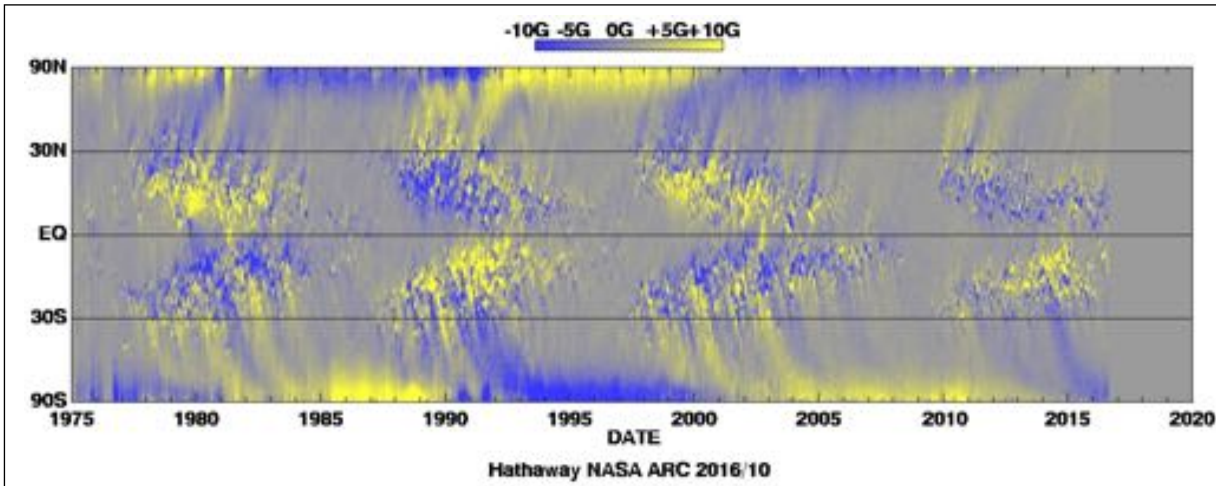


FIGURE 2.5 The Butterfly Diagram for the Sun's magnetic field, spanning the years 1975-2016 (horizontal axis). This diagram, based on observations, tells the story of the 11-year cycle of the Sun's magnetic field. The vertical axis represents latitudes both above and below the equator of the Sun. The colors in the plot indicate the magnitude of the solar magnetic field. SOURCE: Courtesy: David Hathaway, NASA Marshall Space Flight Center.

disordered small-scale velocity and magnetic field fluctuations is counter-intuitive. However, understanding this behavior is likely required to predict the long-term dynamics of magnetic fields that govern everything from the space climate to the launching of powerful jets during neutron star merger events.

Advances in Waves, Turbulence, and Dynamos

During the last decade, there has been tremendous progress in our understanding of waves, turbulence and dynamos in both laboratory plasmas and plasmas in Nature, aided by theory, simulation and experimental observations. A few highlights of that progress include:

- Plasma in the Universe is often magnetized and turbulent. Plasma fluctuations in space can span a huge range of scales, from hundreds of parsecs (1 parsec is 3.26 light years) to hundreds of kilometers. Observations of the solar wind and the interstellar medium (ISM) reveal qualitatively similar scaling laws for magnetic, velocity, and density fluctuations, which extend down to the ion gyro-radius. (See Figure 2.6.) At large scales, MHD provides a good description of plasma dynamics. The plasma beta (the dimensionless ratio of the plasma pressure to the magnetic energy density) in space and astrophysical plasmas is often close to or greater than unity, which distinguishes these plasmas from plasmas in the Sun's atmosphere or laboratory that are confined by magnetic fields and typically have small beta values (including fusion plasmas). Typically, space and astrophysical plasmas are large-scale highly supersonic flows, such as solar and stellar winds, which have large flow Mach numbers, but nonetheless can have small turbulent Mach numbers. At small scales, at or below the ion gyro-radius, plasma dynamics become much richer, as two-fluid, and kinetic effects become important. These scales are harder to address analytically. However, two-fluid, gyro-kinetic and kinetic plasma simulations have produced promising results in addressing these small scales, such as suggesting scaling laws that bridge different energy dissipation mechanisms. These simulations have also shed light on the role of anisotropic pressure-driven instabilities that self-regulate the nature and structure of turbulence and magnetic reconnection processes.
- Weak MHD turbulence is dominated by Alfven waves that weakly interact with each other. The practical application of this finding is limited in nature where turbulence is typically strong. However, weak MHD turbulence can be addressed analytically and serves as a test bed for fundamental studies of the theory of MHD turbulence and energy cascades. This understanding sets the stage for the stronger turbulence seen in Nature and the laboratory. Describing strong turbulence using MHD assumes that there is a balance between linear wave propagation and nonlinear interactions. However, this assumption is not based on a rigorous analytical treatment. As a result, good physical models, numerical simulations and targeted laboratory experiments (such as at the Large Plasma Device (LAPD) at UCLA) are critical to developing better understanding of turbulence. A fundamental property of strong

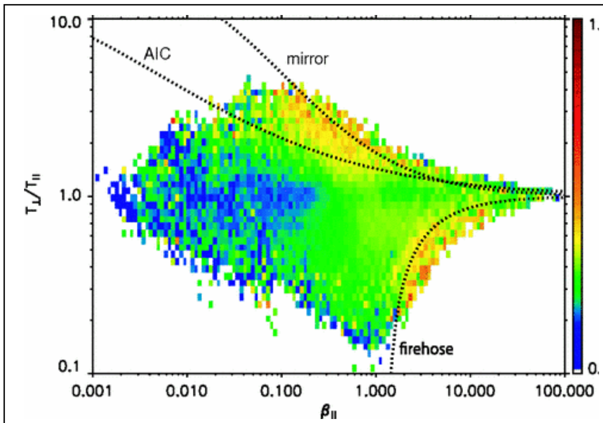


FIGURE 2.6 The magnitude of magnetic field fluctuations in the solar wind, measured by in situ spacecraft. The fluctuations are binned as a function of the ratio of the temperature perpendicular and parallel to the magnetic versus the plasma beta parallel to the magnetic field. The data seems to lie within the parameter space constrained by the so-called firehose and mirror instabilities, which are driven by pressure anisotropy, and not by a cyclotron instability. (AIC). SOURCE: Phys. Rev. Lett. 103:211101, https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.103.211101.

MHD turbulence is its inherent local anisotropy. Small-scale fluctuations are progressively more anisotropic as the scale length decreases. The balance between linear and nonlinear interaction times is postulated to be preserved independently of scale length in collision-less plasmas, which is called the critical balance condition. The validity of the critical balance postulate in kinetic turbulence is being investigated with interesting results.

- Interaction of turbulence with non-uniform plasmas represents a difficult problem. Methods for investigating turbulence in spatially non-uniform plasmas has been an active area of research, especially for fusion plasmas and the interplanetary medium. Turbulence in such plasmas does not seem to directly conform to the classical Kolmogorov-like picture of turbulence whereby energy cascades from driven large scales to small scales until the energy thermalizes. What seems to occur instead is that turbulence saturates by channeling energy into stable modes that exist at the same spatial scales as the instability that drives the turbulence. Multiscale analysis of inhomogeneous turbulence has produced transport equations that need to be tested against experimental observations. This leads to extremely demanding computational problems, approaching or exceeding the exascale. For example, multi-scale, multi-physics, whole-device models for fusion plasmas based on gyrokinetic theory, needed to address inhomogeneous turbulence, need the power of state-of-the-art computing hardware. Fortunately, both computer simulations and theory are well positioned to make progress on these topics, which can have a strong impact on applications as diverse as coronal heating, evolution of the solar wind as it expands from the Sun, space weather, cosmic ray propagation and galactic turbulence.
- Coherent structures are sustained nonlinear perturbations which are localized in space and time. On the other hand, waves are localized in wavenumber or frequency—meaning that they typically have a well-defined wavelength or frequency. Examples are solitons, ion or electron phase-space holes or double layers (see Figure 2.7) which are now widely observed in Nature through progress in observational techniques. (A phase space hole is a region of coordinates and velocities that are devoid of an electron or ion.) Such coherent structures, observed in space and laboratory experiments, occur over a wide range of spatial scales, ranging from Debye to Alfvenic lengths. Coherent structures can be electrostatic as well as electromagnetic, and are thought to be a nonlinear end state of some forms of turbulence.
- With the advent of high-power lasers and pulsed-power devices, some astrophysical environments can now be reproduced in the laboratory. This is the realm of high energy density (HED) physics. This capability has led to the study of astrophysical processes in scaled laboratory experiments, including magnetic reconnection, collision-less magnetized shocks, Weibel-mediated shocks, the generation of magnetic seeds at shocks by the Biermann effect, and the small-scale turbulent dynamo. In conjunction with new capabilities in high-performance computing, these developments have set the stage to achieve significant scientific advances.

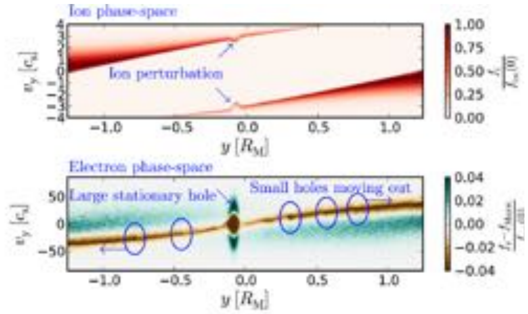


FIGURE 2.7 Phase space holes growing in a cross-field plasma wake. Here the background magnetic field is in the y-direction. Most holes move out at the electron orbit speed. One hole remains stationary and grows large enough to perturb the ions. SOURCE: Physics of Plasmas 24, 055601 (2017); https://doi.org/10.1063/1.4976854

Current and Future Science Challenges and Opportunities

Challenge 1: Understand and be able to predict plasma behavior under extreme conditions that challenge our present models.

Waves and turbulence in weakly collisional, high-beta plasmas is poorly understood, despite recent advances in analytical theory and simulation. An intriguing aspect of this state of matter is the relevance of the magnetic field. Although the magnetic field (in the absence of reconnection) is not the dominant source of energy, it does influence the transport properties of the plasma by imparting directionality and new degrees of freedom, thereby influencing the large-scale dynamics. The magnetic field-induced anisotropy introduces a fundamental difference between the dynamics of magnetized plasmas and collisional plasmas or those that have weak magnetic fields. An unique feature of weakly collisional, magnetized, very high beta plasmas is that kinetic microinstabilities can make them unstable. (That is, small variations in the velocities can be amplified exponentially to the point of producing turbulence.) The dynamics of such plasmas are governed by complex, multiscale interactions between kinetic physics and large-scale bulk plasma motion. Strategic areas for future investigations include: (1) identifying the most important linear kinetic instabilities; (2) determining how kinetic instabilities interact with other plasma processes, such as reconnection, heat fluxes, and particle acceleration; and (3) determining how fluid transport on large scale lengths interacts with kinetic transport on micro-scales.

Challenge 2: Quantify and, in the laboratory control, how plasma processes direct the conversion of energy from one form to another, the transfer of energy across a vast range of scales, and the transport of energy in the laboratory and nature.

In typical occurrences of turbulence, energy is transferred from large scales to small scales through a cascade process. The range of length scales in MHD turbulence has a "break-point" where the dissipation of energy becomes more rapid as the length scales get smaller. Turbulent fluctuations with scale lengths smaller than that of the break point form the dissipation range. In weakly collisional space and astrophysical plasmas, the scale lengths where this breakpoint occurs often has a two-fluid or kinetic origin (e.g., the ion skin depth or ion gyroradius). While there is clear evidence of these breakpoints in observations of plasma turbulence in the solar wind or ISM, there are no definitive theories that describe the transition. Theoretical and computational models based on two-fluid (or Hall MHD, where electron inertia is ignored) equations, gyro-kinetic equations and fully kinetic equations have been developed to compare with specific observations, with some success. The results suggest that the dissipation range may itself be multi-scale with wave damping or particle heating occurring at short scale lengths. Determining the causes of such electron and ion heating is one of the critical unsolved problems in the study of space and astrophysical turbulence. Observations to be made by the Parker Solar Probe mission will provide needed insights to the source of this heating.

Even for a plasma that satisfies the MHD approximation, the large-scale dynamo problem remains unsolved—what are the mechanisms whereby magnetic fields erupt and decay? Until recently, it was generally accepted that small-scale fluctuations in the plasma can lead to catastrophic quenching of the growth of large-scale magnetic fields. However, recent theoretical work on systems with flow shear suggests that small-scale dynamos, after saturation, can drive the growth of large-scale fields. (Saturation of a dynamo occurs when an exponential growth of the magnetic field produces magnetic forces that balance those producing the turbulence.) In the kinetic regime, even less is known. Recent studies have started to explore kinetic effects on dynamos. However, our understanding of dynamos in weakly collisional and collisionless plasmas is limited. The topic is complex, simultaneously touching kinetic turbulence, collisionless reconnection, non-thermal particle acceleration, and diffusion.

Challenge 3: Predict self-organization of plasmas and, where needed, control that self-organization.

When influenced by waves, instabilities, and turbulence, self-organization in plasmas becomes even more complex, bringing forth new and unresolved questions. There appears to be no explanation for dissipating energy in plasmas that is as successful as Taylor's relaxation theory for MHD plasmas. In this theory, energy is minimized while magnetic helicity is kept approximately constant in a dissipative plasma, with the outcome producing a unique, force-free state as a result of self-organization. However, in MHD systems that are not particularly turbulent, there is a tendency to relax into states that have more free energy than Taylor states (as seems to be true for quasi-steady states in fusion plasmas). A unifying principle to describe such states remain elusive. The picture is even more incomplete for kinetic plasmas that self-organize to form coherent structures. Scientific questions that remain unanswered include: How and under what conditions will plasmas self-organize? What are the natural processes that produce the nonlinear instabilities that may produce self-organization? Once formed, what role does self-organization play in defining plasma transport coefficients such as electrical or thermal conductivity or diffusivity? Are the processes responsible for self-organization also responsible for significant electron acceleration, for example, in Earth's radiation belts, at reconnection sites, in the solar corona and wind, and in astrophysical objects? To what extent does self-organization generate or scatter traveling plasma waves, such as Alfven waves or whistler waves? How long do self-organized structures last? What are the mechanisms that cause them to break up or dissipate?

DUSTY PLASMAS: FROM COMETS TO FUSION REACTORS

In a dusty plasma (sometimes referred to as a "complex plasma"), the typical plasma components of ions, electrons, and neutral atoms are joined by a fourth component: solid, charged particulate matter or "dust". These dust grains are often nanometer- to micrometer-sized objects that acquire charge either through the direct collection of electrons and ions from the surrounding plasma or through other processes that can lead to charging (such as the photoelectric effect resulting from UV and VUV illumination or ionizing radiation). In space and astrophysical environments, dust grains can acquire either a net positive or a net negative charge, depending upon the conditions of the local space environment. In either case, the dust grain charge is the key property that couples the particles to the surrounding plasma and governs the resulting dynamics of the four-component dusty plasma. An equally important property that distinguishes a dusty plasma is the possible influence of gravity. In most other plasma systems, the gravitational force effectively plays no role in the dynamics of the plasma because the electrical, magnetic and fluid forces are all large compared to gravity. However, for dust grains of several microns in size and whose mass can be millions to billions of times larger than the ions and electrons, gravity can play a dominating role in the behavior of the dust component.

Relevance and Benefits

Dusty plasmas are ubiquitous and appear in a variety of contexts in science as well as technology. In the laboratory, a dust particle of the size of a few microns can attract 10,000 electrons or more at room temperature. Dusty plasmas are often described by the coupling constant Γ, which is the ratio of the average electrostatic energy to the average kinetic energy. For plasmas with these large, heavily charged particles, Γ can be much larger that unity enabling such plasmas to behave as though they were liquids or solids. The large size of the dust particles enables them to be tracked and illuminated with lasers, providing novel tools to study and diagnose strongly coupled plasma dynamics. Dusty plasmas have been used to experimentally and theoretically investigate fundamental properties of soft condensed matter such as the phase transition from the liquid to the solid state, defect formation, and melting produced by waves and instabilities.

Dusty plasma research is highly interdisciplinary. It is strongly relevant to studies of astrophysical objects, particularly star-forming regions and the ISM, as well as cometary tails and planetary rings. Charged dust is found on numerous airless bodies throughout the solar system - from comets to meteors to moons, and can pose both a danger (e.g., due to contamination of space systems) and a benefit (e.g., as surfaces where water and other volatile material could be trapped) for human exploration of the Moon and Mars. Controlling dust-particle interactions with the plasma and the growth of particles in reactive plasmas form the basis for understanding and actively manipulating dust particles for industrial applications in a variety of low temperature LTPs (Chapter 5).

Within the United States, the dusty plasma community is supported by NSF, DOE, and NASA with researchers distributed across institutions that range from predominantly undergraduate institutions to PhD granting institutions to national laboratories. Maintaining a healthy and active U.S. research community remains a challenge.

Progress and Achievements

There has been substantial progress in understanding the physical properties of dusty plasmas over the past decade. Some highlights include (see Figure 2.8):

- *Anisotropic and non-reciprocal interactions*: These studies investigate systems in which the action-reaction symmetry (well-known from Newton's second law) can be broken for mesoscopic particles when their effective interactions are mediated by a non-equilibrium environment. Dusty plasmas have provided an ideal medium in which to explore the role of symmetry-breaking.
- *Binary mixtures and non-equilibrium phase transitions*: Most laboratory studies of dusty plasma focus on particles have the same size, composition and mass—that is, they are monodisperse. For the same plasma conditions, these particles will acquire the same charge enabling a simpler description of the plasma. Between monodisperse and the fully polydisperse systems (particles that have different shapes, masses and compositions) that are found in Nature, recent studies have focused on binary dusty plasmas consisting of two different monodisperse dust particle species. These binary mixtures have enabled investigation of a variety of

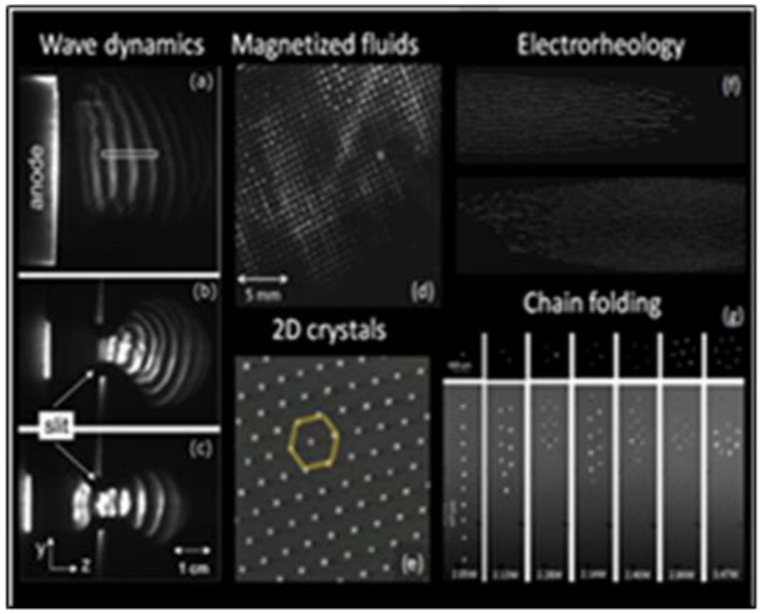


FIGURE 2.8 Dusty plasma analogues: (a) nonlinear waves and (b), (c) shocks (University of Iowa), (d) dust grid pattern in external magnetic field (Auburn University), (e) 2D honeycomb monolayer (Max Planck Institute), f) electrorheological dusty plasma (Plasma-kristall-4 experiment, International Space Station), (g) folding of filamentary structures (Baylor University). SOURCE: (a-c) Merlino, R.L., Heinrich, J.R., Hyun, S.-H. and Meyer, J.K., Phys. Plasmas 19, 057301 (2012), (d) Thomas, E.J. et al., J. Plasma Phys. 81, 345810206 (2015), https://www.cambridge.org/core/journals/journal-of-plasma-physics/article/magnetized-dusty-plasma-experiment-mdpx/705433918E9D5311A2F68406ACBE1F48; (e) adapted from https://onlinelibrary.wiley.com/doi/abs/10.1002/ctpp.200910022, doi: 10.1002/ctpp.200910022, courtesy of the Max Planck Institute; (f) http://eea.spaceflight.esa.int /portal/exp/?id=9452, DLR (CC-BY 3.0); (g) Hyde, T. W., Kong, J. & Matthews, L. S., Phys. Rev. E 87, 053106 (2013).

phenomena including the dynamics of de-mixing and the formation of lanes as a pattern, relevant for many applications.

- *Atomistic modeling of fluids*: The physics of undercooled liquids (i.e., liquids having temperature below their usual freezing point), especially near the glass transition, is a challenging topic in fluid physics. Since dusty plasmas enable visualization of kinetic phenomena on a particle-by-particle basis, it is possible to investigate critical phenomena in statistical mechanics such as the dependence of the structural glass transition on the number of spatial dimensions.
- *Precision monitoring of particle size evolution*: The dust particle mass, surface potential, and charge all depend critically upon the size and shape of the particle. Although it is generally assumed that in experiments, the dust grain size generally remains constant, recent *in situ* measurements of particles reveal that this is not always the case due to plasma-surface interactions. In the next decade, diagnostics that can provide real-time, *independent* measurements of the particle size and charge are a critical need.

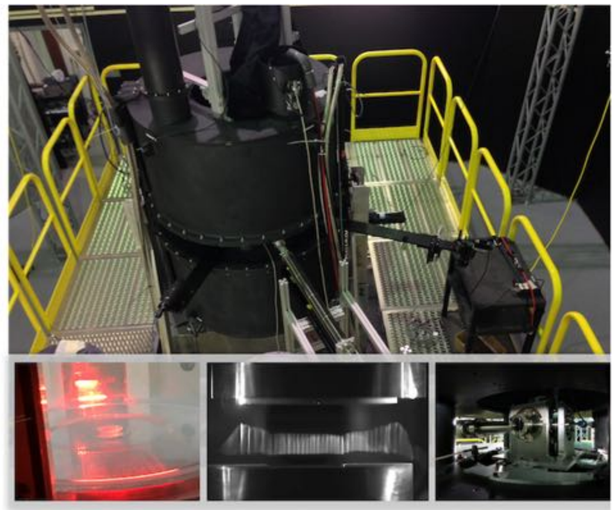


FIGURE 2.9 *The Magnetized Dusty Plasma Experiment (MDPX) device*. The MDPX device is a high magnetic field (up to 4-Tesla), superconducting magnet system with a split, open bore at the center to accommodate substantial radial and axial access to the plasma. The overview image is a top view of the laboratory facility. The three insert images represent experiments from collaborative users: (Left) Image of a plasma crystal based on Jaiswal et al., (Middle) Image of growing silica nanoparticles in vertical "plasma filaments" based on Couëdel et al., (Right) Image of a calibration setup for the Wisconsin In-Situ Penning (WISP) Gauge for the Wendelstein 7-X stellarator that was tested on the MDPX device. SOURCE: Top: Magnetized Plasma Research Laboratory, Auburn University; bottom, left to right: Physics of Plasmas 24:113703, 2017; https://doi.org/10.1063/1.5003972; courtesy of Edward E. Thomas, Jr., Auburn University; courtesy of Oliver Smitz and Thierry Kremeyer, University of Wisconsin-Madison.

Current and Future Science Challenges and Opportunities

Dusty plasma research is connected to the four strategic challenges previously discussed.

Challenge 1: Understand and be able to predict plasma behavior under extreme conditions that challenge our present models.

Strongly coupled dusty plasmas are inherently an "extreme" plasma state, characterized by values of the coupling constant greater than unity. The presence of the dust particles enables direct visualization of plasma phenomena at the single-particle and collective scales simultaneously—enabling unprecedented measurements of the time and space evolution of a plasma component through the direct reconstruction of the distribution function. Dusty plasmas therefore provide an excellent model system upon which to test models of statistical physics, plasma physics, and soft-condensed matter.

The large mass of the dust particles— compared to that of electrons, ions and neutrals—and the resulting very small charge-to-mass ratio, means that dusty plasmas can be studied in regimes that are beyond those of typical laboratory LTP systems. With gravity often a dominant force in laboratory dusty plasmas, moving to microgravity environments is a method to study the smaller scale, inter-particle forces. In another regime, very large magnetic fields (or very small particle sizes) are required to investigate the properties of magnetized dust. In both microgravity and magnetic field studies of dusty plasmas, the last decade has seen technological developments that will enable new advances.

The leading efforts for microgravity studies of dusty plasmas is centered on the "Plasmakristall" (PK) series of experiments on the International Space Station (ISS). PK-4 is the current ISS experiment with the focus on fluid-like dusty plasma behavior. PK-5 (also known as "Ekoplasma") is under development. Without a dedicated U.S. microgravity facility, partnership in the PK-4 and PK-5 consortia are *essential* to accessing microgravity conditions. The long-term future of the ISS as a research platform, support of the national agencies (in the United States and abroad), and developing a distributed, possibly multi-agency, support for hardware development are all critical challenges facing the future of microgravity dusty plasma research in the next decade.

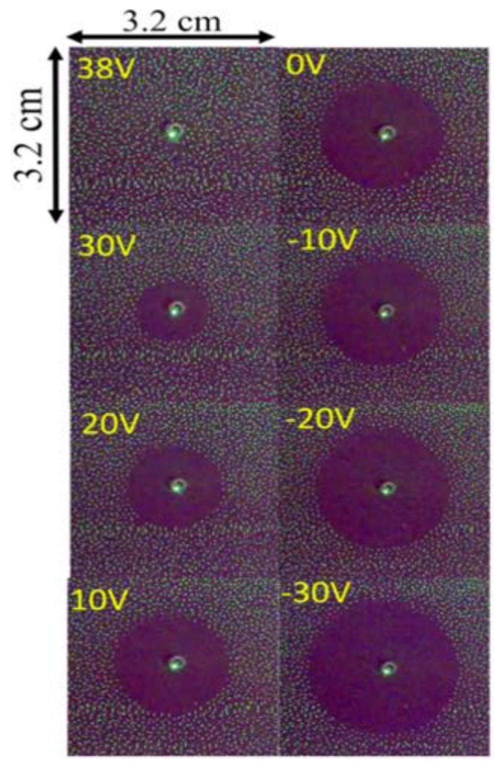


FIGURE 2.10 Example of a "probe-induced" void in a laboratory plasma. A range of voltages are applied to a small wire electrode (central bright spot in each image). A void (dust free region) is formed between the electrode and the surrounding cloud due to a competition between electric and ion drag forces on the dust particles. When those forces come into equilibrium, the void boundary is formed. Image adapted from Phys. Plasmas. SOURCE: Physics of Plasmas 25, 053705 (2018), https://doi.org/10.1063/1.5029338.

The last decade has also seen substantial progress in magnetized dusty plasma experiments, made possible by a reduction in technology costs, improvements in experimental design as well as knowledge of plasma operations to ensure plasma stability. For some time, high magnetic field facilities have been operated in Japan, Russia, and Europe, but within the last 5 years, a multi-user, collaborative research facility, the Magnetized Dusty Plasma Experiment (MDPX) has begun operating at Auburn University in the United States. (See Figure 2.9.) For the next decade, understanding the extended study of steady-state, low-temperature plasma and dusty plasma regimes at high magnetic field is a critical goal.

Challenge 2: Quantify and, in the laboratory control, how plasma processes direct the conversion of energy from one form to another, the transfer of energy across a vast range of scales, and the transport of energy in the laboratory and nature.

Dusty plasmas are a thermodynamically open, non-equilibrium system in which energy flows freely between the electrons and ions (at the microscopic scale) to the dust particles (at the mesoscopic scale). In spite of the large-scale separation between the dust particles and the surrounding plasma particles, there is a continuous exchange of energy between the microscopic and mesoscopic scales. An important emerging area of dusty plasma science concerns the deliberate growth of nanoparticles (dimensions of a few to tens of nm) to microparticles (a few to tens of microns) through the chemical energy conversion processes in reactive plasmas. By leveraging inter-particles forces and plasma chemistry, technologically important nanoparticles with unique particles can be produced. (See Chapter 5 for more details.)

Challenge 3: Predict self-organization of plasmas and, where needed, control that self-organization.

Dusty plasmas can be "tuned" via the Coulomb coupling parameter to exhibit self-organized behavior ranging from solid-like to gas-like, while the particles remain suspended in the plasma. In the presence of a magnetic field, this ordering can undergo significant modifications in ways that are not well understood. Dusty plasmas containing nano- to micro-particles exhibit tendencies to form a wide variety of self-organized and imposed-structures, such as voids. An example of a "probe-induced" void is, shown in Figure 2.10. While progress has been made in providing plausible theoretical models for void formation, a comprehensive theoretical framework for predicting self-organized structure formation in dusty plasmas remains elusive.

Challenge 4: Control and predict the interactions between plasmas and solids, liquids and neutral gases.

Dusty plasmas are the embodiment of a plasma system that defines the challenge of controlling plasma surface interactions. Dust particles are charged solid matter that are embedded in a plasma environment. All of the fundamental properties of a dusty plasma are defined by the interaction between solid particles and plasmas. A key mission for dusty plasma research is to achieve control over these interactions. Some future challenges include:

- *Determining the dust particle charge.* The most fundamental parameter for a dusty plasma is the charge on the particle. While a number of techniques are used to make charge measurements (e.g., two-particle collisions and/or resonant oscillations), these measurements give the charge-to-mass ratio, and an assumed particle mass is then used to determine charge. A future challenge is the development of non-invasive, non-perturbative techniques that independently determine the particle mass and charge. This is particularly important for chemically reactive dusty plasmas in which the particles grow (or erode), meaning that their size, mass and charge can be functions of position and time.
- *Tuning of plasma–dust grain interactions for precision control of trajectories and growth of nano- and micro-particles*. In the bulk plasma, the dust particle interaction with the plasma is isotropic. These interactions produce self-organized structures, for example, single or multiple layers of hexagonal lattices. However, when particles interact with anisotropic ion fluxes, as can occur in and near sheaths, the self-organization structures take on different forms, such as linear strings. This qualitative change in self-organized structures is due to the production of local space charge through altered dust-dust and dust-plasma interactions triggered by anisotropic ion fluxes. Correspondingly, in strongly magnetized plasmas, where ion and electron motion is limited by their gyromotion, experiments show that the magnetic field may also impose a directional order to the dust particles. A strategic challenge is to actively control dust-plasma and dust-dust interactions. This capability allows the preparation of the dust particle state in the plasma, and then the use dust particles as microscopic diagnostics to provide information about the state of the plasmas and to control the properties of the plasma. Achieving this goal requires the development of plasma chambers with variable internal

geometries and multi-electrodes to manipulate plasma density and the electron temperature, using controlled mixtures of particle sizes, or using shaped magnetic geometries, and associated sheath and pre-sheath structures, to manipulate the dust particles.

Dusty Plasma Facilities on Earth and in the International Space Station

The development of dusty plasma research has been dominated by "table top" experiments. This is likely to be the dominant mode of exploration for the foreseeable future. The greatest need for current experiments is the development of new diagnostic tools that can provide real-time, spatially resolved measurements of both the plasma and the dust particles. Key unresolved questions that may be addressed by a next generation of diagnostics would include: (a) non-invasive, real-time measurements the dust grain charge; (b) confirmation of the ion flow dynamics and the formation of the ion wake field in the vicinity of dust particles; and (c) the development of new image analysis tools—possibly leveraging new developments in machine learning—to rapidly process and identify the full three-dimensional motion of particles, particularly in cases where multiple synchronized cameras are used or using new types of light wave (e.g., plenoptic) cameras.

Two areas in which larger collaborative teams have advanced dusty plasma research are the study of dusty plasmas under microgravity conditions and in magnetized plasmas. The next decade will hopefully see the continued operation of the PK-4 microgravity facility on the ISS followed by a successor instrument, PK-5 (Ekoplasma). The U.S. should consider supporting researchers to pursue microgravity studies as well as supporting the development of experimental hardware for those facilities.

In exploring dusty plasmas in magnetized plasmas and magnetized dusty plasmas, the last decade has seen the development of several experimental platforms—many involving superconducting magnet systems. All these laboratories are generally extensions of the "tabletop" scale groups but requiring substantially more personnel and diagnostic infrastructure than a single PI laboratory. The MDPX device at Auburn University is the first facility in the United States specifically designed for supporting external users. Since beginning operations in 2014, researchers from the United States, South Korea, India, Germany, and France have conducted studies ranging from dust charging effects and particle growth to materials processing to calibrations of fusion diagnostics at magnetic fields up to 3 Tesla. For both microgravity and high magnetic field studies, partnerships are critical—both through leveraging federal agencies partnerships (see Table 1.1 in Chapter 1) and promoting national and international partnerships within the community to grow the field.

NON-NEUTRAL AND SINGLE-COMPONENT PLASMAS: CONFINED IN THERMAL EQUILIBRIUM FOR DAYS

The classic definition of a plasma is an ionized gas composed of negative and positively charged particles that, on average, is electrically neutral. The classic plasma can only be non-neutral over very short times (defined by the plasma frequency), very short lengths (defined by the Debye length) or near the boundaries of the plasma where large electric and magnetic fields are applied (defined by the sheath thickness). Most properties of classic plasmas result from being composed of discrete negative and positive charges, attempting to assume on the average an electrically neutral state.

In non-neutral plasmas, particle species with only a single sign of charge predominate—that is, the plasma is intentionally out of charge balance. Often, only a single particle species appears in the plasma (a single-component plasma). A few examples of non-neutral plasmas produced in the laboratory are pure electron plasmas and pure positron plasmas (both of which are single-component plasmas), electron-anti-proton plasmas, and ion plasmas consisting of one or more species of positive ions. Since the natural response of collections of charge particles with a net charge density is to produce forces that reduce the charge density, creating non-neutral plasmas requires specialized experimental techniques.

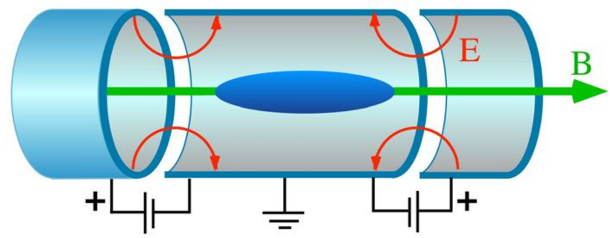


FIGURE 2.11 Schematic of a non-neutral plasma confined in a simple cylindrical Penning trap by electric and magnetic fields. The electric field **E** is indicated by red lines. The magnetic field **B** is parallel to the axis of the cylinder and indicated by the green line. The open ends of the cylinder allow plasma flow. SOURCE: https://commons.wikimedia.org/w/index.php?curid=61934417; Creative Commons Attribution-NonCommercial 4.0 International.

Non-neutral plasmas have useful properties not shared by neutral or quasi-neutral plasmas. One important advantage is the existence in non-neutral plasmas of a *confined thermal equilibrium state* using only static electric and magnetic fields (the "Penning-Malmberg trap" configuration). In contrast, there is no confined thermal equilibrium for classical neutral plasmas in static fields, which is the fundamental reason why neutral plasma confinement is such a difficult problem. (See Figure 2.11.) In non-neutral plasmas, the existence of a confined thermal equilibrium state enables plasma confinement for long times (up to hours, days or even weeks), enables experiments with an exceptionally high level of reproducibility and accuracy, and enables precision industrial plasma applications.

A second feature of non-neutral plasmas is the ability to access extreme strongly coupled and strongly magnetized states of matter. Unlike neutral plasmas, non-neutral plasmas can be cooled to cryogenic temperatures without electron-ion recombination (whose rates greatly increase as the temperature decreases), because there is no oppositely signed charge species with which to recombine. This enables the study of novel strongly coupled and strongly magnetized plasma states in thermal equilibrium (such as pure ion liquids and crystals), which is not possible in any other classical plasma system. The combination of strong magnetic fields (required in Penning-Malmberg trap confinement) and cryogenic temperatures produces novel strongly magnetized and quantum plasma states with non-ideal Γ-factors that can be similar to those in the environment of highly magnetized neutron stars and white dwarfs.

Relevance and Benefits

Non-neutral plasmas were among the first plasmas studied or employed in industrial applications. Electron beams used in vacuum tubes, and later in high-intensity radiation sources such as magnetrons, gyrotrons, and travelling wave tubes are a form of non-neutral plasmas. Understanding collective non-neutral plasma dynamics and radiative interactions is essential to the continuing development of these radiation sources, as well as other vacuum electronics applications in both the nonrelativistic and relativistic regimes of operation.

The Penning trap configuration used in non-neutral plasma confinement is also used to stably confine charged particles for fundamental atomic physics studies, such as measurements of the g-factors (a measure of the magnetic moment and angular momentum) of elementary particles, as well as for high-resolution cyclotron mass spectrometry. Such Penning mass spectrometers are found in laboratories world-wide. The last decade has seen the development of new science involving low-energy non-neutral *antimatter* plasmas (i.e., positron plasmas or antiproton plasmas) at energies ranging from 100 eV to less than 10^{-3} eV. Much of this progress has been driven by the development of new plasma-based techniques to accumulate, manipulate, and deliver antiparticles for specific applications.

The ability to precisely control and manipulate cryogenic non-neutral plasma crystals has made them attractive systems for use in quantum information studies, which have blossomed over the last decade. Pure ion crystals consisting of up to several hundred trapped ions are now used to form lattices of quantum q-bits whose interactions and entangled states can be controlled and manipulated using lasers and microwave signals. These non-neutral plasma crystals are among the most promising technologies for quantum computation and quantum simulation.

More generally speaking, the research in this area of fundamental plasma physics has strong interdisciplinary connections, contributing to and borrowing from the wider world of plasma physics, atomic physics, fluid dynamics, astrophysics, soft condensed matter physics, and statistical physics. Using results from non-neutral plasmas, fundamental questions are being addressed in all of these broader areas.

The U.S. non-neutral plasma community collaborates with many groups outside the United States on a variety of physics projects. Perhaps the largest international collaborative effort is the CERN (European Organization for Nuclear Research) based effort to produce and study trapped cold antimatter such as antihydrogen (made of a positive positron and a negative anti-positron). Another international collaboration involves the production and magnetic confinement of a neutral positron-electron plasma. The U.S. non-neutral plasma community is also active in the world-wide efforts to trap charged particles for a variety of purposes, including spectroscopy of trapped high atomic number ions, metrology, quantum information studies, and high-resolution mass spectrometry of trapped radionuclides.

Progress and Achievements

In the past decade, non-neutral plasmas have continued to provide a rich source of fundamental physics advances across several areas. Below are a few highlights of recent work.

- Laser-cooled cryogenic pure ion plasmas have been a productive testbed for theories of plasma transport properties over the years. Recently they were employed to experimentally determine, for the first time, the Salpeter enhancement to nuclear reaction rates in plasmas for $0 < \Gamma < 20$. (The rates of nuclear reactions are enhanced by a surrounding plasma that leads to the lowering many-body Coulomb barriers.) This enhancement is predicted to increase the rate of nuclear reactions in astrophysical plasmas by orders of magnitude for $\Gamma > 1$, but has not until now been observed in experiments. The experiments supported the Salpeter theory while challenging competing dynamical screening theories.
- The dynamics of 2-dimensional (2D) inviscid incompressible fluids have been studied in non-neutral plasma experiments with Reynolds numbers as high as 10^5. These experiments enabled precise control and characterization of non-equilibrium and even turbulent 2D flows. Recent studies have focused on vortices driven by external time-dependent shear flows, characterizing several novel effects including vortex stripping.
- Neoclassical transport in magnetized plasmas is a form of cross-magnetic field transport of particles, momentum, and energy that is enhanced by symmetry-breaking magnetic and electric field “errors”. Such errors are inherent in many plasma experiments. This transport can induce damaging losses of energetic particles in fusion devices. Non-neutral plasmas provide an excellent testbed for neoclassical transport studies since these plasmas can be confined without the turbulent fluctuations that mask the effect in conventional plasmas, and controlled symmetry-breaking fields can be applied. Recent theory and experimental work have led to breakthroughs in understanding neoclassical transport in fusion plasmas.
- Antihydrogen atoms created through the controlled mixing of cryogenic non-neutral antiproton and positron plasmas, have been trapped and studied. Directly measuring differences, if any, between matter and antimatter atoms may help us understand why the Universe is made up almost entirely of matter when both matter and antimatter should have been produced in equal amounts in the Big Bang.
- Quantum simulation of spin models can provide insight into problems that are difficult to study with classical computers. Trapped ions have recently been shown to be a practical system for carrying out such simulations. Experiments have studied the quantum spin dynamics in a 2D ion crystal consisting of several hundred ions in a Penning trap geometry. Good agreement with ab initio theory lays the

groundwork for simulations of more complex interactions (e.g., transverse-field Ising models with variable-range interactions) that are generally intractable with classical methods.

Workforce Development

From the point of view of student education and workforce development, most non-neutral plasma experiments are table top or few-investigator devices compatible with university laboratories. As such they provide excellent training opportunities for experimental physicists by providing hands-on experiences. The overlap of non-neutral plasmas with atomic physics, condensed matter physics, astrophysics, and fluid dynamics makes this area attractive to both theory and experimental students with a range of interests and backgrounds. Undergraduates with minimal background in plasma physics can gain useful research experience.

Current and Future Science Challenges and Opportunities

Challenge 1: Understand and be able to predict plasma behavior under extreme conditions that challenge our present models.

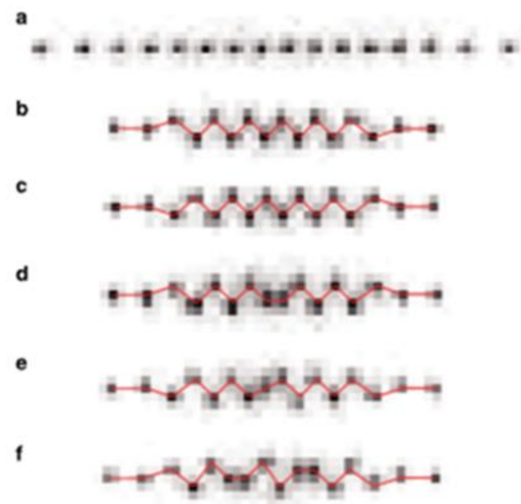


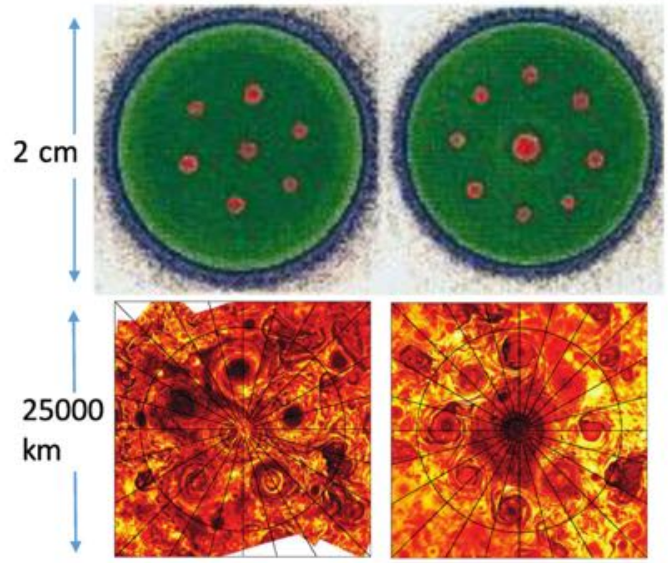
FIGURE 2.12 Defects induced in a 16 ion plasma crystal confined in a linear Paul trap, imaged using laser fluorescence. (a) linear phase. (b-c) zig-zag phases. (d-f) with different dislocations. 1 pixel = 1.7 micron. SOURCE: S. Ulm, J. Roßnagel, G. Jacob, et al., Observation of the Kibble–Zurek scaling law for defect formation in ion crystals, Nat Commun 4, 2290 (2013), https://doi.org/10.1038/ncomms3290.

Non-neutral plasmas can be cooled into the cryogenic regime of strong coupling, having $\Gamma >> 1$. Strong magnetic fields can be applied, such that the cyclotron radius of all species is smaller than even the distance of closest approach between particles. (This magnetization regime is difficult to achieve in "hot" neutral plasmas, requiring ultra-large magnetic fields exceeding 10^9-10^{10} Gauss.) Being able to sustain non-neutral plasmas under these extreme conditions poses science challenges: (a) What are classical and quantum non-equilibrium transport coefficients in strongly coupled and strongly magnetized plasma (particle diffusion, thermal conduction, viscosity, collision rates)? (b) Progress in understanding the dynamics of defect formation and growth has been achieved in 1D plasma crystals confined in a linear Paul trap. (See Figure 2.12.) In this area bordering plasma and soft condensed matter physics, how do defects form and propagate in 2D and 3D plasma crystals?

Challenge 2: Quantify and, in the laboratory, control how plasma processes direct the conversion of energy from one form to another, the transfer of energy across a vast range of scales, and the transport of energy in the laboratory and nature.

The most fundamental energy and momentum transfer mechanisms in a magnetized plasma, collisional heat conduction and viscosity, are not fully understood. Recent experimental and theoretical work in non-neutral plasmas has shown that classical cross-magnetic field thermal conductivity and shear viscosity applies only to plasmas for which the plasma frequency is large compared to the cyclotron frequency. For plasmas where this is not the case (i.e., plasmas in strong magnetic fields), the classical

"Braginskii" coefficients (with transport coefficients to account for the effects of magnetic fields) may be incorrect by orders of magnitude. In fact, transport coefficients (thermal diffusivity and kinematic viscosity) are *independent* of magnetic field in this regime. The classical coefficients neglect transport induced by weakly damped waves carrying energy and momentum across the magnetic field. It has been predicted that such long-range wave-induced transport will dominate thermal conduction and viscosity in any quiescent plasma of sufficient size. Investigations of fundamental transport coefficients in non-neutral plasmas hold the promise of providing data required to develop theories of cross-magnetic field transport applicable to several problems in PSE.



2.13 *Cyclonic Self-organization* Vortex crystal states were first observed to spontaneously form from relaxing 2D turbulent flow in an electron non-neutral plasma, shown in the top image. Similar cyclones have been observed at the north and south poles of Jupiter forming apparent vortex crystal states. There are opportunities to develop scaling laws in laboratory non-neutral plasmas that may be applicable to planetary scales. SOURCE: (top) Phys. Rev. Lett. 75, 3277, 1995; (bottom) Magnetized Plasma Research Laboratory, Auburn University.

Challenge 3: Predict self-organization of plasmas and, where needed, control that self-organization.

One of the phenomena most difficult to explain in Nature is the appearance of order out of disorder. Turbulent hot plasmas are arguably one of the most disordered "high entropy" states of matter that can be achieved; and yet it is possible for ordered states to appear spontaneously in such systems. One way this can occur involves a "backwards flow" (inverse cascade) of energy from fine scales in the turbulence to larger scales, through the merger of nearly 2D vortical structures into ever-larger size scales. One example is the appearance of "vortex crystals" from decaying 2D plasma turbulence, first documented in pure electron plasma experiments. (See Figure 2.13.) A similar inverse cascade is responsible for Earth's jet stream and the H-mode that appears in fusion reactors, both of which are self-organized large-scale flows arising from a finer-scale incoherent turbulent background. Recently, vortex crystal states have been observed in the atmosphere of Jupiter, having formed spontaneously from the driven turbulence of Jupiter's atmosphere. Advances in our understanding of inverse cascade produced self-organization from non-neutral plasma experiments and theory will have wide applicability, from fusion plasmas to atmospheric dynamics for earth and planets.

Challenge 4: Control and predict the interactions between plasmas and solids, liquids and neutral gases.

Non-neutral plasmas are typically confined away from contact with liquids and solids. An exception to this rule is in the use of low-energy monoenergetic antimatter beams as a probe of solid materials, and for use in studies of the interaction of antimatter with individual neutral atoms. These studies rely on ongoing advances in positron plasma control and confinement. Non-neutral plasma–gas interactions are also of importance in a number of other contexts. For example, the collisional drag between the plasma and background neutral gas can limit the plasma confinement time, heat (or cool) the plasma and cause deleterious effects such as decoherence in quantum information studies. This particular process is for the most part well-understood. However, the chemical reactions that can occur between plasma charges and background gases are not well understood. These reactions, such as charge-exchange collisions and charged molecule formation and break-up, are of interest in a number of contexts, including the reactions occurring in low temperature molecular clouds in interstellar space. Some of these reactions are predicted to have timescales of hours or days, depending sensitively on the plasma temperature and density, and therefore are very difficult to measure by standard means. However, in a non-neutral plasma where the charges are confined for days or weeks, such measurements are possible. The appearance of new charged ion species could be measured in situ using the newly developed method of ion cyclotron thermal mass spectroscopy, or in some special cases by means of laser fluorescence diagnostics. This is another example of where fundamental studies of non-neutral plasmas have impact well beyond the laboratory and, in this case, to interstellar astronomy.

PLASMA INTERACTIONS WITH LIQUIDS, SOLIDS, AND GASES

Fundamental plasma research is often focused on the physics of waves and instabilities, which are properties of the bulk plasma far from boundaries. In fact, in these studies the edge effects produced by boundaries in laboratory plasmas are undesirable. However, laboratory plasmas are intrinsically bounded and the bounding interface can have a huge impact on the plasma properties. Although plasma boundary interactions may be undesirable in the context of studying bulk properties, plasma-boundary interactions are the basis of nearly all plasma materials processing, plasma based biomedical applications and plasma enhanced environmental stewardship. The fabrication processes used in the optics, solid-state lighting and microelectronics industries are based on plasma-boundary interactions. The importance of solid interfaces in plasmas can even be extended to space plasmas where the presence of dust provides a plasma-solid interface.

The science challenges more closely aligned with technologies using plasmas are discussed in Chapter 5. From a fundamental perspective, why are plasma-interfacial interactions so important and why can they have a dominant impact on plasma behavior? *Plasma-interfacial interactions can be highly complex due to the possible strong coupling between plasma properties and the interfacing material surface properties*. This coupling can be due to different mechanisms depending on plasma and interface properties:

- Surfaces can act as electron sources upon ion or energetic species impact, surface heating or high interfacial electric fields induced by the plasma.
- Surface charging of dielectric interfaces can lead to enhanced or decreased electric fields near surfaces even leading to the possible extinction or generation of plasmas.
- Liquids have generally smaller energy barriers for species transfer at the interface and can therefore have a much more pronounced influence on the plasma state. Evaporation of the liquid phase induced by the plasma can dramatically change the gas composition near the plasma-liquid interface and so change plasma properties.
- The surfaces of liquids and soft matter can deform upon plasma exposure. These deformations can cause increasingly inhomogeneous electric fields and plasma self-organization.
- In reactive plasmas, the surface properties can be changed during plasma exposure leading to a continuous change in plasma-surface interactions.

The complex interaction of plasmas with solids and liquids leads to many interesting scientific questions including what happens to the structure and non-equilibrium properties of the plasma-solid/liquid interface during plasma exposure, and the transport mechanisms of charged and reactive species across the plasma-solid/liquid interface. The study of these interfacial processing involves in addition to plasma science solid state physics, material science, and chemistry, and is a highly interdisciplinary subfield of plasma science.

A significant part of the plasma physics community is concerned with studying collective phenomena in plasmas generated at very low pressure and in noble gases to reduce or even eliminate collisional effects. Nonetheless in many plasmas of interest, both atomic and molecular gases are present at significant densities or intentionally introduced. This leads to a rich spectrum of collisional processes and the generation of a multitude of species and chemical reactions. These studies have provided the foundation of many plasma-based applications and rely heavily on atomic and molecular physics. As collisional effects strongly impact the distribution of electron energies, reactions directly impact the plasma dynamics and electron kinetics leading to new plasma phenomena. An example is the recently discovered ultrafast gas heating mechanism in atmospheric pressure air plasmas due to rapidly dissociating, electronically excited molecules. Many of these collisional interactions lead to new plasma phenomena enabled by the enhanced complexity of collisional plasmas.

Variations in gas composition and densities can also have a strong effect on plasma dynamics and properties. An example of the use of changes in gas composition to control plasma generation is the so-called cold atmospheric pressure plasma jet, shown in Figure 2.14.

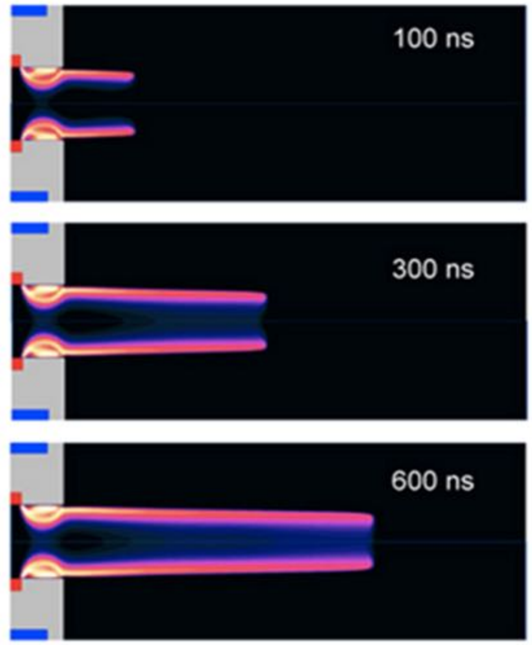


FIGURE 2.14 Model of a guided streamer. In the last decade cold atmospheric pressure plasma jets have been investigated for their use in biomedical applications and materials processing. The plasma is generated in a tube through which, for example, helium is flowed, leading to the formation of a helium channel surrounded by air outside the tube. The figure shows the electron density in a developing ionization wave, or streamer, in such a helium channel. As the ionization coefficient is much larger in helium compared to the surrounding air, a guided streamer is created by the gas channel and the surrounding air radially confines the discharge. SOURCE: J-P Boeuf *et al* 2013 *J. Phys. D: Appl. Phys.* **46** 015201.

Relevance and Benefits

Magnetic fusion: In fusion reactors, about 20% of the energy produced cannot be captured to produce electricity and is instead exhausted in the form of heat and plasma particles in the divertor area. The huge particle and energy flux, due to the high power density in fusion plasmas leads to unique plasma-material interactions making it a key challenge on the path to the development of fusion for sustainable electrical power generation. Plasma-material interactions, which include interactions between plasmas with solids as well as liquid interfaces at boundaries, is a very important area of research, with significant implications for the performance of fusion reactors. (See Chapter 6.)

Plasma-material synthesis and processing: Many plasma interactions with solid surfaces have been exploited for societal benefiting applications ranging from semiconductor processing and synthesis of nanostructured materials with unique properties to arc welding and the development of plasma-based medical applications. Plasma-material interactions are utilized as a key enabling technology in the semiconductor industry, a top 10 industry in the United States, serving a roughly $2 trillion electronics market. (See Chapter 5.)

Dusty (space) plasmas: Dusty plasmas are the embodiment of plasma-surface interactions as the highly dispersed solid phase leads to an exceptionally large surface-to-volume ratio. A better understanding of dusty plasmas will contribute to our understanding of star-forming regions as well as comets and planetary rings. Dust particles are also believed to play a key role in molecule formation in space as studied in astrochemistry.

Plasma-liquid interaction: In addition to its importance in magnetic fusion reactors where liquid walls are being investigated, plasma-liquid interactions have a vast array of applications ranging from water treatment to wound healing and material and chemical synthesis. In the last decade an extreme type of multi-phase plasmas has emerged, which can be seen as an equivalent of dusty plasmas, though with the dust replaced by liquid droplets or aerosols having sizes of a few microns to a mm. The "plasma-aerosol," a dynamic suspension of liquid droplets dispersed in a gas, encompasses a wide range of scenarios that can involve single microscopic droplets up to full sprays and jets while the plasmas themselves vary from non-equilibrium low temperature to thermal plasmas. Plasma aerosols enhance the transfer of activation energy from plasma to the liquid thanks to the large surface-to-volume ratio and the production of species in close proximity of the droplet surface. Demonstrated and potential benefits include on-demand delivery of designed micro/nanomaterials and delivery of short-lived species synthesis of high value chemicals, drugs and nanomaterials. Enhancing transfer of reactivity from plasma to aerosols will enable on-demand, point-of-use and energy efficient production and delivery of chemical activity, for fertilizer production, sterilization and indoor agriculture.

Progress and Achievements

There has been impressive progress in understanding of the interaction of plasmas with gases, liquids and solids over the past decade.

- Low temperature plasma (LTP) research has increasingly extended plasma-surface interactions studies from solid materials to liquids and soft matter. While our understanding is still limited, major advances in modeling and diagnostics have been made. This led, for example, to improved understanding of the role of solvated electrons and H radicals in plasma-liquid interactions and the role of plasma-produced species on plasma interactions with living matter. An example is the role of plasma-produced $O_2(^1\Delta)$, a very long lived electronically excited state of the oxygen molecule, in the oxidation of capsid proteins of virus and the potential role of $O_2(^1\Delta)$ selectivity of plasma-treatment of cancer.
- A detailed understanding of the influence of metal vapor in thermal plasmas, particularly in welding arcs, has been developed. Three-dimensional time-dependents models and spatially resolved time-dependent measurements have clarified the mechanisms driving metal vapor transport, and the influence of metal vapor on arc properties.
- The last 10 years have seen a move to more advanced control of power delivery and plasma kinetics leading to control of plasma-surface interactions at length scales of a single atom, an example being atomic layer etching. This process has been enabled by an increased knowledge of the underpinning plasma processes by a combination of modeling and diagnostics.

- The implementation of advanced diagnostics has enabled a broader understanding of the interaction of plasmas with polymers, including the role of UV photons and the effect of plasma-produced radicals on surface modification and etching.
- Boronization (or an equivalent, such as lithiumization), is the plasma deposition of a thin boron (or lithium) containing film on the inner walls of the fusion reactor chamber through the injection of boron into the plasma. Boronization has been used successfully in tokamaks for many years as a means of controlling impurities, oxygen in particular. However, the boronization process is poorly understood and undoubtedly less than optimal. Lithium micro-granule injection, often dubbed powder or aerosol injection, has been successfully investigated in fusion research demonstrating improvements in terms of wall conditioning and opening access to high performance scenarios.
- Multiple existing experiments are studying tungsten for first walls for fusion reactors in preparation for its use in ITER. However, the occurrence of melting in these experiments has been greater than expected. The extrapolation of tungsten erosion estimates to DEMO (the follow-on fusion reactor to ITER) indicate unacceptably short lifetimes for the plasma facing components. Concerns such as these have served to increase interest in the use of liquids as plasma facing materials. A flowing liquid surface would be melted by design and erosion and re-deposition would have no long-term effects. However, how liquid films survive real fusion machine environments is still unclear and a subject of much debate.

Current and Future Science Challenges and Opportunities

In view of the huge potential benefits of the interaction of plasmas with liquids and solids summarized above, research is supported by a broad set of programs and divisions within NSF, DOE and DOD that support materials or plasma research. While these diverse funding sources are in some respects a strength of the field, it has unfortunately led to a silo effect between studies focusing on plasma physics and on synthesis/material processing from a materials perspective. A key challenge in the next decade is to bring together experts in plasma science, materials research and chemistry to tackle the major science challenges highlighted below. *This will require coordinated initiatives between materials-focused and plasma-focused programs in federal agencies enabling advances in the science and technology of both fields, as recommended in Chapter 5.*

Challenge 1: Understand and be able to predict plasma behavior under extreme conditions that challenge our present models.

Materials for plasma-facing components are often exposed to enormous fluxes of energetic particles and energy corresponding to extreme conditions that are far from the conditions under which material properties have been studied. Similarly, extreme non-equilibrium plasma conditions can be achieved at the interface between low temperature plasmas and solids/liquids due to huge fluxes of energetic species at near room temperature. Our current understanding of these unique conditions is extremely limited and requires the development of detailed in situ diagnostics complemented with modeling efforts if our understanding is to improve.

Major efforts have also been devoted to study plasma generation in liquids requiring much higher electric fields than in their respective gases/vapors due to the significantly higher density of liquids. Recently, mechanisms have been formulated to explain plasma generation in liquid water without the need for bubble generation, complemented with experimental work reporting plasma produced pressures up to 1 GPa. This research is closely tied to many unresolved questions of the change in structure and properties of liquids under extreme conditions (such as high electric fields, pressure and temperature) and its ability to create extreme plasma conditions.

Another example of such a new scientific frontier are atmospheric pressure microplasmas that can lead to relatively high power density LTPs having microscopic dimensions. In some cases, LTP plasma densities can approach values typical of fusion plasmas (10^{14}–10^{17} cm^{-3}). While the electron temperature is of the order of a few eVs, the large surface to volume ratio leads to significant losses. This combination results in relatively low neutral gas and ion temperatures of about 0.1 eV. The interfacial region between the bulk plasma and the solid surface consists of a plasma sheath with dimensions ranging from a micron to tens of microns in which an intense electric field induces Fermi level shifts near the solid interface. These conditions can result in field emission of electrons and field ionization in some cases. The interaction of relatively dense and cold plasma with solid-state materials is a largely unexplored topic. The coupling between plasmas and surface increases for higher-pressure plasmas, and challenges remain in resolving the huge spatial gradients in species densities near interfaces.

FIGURE 2.15 *Self Organization in Plasma Liquid Interactions*. The interaction of plasmas with soft and liquid surfaces produces a feedback mechanism that leads to self-organization. In this image, an atmospheric pressure plasma jet sustained in helium enters room air and strikes a salt solution that serves as the anode. The plasma self-organizes on the surface of the liquid. These patterns often rotate or slowly evolve into different shapes. SOURCE: Y. E. Kovach, IEEE Trans. Plasma Science v47, p. 3214 (2019).

Challenge 2: Quantify and, in the laboratory control, how plasma processes direct the conversion of energy from one form to another, the transfer of energy across a vast range of scales, and the transport of energy in the laboratory and nature.

The key distinctive feature of LTPs is that energy coupling mainly proceeds through electrons in the bulk plasma and possibly ions in the sheath regions adjacent to surfaces. This leads to highly non-equilibrium plasma kinetics. The kinetic energy of electrons is transferred to atoms and molecules by collisional processes between electrons and neutral gas atoms and molecules. These collisions can lead to the generation of tens to hundreds of possible species depending on the gas mixture and electron energy distribution (EED). The control of ion energies striking surfaces is a dominant need in customizing plasmas for materials processing. The fundamental LTP challenge involves controlling the energy distribution of electrons to channel the energy deposition into the production of ions, excited, radical and reactive species that drive the desired processes in the gas phase or at interfaces. Similarly, controlling the distribution of ion fluxes to surfaces enables control of surface processes having energy thresholds.

The ultimate LTP challenge is achieving predictive control of the plasma initiated chemical processes. This is particularly complex due to the sensitive two-way coupling between the EED, and the gas composition, including the species produced through collision processes. Many plasma kinetics and chemistry models have been developed but a thorough experimental validation of models is the exception due to the large complexity of the composition of the plasma. Understanding complex molecular plasmas requires the development of validated predictive capabilities which in turn requires a large team and long-term efforts. This challenge includes developing highly controlled and accurate benchmark experiments. While recognizing the increased complexity due to the non-equilibrium nature of LTP, the community could highly benefit from establishing validated reaction sets complemented with benchmark

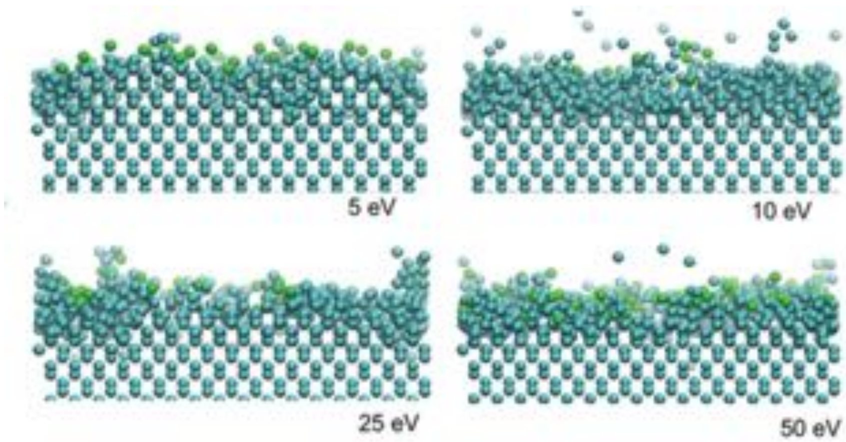


FIGURE 2.16 *Plasma surface interaction models* – Plasmas interacting with surfaces are key to the majority of applications of low temperature plasma leading to societal impact. Key processes as secondary electron emission are not well understood. Currently most plasma models use often experimentally determined coefficients to describe surface processes such as secondary electron emission without considering the underpinning atomic scale processes. Combining plasma models with atomic level models of the interface combined with new in situ surface diagnostics would enable us to move beyond an empirical understanding of plasma-surface interactions and enable us to apply our new understanding to a much broader class of plasma conditions and materials. These processes play a key role both in solids and liquids. In this image, molecular dynamics techniques are used to simulate argon ions (5-50 eV) interacting with a chlorine passivated Ge lattice for atomic layer etching (ALE). SOURCE: Phys. Chem. Chem. Phys., 2019,21, 5898-5902, https://pubs.rsc.org/en/content/articlelanding/2019/cp/c9cp00125e#!divAbstract.

experimental studies similar to GRI-mech used in the combustion community. This effort should be coupled to transport models and plasma-surface interaction models.

Challenge 3: Predict self-organization of plasmas and, where needed, control that self-organization.

As in many physical, chemical, and biological systems, self-organization is a common phenomenon at the interface between a plasma and a solid or liquid. While some aspects of the phenomena for specific cases are understand, currently the mechanisms responsible for self-organization in plasmas interacting with surfaces are not well understood. There is a need for the development of an overarching model explaining the large variety of often very similar self-organizing phenomena occurring over a broad range of pressures and power densities. Typically, self-organization occurs in the anode or cathode layer at the interface between a plasma and a resistive or dielectric medium, which could be a liquid. (See Figure 2.15.) When ionization fronts impinge on a dielectric surface the discharge tends to branch and develop surface ionization waves that can have self-organized patterns. There is a need to develop more comprehensive plasma models with detailed kinetics capable of predicting the occurrence of and transitions between these patterns. Detailed spatially resolved measurements other than fast imaging for model validation are also lacking. Similarly, while 3D simulations of ionization waves and streamers have been performed in the gas phase (see Chapter 5), surface ionization waves have only been very recently modeled and the intrinsic 3D phenomena of self-organization phenomena in surface ionization waves have not been addressed.

Challenge 4: Control and predict the interactions between plasmas and solids, liquids and neutral gases.

While *in situ* diagnostics for surface characterization during plasma exposure are emerging, a majority of material characterization to date is based on *ex situ* diagnostics where the material is analyzed after plasma exposure. The lack of *in situ* diagnostics adds an additional layer of complexity in the analysis and interpretation of the actual plasma-material processes. There is a strong need for the development of *in situ* diagnostics amenable to a harsh and complex plasma environment. This is absolutely critical as there is a lack of understanding of the basic processes underpinning many plasma-material interactions and there remains a need for model validation.

Significant progress has been made in plasma-surface interaction modeling. (See Figure 2.16.) However, comprehensive models with a two-way coupling of non-equilibrium kinetics in plasmas intersecting with interfaces address only specialized systems. The physical processes at the interface of a plasma and a solid or liquid are extremely complex, involving a large number of elementary processes in the plasma and in the solid as well as fluxes of energetic species across the interface. An accurate and unified theoretical treatment of these processes is very difficult due to the vastly different system properties on both sides of the interface: quantum versus classical behavior of electrons in the solid and plasma, respectively; as well as dramatically differing electron densities and length and time scales. Liquids provide additional challenges over solids as they can have a much more pronounced influence on the plasma state.

In many models of bounded plasmas, the surface processes are either neglected or treated using phenomenological parameters such as sticking coefficients, or sputtering rates and secondary electron emission coefficients given by simple theories. These parameters are known from measurements or fundamental, materials specific theories or computations only in specialized cases and with limited accuracy. Similarly, surface physics simulations are usually not linked self-consistently to the plasma. As a result, the collective influence of the plasma and correlations with surface processes are usually not accounted for. Such an approach does not account for the mutual influences between plasma and solid surface, and so do not have broadly applicable predictive capabilities. Integrated modeling of the entire plasma-solid/liquid interface is needed and is a major challenge for the plasma community.

FINDINGS AND RECOMMENDATIONS

The science challenges in basic plasma physics are immense and the opportunities to translate advances in fundamental plasma science to develop applications are strategic. Addressing these challenges and leveraging these opportunities requires the availability of a dynamic theory-based workforce. As endorsed in this report, computational PSE is critical to the future of the field. As a necessary complement to the effort in computational PSE, there is a need for supporting fundamental theory and developing a workforce of the future that is schooled and expert in theory.

Finding: The theoretical PSE workforce is not large enough to meet our current needs and will become even less able to do so in the future without deliberate measures.

Recommendation: In developing their research agenda, federal agencies supporting plasma science (e.g., NSF, DOE, DoD, NASA) should make deliberate efforts to support theory.

Finding: Investigations of fundamental plasma science provide the understanding of these complex processes that underpin the behavior of plasmas across the entire realm of plasma science and engineering (PSE). Studies of fundamental processes tie together seemingly disparate phenomena across the PSE discipline and provide a unifying perspective to the vast array of PSE applications.

However, basic plasma science investigations are often perceived as being separate from application-inspired research and are often funded separately. As a result, it is increasingly difficult for fundamental studies and applications to leverage each other's efforts.

Finding: A widening gap between fundamental studies and application-inspired research impedes progress in both fundamental studies and application-inspired research and slows the rate of translational research that leads to societal benefiting technologies.

Recommendation: Federal agencies that fund PSE should forge partnerships with other plasma-focused agencies as well as agencies focused on applications benefiting from plasmas (or programs within agencies) to close the widening gap between fundamental plasmas science research and translational research leading to applications.

This recommendation extends to partnerships between programs within a single agency (e.g., FES and BES within the DOE Office of Science). The committee specifically draws attention to the numerous examples of such partnerships listed in Table 1.1 in Chapter 1 for possible adoption of some of these potentially cutting-edge partnership projects.

Finding: There has been a general loss of broad collaborative activities within the PSE community over the last decade.

Finding: In both experimental and theoretical/computational areas, the creation of teams with the critical mass to address important and complex issues in basic plasma science are needed.

Finding: Center-type activities can provide opportunities that strengthen the overall health of the PSE community while providing important incubators for the development of the PSE workforce.

Recommendation: The DOE should broaden its support of Plasma Science Centers through recurring solicitations at critical funding levels to provide both new opportunities to advance important areas of plasma science as well as to improve the impact of the plasma science community.

Partnerships with other federal agencies are encouraged, and the committee refers to Table 1.1 in Chapter 1.

Finding: While many of the basic plasma science facilities are aging, the last decade has seen important investments in several new or expanded facilities in the range of $1 million to $4 million.

Finding: Many U.S. plasma science facilities were built during the last decade with funding provided by the NSF Major Research Instrumentation program, and many of these facilities provide opportunities for external researchers to conduct collaborative experiments with the host institutions. However, the experimental facility needs of different communities that are pursuing basic plasma science can vary widely.

For example, there are important collaborative, multi-PI research activities that may require significantly larger facilities. The recent *Report of a Workshop on Opportunities, Challenges, and Best Practices for Basic Plasma Science User Facilities* (2019) makes strategic recommendations on the types of facilities that are considered important enough to a broader science community to justify significant investment of resources.

Finding: Today, facilities at a spectrum of scales and reflecting the requirements for addressing different problems at the frontiers of plasma science (in the range $1 million to $20 million) are needed.

Recommendation: NSF, DOE, NASA, and other federal agencies with an interest and programs in plasma physics should provide regular opportunities for the continued development, upgrading and operations of experimental facilities for basic plasma science at a spectrum of scales.

There are several existing and planned laboratory user facilities that are able to address the challenges in basic plasma science described here. Currently, the primary mechanism for obtaining support for users of these facilities is through the NSF/DOE Partnership in Basic Plasma Science and Engineering (PBPSE). While many users have been successful in obtaining this support (typically 3-year grants), there are some projects that do not require a full 3 years of funding to be executed (e.g., performing a one-time experiment to validate a model or theory).

Finding: Many potential users of these experimental facilities would benefit from small levels of support to gain experience with and obtain initial data for *proof-of-concept demonstrations* that are usually expected in a full proposal to *PBPSE*. A mechanism to provide one time-short term funding to perform these experiments would address this critical need.

Existing funding models that might be used are the National Laser User's Facility (NLUF) program at the Laboratory for Laser Energetics at the University of Rochester and the Matter at Extreme Conditions (MEC) facility at the SLAC National Accelerator Laboratory. Coordination across existing user facilities would be beneficial in implementing this funding mechanism; a model that might be followed is that used by LaserNETUS.

Finding: In addition, to a shared funding resource for user support, a network of basic plasma science facilities might also coordinate on proposal selection, users groups, and outreach activities, thereby addressing the STEM pipeline into plasma science.

Finding: A network of basic plasma user facilities that would provide opportunities for access to new and upgraded plasma science facilities needs more coordination and support than currently exists.

Recommendation: Federal agencies, particularly DOE-FES and NSF-MPS, should implement a program for one-time, short-term funding for users of basic plasma science facilities.

Recommendation: A community wide workshop led by a partnership of DOE-FES and NSF-MPS should define the parameters and participation of such a program and network of user facilities.

For the most part, computation remains the province of experts. Most non-commercial simulation codes are primarily used by their developers and a small cohort that can be supported by direct access to the developers.

Finding: Plasma simulation is not optimally accessible to the wide range of potential users, including experimentalists and industrial users.

As more sophisticated hardware becomes available in the exascale era, codes that were developed using older technologies face an increasing technology gap and need to be ported to new architectures.

Finding: Funding agencies have not traditionally supported code usability to the extent needed to make research codes user-friendly, support users of codes, or to transition existing codes to new computing architectures.

Recommendation: Funding agencies, and in particular DOE and NSF, should support mechanisms for making computational plasma software more widely accessible to non-computing experts, and to transition current codes to new computing architectures.

For example, these agencies should examine the role for public-private partnerships that could make easily used software available on agency computers. In this regard, to make the broadest impact, open source software being sponsored by NSF and DOE should be accessible to the non-experts and useable on a broad range of computing architectures,

Finding: At the time of this writing, opportunities for machine learning (ML) and artificial intelligence (AI) that impact computations (and experiments) are only beginning to be realized. This is an extremely rapidly developing field. Leveraging these advances may require new approaches to computation.

Recommendation: To assure that PSE computations take advantage of advances in ML and AI, a periodic workshop should be held to share best practices, jointly sponsored by NSF, DOE and NASA.

Finding: There is a lack of modern educational and review material in computational PSE that addresses the methods of computation and how to make effective use of computations.

The latter above is becoming an even greater need as more of computational plasma physics transitions to a situation where fewer but more widely accessible codes exist, each with many users who are not necessarily the developers.

Finding: With the rapid growth of interdisciplinary research in plasma physics, it is time to consider the establishment of an annual journal that reviews major developments in all areas of plasma physics, much like the Annual Reviews of Astronomy, for example.

Recommendation: Computational PSE, supported by NSF, should include projects for writing textbooks and developing courses to train the current and next generation of computational plasma scientists, and to enable non-computer experts to make optimal use of computations.

3

Laser-Plasma Interactions: Compact Particle Accelerators, New Optics, and Brilliant X-Ray Sources

LEVERAGING AND CONTROLLING THE MOST INTENSE LIGHT ON EARTH

An ordinary lightbulb produces only a few to tens of watts of optical power. The Watts-per-unit area is a measure of its intensity, and for an ordinary lightbulb, the intensity even at the bulb's surface is at best tenths of a W/cm^2. The sun is an extremely powerful source of radiation. However, at the surface of Earth, 93 million miles from the Sun, the intensity of solar radiation is only 0.1 W/cm^2. Lasers (light amplification by stimulated emission of radiation) are devices that are capable of producing intensities perhaps beyond any source found in nature. An ordinary laser-pointer has a continuous intensity of about 1 W/cm^2. Industrial lasers used for cutting and welding may produce intensities of more than 100 kW/cm^2 in the desired spot size (cross sectional area of the laser beam) of only a mm in radius.

The greatest intensities are obtained from pulsed lasers or particle beams. These devices take a given amount of energy, and from that produce a very large power by putting all that energy into a very short pulse (power is energy/time). A 10 Joule laser having a pulse length of 50 fs (a fs, or femtosecond, is 10^{-15} seconds, a millionth of a billionth of a second) produces 200 TW of power (1 TW = 10^{12} Watts). Focusing that laser pulse to a small spot, say 50 μm in diameter, produces an intensity of more than 2×10^{18} W/cm^2. Such intensities immediately ionize any material, converting it to a plasma. When, subsequently, lasers with such high intensity are focused inside the plasma, an entirely new realm of physics opens up. This realm corresponds to the physics of the largest electric fields ever produced by humankind. This is the field of laser-plasma-interactions (LPI). In this field, there are many challenges, in controlling this intense light, in using this intense light (e.g., for acceleration of charged particles), and in generating light of even greater brightness (brightness controls the ability to focus the light to a given intensity).

Since high-intensity laser fields immediately turn anything into a plasma, plasmas are the only way to control and harness such laser fields. This has led to the new field of plasma optics, in which the plasma is configured to act as an optical element. By controlling the properties of the lasers and plasmas, the plasma can be used to scatter, absorb, reflect, focus and refract the laser light—much like conventional mirrors and lenses are used to manipulate ordinary light. Plasma optics also encompasses waveguiding, creation of atmospheric filaments, plasma compression, laser beam combiners and transfer of energy between laser beams. It additionally includes forming light with a structure that enhances or suppresses some particular effect. The plasma can be used to amplify and polarize lasers. Since the plasma can switch the state of light and can control unprecedented intensities, this field is often known as Plasma Photonics or the Nonlinear Optics of Plasmas (NLOP). (See Figure 3.1.) In the last 10 years, new methods of controlling sequences of laser pulses and laser bandwidth control, together with a new understanding of multi-beam interactions in plasmas, have transformed the field. NLOP offers the potential to mitigate instabilities that occur in laser driven inertial confinement fusion (ICF, covered in chapter 4), and to shape and control light. The fundamental challenge is: *How can plasma optics shape*

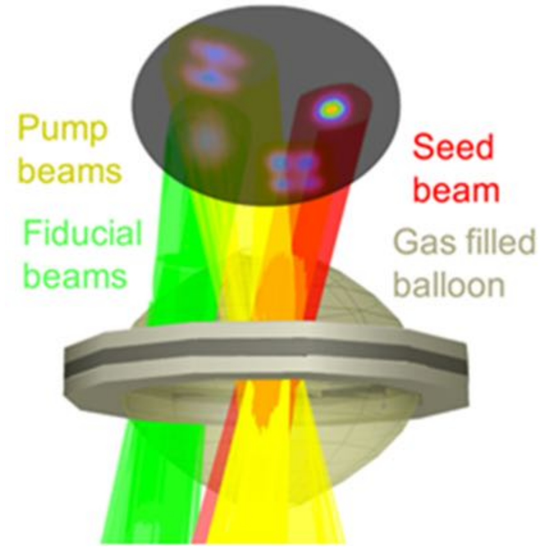


FIGURE 3.1 *Transferring energy between laser beams*. Recent advances in plasma optics have significantly improved laser beam performance. As shown in the image, multiple laser beams intersecting in a preheated gas plasma preferentially transfer their energy to a single red shifted beam. In experiments, more than 3 times the output power was produced than was present in any of the pump beams. This technique can be used to extend the beam power available in any single laser beam. More than 20 years of research has demonstrated the potential for plasma optics to provide higher performing beams. SOURCE: R. K. Kirkwood et al, Nature Physics, 14, 80, (2018).

and be shaped to manipulate controllably ultra-intense radiation, to enable laser conditions physics regimes, and applications unobtainable by conventional optics?

Harnessing the extreme fields of plasmas offers a new generation of compact particle acceleration methods. In the absence of a waveguide, an electromagnetic wave cannot continuously accelerate charged particles because the electric field is transverse to the direction of wave propagation, so that the accelerated particles leave the region of the laser field. However, the interaction of a laser pulse or particle beam with a plasma can generate longitudinal electric fields, so called wakefields, for which the generated electric field is oriented along the direction of propagation of the particle. The accelerated charged particles can move with the accelerating field for long distances, and consequently be accelerated to very high energies. (See Figure 3.2.) The rate of acceleration can be enormous, approaching 100 GeV/m. (1 eV is the energy gained by an electron falling through 1 volt of electrical potential.) For comparison, conventional accelerators like the linear accelerator at the SLAC National Accelerator Laboratory accelerated electrons to 50 GeV over 3.2 km, or 16 MeV/m, i.e., smaller by more than three orders of magnitude. There is a practical limit of around 100 MeV/m with conventional acceleration since for an electric field of that strength, electrons are pulled out of ordinary material. Now with the ability to control plasmas, wakefield acceleration is under consideration for the development of future high energy particle physics (HEP) colliders to extend our understanding of the basic laws of the universe. (A collider is a pair of accelerators that produce particle beams moving in opposite directions, that then collide head-on. At the current energy frontier, electron and positron colliders will need to be linear to reduce radiation losses from these light particles.) In another method, Direct Laser Acceleration, the particles interact with the laser fields nonlinearly in order to experience continuous acceleration. The existence of multiple acceleration mechanisms attests to the richness of this field. A community roadmap, the *DOE Advanced Accelerator Concepts Research Roadmap* [DOI: 10.2172/1358081], is guiding the field towards developing applications in the near term and addressing the challenging requirements of future colliders. A fundamental question is: *How can we control the interactions of ultra-intense (relativistic) lasers and particle beams with plasmas through shaping the laser fields and plasma profiles to efficiently generate ultra-bright, high energy charged particle beams?*

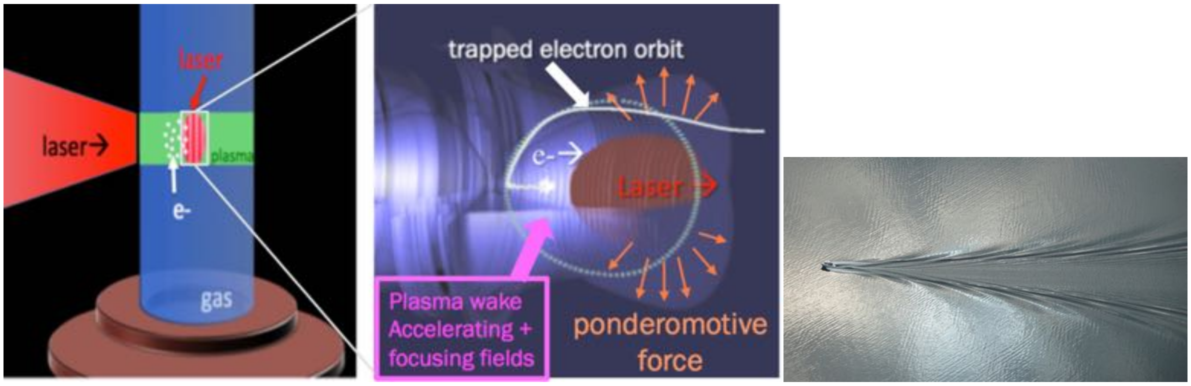


FIGURE 3.2 *Basics of laser particle acceleration*: (left) Compact high energy plasma wakefield accelerators are created when an intense short pulse laser (or charged particle bunch) driver is focused into a low density gas or plasma, such as for example into the plume of a gas jet. (center, showing inset). The driver propagates though the plasma and its radiation pressure (or space charge for a particle bunch) displaces electrons creating a density wave or 'wake'. Because the electrons and ions are separated, electric fields are created, which can be orders of magnitude larger than those achievable in conventional structures. The wake travels at the velocity of the laser, close to the speed of light, allowing it to trap and accelerate electrons to high energy. (right) Wakefield acceleration can be thought of as analogous to the wake of a boat, where the boat displaces water creating a height oscillation on whose gradient a rider can surf, gaining energy without use of a tow rope. SOURCE: Left to right: Courtesy of Cameron Geddes, Lawrence Berkeley National Laboratory; Courtesy Remi Lehe, Lawrence Berkeley National Laboratory; https://upload.wikimedia.org/wikipedia/commons/5/5c/Fjordn_surface_wave_boat.jpg, CC BY-SA 3.0.

Ion acceleration by the extreme electric fields produced in plasmas uses a different mechanism, principally acceleration by the plasma sheath, a region of strong electric field that forms at the edge of a plasma. In this method, the laser ejects electrons beyond the plasma, and the associated sheath accelerates (drags) the ions along to high energies. The goal is to produce compact, ultrafast sources of energetic ions. Optimizing this process requires a higher energy density in the plasma than is typical for wakefield acceleration of electrons. In the last 10 years, high gradient acceleration of ions by the sheath electric fields has been refined and new physics regimes have been developed. Radiation pressure and magnetic vortices have been investigated to provide high performance compact ion beams, which may be useful in medical therapy and for electric and magnetic field probes in high energy density (HED) plasmas. A fundamental question, in analogy with that of electron acceleration, is: *How can mechanisms of high density laser coupling and ion acceleration be understood and controlled to efficiently produce quasi-monoenergetic high energy ion beams?*

The electrons accelerated by LPI are a further source of very bright x-ray beams. The electrons oscillate transversely in the laser-induced plasma fields, and this transverse oscillation (called betatron oscillation) causes the generation of x-rays, just like oscillating current in an antenna produces radio waves. This light has very high brightness, which means that it can be focused down to greater intensities using less powerful lenses. (Brightness is a technical concept that is roughly the product of the beam angular divergence and the length scale of the light source.) Another mechanism to produce x-rays is to collide the accelerated electrons with yet another laser. In either case, one may generate bright x-ray beams in a device much smaller than current approaches that utilize large laboratory light sources. The resulting photons may reduce radiation dose and increase resolution for nuclear security, medicine and industry, as well as being diagnostics for HED science. The fundamental question is: *How can we understand, develop and control novel plasma-based radiation x-ray sources to enable new capabilities in imaging for medicine, biology, national security and physics diagnostics?*

The combination of high intensity lasers and particle beams in plasmas will open up new physics. One example is nonlinear high field Quantum ElectroDynamics (nQED) with collective plasma interactions. nQED describes how light and matter interact while incorporating both quantum mechanics and special relativity. Under conditions of very strong light intensity, it has been predicted that the light will spontaneously convert to matter and antimatter, in keeping with Einstein's famous equation $E=mc^2$. Over the past 10 years theoretical frameworks have been developed that predict specific signatures, show how newly developed laser and beam capabilities can be used for initial tests, and these can advance capabilities presently on the horizon. Work has been started to develop the required models and to integrate these into plasma simulations. Note that related opportunities in quantum and exotic states of matter are described in Chapter 4. The fundamental question is: *How to develop more complete theoretical models, with the computational capabilities to capture those models, and to design experiments for current and new laser capabilities to open up new physics frontiers?*

High-level science challenges for the field of LPI have been described in reports over the past decade, over the past decade, including the following: *Basic Research Needs for High Energy Density Laboratory Physics* (2009), *Frontiers in High Energy Density Physics: The X-Games of Contemporary Science* (2013), and *Workshop on Opportunities, Challenges, and Best Practices for Basic Plasma Science User Facilities* (2019), as well as the preceding *Plasma 2010* decadal study. These reports, and an ongoing two-year effort started in 2018 by the Department of Energy Office of Fusion Energy Sciences (DOE-FES) to establish a long-term strategy for the field, have provided key insights to this study. The areas addressing fundamental science challenges are intimately tied to rapidly developing advanced capabilities in high-intensity ultrafast laser facilities. These capabilities include increasing pulse energies, repetition rates and control, all enabling new areas of research. For example, chirped pulse amplification, the subject of the 2018 Nobel Prize in Physics, is the basic technique used to produce short (<10s fs), high energy (0.1–10 J) laser pulses, and has had particular impact in enabling higher laser powers. High-level laser development challenges have been described in recent reports, including *Workshop on Laser Technology for Accelerators* (2013), *Workshop on Laser Technology for k-BELLA and Beyond* (2017), and *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light* (2018).

Funding for laser-plasma optics, particle acceleration and laser sources is spread over several federal agencies. This funding is often mission or result focused rather than oriented towards investigating the basic science that underlies the applications. For example, DOE-HEP funds development of laser-plasma wakefield acceleration (LWFA) and particle beam driven plasma wakefield acceleration (PWFA) as a path to future lepton colliders and, under its Accelerator Stewardship program, also addresses mid-term applications of high-intensity lasers. DOE-FES funds ion acceleration and plasma optics as part of its stewardship Discovery Plasma Sciences (DPS). DOE-NNSA funds laser-plasma interactions with emphasis on coupling for ICF and HED science experiments. NSF funds broad basic research in all of these areas, including as part of the NSF/DOE Partnership in Basic Plasma Science and Engineering. The Naval Research Laboratory (NRL) has a broad internal program in LPI. The Air Force Office of Scientific Research (AFOSR) funds internal and university projects on LPI and formation of plasma filaments. Other offices within DOE, such as Basic Energy Science (BES), have occasionally funded projects relevant to LPI, such a free electron laser (FEL) development. There are many opportunities for these agencies to coordinate and collaborate on supporting both the fundamental science and translating that science to applications. This coordination and collaboration will be to the betterment of the science and the application.

There are strong linkages of LPI across plasma science in the underlying physics, applications, enabling capabilities, and methods (computations, diagnostics). Plasma physics linkages include resonant excitation processes and control of the particle-wave interactions that underlie accelerators and plasma optics. LPI can be accomplished with high precision and at high repetition rate at relatively modest cost compared to other HED systems. This provides the ability to flexibly manipulate and precisely measure states in plasma-wave-radiation interactions, and space-time control of such interactions, that can benefit other areas of plasma science. Access to high field physics, including nQED, has broad impact across science. Newly developed precision, ultrafast photon and particle sources can serve as high resolution probes and diagnostics for other plasma experiments (HED sciences, ICF), and potentially other areas such as Fusion Materials and Technology (FM&T), and magnetized experiments. Computational methods being developed for LPI have strong overlap across other areas of plasma science. These methods include particle-in-cell (PIC), direct-simulation Monte Carlo (DSMC), fluid and Vlasov methods for simulating acceleration; and 3D magnetohydrodynamics (MHD), fluid, and PIC-DSMC codes for analysis of irradiated targets. (See Figure 3.3.) Advances in computations needed to investigate the new LPI regimes include reduced and integrated models, the ability to capture comprehensive physics including wall and boundary effects. A further important need is to reduce barriers to entry for use of codes by non-experts. There are many opportunities for collaborations between programs focused on LPI and those science areas that would benefit from LPI capabilities. This coordination and collaboration will improve both the science and the application.

In the following sections, we discuss accomplishments, opportunities and challenges in the application areas of plasma optics, LPI acceleration of light particles, LPI acceleration of heavy particles (ions), bright x-ray generation and non-linear QED. The underlying science challenges to these applications areas include:

- What are the fundamental processes that occur during the interaction of ultra-intense (relativistic) laser pulses and beams with plasmas?
- How can we use these interactions to generate and control energetic particle beams, and enable new physics regimes, including addressing frontier HEP and nQED questions?
- How can LPI research be translated into compact photon and ion sources that offer revolutionary performance for medicine, national security and industry?

PLASMA OPTICS

Plasma optical techniques have been developed in the last decade that can control and improve LPI performance in regimes beyond those accessible by conventional means. Plasma-based optical components, already consisting of ionized gas, have substantially higher damage thresholds than solid state components and can be inexpensively and rapidly replaced, for instance, at the repetition rate of a gas jet or capillary. Similar to conventional optics, the time and spatially dependent phase of a laser pulse propagating in plasma is determined by the refractive index—and that refractive index is dominantly determined by the plasma density. By controlling the spatial variation, evolution, or nonlinearity of the plasma density, the plasma can produce dispersion, refraction, or frequency conversion. In principle, a plasma can be made to mimic any solid-state optical component.

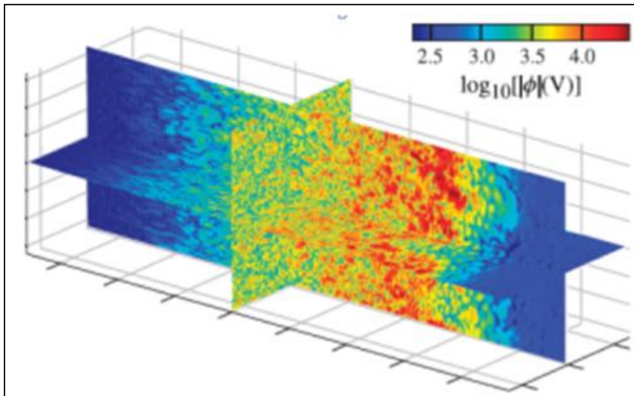


FIGURE 3.3 *Using simulations to understand LPI.* Simulations showing electrostatic perturbations driven by two-plasmon decay (TPD), a key laser-plasma instability in fusion experiments. The simulations were performed using the LPSE (Laser Plasma Simulation Environment). The effects of laser-bandwidth and pulse structure on TPD and more generally laser-plasma instabilities (LPI) could help control LPI and expand the ICF and HED science design space. SOURCE: Physics of Plasmas 24, 102134 (2017), https://aip.scitation.org/doi/10.1063/1.4998934.

Plasma optical components include plasma gratings; plasma waveguides that combat diffraction, extending the interaction length in LWFAs; and plasma mirrors, along with optical pulse shaping to enhance or suppress specific dynamics. These components can increase intensity contrast by orders of magnitude, allowing for impulsive laser-matter interactions nearly free of premature heating; and redirect laser pulses in multi-stage LWFAs without degrading electron beam emittance. This advance resulted from improved understanding of and ability to shape laser-plasma interactions. As such, control of high intensity laser pulses is enabled in ways not otherwise possible. In turn, these new methods allow excitation and control of plasma states both for investigation of fundamental physics and applications.

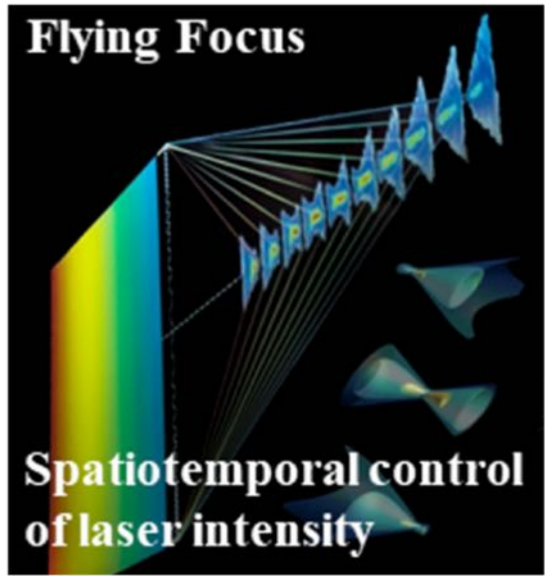


FIGURE 3.4 *Focusing on the fly*. A chromatic focusing system coupled to a spectrally chirped laser pulse can be used to generate a "flying focus". This is a structure that enables a laser's peak intensity to propagate over long distances and at any velocity—including faster than the speed of light. A flying focus is produced by creating plasma lenses that focus colors at different distances with a chirped laser beam (a laser with colors that change in time). Combining such novel optical designs with plasmas is opening opportunities for laser-plasma applications including acceleration and amplification. SOURCE: Image courtesy of Dustin H. Froula, University of Rochester.

Progress and Achievements

Inertial confinement fusion (ICF) was one of the earliest applications to harness high-power lasers. The field has implemented innovative optical techniques that produced step-changes in performance. These techniques include efficient optical frequency tripling, spatial coherence control (phase-plates), and induced temporal incoherence (e.g. Induced Spatial Incoherence, ISI, and Smoothing by Spectral Dispersion, SSD). Techniques that take advantage of the bandwidth available on current laser systems have been developed that can inhibit low-frequency laser-plasma instabilities that are detrimental to ICF. For example, stimulated Brillouin scattering (SBS) can be avoided by detuning the interaction between multiple laser beams or to move speckles before the instability can grow.

ICF experiments must still navigate around laser-plasma instabilities, the consequences of non-uniform laser illumination and damage by scattering laser light into unwanted directions. Such instabilities can generate super-thermal electrons that preheat the fusion fuel, reducing its compressibility, and seeding instabilities. Plasma optical manipulation of plasma states, including use of bandwidth or STUD (spike trains of uneven duration and delay) pulses, provide solutions to these issues. The emergence of high-power, high-repetition-rate (> kHz) ultrashort pulse lasers enables creation and investigation of nonlinear propagation and material interactions governed by a combination of non-thermal and thermal modifications to matter.

Shaping of the optical drive of the plasma has been extended to techniques that control the apparent velocity. This opens new regimes in exciting Raman amplification, photon acceleration, wakefield acceleration, and THz generation. Spatiotemporal shaping can produce laser pulses that appear to violate special relativity. The peak intensity of a self-accelerating light beam can follow a curved trajectory in space, while the peak intensity of a "flying focus" pulse can travel at an arbitrary velocity, surpassing even the vacuum speed of light (see Figure 3.4). These arbitrary velocity intensity peaks result from the chromatic focusing of a chirped laser pulse. (A chirped laser pulse has a frequency that is a function of time or space.) The chromatic aberration and chirp determine the location and time at which each frequency component within the pulse comes to focus and reaches its peak intensity. By adjusting the chirp, the velocity of the intensity peak driving the many plasma processes can be tuned to nearly any value, either co- or counter-propagating along the laser axis.

Propagation of an intense laser pulse in air balances self-focusing and ionization of the air to create extended plasma filaments. Plasma filaments are long, narrow strings of plasma whose non-linear properties (e.g., self-focusing) create more plasma having similar string-like properties. Experiments have shown that a train of laser pulses can heat air through a combination of thermal and nonthermal effects, such as thermal blooming, ionization and Raman excitation processes, leaving behind a long-lasting low neutral density channel that can guide subsequent laser pulses. This delicate multi-physics process has numerous applications, including enhancing the collection efficiency of photons for remote detection. In high-repetition rate laser-material interactions, a laser pulse will interact with matter than has been strongly modified by the non-thermal heating of previous pulses. This heating can create periodic surface structures, change the reflectivity and absorption, or alter the molecular composition altogether.

Orbital angular momentum (OAM) laser pulses can impart angular momentum to a plasma. This transfer of momentum can modify the topology and dispersion of the plasma waves produced by the laser and the phase space of the charged particles they accelerate. For example, a laser pulse with a helical intensity profile, or "light spring," can nonlinearly excite a wakefield that traps and accelerates a vortex electron beam—a beam that rotates around the optical axis. OAM can also modify the nonlinear propagation and interaction of high-power pulses with transparent media, resulting in helical plasma filaments or high harmonic radiation with vortex phase structure. Special phase plates are used to impart angular momentum to laser pulses.

Plasma laser amplifiers use multi-wavelength interactions to transfer energy from a long laser pulse seed to amplify a short laser pulse. Progress has been made in the amount of energy transferred and in the gain of the short pulse. The technique could eventually provide a final power-amplification stage for high energy applications or to operate in novel wavelength regimes.

Current and Future Science Challenges and Opportunities

Plasma-based optical components could provide the disruptive technology needed to usher in the next frontier of laser-plasma research. Plasma optics also has the potential to enable new capabilities in broader high-energy and high-average-power laser applications; and to enable guiding/steering and controlling x-rays in ways unattainable today. The unexpected features of the combination of structured light and LPI are relatively unexplored due to the technological challenges of creating such structured pulses. The further development of ultrafast pulse shaping techniques to manipulate the spatiotemporal optical properties of plasmas would bring about novel laser-plasma interactions.

Laser, target and diagnostic capabilities, together with simulation, are enabling understanding and control of plasma states that will enable plasma optical components to have increasing impact. Already, plasma waveguides are core parts of advanced particle accelerators. Other plasma optics components, while still in the early stages of development, have been successfully demonstrated in experiments that include: lenses, waveplates and polarizers, q-plates, beam-combiners, compressors, and amplifiers. Advancing these methods will provide access to new laser and plasma parameter regimes. A critical need to achieve these goals is the development of novel diagnostics that measure not only the bulk hydrodynamic properties of the plasmas but also the underlying particle distribution functions. Diagnostic accomplishments and needs are discussed below.

Concepts have been developed for further control of instabilities using broad bandwidth lasers. Broad bandwidth lasers for ICF could deliver pulses with the temporal incoherence necessary to suppress high frequency instabilities like two-plasmon decay and stimulated Raman scattering, while also providing smoothing to mitigate disruption of the capsule. Generally speaking, the broad-bandwidth mitigates laser plasma instabilities by detuning the interaction between multiple waves or incoherently drives many small instabilities instead of a single coherent instability. Bandwidth can also be used to coherently create controlled trains of shorter pulses (in the ps range) within the longer pulse envelope (in the ns range). If these manipulations can be performed faster than the growth of electron plasma waves, the train of pulses can be used to control the excited plasma state. This STUD concept, introduced above, opens the possibility of coherent laser control of plasma states and hence of laser coupling and transport. STUD and other sculpted time dependent wave structures could further be harnessed to drive far more controlled nonlinear responses in plasmas. Experiments using high repetition laser pulses aided by machine learning could identify time sequences and profiles of laser pulses that could tame the highly nonlinear kinetic and chaotic responses exhibited by plasmas driven strongly by laser beams over long periods of time. Such techniques could mitigate laser plasma instabilities by modulating the intensity to shrink individual hot spots and disperse hot spot patterns. This well controlled laser illumination could further help steer the flow of energy in plasmas to self-organized and self-sustaining states far from equilibrium or make and control plasma structures on demand to direct photons as in plasma optics.

Spatiotemporally structured ionizing laser pulses enable control over the velocity of an ionization front, thereby allowing the tailoring of the target plasma for acceleration. Controlling the plasma rise and fall and its width as a function of longitudinal distance allows improved matching of the pump laser pulse that creates the accelerating electric field and it controls the transverse focusing of the electron beam in beam-driven systems. There are numerous opportunities here for finding more optimal systems or new systems altogether.

Control of plasma optics is likely to advance several other plasma-based applications, including Raman amplification, photon acceleration, relativistic mirrors, and THz generation. Orbital angular momentum may offer an additional degree of freedom through which laser-plasma instabilities can be mitigated or controlled. As in cross-beam energy transfer, multiple interacting beams could drive a spectrum of plasma waves each with a different value of orbital angular momenta instead of a single coherent plasma wave with no angular momentum. A next-generation high-power laser with plasma optics could deliver extremely high intensity pulses with unprecedented control of plasma states and laser propagation. These methods could transform the landscape of laser-plasma interactions, from acceleration to fusion to applications such as remote sensing and X-ray sources.

PLASMA ACCELERATION OF LIGHT PARTICLES

Over the past decade, compact plasma-based accelerators have progressed from first demonstrations to a well-developed field. (See Figures 3.5-3.7.) These devices utilize the strong longitudinal electric fields present in laser or particle beam driven plasma waves to provide accelerating gradients (energy gain per unit length) that are orders of magnitude greater than those sustainable in conventional metallic accelerating structures. Electron bunches that are loaded (or injected) into the plasma wake of the driving pulse can gain energy at rates of 1-100 GeV/m. Milestones that were achieved prior to the previous *Plasma 2010* decadal survey included the injection and acceleration of plasma electrons in a laser-driven plasma wakefield accelerator (LWFA) in 2004. The electrons were accelerated up to 100 MeV over a distance of millimeters, producing a mono-energetic beam with tens of pico-Coulomb's (pC) of charge. In 2006, particle-driven plasma wakefield accelerators (PWFA) provided up to 30 GeV gain in energy to the most highly accelerated particles of a wake-driven electron beam over a distance of one meter. These experimental results were the outcome of decades of work since the inception of the field in the late 1970s, and demonstrated clearly the promised large accelerating gradients. In the ensuing decade, the field has grown significantly and great progress has been made toward realizing the first application-ready plasma accelerators. There have been multiple demonstrations that achieve nearly 10 GeV of energy gain in a single LWFA and PWFA. Several sophisticated techniques have been developed to improve the quality of the outgoing electron bunches. Based on the promise shown by plasma accelerators, the DOE roadmap *Advanced Accelerator Development Strategy Report* was developed in 2016 that provides a plan for realizing plasma-based high-intensity X-ray photon

FIGURE 3.5 *Laser Acceleration of Electrons to 8 GeV*. (left) Compact high energy laser-plasma wakefield electron accelerators are created when an intense short pulse laser is focused plasma, here created in a capillary tube. Scaling to higher electron energies requires longer plasmas at lower plasma densities, which in turn requires new techniques for guiding the laser pulse. (center) Use of a laser to locally heat a capillary discharge plasma steepens the radial plasma density profile, enabling guiding at lower density and over longer distances. (right) This improved capability enabled production of 8 GeV electron beams at Lawrence Berkeley National Laboratory in just 20 cm of plasma, an energy conventional linear accelerators would require the better part of a kilometer to produce. SOURCE: Courtesy of Anthony Gonsalves, Lawrence Berkeley National Laboratory; middle image from Gonsalves et al., Phys Rev Letters 122, 084801 (2019).

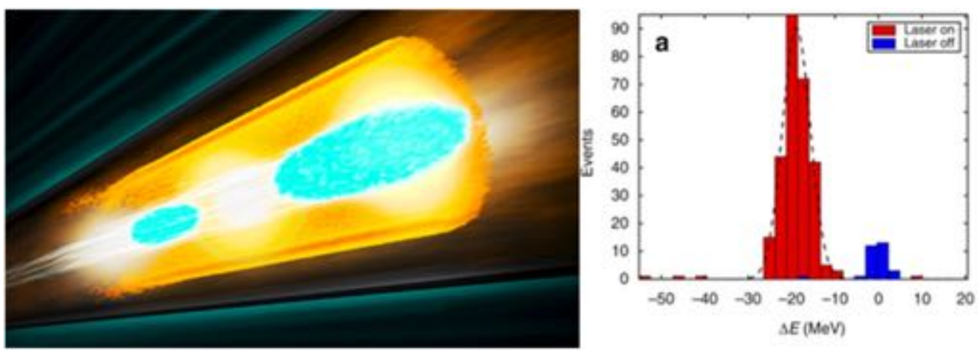


FIGURE 3.6 A *hollow channel plasma wakefield accelerator.* (left) Image of a bunch of positrons (blue), the antimatter siblings of electrons, travels down the center of a tube of plasma (orange), and creates a wake in the walls (shaded orange) which accelerates a trailing positron bunch. (right) Data from SLAC FACET experiments shows an energy loss in the driving beam consistent with a high field of 230 MV/m excited in the plasma channel. The process will also work using a laser or electron driver and a positron witness bunch. The experiment is being used to engineer the plasma in a way that de-couples the accelerating and focusing forces to provide a path for high-gradient stable positron acceleration. SOURCE: Left: Courtesy of Greg Stewart, SLAC National Accelerator; right: S. Gessner, E. Adli, J. Allen, et al., Demonstration of a positron beam-driven hollow channel plasma wakefield accelerator. Nat Commun 7, 11785 (2016), https://doi.org/10.1038/ncomms11785.

sources and ultimately, a plasma-based high energy physics collider. A TeV-class electron-positron collider based on plasmas would potentially reduce the size of the machine from tens of kilometers to hundreds of meters, and with lower cost.

Progress and Achievements

Plasma-based accelerators are now able to regularly provide multi-GeV energy gain to mono-energetic beams of 100 pC to 1 nC in a single plasma accelerator. (An electron bunch of 1 pC of charge contains 6 × 10^6 electrons. A 1 nC bunch contains 6 × 10^9 electrons.) LWFAs have utilized high peak-power laser systems (100 TW to 1 PW) fired into plasma sources that are centimeters in length with plasma densities of ~10^{17} to 10^{19} cm^{-3}. PWFAs used up to ~20 GeV electron drive beams with ~1 nC of charge in plasma sources roughly 1 meter in length with plasma densities of ~10^{16} to 10^{17} cm^{-3}.

Several laboratories are now able to regularly accelerate 10–100 pC of charge to energies of 10–100 MeV in multi-millimeter-length, high-density gas jet plasma sources using laser pulses with a more modest peak power (10–100 TW). These LWFAs often rely on the relativistic self-SPU focusing of the laser pulse in the high-density gas jet to achieve laser intensities that would be inaccessible by other means. Such gas jet LWFAs, though more modest in terms of energy and beam charge, have led to vibrant and growing plasma accelerator research at university laboratories the world over. While national laboratories have continued to carry out most of the research at the energy frontier, much of the fundamental physics research has been conducted at smaller university laboratories. This synergistic research has, in turn, rapidly increased the pace at which the field is advancing.

The record for energy gain in a LWFA was set at the BELLA (Berkeley Lab Laser Accelerator) facility at Lawrence Berkeley National Laboratory (LBNL) in 2019, accelerating about 10 pC of electrons from rest to 8 GeV in a 20 cm-long capillary discharge plasma source, driven by a ~0.85 PW laser pulse. This result was achievable thanks in large part to the development of an advanced capillary discharge plasma source that provided a guiding channel for the wake-driving laser pulse. (See Figure 3.5.) The plasma waveguide was generated by pre-heating the discharge plasma column with a separate nanosecond laser pulse ahead of the femtosecond wake-driving pulse, deepening the channel that is formed naturally through hydrodynamic expansion of the initial plasma filament. This structure enabled guiding of the wake-driving pulse over a longer distance, thereby increasing the total energy gain of the electron beam.

The highest energy gain achieved for a low energy spread PWFA bunch was at the Facility for Advanced Accelerator Experimental Tests (FACET) at the SLAC National Accelerator Laboratory in 2015. This demonstration provided 9 GeV of energy gain to ~100 pC electron bunch with an initial energy of 20 GeV in a 130 cm-long lithium heat pipe oven plasma source driven by a 20 GeV, ~1 nC electron bunch. The energy transfer efficiency from the driver to the accelerated beam was as high as 30% in the FACET PWFA experiments. This efficiency is a critical parameter in determining the power cost for future high energy, high repetition rate applications. Coupling of two high-energy LWFAs (known as "staging") was demonstrated for the first time at BELLA in 2018 by refocusing the electron beam between the two plasma stages with an active plasma lens. (See Box 3.2.) This provided roughly double the energy gain to the electron beam compared to the acceleration received in a single plasma stage. The ability to perform efficient staging is also critical to future high energy applications in order to reach the final target energy. Overall, great advances have been made in the past decade in providing high energy gain with low energy spread for a significant level of charge in both laser-driven and particle beam-driven plasma accelerators.

Significant strides have also been made in improving the quality and stability of the accelerated beams. (See Figure 3.7.) The quality of the accelerated electron beam in a LWFA or PWFA is determined by the trapping and focusing dynamics in the plasma wake. There are multiple methods of controlling the electron beam injection process to produce output electron beams with minimal energy spread and emittance. (Minimizing emittance means containing electrons in the smallest volume in the 6-D phase space of spatial coordinates and velocity.) In these techniques, background electrons move from untrapped orbits that are part of the fluid motion sustaining the plasma wave to trapped orbits comprising the accelerated electron bunch. Laser-based and density-gradient-based triggering of particle trapping has been a topic of active research and has enabled a continuous improvement in beam quality. Energy spreads of less than 1% in the accelerated beams and emittances of less than 1 mm-mrad have been regularly achieved, comparing favorably with conventional accelerators.

SLAC's FACET facility was able to provide high energy (20 GeV), high charge (~1 nC) positron beams in the past decade and used them to explore the acceleration of positrons in beam-driven PWFAs. Positron bunches were successfully accelerated in a hollow channel PWFA, producing a few hundred MeV gain in energy. (See Figure 3.6.) To achieve this outcome, custom diffractive optics focused a ~1

TW laser pulse into a non-diffracting, high-order Bessel intensity pattern that was sustained over tens of centimeters to ionize a tube of neutral gas in a flooded vacuum chamber, thereby forming the hollow channel plasma source. The transverse wakefield theory was studied and confirmed by inducing transverse kicks to the beam prior to entering the hollow channel PWFA. In another experiment at FACET, a single, high energy (20 GeV), high charge (~1 nC), short (~30 µm) positron bunch was launched into a 30 cm-long lithium heat pipe oven plasma source. The results surprisingly produced a mono-energetic positron beam that gained several GeV of energy, revealing a previously unpredicted regime of non-linear positron PWFA physics. With the assistance of particle-in-cell (PIC) computer simulations using the code QuickPIC, the dynamics of this interaction were understood. The mechanism was shown to rely on a longitudinal and transverse self-loading of the wake by the positron beam.

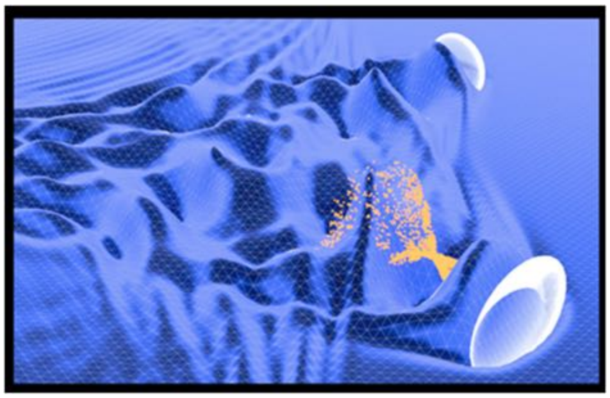


FIGURE 3.7 *Injecting particles in a Laser Plasma Accelerator.* Plasma accelerators are driven by plasma waves at the tens of micron scale, creating the need for new methods to inject the particles that will be accelerated. Injection methods include several techniques using multiple laser pulses and/or density structures to create the injector inside the plasma. Here a simulation shows injection of particles (yellow) via interaction between the plasma wakes (blue) driven by two laser pulses (white) modeling experiments at the Extreme Light Laboratory, University of Nebraska, Lincoln. Such methods promise unprecedented acceleration phase control, as well as the injection of electrons into multiple accelerator buckets. SOURCE: Courtesy of Grigory Golovin and Donald Umstadter, University of Nebraska-Lincoln.

At CERN (European Organization for Nuclear Research), the Advanced Proton Driven Plasma Wakefield Acceleration Experiment (AWAKE) experiment demonstrated the ability to accelerate electrons in a high-energy proton beam-driven plasma wakefield accelerator (PDWFA). The motivation for building such a machine is to take advantage of existing infrastructure to produce high energy, high charge proton beams and to transfer that energy to an electron beam over a relatively short distance. This approach could produce lepton collisions at high energy without the need to build a new, 30 km long linear accelerator that would be needed if using conventional technologies. Another attractive feature of the PDWFA is that it requires only one (albeit long) plasma stage, avoiding the complications associated with staging. A challenge of PDWFA is that the drive beam needed is significantly longer than the wake period.. The problem is mitigated by inducing a laser-triggered beam-plasma instability that segments the proton beam into "bunchlets" that are spaced at the plasma period, thereby creating a wakefield train that can then be loaded with a train of electron bunches to be accelerated. Another challenge presented by PDWFA is the efficient coupling of an electron beam into the plasma accelerator. In spite of these challenges, a proof-of-principle experimental demonstration has been accomplished, with the acceleration of ~10 pC of electrons by 2 GeV over a distance of 10 m.

A key to successful plasma accelerator applications is the ability to produce bright (i.e., high charge, high energy, low emittance, low energy spread, ultra-short) electron beams. The outsized longitudinal electric fields in plasma accelerators can serve to achieve this goal through the process of controlled electron beam injection. The main principle of injection in a plasma accelerator is to trap a dense, small cluster of electrons in the plasma wake and to accelerate them to ultra-relativistic speeds as quickly as possible. Plasma electrons can be directly trapped in the breaking plasma wave at the rear of the wake bubble, a region where plasma electrons are completely evacuated. However, the stochastic nature of this process often leads to significant fluctuations in the properties of the beam that is produced. Researchers have therefore devised and begun experimenting with various forms of controlled injection.

One such method is to produce a sharp "density downramp"—that is, a rapid longitudinal decrease in plasma density near the start of the plasma source. This results in a rapid elongation of the plasma wake, permitting local plasma electrons to be preferentially trapped and suppressing the subsequent trapping of additional electrons further downstream. Another method utilizes a plasma source generated by a lower ionization threshold (LIT) gas, such as hydrogen, to form the plasma accelerator in the presence of a background of neutral high ionization threshold (HIT) gas, such as helium. A wake driver is sent into the LIT plasma source, and a small volume of the HIT gas is ionized directly inside the blowout wake following the driver. (The blowout regime refers to plasma electrons being completely exclude from bubble-like region behind the wake driver.) The ionized HIT gas electrons are then trapped and rapidly accelerated to produce an ultra-high brightness beam. Ionization mechanisms that have been used in such experiments include a dedicated laser pulse, and the strong electric fields of the wake-driving electron beam.

There are now many university laser labs capable of carrying out fundamental LWFA research, and a growing number of national laboratories throughout the world with facilities appropriate for—and in many cases solely dedicated to—energy-frontier plasma accelerator research. Petawatt laser systems to be used for high-energy LWFA research in the next decade, include BELLA at LBNL, ZEUS/Hercules at University of Michigan, DIOCLES at the University of Nebraska, and the Texas Petawatt Laser System at the University of Texas at Austin, as well as many facilities in Europe and East Asia. High energy PWFA research facilities in the next decade will include FACET-II at SLAC, the Advanced Test Facility (ATF) at Brookhaven National Laboratory, FLASHForward at DESY (German Electron Synchrotron), and AWAKE-II at CERN. There is ongoing research at various 100 TW-class LWFA laboratories and lower energy accelerator facilities. This increases access for universities, to facilitate a more widely distributed base of fundamental research on LWFA, PWFA and PWFAs driven by LWFA electron beams.

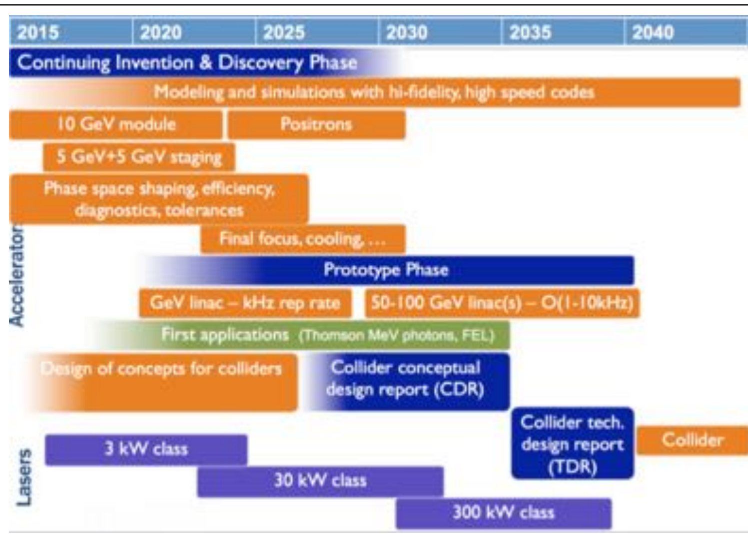
Sophisticated diagnostics have been developed to more directly probe the plasma accelerator itself. One of the more commonly used techniques, typically referred to as "shadowgraphy", analyzes the phase pattern imprinted on a low energy, ultra-short laser pulse by the plasma. This can be used to study the plasma source profile prior to the arrival of the wake driver, though more advanced co-propagating schemes have been able to study the structure of plasma wake itself. The latter application currently represents the most direct method of observing these speed-of-light wakes, and their use will likely expand in the coming decade.

Due to the great challenge of developing and applying experimental diagnostics for plasma accelerators, theory and computer simulations have been a cornerstone in the research portfolio over the past decade. Various PIC and related codes, including OSIRIS, VSim, QuickPIC, WARP, and EPOCH, have provided deeper understanding into the physical processes than could have been gained otherwise. These tools have been used both to design experiments and to interpret experimental results. Computer simulations have also played a major role in studying the limits of the capabilities of plasma accelerators, helping to shape the research roadmaps and community consensus on where to prioritize research efforts. As the power of parallel and device-based (GPU) computing has increased over the years, so too has the speed of the major codes. The concurrent improvements in computing hardware and in advanced algorithms that are able to take advantage of the new hardware have permitted simulations of exceeding high detail and scope. The quality and scale of these simulations would have been difficult to predict in the prior decade.

Current and Future Science Challenges and Opportunities

The major milestones that are likely to motivate and guide the next decade of plasma accelerator research include the production of high quality electron beams that can be utilized for X-ray free electron lasers (X-FELs) and other photon sources. These would be electron beams with sufficient control and reproducibility that they can be used in production-level applications, requiring elimination of instabilities and kilohertz-level repetition rates. Meeting these goals will require the mastery of controlled injection techniques, improved loading of the plasma wake to minimize beam energy spread, beam emittance preservation at the plasma-vacuum interface, and the highest possible energy transfer efficiency. Alongside research motivated by these goals will be continued research into more novel applications, such as positron acceleration and proton-driven plasma accelerators. In addition, improvements in staging efficiency will need to be studied and perfected. These will drive the continued development of plasmas accelerators for particle colliders to address the needs of the high energy physics (HEP) community.

A community roadmap has been developed to guide efforts towards enabling photon source applications in the nearer term and the challenging requirements of future colliders. (See Figure 3.8.) If the goals of the roadmap are realized, during the next 10 years we will achieve improved control of particle injection and laser guiding to enable phase space shaping and efficiency, 10 GeV laser particle accelerator modules, staging of multi-GeV modules, controlling emittance, and demonstration of positron acceleration. To facilitate these science advancements, lasers having repetition rates of kHz and average powers of kW will need to be developed to enable higher precision experiments by leveraging active feedback control. Several different methods of initiating electron trapping in the pondermotive potentials have been proposed to improve the beam quality (e.g., beam emittance and brightness) significantly beyond the current state-of-the-art, and it is likely that others will be discovered. Research is ongoing on how to efficiently excite large amplitude nonlinear electron plasma waves over long distances. Achieving this goal requires greater understanding of the nonlinear laser-plasma interaction, including energy deposition and laser propagation physics. The latter depends on many processes, including relativistic self-focusing, pondermotive self-channeling, interaction with preformed plasma channels and laser-excited plasma wakefields, and short-pulse laser-plasma instabilities, such as laser self-modulation and hosing (defined below). Plasma source development will be a major topic of research. Multiple



Currently	Developing
E: Stable few %	<1%
ΔE: Stable at 10%	<1%
Diverg: ~ mrad	< 0.1mrad
Point: ~ mrad	< 0.1 mrad
Emittance: 0.1 µm	0.01 µm
Charge: ~10 pC	~100pC
Efficiency: few %	~30%
Rate: Hz	≥ kHz
e- only	e-, e+

FIGURE 3.8 *The LWFA Roadmap*. The plasma-based accelerator field benefits from having a guiding roadmap for advanced accelerator research and development. (Left) Representative development goals from the roadmap for laser-plasma acceleration which is similar to that for particle bunch driven systems. SOURCE: *Advanced Accelerator Development Strategy Report: DOE Advanced Accelerator Concepts Research Roadmap Workshop*, 2016. (Right) Status of the development effort.

E_e	E_L	Tau_L	Rep	Example Science/Applications
~20 MeV	5-20 mJ	4 fs	kHz	UED, keV Thomson medical…
~1 GeV	2-4 J	30 fs	kHz	High performance LPA, photon sources
~10 GeV	10-80 J†	100 fs	50kHz	10 GeV collider stages
~50 GeV	0.2-1 kJ	250 fs	low	High E or Q, high field physics, HEDS

Parameters shown are for λ=1 μm driver. † range corresponds to linear or nonlinear regimes

FIGURE 3.9 Primary accelerator laser driver parameter ranges of interest for plasma accelerators. The boxed lines two and three could be part of a single development track. The other two classes would be separately developed. Note that additional beams are desired for injection and guiding control but are typically at lower energy and do not hence drive overall laser development. SOURCE: Courtesy of Cameron Geddes, Lawrence Berkeley National Laboratory.

techniques are being considered for improved plasma sources, including laser ionized guides, discharge and helicon plasmas, using gas jets, capillary tubes, clustered targets, and alkali heat pipe ovens.

The topic of hosing has garnered much theoretical interest over the past decade but has yet to be thoroughly studied experimentally. Hosing is an instability driven by head-to-tail transverse wakefield effects acting on the accelerated electron beam that can lead to catastrophic beam break up. As LWFA and PWFA beam quality continues to improve, the beams will become more sensitive to this instability. Some theoretical solutions have recently been proposed and are currently under study using PIC simulations. One such solution utilizes a modest degree of ion motion within the blowout cavity, which can suppress the resonance in the beam's transverse motion that leads to hosing. Further work in this area is needed.

A goal of a future high energy physics lepton collider is to collide counter propagating electron and positron beams with center of mass energies of and beyond 1 TeV. Plasma accelerators are able to accelerate positron beams, although it poses significant challenges. In the highly nonlinear blowout regime used in most high energy plasma accelerators, the plasma electrons are completely evacuated in a bubble-like region behind the wake driver. This leaves behind a column of positive ions that can provide transverse focusing to a negative electron beam due to the Coulomb forces. Unfortunately, positively charged positron beams are defocused by the positive ion column. Nonetheless, significant progress has been made toward high gradient acceleration of positron beams in the past decade, both in theory and experiment. One theoretical proposal is to accelerate positrons in the linear wake regime, which, unlike the blowout regime, responds symmetrically to electrons and positrons. Here challenges include overcoming scattering in the plasma and the natural tendency for the beam to focus in the plasma until it drives a nonlinear wake and ruins the beam. Another proposal is to use hollow channel plasma accelerators, which avoid the production of an ion column altogether. Challenges for this scheme include the minor transverse asymmetries in the beam profile or position with respect to the plasma channel that can lead to the buildup of strong transverse wakefields that induce a beam break up (BBU) instability, which again ruins the beam.

To address future high energy physics collider applications, staging of multiple plasma accelerators in series will provide the highest system gradient and is desirable in managing the charge and phasing of the bunches of charge that are accelerated. This challenging process has been demonstrated by accelerating electrons to the 0.1 GeV level using a 100 TW laser driver. Multi-GeV experiments are in preparation (See Box 3.2). Simulations indicate that managing the pulse shape of laser drivers can achieve high efficiency acceleration and high beam quality.

Major efforts are needed to develop more advanced plasma sources over the next decade in order to achieve most of the aforementioned goals. (See Figure 3.9.) It is likely that there will be no "one size fits all" solution, but rather there will be specialized plasma sources that serve particular goals. For example, a laser-ionized gas plasma source may be well suited for electron beam-driven PWFA purposes, whereas a helicon plasma source may be better for a proton beam-driven PDWFA. Continuous evolution of gas jet plasma sources for LWFA are likely to lead to improved injection control and beam extraction capability for lower energy beam sources, while advancement in semi-hollow plasma waveguides will lead to greater beam energy and quality for high energy beam sources.

Progress in plasma acceleration and X-ray sources has been driven by parallel and mutually reinforcing advances in laser (and particle beam) driver technologies and deeper understanding of the laser-plasma and beam-plasma interaction physics. In this regard, the maintenance and upgrade of existing facilities and facility networks is essential. However, the improving the repeatability, reliability, and repetition rate of plasma accelerators depends on the development of new laser technologies for increased precision, control and repetition rate. (See Figure 3.9.) There are three areas with distinct needs for laser development. For colliders and many photon sources, the main stages must operate at high efficiency with charge and laser energy requirements perhaps uniquely set by the interaction point physics. The properties of these lasers may differ from those of the injector stage that may benefit from long wavelength drivers. For HEP applications, stages have tens of GeV acceleration are likely required, while for HED probes, electron bunches having high charge are of interest. Both applications motivate higher powers but perhaps different architectures. For low energy applications such as medical and ultrafast electron diffraction, laser systems have pulse energies of a tens of mJ and pulse derations of a few-fs systems are needed. Laser technology is discussed in the section on Facilities.It is important for theoretical models and computer simulations to continue improving in terms of physical accuracy (e.g., suppression of artificial numerical instabilities), to reduce computational cost, scalability, and include more physics to help solve the more challenging problems facing the community in the next decade. One area that needs to be addressed is in the modeling of plasma sources, which has received less attention compared with the acceleration process. These improved models will help in the development of plasma targets with precisely shaped density profiles, using methods that have strong overlap with low temperature plasmas to, for example, match the laser and particle pulses into the plasma. End-to-end simulations of plasma accelerator systems that are capable of resolving detailed dynamics within the electron beam and (where appropriate) laser pulse will be required. In addition, there is a call for modestly simplified simulations that can be run with sufficient speed so as to provide rapid feedback to running accelerator systems in real-time. All of these modeling goals are extremely challenging and will require deliberate effort and investment to achieve. Deliberate investments in this area would produce a much needed improvement in the ability to predict and understand the behavior of actual, physical plasma accelerator systems.

Particle acceleration using plasmas is rapidly progressing in terms of beam quality, stability, and diagnostics, and in the important physical understanding that is the basis for improving performance. The next steps in advancing the field include the transition to kHz repetition rates which will enable stabilization and precision, and application relevant average powers. Taking these steps will require new laser technologies. Progress is being made towards meeting the challenge of phase space shaped particle beam generation and manipulation of ultra-bright beams, and the applications these capabilities would enable. Advanced plasma accelerators and photon sources will enable advances in fundamental science as well as society benefiting applications, from compact TeV class HEP colliders to medical imaging technologies.

LPI ACCELERATION OF HEAVY PARTICLES (IONS)

Laser-driven acceleration of ions has a long history, starting with the acceleration scheme proposed by Veksler in 1957, and has become a very active area of research worldwide. (See Figure 3.10.) In particular, high-intensity ion beams driven by short pulse lasers have emerged as an important area of plasma research. Ion acceleration mechanisms are different from those for light particles because of the different dynamics. A light particle at 100 MeV is ultra-relativistic, whereas that energy is very sub-relativistic for a heavy particle. One cannot easily trap sub-relativistic particles in the near relativistic plasma waves produced by laser-plasma interactions, and so a different mechanism is necessary.

The methods of ion acceleration include target normal sheath acceleration (TNSA), shock wave acceleration, and mechanisms that rely on volumetric laser plasma interaction due to relativistically induced transparency and radiation pressure. The most studied mechanism, TNSA, works by using the plasma sheath, which forms at a plasma boundary, in this case a narrow plasma that comes from hitting a foil with a laser. The radiation pressure pushes the electrons out the far side; the charge imbalance creates a plasma sheath that accelerates the ions. In the last 10 years, high gradient acceleration by the sheath fields created in dense plasma targets has been refined into a controllable technique. Motivating this research are numerous potential applications discussed below.

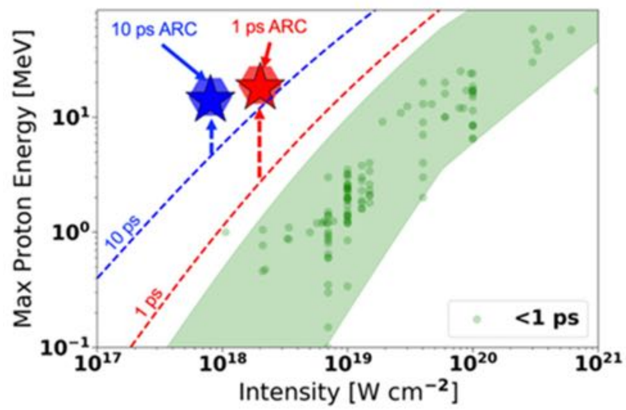


FIGURE 3.10 *Advances in Proton Acceleration*. Recent investigations into proton acceleration with multi-ps, kJ-class lasers have revealed the role of new acceleration mechanisms such as Direct Laser Acceleration (DLA) and the time-dependence of short-pulse laser-matter interactions to accelerate particles. This plot of maximum proton energy as a function of laser intensity shows the 5-10 times higher proton energies measured on the NIF-ARC relative to other short-pulse facilities at sub-ps pulse lengths at comparable intensities. SOURCE: Mariscal et al., Phys. Plasmas 26, 043110 (2019) https://aip.scitation.org/doi/10.1063/1.5085787.

Laser-driven ion accelerators are projected to have multiple applications. Biomedical applications include cancer therapy and production of isotopes for Positron Emission Tomography (PET). Laser-driven ion beams can also be a path for producing fusion energy through fast ignition. They could enable compact neutron sources for security and industry, advanced proton radiography and isochoric heating for high energy density science, and ultrafast beams for radiation damage and single event effects. Once the ions are accelerated by the laser-irradiated target, the beam has to be transported and delivered based on the requirements of a specific application. A major goal is to design a system whose ion beams can be used for applications, the challenges for which are similar to those faced in accelerator physics and significantly more research is required in this area.

Progress and Achievements

The ion acceleration field recently made major advances due to the availability of ultrahigh power lasers with focused intensity up to 10^{22} W/cm^2, and laser technologies that allow a temporal intensity contrast of 14 orders of magnitude. Maximum proton energies approaching 100 MeV have been achieved experimentally using ultra-thin targets. These experiments have produced proton beams from a variety of targets, ranging from nanometer to micron scale foils of solid density, to near-critical plasma density

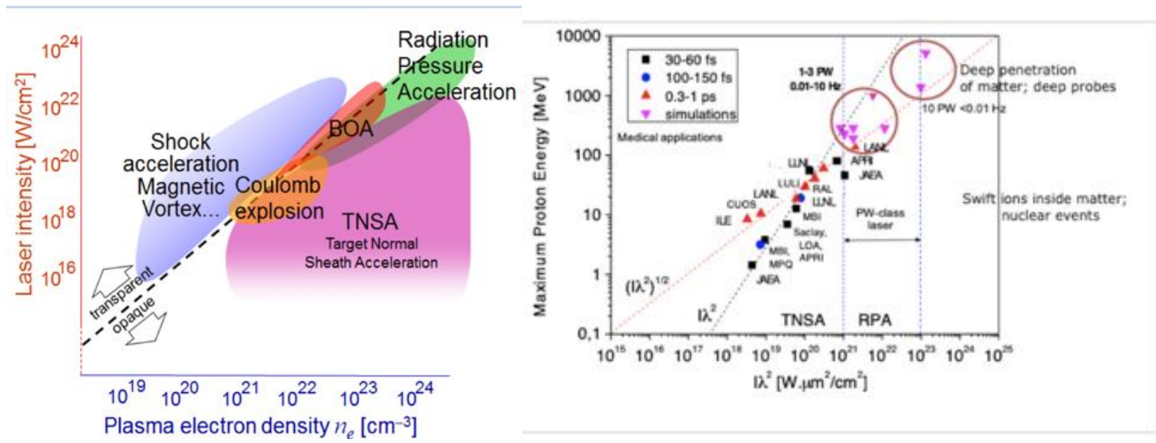


FIGURE 3.11 *The future of ion acceleration*. New regimes of laser-driven ion acceleration and high performance are becoming accessible. (left) The parameter space of the laser intensity (W/cm^2) vs surface density $n_e l_0$ of the target (n_e is the electron density in the target and l_0 is the target thickness). PW-class laser systems enable access to new regimes such as radiation pressure and magnetic vortices. (right) The maximum proton energy vs normalized laser intensity. Experiments (black, blue, and red) are shown along with simulations projecting future regimes (purple). SOURCE: Left: Courtesy of Paul McKenna, University of Strathclyde, Glasgow; S.S. Bulanov, E. Esarey, C.B. Schroeder, S.V. Bulanov, T.Z. Esirkepov, M. Kando, F. Pegoraro, W.P. Leemans, Radiation Pressure Acceleration: the factors limiting maximum attainable ion energy, Phys. Plasmas 23, 056703 (2016).

targets (see Figure 3.11). Recent results from large laser facilities (National Ignition Facility-NIF, Advanced Radiographic Capability-ARC and the Omega EP laser at the University of Rochester) have shown that a dramatic increase of proton energies can be achieved by increasing the laser pulse duration. (See Figure 3.10.)

A technology advance that has had a transformational impact on ion acceleration is the use of plasma mirrors (see section on plasma optics). Plasma mirrors made it possible to dramatically reduce the laser pre-pulse, which allowed ultra-thin and structured targets to remain intact without losing their structural integrity prior to the arrival of the main part of the laser pulse. Plasma mirrors enabled the experimental demonstration of mechanisms relying on relativistic transparency in ultra-thin targets. Another breakthrough is the development of novel target designs to better couple laser energy to the target. These include nano-structured targets that enable one to reduce the average target density. There are also targets with a structure whose size is comparable to the laser wavelength. These targets enable guiding of the laser pulse without defocusing. Such features have been utilized to increase coupling and performance of ion acceleration regimes. Recently developed liquid crystal thin-film targets, together with liquid and cryogenic jets, can enable higher repetition rate experiments, which important as PW lasers have made the transition from shots per day to shots per second. (1 PW = 10^{15} W.) The same approach can be used for plasma mirrors.

The results obtained in the last 10 years for ion acceleration demonstrate a high level of synergy between theory, computer simulations, and experiments, which will be a prerequisite for all future advancements in the field. The rapid development of high-performance computing resources that occurred over the last decade enabled fully 3D kinetic simulations in many regimes of laser-plasma interactions relevant to ion acceleration. This has had a tremendous impact since 2D simulations were unable to capture the ion energy gain by a quasi-static plasma electric field. 3D simulations made it possible to provide quantitative predictions for meaningful comparisons with experimental results. It has also been shown that kinetic simulations might have to be coupled to hydrodynamic simulations in order to reproduce the physics that takes place at lower intensity prior to the arrival of the main laser pulse. This approach has produced results that can quantitatively reproduce experimental results.

Current and Future Science Challenges and Opportunities

There are many challenges and opportunities in the field of heavy particle acceleration. Multiple new regimes have been proposed for the next generation of laser systems with higher power and/or intensity and better contrast. These regimes are expected to enable a significant increase in ion energies. They are also predicted to deliver mono-energetic beams. Novel and efficient acceleration regimes have been proposed. To be useful for applications, energies have to be increased, and the systems have to become more stable. This leads to technical challenges as well, in the development of targets and other areas. This is an opportune time to address these challenges, with increased access through LaserNetUS, new high-power lasers in the European Extreme Light Infrastructure and Asia, and the opportunity for a next generation of domestic facilities.

Application challenges include stable ion acceleration with well-controlled and predictable ion beam parameters. Two particular challenges are increasing ion energy gains well beyond 100 MeV (this is the key to many applications since the stopping distance is directly correlated to the energy) and the generation of mono-energetic ion bunches with charge in the nC range. Even though multiple theoretical and computational models predict such parameters, it has not been possible to experimentally demonstrate these values with currently available laser technology. While experimental results exhibit a promising trend towards higher ion energy, further improvements in technology are necessary to achieve the predicted ion acceleration performance. This will require a multi-faceted approach that involves further developments in both laser technology and targets to fully exploit effects such as relativistic transparency, radiation pressure, and magnetic vortices. At the same time, these topics advance the fundamental plasma science of laser-plasma coupling, heating, and acceleration.

Technological challenges include progress in targets, in laser contrast and intensity. Advanced targets, such as those with structure, have shown great promise in terms of improved and well-controlled laser energy coupling to the target. However, these targets remain expensive and the cost may become prohibitive for experiments with high-repetition rate laser systems, and certainly for applications. A challenge is to significantly reduce cost while improving target control. In the absence of reusable targets, technologies must be developed for replacing the targets at an appropriate rate, which may include evolution of liquid crystal or liquid jet targets. Another important technological challenge is to increase on-target laser intensities with very high contrast. Multiple ion acceleration regimes with unique properties have been predicted at intensities that are yet to be reached experimentally. Hence, the upcoming development of multi-PW laser systems in a variety of pulse duration regimes is important, as are methods for laser contrast and pulse shaping in space and in time.

Theory and simulations predict that a PW-class laser system can generate ion beams with a maximum energy of several hundred MeV. Further scaling to systems at the tens of PW level is of great interest and an opportunity for future facilities. A breakthrough in laser-driven ion acceleration is expected once the high-power high-intensity laser facilities at the European Extreme Light Infrastructure (ELI NP) and ELI Beamlines become available to users, delivering previously inaccessible laser parameters. These laser systems will enable experimental access to new regimes that have been explored only via numerical simulations and analytical theory. Significant increases in ion energies and charge will likely open up opportunities in biomedical research fast ICF ignition, compact neutron sources for security and industry, advanced proton radiography and isochoric heating for high energy density science, hadron cancer therapy, ultrafast beams for radiation damage and study of single event failure effects in electronics, and drivers and probes for the studies of warm dense matter and HED physics. To enable these opportunities, major prerequisites are not only high performance but also reliable and reproducible beam characteristics.

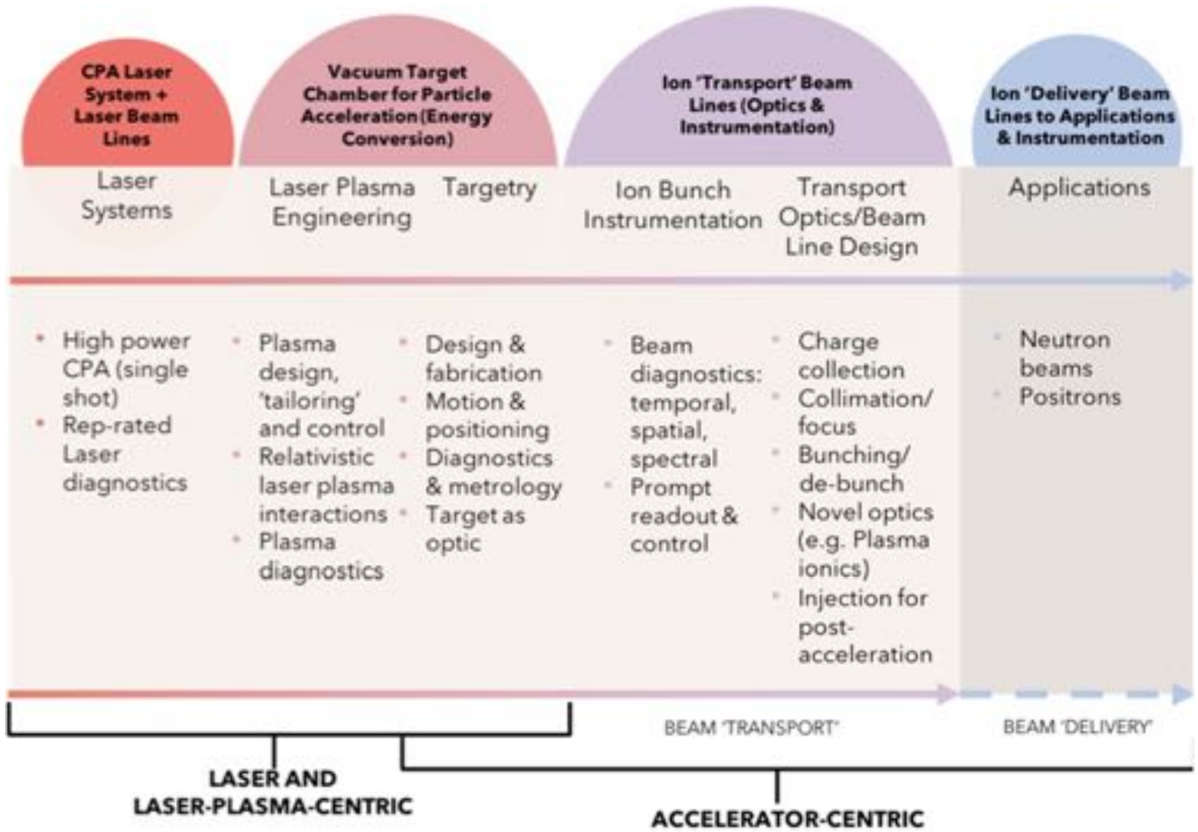


FIGURE 3.12 *Roadmap for ion acceleration*. The roadmap for ion accelerations has several stages. These stages include: the laser system, target development and ion beam delivery across components of the integrated laser-driven ion accelerator system, and potential applications. SOURCE: Alexey Arefiev, UCSD; Adapted by Miriam Holtzman from J. Schreiber, P.R. Bolton, and K. Parrodi, Rev. Sci. Instrum. 87, 071101 (2016).

The ion acceleration community has identified a path forward to achieve many of these goals. A road map towards an ion accelerator based on laser-driven plasmas is shown in Figure 3.12.

BRIGHT X-RAY GENERATION

A bright beam is one with a large amount of energy in a small region of phase space—that is, short time, small dimensional, and with small angular spread. Because of phase-space volume preservation, a brighter beam can be manipulated more easily to place a large amount of energy into a small physical volume. Said another way, less powerful lenses are needed to focus the energy into a particular volume. As a result, brighter beams are more effective for diagnostics, because they provide greater reactivity in a smaller volume. Light generated through laser-plasma interactions is naturally very bright in part because it is produced in a small volume, so that with some directionality, it then occupies a small phase space volume.

Compact photon sources with narrow divergence, producing femtosecond bursts, are enabled by plasma acceleration of electrons. Broadband betatron X-ray emission results from the betatron oscillations of particles in the plasma and/or laser fields and is a diagnostic of the beam properties inside the accelerator. Nearly monoenergetic Compton, or Thomson, scattering of a laser beam from the particle beam produces tunable, narrow bandwidth X-rays of higher energy and flux than betatron radiation, and can extract detailed beam evolution information for studying beam interactions with plasma waves. Coherent free-electron lasers are being developed using conventional magnetic undulators (or wigglers), with future concepts for compact plasma undulators. Coherent X-ray emission can also be created in plasmas via population inversion and from harmonics of laser field generated in plasma interactions. In these cases, plasma optics is an important ingredient. Control of these mechanisms and photon sources requires precision shaping of the laser pulses. Additionally, one must have sensitive control of the plasma profile, preparation, and pumping by the laser pulse.

High performance X-ray light sources enable precision measurement in materials science, industry, security, nuclear nonproliferation, and medicine. Plasma-based X-ray and EUV radiation sources are both important frontiers in plasma physics with broad application, and an enabling technology to provide diagnostics (and potentially pumps) for high energy density plasma (HED) science, and high resolution and low radiation dose imaging. (See Figure 3.13.)

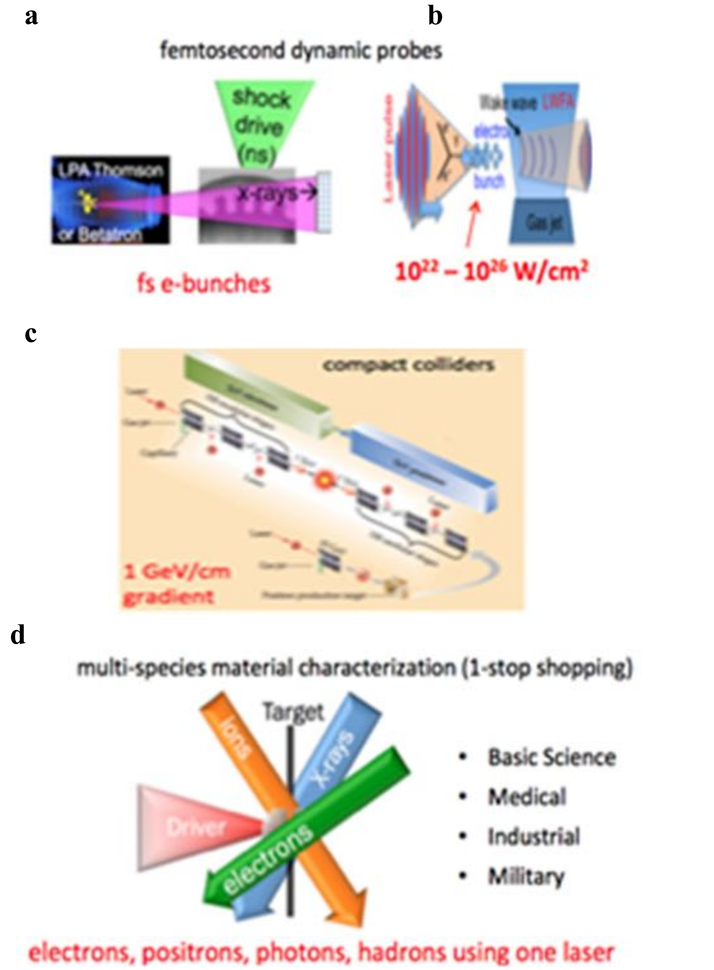


FIGURE 3.13 *Applications of LPI Produced X-Rays***.** Plasma acceleration-based sources can enable: (a) precision high performance X-ray and MeV photon sources in compact packages suitable for applications in nonproliferation, industry, security, medicine and other areas. These X-ray are produced from Thomson scattering and Free Electron lasers. (a-b) brilliant probes for high resolution High Energy Density Science, (c) Future colliders can extend the reach of our understanding of the universe, and (d) multi-modal sources from a single laser to combine capabilities. SOURCE: (a) Courtesy of Cameron Geddes, Lawrence Berkeley National Laboratory; (b) S.S. Bulanov et al., On the design of experiments to study extreme field limits, AIP Conf. Proc. 1507, 825 (2012), doi: 10.1063/1.4773805; (c) Reproduced from Physics Today 62 (3), 44 (2009) 2009, with the permission of the American Institute of Physics (d) Courtesy of Cameron Geddes.

Progress and Achievements

Coherent soft X-ray sources have been demonstrated using solid and gas targets for High Harmonic Generation (HHG). These demonstrations include sources in the attosecond domain, thereby permitting attosecond temporal resolution, which is the scale of atomic processes, hence allowing one to observe atomic dynamics. X-ray lasers have been demonstrated with mJ/pulse energies down to wavelengths of 46 nm, and from energies of μJ down to 6.8 nm using multi-pulse ps lasers. Population inversions can be driven by a variety of mechanisms including electron impact excitation, collisional recombination, and photoionization. Plasma target shaping including nano-wire arrays has greatly improved coupling of laser energy into the X-ray producing plasma. Seeding (initiating) coherent X-ray amplifiers with HHG has been exhibited and allows full coherence. Power scaling is being explored to produce sources that could meet the needs for lithography in the semiconductor industry and other applications.

Several brilliant, ultrafast, synchronized X-ray sources based on plasma accelerators have been demonstrated. These sources enable advanced X-ray capabilities in compact laboratory setups with broad-reaching impact while also improving our understanding of the plasma accelerators. Experiments have shown the unique properties and advantages of these sources. Betatron emission (from the transverse oscillations in the generated plasma wave) produce keV broadband radiation sources with micron emission spot sizes that have been used to enable sensitive phase contrast imaging and ultrafast diagnostics of high-energy density experiments. These experiments demonstrate that the beam quality of x-rays produced by plasma accelerators can be competitive with that obtained in conventional X-ray sources. Thomson scattering of a laser pulse from the electron beam has been used to produce quasi-monoenergetic X-rays at selectable energies from keV to multi-MeV. Experiments have verified that these low-energy spread beams could simultaneously reduce radiation dose and increase sensitivity in X-ray applications ranging from medicine to security. Several programs are investigating plasma driven FELs to enable compact, ultrafast coherent sources.

CURRENT AND FUTURE SCIENCE CHALLENGES AND OPPORTUNITIES

Developments over the past 10 years have established the single shot parameters needed for X-ray applications, including keV to MeV mono-energetic sources produced by Thomson Scattering, keV broadband betatron sources and plasma based soft X-ray lasers. Experiments have begun to demonstrate the benefits of these sources at the few-Hz repetition rates allowed by current laser systems, primarily for fundamental physics studies. However, applications require repetition rates at kHz and beyond.

Current photon sources including Thomson and betatron, and the ongoing development of FELs, are attractive for investigating near-term applications. These sources typically use GeV-class LPAs, which map to laser pulses of few Joules in tens of fs. The energy spread of the accelerated beams needs to be in the range of 0.1 to 10%, and emittances from nm to µm. These capabilities, with improvement in beam transport and beam disposal, will enable experiments now and in the next few years using state of the art LWFAs. These technology improvements for photon sources will also benefit long term research on advanced colliders. Repetition rates of kHz are needed for applications and developing such sources are now realistic at the required few-Joule-per-pulse energies. The first PWFA applications are likely to be a single-stage afterburner (e.g., the use of plasma acceleration to double the energy of an already substantially accelerated charged particle beam) for a Free Electron Laser (FEL), or high brightness, broadband betatron X-ray or gamma ray sources. A brightness transformer for FEL operation may also be within reach.

Plasmas offer the potential for photon sources which are both more compact and more advanced in performance than conventional systems. For example, LPA based photon sources have demonstrated the ability to decelerate the electron beam after photon production. (See Box 3.2). For Thomson scattering, the plasma can also guide the laser to reduce required electron current per photon produced. Both of these capabilities reduce undesired radiation generation. The Thomson process can also provide details on electron beam evolution for studying beam interactions with plasma waves. An LPA produced electron beam could be used in an FEL with appropriate transport and phase-space manipulation (for example, by de-compressing the ultra-short beam). Such a compact FEL would be an enabling capability for many scientific disciplines and several projects are in progress.

Particle accelerators and the X-ray photon sources they power are fundamental technologies supporting basic science, medicine, industry, and national security. Advanced X-ray light sources enable precision measurements that have revolutionized a broad range of basic and applied sciences at large user facilities. However, the size of these sources means that they are not accessible to many applications.

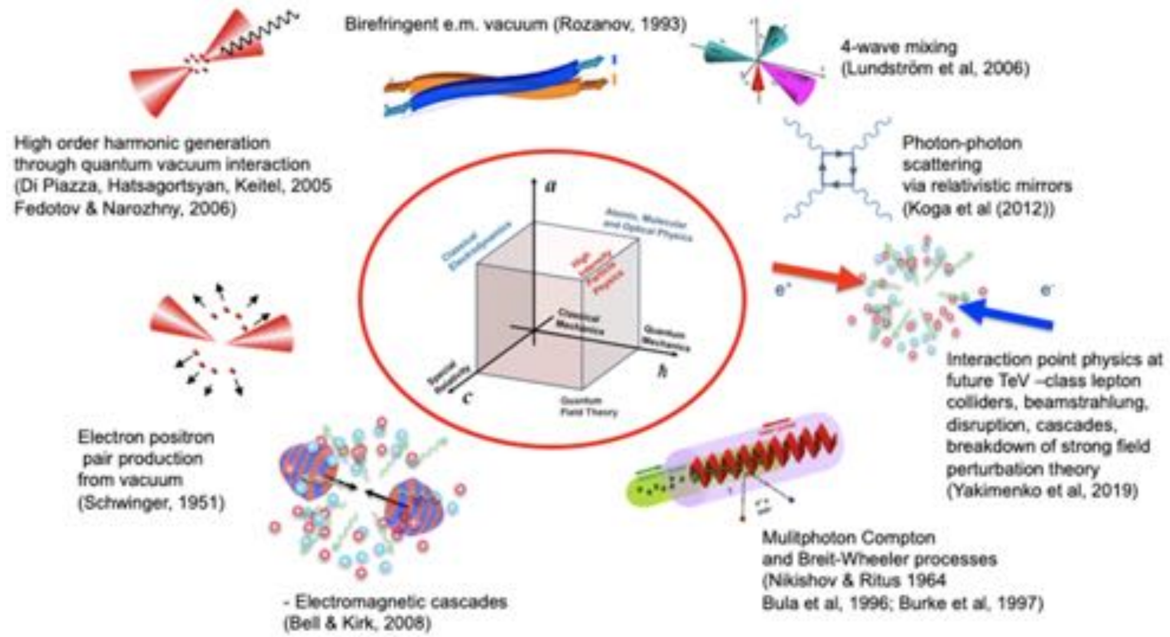


FIGURE 3.14 *The classification of collective high intensity processes:* Collective, high intensity processes address special relativity, quantum mechanics and atomic/molecular physics. These fields and their interactions can be visualized as a cube of theories, with the three axes corresponding to: relativistic, quantum, and high intensity effects. The vertices of the cube are classical mechanics, special relativity, quantum mechanics, quantum field theory, classical electrodynamics, atomic, molecular, and optical physics, and high intensity physics. SOURCE: Central Image: Phys. Rev. A 87, 062110 (2013). 4-wave mixing: Phys. Rev. A 74, 043821. Surrounding images courtesy Stephan S. Bulanov, Lawrence Berkeley National Laboratory

Compact plasma based sources could enable broadly accessible mono-energetic hard X-rays from keV to MeV energies with smaller emission spots, and coherent X-ray free-electron lasers at venues outside of km-scale facilities. Realizing this vision would produce enormous benefits to industry, security, nuclear nonproliferation, and medicine, or for high energy density science.

NONLINEAR QED

Extremely intense lasers under development and being proposed will give rise to a new field of strong-field quantum electrodynamics (SF-QED). This is the study of electron-positron pairs and plasmas directly produced from the intense laser fields. In essence, with strong laser fields, one can create a plasma from the vacuum.

A large body of mostly theoretical effort has indicated that SF-QED can fundamentally change the nature of the interaction of charged particles and plasmas with strong electromagnetic fields. These interactions include significant transfer of beam energy to radiation, prolific production of electron-positron pairs and radiation dominated regimes, where particle motion is mainly determined by the radiative processes. These theoretical efforts have greatly advanced our understanding of charged particle interactions with intense electromagnetic (EM) fields and their linkage to collective plasma effects. The next generation high intensity laser and accelerator facilities will access a regime dominated by SF-QED effects to test these theories and enable new applications. These facilities will provide new sources of particle beams for material and nuclear science studies. (See Figure 3.14.)

Progress and Achievements

In the last 10 years a large body of mostly theoretical effort was devoted to the study of multiphoton Compton and Breit-Wheeler (BW) processes and subsequently, the EM cascade, was identified as a new phenomenon. (Compton processes are the scattering of photons from high energy particles that change the wavelength of the photon. Breit-Wheeler processes produce positron-electron pairs from the collision of two high energy photons.) Workshops and reviews have outlined the principal schemes, and the methods needed to study these effects experimentally. See, for example, *Workshop on Opportunities, Challenges, and Best Practices for Basic Plasma Science User Facilities (2019* and *Summary of strong-field QED Workshop (2019) [arXiv:1905.00059v1]*.

Electron beam collisions with high intensity laser pulses produce SF-QED effects at the lowest laser intensities. Two experiments demonstrated the depletion of the beam energy due to photon emission in multi-photon Compton process and initiated a new era of experimental exploration of SF-QED effects using current PW-class lasers, advances possible by rapid progress in laser technology and by LWFA of electrons.

CURRENT AND FUTURE SCIENCE CHALLENGES AND OPPORTUNITIES

In the course of the study of multiphoton Compton and Breit-Wheeler processes, it was understood that they cannot be treated analytically in either vacuum or plasma. Several numerical approaches have been developed, from simple reduced order estimates for Compton and Breit-Wheeler effects, to massive 3-dimensional simulations. QED-PIC codes are extensively used to study the interactions of high intensity EM fields with energetic beams of charged particles and photons, and plasmas of different composition and density. Computer simulations of multiple shower-like photon emissions and pair production and relied on the separation of scales. The characteristic scale of the SF-QED emission process is much smaller than that of EM Field or plasma phenomena scales. Apart from either enhancing or suppressing acceleration, the strong fields were found to modify the trajectories of charged particles in the radiation dominated regime. In this regime positrons and electrons are trapped on stable or quasi-stable trajectories inside the EM fields. Development of such models continues to be an active and important topic.

Current models are not capable of describing new regimes of collective high field interaction. One example is the Local Constant Field Approximation (LCFA), which is the backbone of almost all numerical tools now being employed. Recent studies point out the parameter regimes where LCFA predictions are significantly different from full QED calculations. A number of solutions to this problem were proposed by modifying the LCFA for plane Waves. However, there are processes that cannot be described by the plane-wave model and a self-consistent treatment is needed. Furthering our understanding of these phenomena will require well-orchestrated collaborations between development of new computational capabilities and new facilities and diagnostics. (See Figure 3.15.)

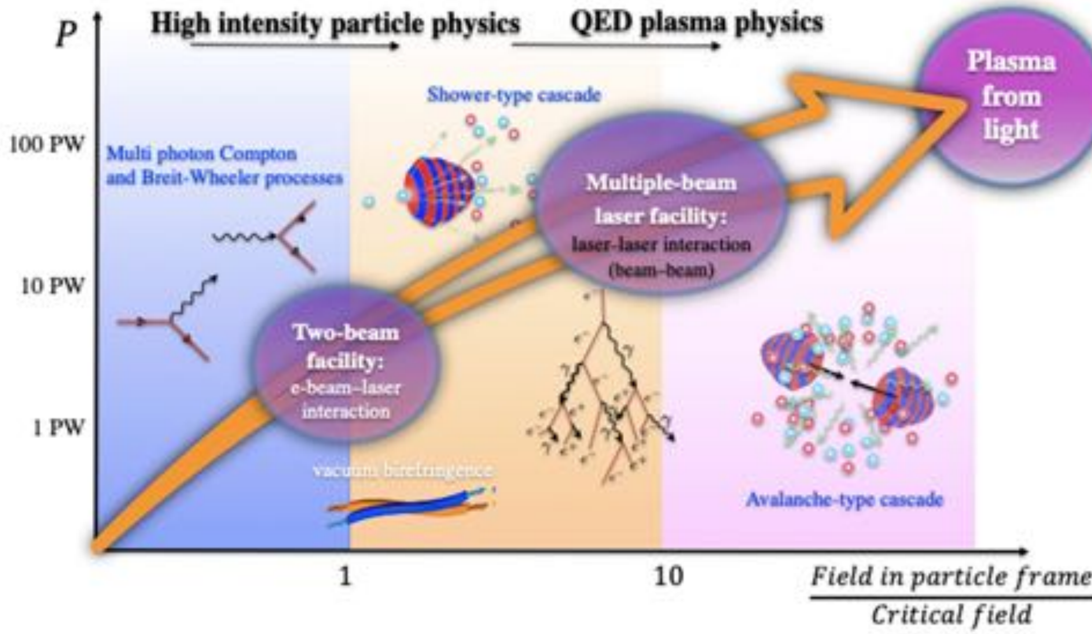


FIGURE 3.15 *Timeline of the QED-plasma studies envisioned as a two-stage process*. A near term facility, potentially an extension of current PW-class lasers combining multi-GeV electron beams and intermediate laser intensities, can enable the study of fundamental strong-field QED processes. A future multi-beam facility at extreme laser intensities could study the interplay between collective plasma effects and strong-field quantum processes. SOURCE: NSF Workshop on Opportunities, Challenges, and Best Practices for Basic Plasma Science User Facilities (arXiv:1910.09084),

Another open question is the consequence of back reactions, either pair production or photon emission, on the intense electromagnetic field. Usually these processes are considered using an external field approximation. However, it has been pointed out that the creation of new particles can lead to the depletion of the electromagnetic field energy, which invalidates the approximation of the external field. Theoretical and simulation studies of the cascades up to now have relied on the formation length and time being much smaller than the spatial and time inhomogeneities of the electromagnetic field. However, a full QED treatment of these processes has yet to be achieved. Another example of the scientific and computational challenge is the interaction of charged particles with super strong EM fields. For these conditions, strong field perturbation theory is no longer applicable, since the contribution of the second order process becomes comparable with the first order ones. Proper treatment of spin and polarization effects on plasma dynamics is also of interest.

Further theoretical and numerical studies of SF-QED will not only advance our understanding of the EM field interaction with plasmas at highest intensities but will also provide critical insights into allied scientific fields, such as accelerator research and high energy physics. Advancing our understanding of SF-QED also requires a concentrated experimental effort, which requires a collaboration between these allied scientific fields, to validate the findings, test theoretical and numerical models, paving the way for future applications and exploring new phenomena. The study of SF-QED effects requires high power laser facilities and sources of high energy (multi-GeV) electron beams, either from LWFA or conventional accelerators. In this sense SF-QED has strong connection with laser and accelerator technologies. Moreover, different regimes of charged particles interacting with high intensity EM pulses might lead to the development of high brightness sources of X-rays and gamma-rays.

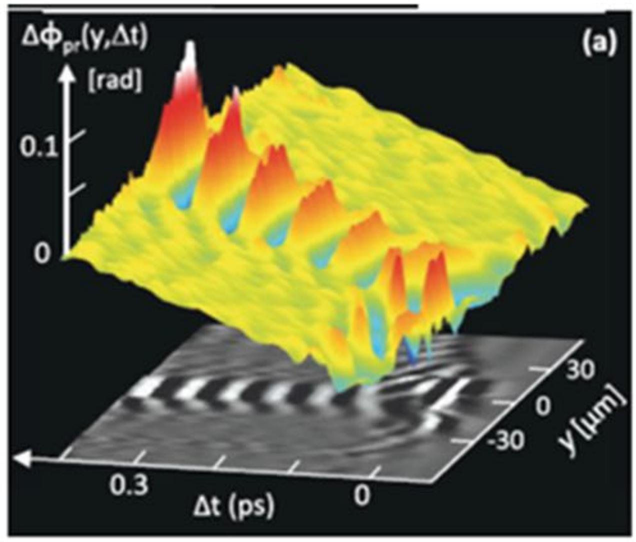


FIGURE 3.16 *Measuring Plasma Waves*. The structure of a plasma wave accelerator has been directly measured using optical holography with a separate probe laser pulse. This is an example of advanced diagnostics that are enabling tuning and control. The image is the phase oscillation profile of the wake (colored surface) that a 30 TW pump pulse generated in He^{2+} plasma with density 2.2×10^{18} cm^3, suitable for GeV-class acceleration. The grey-scale image is a projection onto a plane. Original citation: P. Dong et al., New J. Phys. 12, 045016 (2010). Meta-citation: M. C. Downer et al., Rev. Mod. Phys. 90, 035002 (2018). SOURCE: P Dong et al 2010 New J. Phys. 12 045016.

As laser intensities continue to increase SF-QED effects will become increasingly important, entering the regime of QED-plasma, where the number of produced particles is so large that they begin to demonstrate collective behavior, other plasma-based processes start to be affected by them. These processes include laser driven ion and electron acceleration and high harmonics generation. A series of experimental regimes will become accessible with laser technologies that will result from following the roadmap. These new regimes start with advanced experiments in collisions of beams with lasers accessible on near-term PW laser facility extensions. Over the longer term, tens of PW multi-beam laser facilities could enable new regimes strongly affected or even dominated by SF-QED-plasma interactions. (See Figure 3.15.)

The study of SF-QED phenomena opens new physics across many fields. With SF QED effects entering the regime of QED-plasma, where the number of produced particles is so large that they begin to demonstrate collective behavior, other plasma-based processes start to be affected. These processes include, for example, laser driven ion and electron acceleration, and high harmonics generation. The field shares a common analytical basis, as well as common plasma accelerator technology needs, with high energy physics. SF-QED plasma studies can potentially relate to studies of high-energy hadron interactions and the creation of quark-gluon plasmas as well as the interaction point of future lepton colliders Future light sources built on the SF-QED effects will provide photon beams that could be used in nuclear and material science as drivers and as probes. The construction of second beamlines, targets, and diagnostics at high-repetition-rate (1 Hz) PW facilities as well as support for theory and simulation programs should be a near term priority in order to achieve rapid progress in SF-QED studies in the United States. In the longer term a many-PW facility will be needed to fully exploit this regime.

DIAGNOSTICS

Diagnostic and computational advances have enabled deeper understanding of the plasma state. For example, collective Thomson scattering has proven to be a valuable tool for diagnosing the hot plasmas typical of inertial confinement fusion, providing either spatially or temporally resolved measurements of the plasma density, electron and ion temperatures, ionization state, and flow velocity. Recent experiments have even exploited the Faraday rotation of the Thomson scattering probe laser to measure the dynamo amplification of magnetic fields in a turbulent plasma. In the past decade, optical interferometry has provided insight into the spatiotemporal dynamics of plasmas from the spatial structure of laser driven wakefields to the ultrafast transition of matter from a gaseous to plasma state.

Development of new diagnostics to measure the plasma distribution function, wave amplitudes and distributions, and particle phase space, continue to be required. (See Figure 3.16.)

A critical component is the development of novel diagnostics that can measure not only the bulk hydrodynamic properties of the plasma, but also the underlying electron velocity distribution functions (eVDFs). Experiments have begun using Thomson scattering to measure the shape of the eVDF. These experiments have demonstrated that processes such as cross-beam energy transfer (an interaction in ICF and many plasma optics) and Raman amplification cannot be predicted without considering the shape of the eVDF. Fundamental processes such as inverse Bremsstrahlung absorption, collisional ionization and atomic processes, and heat transport can all modify the eVDF in ways that effect laser plasma interactions. For example, the flattening of the eVDF at low velocities due to collisional absorption can reduce the energy transfer between crossing laser beams—an effect that could be misinterpreted as a nonlinear saturation process. A similar effect could arise in Raman amplification due to electron heat flux. The heat flux can alter the Landau damping of the plasma waves leading to erroneous predictions for the length of the amplifier required to reach saturated gain (i.e. pump depletion).

Virtually all of the needed technological advances described above and science advances that will be enabled by those technologies require diagnostics to characterize the state of the plasma. This is true in all sub-fields of plasma science and particularly challenging in LPI due to the small volumes and short durations of the laser- or particle beam-plasma beam interactions. The HED community has been quite successful in leveraging diagnostics in a synergistic way to improve laser and pulsed power technologies while advancing our fundamental understanding of the underlying plasma physics. The LPI field would greatly benefit from a similar collaborative development of diagnostics.

COMPUTATION

Computation (or numerical modeling) of plasma acceleration, radiation generation, and the associated laser-plasma interactions has been essential to the development of the field of LPI. Computations are synergistically supported by advances in theory, which new enable improve fundamental understanding required to develop the numerical algorithms. Computation enables one to investigate laser or beam interaction with plasmas that are otherwise unobservable with current diagnostics due to the fact that they occur in very short times in small regions of space. Computation enables the exploration of scenarios, such as electron injection by ionization in mixed gases, prior to incurring the expense of experimental development of such systems, and enables one to consider regimes (such as much higher laser powers) that are not currently available. These computational investigations are essential to defining the experimental path forward. Once that path has been determined, computation enables improved design of experiments by, for example, optimizing the shape and materials of plasma targets.

Computation is intensive and challenging in this field due to the presence of multiple time scales and the need to resolve the long distance of propagation of lasers and beams. The longest time scale is the plasma channel formation time, ~ns, and this physics is typically modeled by magneto-hydrodynamic (MHD) codes. In the low plasma density regime, as needed for high-gain, single-stages, Direct Simulation Monte Carlo, Particle In Cell (DSMC-PIC) codes are now being used. This work is in its early stages. The next longest time scale is that of laser propagation through the channel, tens of ps, followed by the pulse duration, which is approximately the plasma period, ~10-100 fs. The shortest scale is typically the laser period, ~0.3 fs. The laser pulse propagation and plasma wave excitation are typically modeled using particle-in-cell (PIC) codes. However, this is sufficiently challenging that many physics problems can be addressed only with reduced models. Major progress has been made in both computational performance and in reduced models that take advantage of special properties of the interaction, for example by relativistically boosting to a frame that moves with the laser pulse or by averaging over its period. These methods have enabled modeling of meter-scale, multi-GeV experiments. Simulations are now routinely performed in coordination with experiments and theory to design concepts and interpret results. These modeling-experimental interactions improve confidence in our understanding of the physics and improve confidence in computations for designing more advances systems.

In spite of progress in the United States in computations in LPI, we have seen a movement of the center of such computations to non-U.S. venues. At the beginning of the decade, computation in LPI at U.S. institutions was dominant. For example, in 2004 all of the experiments for the *Dream Beam* issue of Nature (Volume 431, Issue 7008, September 2004) showing narrow electron beam spreads with accelerations to near GeV were accompanied by simulations performed with U.S.-developed codes. However, that dominance has steadily eroded. In at least one case, the center of development of codes originating in the United States has moved to non-U.S. institutions. In other cases, codes that were originally open source moved to a closed-source model to obtain sufficient resources for development. One outcome is that a large number of researchers have moved to using codes developed internationally. The resource sharing aspect of these internationally developed codes is good. However, it also means that U.S. researchers will have less influence over the development of features for those codes. The end result is that implementing features in these cases that are specific to U.S. research needs will have lower priority, if implemented at all.

Another result is that in the United States, with all resources concentrated in one code, one will not have the innovation that comes from healthy competition in algorithms and approaches. With university efforts in code development for this field having largely disappeared there is a reduced production of new computational researchers in the United States capable of code development. Although difficult to quantify, it appears that hiring at national laboratories in computations is shifting towards foreign nationals who have this skill set. The lack of intellectual diversity in code development in the United States is in stark contrast to the situation in facilities, where there is a large range of facilities at national laboratories and universities investigating different drivers (beams versus lasers), plasma targets, diagnostics, and scales. Finally, we mention that there is little development in the modeling of plasma sources.

ENABLING TECHNOLOGY AND FACILITIES

Progress in LPI, plasma optics, and plasma acceleration will continue to be driven by advances in laser technology. A healthy ecosystem of facilities, programs and capabilities, having diverse and complementary capabilities and instrument size, is required to enable advances in accelerator, photon source, nonlinear optics, high field, and ion sources. The current ecosystem has supported the impressive progress in the field, and includes laser and beam drivers at multiple scales and LaserNetUS, a newly emerging network for coordination and user experiments. Rapidly advancing laser technology creates opportunities to advance the field, in several forms. Existing laser facilities should be upgraded by adding beams to support injection, shock drive and other capabilities. They should be equipped with advanced beam shaping technologies (spatial and temporal) to enable control of the interaction processes. New facilities will be needed to drive the field forward.

Collaborations have been and continue to be important to the development of the LPI field. Discussions on access between LaserNetUS and similar networks and facilities in Europe have started. International collaborations broaden access to unique facilities and techniques, the combination of which is stronger than any one effort. Roadmap exercises are also an important connection, recent examples being U.S., European and UK accelerator strategies. There are excellent opportunities for student training in LPI due to the growth of this exciting and relatively new field, which attracts students, international and domestic collaborators, users and new researchers. International collaborations will take on increasing importance to exploit state-of-the-art facilities being commissioned in Europe (in particular the Extreme Light Infrastructure -ELI) and Asia, which will in the near term will lead the multi-PW frontier. (See Figure 3.17) The U.S. community is large but fragmented across programs sponsored by the DOE, NSF, and the defense agencies. Little cross-agency coordination exists.

Much of the progress in PWFA research over the past decade has been driven by increasingly precise drivers at national facilities, coupled with a research community at both universities and the laboratories. Major Facilities include the Advanced Accelerator Experimental Tests (FACET) at SLAC National Accelerator Laboratory, the Advanced Test Facility (ATF) at Brookhaven National Laboratory, and the Advanced WAKEfield Experiment (AWAKE) at CERN.

Over the past 10 years compact sources of high-power (up to PW) ultrashort (sub-100 fs) lasers have become available at a few Hz repetition rates. These laser capabilities have enabled broad progress in LPI and LWFA. The availability of laser capability has enabled studies with sufficient statistics to scale resonantly driven plasma acceleration up to the 10 GeV. This is the energy scale that is viable for stages in HEP colliders and X-ray FELs (XFEL). (Other applications such as Thomson sources, medical accelerators, and ultrafast diffraction can use lower electron energies and laser powers.) These low-and-high energy examples emphasize that progress in LPA and photon sources has been enabled by a broad array of facilities at varying scales, from small single investigator university systems to large national laboratories. These many scales have enabled access to the field, training and the ability to take risks in addressing science challenges. In this regard, in 2018, the LaserNetUS facility network (Sidebar 1) was established to provide broad access to mid-scale laser facilities.

To address the science challenges discussed in this chapter will require a range of new facilities in the next decade. In this regard, there are several research and technology frontiers with opportunities to produce new capabilities and science, and provide opportunities for U.S. leadership. Stable, high-repetition-rate lasers accompanied by precise control and diagnosis of target properties are required to push the boundaries of experimental precision. In the near term, modification of existing facilities will be required to develop plasma optics and secondary particle sources, provided that cascade efficiencies of

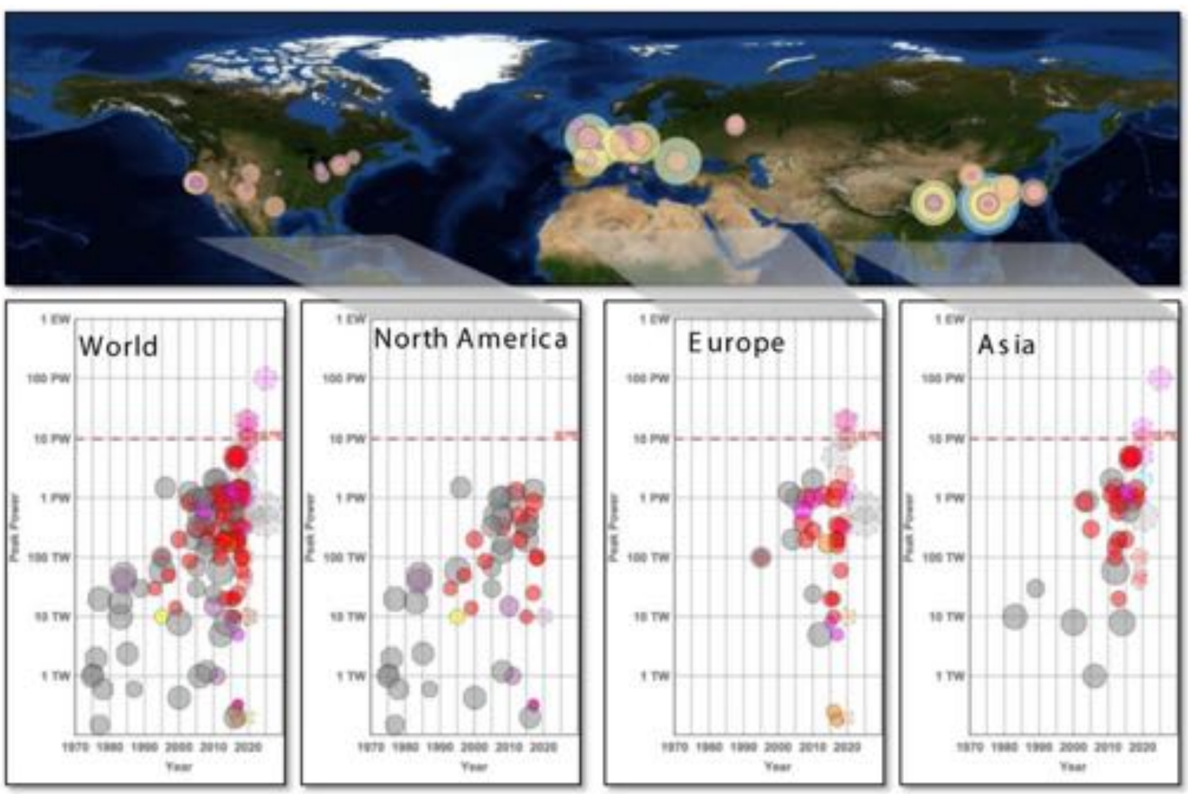


FIGURE 3.17 *Location and Capability of High Power Lasers*. High power laser facilities have developed rapidly over the last decade and continued growth is anticipated. Activity has recently shifted from the United States and is now centered in Europe and Asia. SOURCE: C. Danson et al, High Power Laser Science and Engineering, 7, E54 (2019), doi:10.1017/hpl.2019.36.

the acceleration process, the low emittance of conventional accelerators, and the need to stage acceleration stages are overcome or addressed. In the longer term, co-location of multiple beams will be an enabling strategy, for example, by combining high energy drivers and short-pulse probes. Temporal control at multi-THz bandwidths (for high-energy and high-peak-power facilities) and high-order spatial phase control are necessary innovations. Specifically, the system requirements include: a) multi-kJ ns laser pulses with shaped or stochastic pulse trains co-located with other short pulse beams such as 100 J/100 fs and 30 J/30 fs; b) laser intensities exceeding 10^{21} W/cm^2 for high field physics and new wavelength regimes; and c) kHz-class repetition rates for precision control and machine learning to drive performance, and for accelerator and photon source applications. These needs have been detailed in a community report, (Brightest Light Initiative, Workshop Report, Roger Falcone chair, 2020).

Two technology frontiers define the path beyond current facilities: repetition rate and intensity. High repetition rate, efficiency and control define the core electron/positron accelerator and X-ray source laser requirements. Lasers with repetitions rates of kHz and higher with greater efficiency and control are required for LWFA. These lasers will enable stability and reproducibility of the accelerated electron beams with repetition rates of kHz through feedback control systems. Beam properties are strongly affected by fluctuations in facility properties—ground motion and air motion. The impact of these fluctuations falls off above hundreds of Hz. Operating at higher repetition rate enables more beam fluence in a given time, but also enables active laser feedback control where the pulse frequency (>kHz) significantly exceeds the fluctuation frequency (<kHz) of the facility. Feedback control has been demonstrated on low energy laser systems (mJ-class) and needs to be extended to systems that drive LPAs. This need defines a core accelerator development track—a few-joule-per-pulse, kHz system (with stabilization and shaping) enabling precision. The range of needs motivates a range of facilities addressing different capabilities and approaches. A near term priority is a few-Joule per pulse kHz system that will enable light sources and precision LPA through real-time-control stabilization. In addition to enabling science advances, this system will provide the learning required to develop a 10 J/50 kHz collider stage driver. In the near term many of the control techniques required for high repetition rate lasers can be prototyped on existing lasers or extensions of them. Additional beams for injection and guiding control that are at lower energy do not drive overall laser development, but they do drive facility configurations.

Other lasers are also of interest for accelerators. In particular, these include long wavelength drivers for injectors and large bubble generation. (A bubble is a cavity free of cold plasma electrons.) High energy and high intensity systems are the path to next generation HED science probes, ion acceleration, and high field drivers. These include multi-PW facilities reaching to kilojoules and beyond at tens of femtoseconds to hundreds of femtoseconds depending on application. Correspondingly, repetition rates will be lower than Joule class systems, with rates of one to a few shots/hour being accessible now, and tens of shots/hour in the near future. Such lasers are of particular interest when coupled to high energy ns drivers or additional high intensity beams for heating and target shaping (HED) or particle beam generation (high field science), and for advanced probe capabilities. It is important to have a balance between user facilities where new ideas can be tried at moderate cost, and dedicated engineered beamlines where high performance and control can be advanced.

Plasma acceleration, X-ray sources, and optics have connections to industry both through laser development and through potential applications. A recent *DOE-HEP Basic Research Needs Workshop (Compact Accelerators in Security and Medicine, 2020)* with participation from multiple agencies and industry, discusses the importance that compact accelerators, and electrons and ions, and X-ray sources will have for applications in industry, medicine and security. These applications include nondestructive characterization (security and industrial) and medical imaging with improved resolution and lower radiation dose, new medical therapies via FLASH (high-fluence, short duration) rapid irradiation or endoscopic techniques, and improved security screening. The potential for orders of magnitude improvement in resolution and reduction in dose potentially enabled by laser-plasma sources would have discipline changing impacts. Correspondingly, progress in plasma acceleration has been driven in large part by laser development, and this investment has been reinforcing. Lasers which enable greater capability in LPI produce scientific results that define the need for more capable lasers. The recent heavy investment in Europe and Asia in laser facilities and science advances has shifted the center of high-power laser development to those areas, with follow-on industrial benefits to areas such as shock peening for metallic surface hardening and laser machining. Future investment should combine opportunities in laser development, applications and plasma science, areas that synergistically feed on each other and that drive progress. The improved accelerators resulting from this synergy will similarly advance scientific and technical disciplines that rely on accelerators as scientific tools.

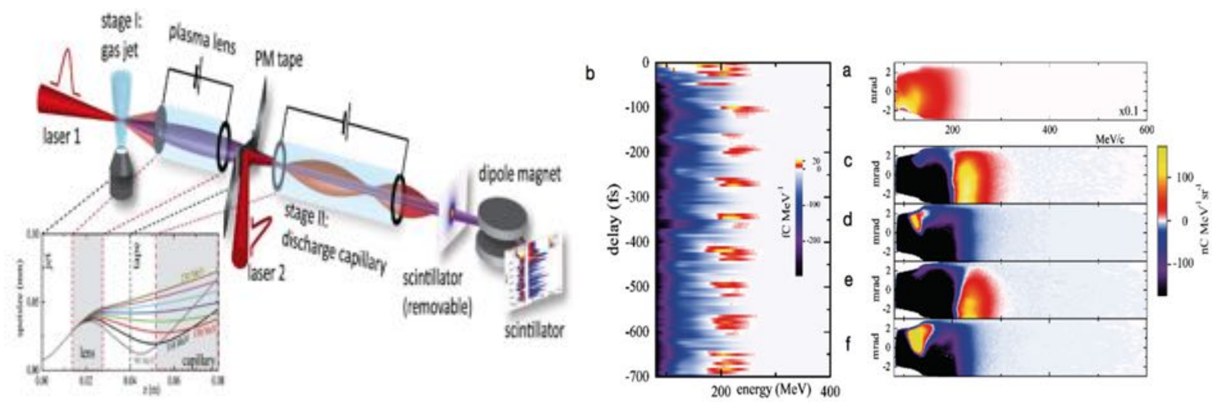
An example of the synergy between technology development and science advances is the development of short-pulse, high-intensity lasers based on chirped-pulse amplification (CPA) by Strickland and Mourou for which the 2018 Nobel Prize in physics was awarded. CPA has made compact sources of high-power (up to PW) ultrashort (sub-100-fs) lasers readily available at Hz-class repetition rates. Although higher laser power and intensities are needed for some investigations (e.g., ion acceleration and SF-QED), many of the fundamental physics challenges described here do not necessarily require higher intensities. Instead, they require laser technology advancements in precision, control, repetition rate, efficiency, and access to flexible regimes of operation (e.g. multiple beams, various wavelengths, coupled external accelerators). Presently, high-peak power, short-pulse systems are based on Ti-sapphire laser technology and operate at 1-10 Hz. This low repetition rate limits feedback control and machine learning that, with higher repetition rates, would enable sub-microradian pointing stability needed for combining stages of LPA. With higher repetition rate enabled control, laser shaping would not be limited by facility fluctuations. This would in turn enable precision control of injection and acceleration. Such control has been demonstrated on kHz lasers with small pulse energies, and achieving the energies needed for LWFA at such repetition rates is a key technical need.

BOX 3.1
The LaserNetUS Facility Network Provides Broad Access and Collaboration Opportunities across a Range of Mid-Scale Laser Facilities

The LaserNetUS network was established in 2018 by the DOE FES to provide U.S. scientists increased access to unique high intensity laser facilities. The LaserNetUS facilities are located at universities and national laboratories distributed geographically throughout the US with one in Canada: University of Texas at Austin, Ohio State University, Colorado State University, Université du Québec, University of Michigan, University of Nebraska- Lincoln, University of Rochester, SLAC National Accelerator Laboratory, Lawrence Berkeley National Laboratory, and Lawrence Livermore National Laboratory. These facilities are listed in the context of others in the community in Chapter 4, Table 4.1. The range of parameters accessible in LaserNetUS facilities will enable U.S. scientists to perform experiments at conditions not available at their home institution. LaserNetUS is designed as a step towards addressing strong international competition and loss of U.S. dominance in high-intensity laser research and related applications. LaserNetUS benefits the entire field of plasma science by providing broad access to state-of-the-art mid-scale laser facilities. The network also provides a platform for training the next generation workforce on short pulse, high intensity laser science and applications. LaserNetUS provides smaller institutions and single investigators access to PW-class laser systems. This type of network can strengthen relationships between national laboratories and universities, provide more cross-collaboration opportunities, and engage a broader community including industrial users. Likewise, improving diversity requires casting a wide net so that all have access to state-of-the-art facilities. Part of the LaserNetUS mission is to provide access to high intensity lasers to the large number of university groups. It will also facilitate interchange with international laser facility networks, which is in progress. Programs to facilitate added capabilities and upgrades for the laser facilities are being discussed.

BOX 3.2
Staging of Plasma Accelerators Sets the Stage for Future Colliders and for More Compact Light Sources

Sequentially combining plasma wakefield accelerators (PWAs) to reach successively higher energies is an attractive path to future high energy physics particle colliders. On the other hand, sequential staging of PWAs to decelerate electrons (after production of photons) may be an enabling technology for broad applications of advanced light sources to reduce radiation shielding that could otherwise dominate size. An experiment recently demonstrated both concepts, and illustrates both progress and challenges in the field. The experiment required a series of laser-plasma accelerator techniques to operate reliably in combination. To produce a stable injector stage, one laser pulse was focused onto a supersonic gas jet, yielding a plasma accelerator with stability but modest beam quality. Stable electron beams with mean energy of 120 ± 5 MeV, a 60% energy spread, charge of 33 ± 5 pC, divergence of 4 ± 0.3 mrad and pointing stability of 0.3 mrad were achieved over hours of run time, thousands of laser shots and over more than 10 days. To couple this electron beam to the decelerating stage, a short focal length electron lens was developed based on the discharge current in a plasma capillary enabling a compact setup and preventing degradation of the electron beam over long propagation distances. The second stage plasma accelerator was powered by a second laser pulse. Plasma mirrors were used to turn the laser at 90 degrees in a few cm before the second stage. The short coupling distance is important both to compactness and to limit ballistic lengthening of the electron bunch as it propagates, which could spoil efficiency. Acceleration and deceleration were observed at alternating timings as expected. Precision experiments to realize high performance, stable accelerators and couple them efficiently and while maintaining beam quality are now in progress for future applications.



Recent experiments combined multiple laser driven plasma accelerator stages, demonstrating a critical capability. (left) A schematic of the apparatus. The inset shows the evolution of the electron beam waist simulated along the beam path. Part of the broad energy spectrum from the first accelerator is focused at the entrance of the stage 2 plasma. (right) Spectra of electron beams from the two coupled laser-plasma stages show the effect of the second structure (a) 100-shot average unperturbed reference before arrival of the second laser pulse. (c)-(f) 2D charge map for the first two maxima and minima of the energy oscillation. SOURCE: S. Steinke, et al. Steinke, S., van Tilborg, J., Benedetti, C. et al. Multistage coupling of independent laser-plasma accelerators, Nature 530, 190–193 (2016). https://doi.org/10.1038/nature16525.

Findings and Recommendations

The study of plasmas driven by intense lasers and particle beams is opening new fields in plasma optics, high field physics, particle acceleration, and radiation sources and enabling new applications across science and society. These include

- Transforming our understanding of the fundamental mechanisms of laser-plasma coupling and particle acceleration, and developing predictive models across experimentally available parameter spaces;
- Implementing plasma optics in laser systems to both support current experiments and access new plasma regimes;
- Advancing control of particle and radiation sources with good reproducibility, detailed on-shot characterization, and high fidelity predictions by simulations/models;
- Developing secondary beams for probes and pumps in HED physics and for applications in security, industry and medicine.

Laser and Beam Plasma Wakefield Acceleration: Many important firsts have been demonstrated in wakefield and underdense acceleration, and brilliant X-ray sources. These accomplishments have established a path to meeting needs in applications ranging from extending the reach of high energy physics to transforming the performance and dose for X-ray imaging. The rich physics of resonant control needs to be explored and exploited to achieve advances in accelerator performance. Next steps in technology development include kHz repetition rates enabling stabilization and active feedback for precision shaping of the plasma state, and new regimes in driver intensity and wavelength.

Ion acceleration: New mechanisms for ion acceleration are now accessible, including via radiation pressure and magnetic vortices. New laser, diagnostic and target capabilities are now emerging to enable higher repetition rate and control. Although existing facilities are being used to demonstrate important fundament concepts, new facilities with increased intensity and contrast are needed to achieve the energies predicted by theory and computations. These compact ultrafast ion and neutron sources could enable more effective cancer therapies, advanced HED science pump and probe sources, and neutron sources for industry and security. (Additional important opportunities in lasers co-located with coherent X-ray light sources are discussed in Chapter 4.)

Strong field science: Laser-plasma interaction studies have opened a new regime whereby the physics of a relativistic plasma is strongly affected by strong-field quantum electrodynamics (SF-QED). These opportunities include laboratory analogies of Hawking radiation in electric fields and Unruh radiation, processes important to cosmology and astrophysics. Advances in strong-field science open the possibility of investigating the basics of astrophysical objects, including black holes, pulsars, and magnetars, in the laboratory; and uncovering the dynamic interaction of inner shell electrons with highly ionized, heavy nuclei. Extensions of existing facilities will enable early experiments of laser-electron beam interactions. Future facilities at and beyond the 10 PW power level are important to fully exploit these opportunities.

Plasma optics: Beyond adjusting parameters like intensity and frequency, the spatiotemporal structure of light offers additional degrees of freedom for controlling the interaction of intense laser pulses with plasma. Broad-bandwidth lasers could revolutionize ICF by providing unprecedented spatiotemporal control over laser-plasma interactions. Magnetization has recently emerged as a new capability to modify collective behavior and manipulate plasma optics.

Across the LPI area, the Chapter 1 findings and recommendations on workforce, demographics and academic representation apply. Importantly, the state of the academic and national laboratory workforce is nearing a critical point and addressing these concerns is crucial to ensure continued progress in LPI. The U.S. workforce issues are particularly critical to LPI. There is unprecedented international growth and competition. The U.S. LPI field is strongly reliant on international graduate students and post-doctoral researchers. As international facilities take the lead over U.S. facilities, the international workforce will be attracted away from the United States, which could place the LPI field in the United States at risk.

Compact plasma accelerators, plasma X-ray sources, and plasma optical methods were in large part invented in the United States, and the United States has held a leadership position in most of the field in past decades. However, as reported in the National Academies study Opportunities in Intense Ultrafast

Lasers: Reaching for the Brightest Light (2017) (RBL) the United States has recently lost dominance in high-intensity laser research, which is impeding progress in the essential areas of plasma science outlined in this chapter. The loss of leadership in large part is due to large investments in new laser facilities and corresponding research programs made and being made in Europe and Asia. (See Figure 3.16.) These international investments have in particular emphasized development of multi-PW systems, and these facilities are driving forward capabilities in all the research areas discussed here. RBL concluded that the research performed on non-U.S. facilities does have great value for the nation. However, without additional U.S. investments in laser facilities, leadership in LPI will drift away from the United States.

Findings and Recommendations

Finding: Compact plasma accelerators, X-ray sources, and optics were invented in the United States. However, as reported in the *NAS Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light*, the United States has lost dominance in high-intensity laser research and related research that is essential to plasma science, accelerators, and their applications.

Finding: There are strategic opportunities in the next 10 years to build scientific facilities that can leap-frog international competition and enable the United States to maintain a leadership position in laser-plasma interactions.

Recommendation: To restore U.S. leadership, DOE and other agencies should formulate a national strategy to develop and build new classes of high-intensity lasers that enable now inaccessible parameter regimes.

Facilities constructed through the strategy above would produce the technologically highest intensities to open up new regimes in high field physics and ion acceleration, having repetition rates at and beyond 1 kHz, with shaped pulses enabling precision control, and with active feedback and machine learning for acceleration and plasma optics.

Finding: Plasma acceleration and controlled laser-plasma optics are rapidly advancing, driven by newly available capabilities in short pulse/broad bandwidth lasers.

On the horizon are kHz lasers with active feedback together with pulse shaping and bandwidth control capabilities that together will drive progress. This will enable new capabilities ranging from X-ray characterization (medicine, industry, and nuclear nonproliferation as well as transformative HED diagnostics) and inertial fusion to medical therapy and future particle colliders. Long term translational and applied laser source development and high repetition laser driver development are required to realize applications. However, there are currently few efforts to achieve these goals.

Finding: Applications require robust, compact drivers. A long-term plan and resources for developing technologies that can leverage science advances into society benefiting applications are needed.

Recommendation: DOE and NSF should lead a collaborative effort with other agencies to develop an extended stewardship program for long-term, application-oriented research to enable the development of revolutionary laser sources that translate to applications.

Very high repetition rate, precision-controlled lasers and plasma methods will need to be included as part of the stewardship program.

Finding: Collaboration between agencies focused on source development (DOE, NSF) and potential user agencies (e.g., NIH, DoD) is needed to ensure that advanced laser capabilities are developed.

Examples of such potential collaborations are given in Chapter 1, Table 1.

Rapid research progress relies on access to the latest laser and related technology, and it is important that access be available beyond the few institutions with large programs. LaserNetUS provides important access opportunities to mid-scale facilities.

> **Finding:** There is need for multiple programs and approaches in experiment, theory and computation, ranging in scale from single investigator experiments to user facilities and dedicated mission focused facilities or centers.

> **Recommendation: Agencies focused on the fundamentals of LPI (NSF-MPS, DOE-FES, DOE-NNSA) should collaboratively augment and create programs in plasma acceleration and optics that support a range of scales and multiple efforts and that coordinate research, user access, and educational support.**

Table 1.1 in Chapter 1 lists opportunities for cross-agency collaborations.

> **Finding:** A blend of science innovation (e.g., development of new physics regimes in high field science) and long-term engineering efforts to develop new facilities has been essential to progress in laser-plasma interactions.

> **Finding:** Together with support from other agencies and DOE support concentrated at the National Laboratories, NSF support devoted to LPI at universities is essential to the field.

> **Recommendation: NSF-MPS, DOE-SC, and DOE-NNSA should strongly support research in the fundamental physics of plasma optics, high field acceleration and laser sources in collaboration with other agencies. This includes research, centers, and mid-scale infrastructure.**

> **Finding:** Computation and theory has been essential to the development of the field of Laser-Plasma Interaction (LPI), providing insights and crucial input into experiment design. U.S. computation, once dominant, has lost that advantage.

Leadership in computations has transitioned to non-U.S. institutions, particularly in Europe where multiple code development efforts are being supported. In contrast, funding in the United States no longer provides significant support for multiple, competing code efforts.

> **Finding:** A range of needed computational tools, both fluid-based and DSMC-PIC, is also needed for modeling plasma sources.

> **Finding:** The innovation that comes from healthy competition would help restore U.S. leadership in computations for LPI.

> **Recommendation: NSF-MPS, NSF-CISE, and DOE-SC should support a diversity of computational and theoretical efforts to help restore U.S. leadership in computations for LPI.**

4

Extreme States of Plasmas: High Energy Density Systems

HIGH ENERGY DENSITY PLASMAS, INERTIAL CONFINEMENT FUSION, AND WARM DENSE MATTER

On the surface of Earth, we live at a pressure of 1 atm. In terms of energy, 1 atm corresponds to about 10^5 J/m^3 or about 0.03 eV per molecule of air. In the types of atmospheric pressure plasmas that are used for sterilizing surfaces for biomedical applications, the electrons can have high energies (3-4 eV) compared to the gas, but the fractional ionization is small, and so the energy density of the system remains small. In arcs, this energy density may rise to 0.5 or 1 eV per molecule, but even these energies are relatively low—low enough that atoms and molecules in plasmas having these energies still interact by forces determined by the electrons orbiting in the outer shells around nucleus. At these low energies, matter predominantly interacts chemically through the breaking and making of bonds facilitated by orbital electrons. Plasma chemistry uses the more energetic electrons to create excited states and radicals to selectively speed chemistry. However only a small fraction of the ordinary matter in the universe exists at the low energy densities that are experienced on Earth.

Most of ordinary matter in galaxies is in a high energy density (HED) state. Stellar interiors, planetary interiors, and supernovae can all be classified as HED matter, where the material energy density is > 10^{11} J/m^3, (or, equivalently, at a pressure of > 1 million atmospheres (1 Mbar)). At these high energy densities, all matter has been ionized and all molecules dissociated. The interactions in HED matter are between highly ionized ions, the deep inner shell electrons that may remain bound to the atoms, the free electrons that have been liberated, and the photons the plasma produces. This definition of HED is not fixed. High energy density physics, HEDP, begin to appear in materials at about that pressure. The plasma regime now known as "warm dense matter" (WDM) approximately covers the range of matter having energy densities well above those of typically industrial plasmas and reaching the lower bounds of HED plasmas. As more is learned about the dynamics of HED systems, new ways of describing that behavior have been proposed - organized complexity, systems far from equilibrium, self-organized structures, and material controlled and manipulated via intense fields—however, these are all systems at HED, as shown in Figure 4.1.

Inertial Confinement Fusion (ICF) is that field in which matter is compressed to high energy densities in an effort to controllably initiate fusion reactions in the laboratory. Many methods have been proposed to accomplish ICF in the laboratory. The two primary methods are compressing pellets of frozen deuterium and tritium (DT) targets (or capsules) using ns pulsed lasers, and compressing targets using the plasma forces enabled by pulsed power. ICF is considered to be part of HEDP because for most of the duration of an ICF implosion, the ablators and the DT core are in the HED regime. Indeed, most HED studies began as support for (and were supported by) ICF needs. While the three fields have historically, and will remain, closely linked, HED, WDM, and ICF are now three independent and flourishing branches of plasma physics.

High energy density plasma physics is also closely linked to other branches of plasma physics. At HED pressures, researchers can study laboratory fusion, create intense x-ray sources, and measure the intrinsic properties of materials at extreme conditions (such as density, strength, opacity, and equation-of-state—the relation between pressure, density and temperature) that are critical to astrophysical systems (such as the Sun and stars, supernovae, giant planets, and exoplanets) and necessary for stewardship of our nuclear deterrent. For example, the plasma property of opacity (the transmission and absorption of radiation) is important across all plasma regimes, but is particularly important in the HED regime as radiation is a dominant form of power transfer. Precise knowledge of opacity is critical to astrophysics, ICF and stockpile stewardship. Fundamental AMO (atomic, molecular and optical) physics data for molecules, atoms, and ions, such as energy levels, collisional-radiative rates, spectral line shapes, equations-of-state, and transport coefficients, are essential for understanding and analysis of all fields of plasma physics; and particularly important to understanding of radiation transport and ionization kinetics in HED physics. The need for this data, which is difficult to experimentally measure, has led to the development of sophisticated computational tools. Continued development of these computational tools is essential to furthering HED physics.

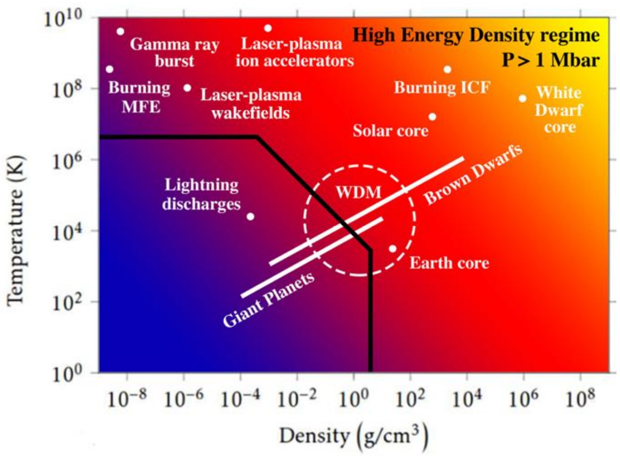


FIGURE 4.1 *The Regimes of HED Plasmas*. Plasmas can exist over an incredible range of conditions – here characterized by their temperature (10 orders of magnitude and density (18 orders of magnitude). High energy density (HED) plasmas occupy the area above and to the right of the black line, having pressures greater than about 1 million atmospheres. This is the regime of astrophysical objects and is now being routinely explored by laboratory experiments. In the case of plasma accelerators, temperature is related to the plasma momentum spread rather than a thermal distribution. SOURCE: Courtesy of Adam Sefkow, University of Rochester, and Gail Glendinning, Lawrence Livermore National Laboratory.

Plasma physics in the HED regime is also important to the field of quantum materials—systems in which interactions between atoms are dominated by quantum effects. New experimental and computational capabilities developed at HED science facilities can tune conditions to produce new phases of materials and preserve metastable states with enhanced properties, both near and far from equilibrium. The realm of quantum materials had previously been limited to low temperatures, limiting the breadth of quantum phenomena that can be investigated and exploited. In the past few years, however, a new generation of HED capabilities has enabled the controlled manipulation of pressure, temperature, composition, and magnetic fields (P-T-X-H) as well as time, enabling development of revolutionary quantum materials. Controlled Mbar (100 GPa or 1 million atmospheres) to Gbar (1 billion atmospheres) pressures enable up to a 1000-fold compression of materials, providing precision control of interatomic distances and thus overlap of quantum orbitals. Dynamic compression can now control the thermodynamic path, states, and processes to still higher (e.g., atomic scale) pressures. These capabilities have crossed into a new frontier of quantum HED matter, one that can leverage quantum properties of materials at high temperature.

The status of ICF and HED was summarized in the Plasma 2010 Decadal report. In this report, there was great optimism for achieving ICF ignition through laser-driven indirect drive (LID) on the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL). It was recognized that shock timing and symmetry would be challenging, and it was anticipated that laser-plasma instabilities (LPI) would add substantial uncertainties to predicted ignition scenarios. However, it was believed that gas-filled hohlraums would mitigate LPI and allow for controlled symmetry, and that implosions could be performed with the available laser energy. The option of laser-driven direct drive (LDD) for ICF, primarily investigated at the Laboratory for Laser Energetics (LLE) using the Omega laser facility, and Naval Research Laboratory (NRL), was not specifically addressed. LPI was expected to be a significant problem for only laser beams interacting with hohlraums. The ignition challenges for laser-driven direct drive were seen as symmetry, laser-seeded hydrodynamic instabilities, and shock timing (very similar to LID). The idea of direct magnetic drive, currently under investigation at Sandia National Laboratories (SNL), was not yet developed at the time of the Plasma 2010 report. In spite of its more recent development, indirect magnetic drive at SNL had achieved high neutron yields in Z-pinch driven wire-array hohlraums (10^{13} neutrons from DD filled targets, which would give ~10^{15} neutrons for a DT filled target). Direct magnetic drive was seen as a possible alternative to LID, especially as a neutron source.

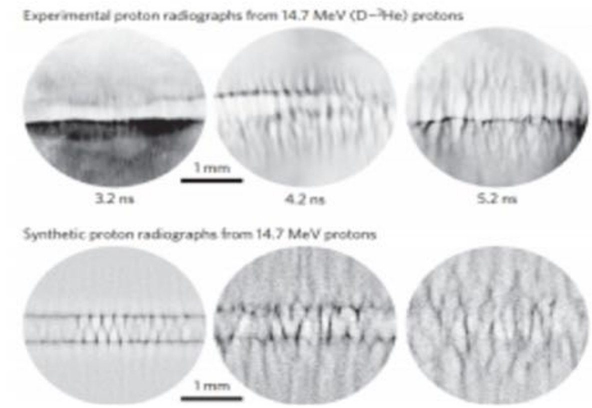


FIGURE 4.2 *Imaging Collisionless Shocks in HED Plasmas*. These proton radiographs from an experiment on the Omega laser at the Laboratory for Laser Energetics show the creation of magnetic fields, in two counterpropagating plasma flows, due to the Weibel instability. Such magnetic fields are believed to be responsible for the creation of shocks in a plasma where the mean free paths of the particles are large (collisionless plasmas). The protons in the radiographs are deflected by the strong magnetic fields created in the originally unmagnetized plasmas. Experimental results are shown on the top and synthetic radiographs from a 3D particle-in-cell simulation are shown on the bottom.
SOURCE: C. Huntington et al., Fiuza, F., Ross, J. et al. Observation of magnetic field generation via the Weibel instability in interpenetrating plasma flows. Nature Physics 11, 215 (2015), https://doi.org/10.1038/nphys3178.

Shortly before the Plasma 2010 decadal survey, HED science had been the topic of a consensus study report ("Frontiers in High Energy Density Science," 2003) with emphasis on the requirements for stockpile stewardship. In order to fulfill those stockpile stewardship goals, the Plasma 2010 Decadal survey listed the following requirements and benefits:

- Accurate understanding of material properties in a wide range of pressure and densities;
- Well-diagnosed experiments for validating codes covering solid-to-WDM-to-weapon-relevant conditions;
- Large-scale 3-dimensional simulations;
- Validating codes through simulations of igniting ICF capsules, and
- Potential to engage new workforce participants for stockpile stewardship due to the scientific challenge of ICF.

Stockpile stewardship falls within the mission of the National Nuclear Security Agency (NNSA) which supports much of the HED investigations performed at national laboratories. While basic science is not the mission of the agency, NNSA in 1998 had established the Stewardship Sciences Academic Alliances (SSAA) and Stewardship Sciences Graduate Fellowship (SSGF) programs. It was predicted in the Plasma 2010 survey that use and applicability of advanced computer simulations of HED plasmas would need to expand to meet both ICF and stockpile stewardship goals. The expanded capabilities were expected to include, for example, density functional theory calculations of equations of state, and extending particle-in-cell (PIC) codes to larger volumes and longer time to study laser-plasma interactions and interpenetrating plasmas. Investigations of coupled radiation and hydrodynamics in HED regimes were seen as relevant to astrophysical systems, particularly radiation driven shocks, radiating shocks, jets, and ablation by radiation. Atomic physics in the HED regime was expected to significantly affect the understanding of opacity, and spectroscopy from igniting cores was anticipated to enable the exploration of new regimes.

The commissioning of the Linac Coherent Light Source (LCLS) was expected to be especially productive and exciting to the WDM field, with a short pulse, monoenergetic x-ray probe coupled to a laser driver. Plasma 2010 particularly emphasized the importance of encouraging strong outside users' programs, such as that at LLE, at other national facilities, as shown in Figure 4. 2. It was anticipated that ion beam drivers would be very useful for creating WDM conditions. The WDM field was poised to begin relevant work on radiative properties in intense magnetic fields, particularly relevant to white dwarf conditions.

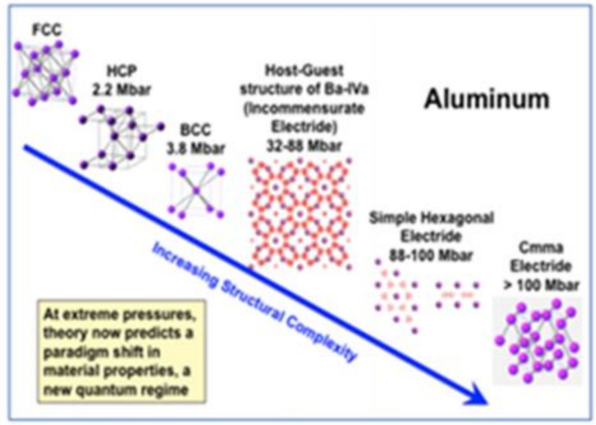


FIGURE 4.3 *Compressing matter to the Extreme.* When even common materials are under extremely high pressures, they take on unique structures. For example, as the pressure is increased in an Al sample, AIRSS (Ab Initio Random Structure Searching) calculations predict that the ion cores of the metal will occupy a larger fraction of the volume. For pressures over 32 Mbar, the valence electrons will be forced into pockets, forming a structure known as an "electride," in which the electrons act as a massless negative ions. Pressures up to 1 Gbar have been achieved on NIF experiments, but the X-ray characteristics required to measure the structures by x-ray diffraction are currently only available from the brightest monochromatic sources (e.g., LCLS). SOURCE: Courtesy: Chris J. Pickard, University of Cambridge, and Gilbert Collins, University of Rochester.

HED PHYSICS —DYNAMIC WITH BROAD IMPACT

The applications of HED science span a tremendous range. In the *NNSA 2018 Stockpile Stewardship and Management Plan*, the challenges and strategy for the Science Program for 2018-2025 includes HED science and the importance of understanding materials and conditions in the HED regime for stockpile stewardship. For example, the Z-machine at SNL has been used to evaluate plutonium aging in weapons by comparing properties of fresh plutonium with those of more than 50-year-old plutonium extracted from the Nation's weapons stockpile. These are exceedingly important and necessary studies that can only be accomplished using HED national facilities. At the other extreme, understanding plasma opacity through HED experiments can contribute to improved industrial designs for extreme ultra-violet (EUV) plasma sources for lithography required for the development of microprocessors having ever smaller features.

The study of plasma physics in the HED regime is closely connected to other branches of physics and can help address many fundamental questions relevant to the broader community. These related fields and questions include

1. *Astrophysics*: How are hydrodynamic shocks and instabilities affected by radiation? What nonlinear process occur when plasmas collide? HED facilities with either high-energy laser or pulsed power drivers can create conditions similar to those in astrophysical systems, and where relevant hydrodynamic problems can be studied in a controlled environment from known initial conditions. Type-II supernova explosions are Rayleigh-Taylor unstable and stellar wind flowing around a

planetary magnetosphere is subject to the Kelvin Helmholtz instability, both of which can be studied in HED facilities to advance astrophysics when applying appropriate scaling parameters. There is an opportunity for astrophysically relevant experiments to investigate the interplay of magnetic fields on hydrodynamics flows, such as the amplification of galactic magnetic fields, and how radiation affects the growth of structures in core-collapse red supergiant supernova explosions. The data produced by HED experiments can aid in validating and guiding astrophysical modeling and theory. An example of such HED data is shown in Figure 4.2. In this experiment on the Omega laser, a collisionless plasma is generated by laser ablation. Where the plasmas interact, the Weibel hydrodynamic instability seeds the creation of magnetic fields, which are detected by the deflection of protons generated by an imploding ICF capsule. The plasma and proton deflections were simulated in three dimensions using a particle-in-cell code.

2. *Material science:* What are material properties at the pressures and densities present in the interiors of planets, or white dwarfs? These are critical issues to understanding the formation and evolution of these astrophysical objects, yet their properties cannot be directly observed. In this pressure regime, which combines classical solid state and plasma physics, first-principles material properties calculations are required. These calculations typically use density functional theory with molecular dynamics that should be benchmarked with experiments. The technique of ramp-compression, in which pressure is gradually increased to minimize heating of the material, has been used on NIF and Z to study samples in the solid state at pressures greater than 10 Mbar, comparable to the interior and formative conditions of terrestrial planets. Dense plasma states are being experimentally generated at even higher pressures, which are difficult to achieve in solids, matching the interior conditions of gas giant planets, non-terrestrial-like exoplanets, and the outer regions of brown dwarfs. The insulator-metal transition in dense fluid deuterium at pressures up to 3-6 Mbar has been experimentally measured, providing benchmarks for theoretical calculations used to construct planetary models.
3. *Nuclear physics*: How are nuclear reactions affected by dense plasmas? Nuclear physics has traditionally been studied in the laboratory using accelerator-beam techniques. In spite of their great value, such techniques may not address issues relevant to astrophysics and ICF, where all nuclear reactions occur in a plasma environment. This class of plasma physics relevant nuclear reactions can be explored using modern HED experimental capabilities. Light-ion fusion reactions are an important topic to both basic nuclear physics and astrophysics. For example, recent studies of T+T fusion reactions, revealed an unexpected dependence of the neutron spectrum on plasma temperature even though the plasma temperature is orders of magnitude less than the nuclear energies involved. This discovery is potentially important for the many nuclear reactions that occur in in plasmas such as those in stellar interiors and supernovae. Similar studies are now being performed on $^3He+^3He$, the last step of the main proton-proton chain. In a plasma, the charged particle fusion reaction rate is enhanced by electron screening of the Coulomb barrier. In stellar cores, the screening effect can enhance some reaction rates by tens of percent. In a high-temperature plasma environment, plasma-nuclear interactions can populate excited nuclear states through processes including nuclear excitation by electron capture and by electronic transitions. Understanding the coupling of nuclear states to the plasma is therefore important for understanding nucleosynthesis, particularly of the heavy elements, in astrophysical environments.
4. *Atomic physics*: Atomic physics and HEDP have a strong synergistic relationship. The product of atomic physics investigations is absolutely essential to the analysis of HED experiments and the development of HED computational models. The validation of atomic physics in these regimes is best performed by the controllable conditions possible in HED experiments. At the heart of this synergistic relation is - *what atomic physics in HED regimes is not treated properly or is missing?* The ionization potential of ions in a dense, strongly coupled plasma is lowered, due to the interaction with the surrounding plasma (continuum lowering). This continuum lowering is intimately connected to the equation of state and, thus, an accurate treatment is crucial for most HED and ICF applications. This is particularly the case for plasma mixtures and conditions having severe gradients in plasma

properties. The standard plasma density-dependent analytical models for continuum lowering are inadequate to describe solid-density plasmas at HED temperatures. For example, measurements of continuum lowering for both single-species and mixture plasmas—the same ion but in different materials at different densities—performed in free electron laser isochoric-heating experiments have highlighted the critical need for new methods and theories to compute equations of states in strongly coupled hot dense plasmas. X-ray spectroscopy is another synergistic atomic physics-HED physics topic. There has been a recent surge of experimental techniques to diagnose HED and ICF plasmas using x-rays, which has already advanced our understanding of both hohlraum and capsule physics.

5. *Opacities in solar and space physics and the semiconductor industry:* What new experimental techniques and new atomic and radiation physics modeling are needed for solar opacity measurements in the laboratory? Just as opacities are critical to HED physics, opacities are critical to the investigation of any plasma dominated by radiation transport. That is particularly true for solar physics where radiation transport is the dominant form of power transfer from the interior to the surface. Opacity experiments are challenging to perform because they require precise understanding of the laboratory drive and equation of state in addition to high precision spectroscopy and control over experimental conditions. As such, techniques developed and measurements made of opacities in HED physics are critical to a wide range of fields, including solar physics, astrophysics and stockpile stewardship. This also includes the high intensity EUV sources used in the semiconductor industry for lithography.

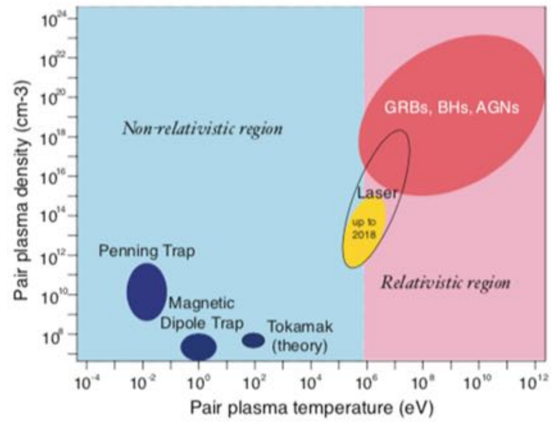


FIGURE 4.4 *Astrophysical HED*. Many of the most energetic phenomena in the university originate from HED plasmas. To explain the energetic events associated with to Gamma Ray Bursts, Active Galactic Nuclei, and Black Holes, one needs to invoke relativistic electron-positron pair plasmas and jets which were major components of the early universe. The image shows the electron-positron pair density as a function of plasma temperature. Although no experimental platforms are yet available that can simulate the relativistic pair plasma processes that replicate astrophysical conditions, laser-generated HED plasmas can produce electron-positron plasmas, shown as the yellow region in the plot. Increasing the pair plasma density over about 10^{15} will require lasers with intensities > 10^{24} W/cm^2. SOURCE: Courtesy of Hui Chen (LLNL), Frederico Fiuza (SLAC) and Bruce Remington (LLNL).

6. *Quantum materials*: What new materials might be achievable in the HED regime? The new science frontier of novel quantum HED structures combines quantitative cutting-edge experiments, theory, and ab initio simulations. These capabilities enable exploration of this extreme quantum regime with the prospect of a new types of synthesis and recovery of novel quantum materials. In the HED regime, theory now predicts new and exotic quantum states. There is a growing list of predictions for such behavior in everyday materials (e.g., Al; see Figure 4.3) with potential energy applications. New HED laboratory capabilities now provide the first platforms on which controlled and calibrated, laboratory-based experiments can be performed into the atomic pressure range, where the quantum shell structure of atoms is destroyed. In addition, novel hydrogen-rich superconductors have been discovered at high (few megabar) pressures with critical temperatures at or above room temperature. The combination of high pressure and hydrogen is predicted to produce a broad range of such superconductors.

IGNITION, INERTIAL FUSION ENERGY, AND STOCKPILE STEWARDSHIP

Inertial fusion energy (IFE), the commercial production of electricity from inertial confinement fusion, offers the prospect of a nearly carbon-free energy source with a virtually unlimited supply of fuel, as with magnetic fusion energy. IFE has been a long-term goal of ICF programs for decades, and several conceptual studies have been performed based on anticipated laser requirements and fuel management schemes. However, the unexpected challenges in achieving ICF ignition has tempered and delayed discussion of IFE systems until that critical demonstration of ignition occurs.

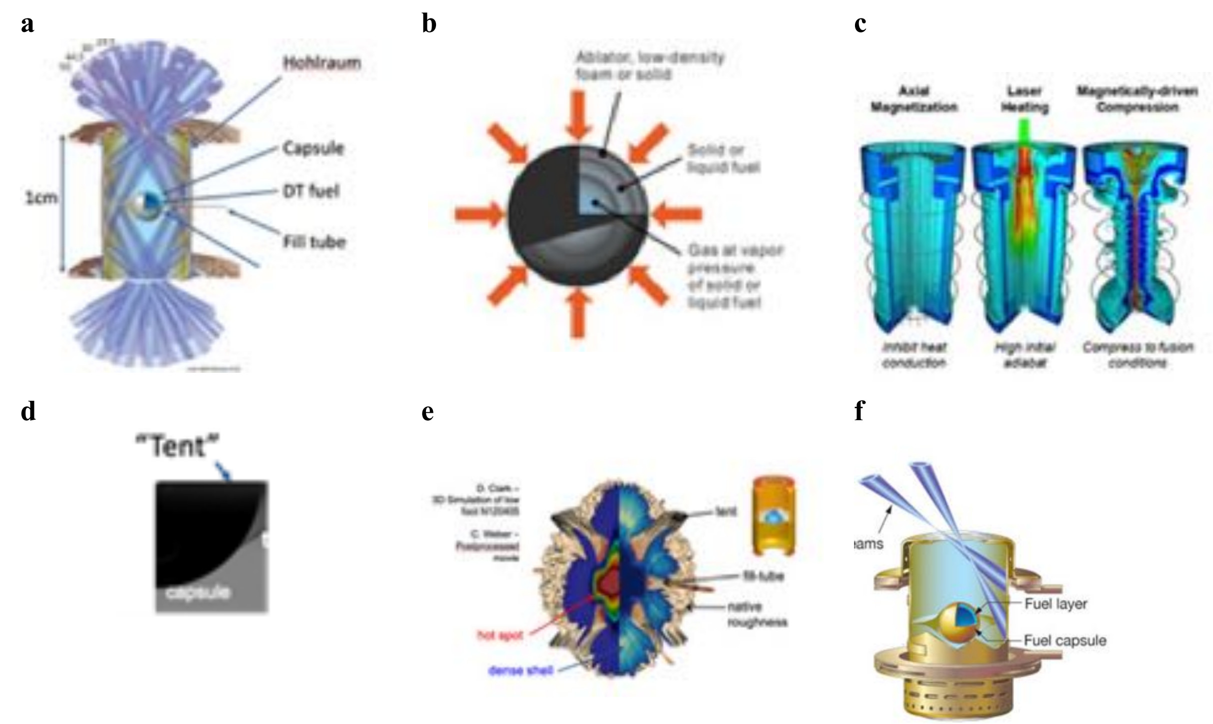


FIGURE 4.5 *Strategies for Ignition***.** There are currently three top contenders for achieving ignition and high energy yields with inertial confinement fusion (ICF). (a) Indirectly driven ICF target, with laser beams striking the inside of a gold cylinder (hohlraum) and bathing the capsule in an X-ray drive. (c) 3D computer simulation of complicated density perturbations in the imploded core of the capsule, seeded by asymmetry in the X-rays, fill tube (used to fill the capsule with DT), and "tent" (capsule mount). (b) Direct drive geometry, where lasers uniformly illuminate a capsule. (c) The drive process for the MagLIF concept of magneto-inertial fusion. First the cylinder of DT inside the high-Z liner is immersed in a static magnetic field; then a laser is fired along the axis to increase the adiabat and stabilize instability growth; finally, the DT is compressed by imploding the liner with the Z-pinch drive. SOURCE: (a-c) Campbell et al., Matter and Radiation at Extremes 2, 37 (2017); https://doi.org/10.1016/j.mre.2017.03.001; (d) Phys. Plasmas 22, 022704 (2015), https://doi.org/10.1063/1.4907179; (e) Reproduced from D.S. Clark et al., Phys. Plasmas 23, 056302 (2016) with permission of AIP Publishing, https://aip.scitation.org/doi/figure/10.1063/1.4943527; (f) https://lasers.llnl.gov/science/icf.

The prospects for IFE were examined in detail in the 2013 NRC report, "An Assessment of the Prospects for Inertial Fusion Energy". The report recommended a series of milestones to be used in a roadmap to assist in planning the recommended national IFE program, leading to a demonstration plant for producing net usable energy. The first milestone is ignition. Achieving ignition is a prerequisite before serious plans for a demonstration plant can be considered. Ignition will provide data and insights that will be required for future decisions on whether to pursue IFE. For example, achieving this milestone will clearly establish the energy requirements for ignition and possible capsule architectures that can be used. The report concluded that various target designs and driver approaches had both potential advantages and uncertainty, and that the best driver approach was not yet established. IFE will require target designs and drivers that can operate at high repetition rates (5–20 Hz) while delivering a net energy gain of ~10 per pulse. (Gain is the ratio of energy produced by fusion reactions compared to the energy used to initiate the fusion reactions. In this context, energy gain is fusion energy compared to the total facility energy.) These capabilities are well beyond the capabilities of existing ICF drivers which have pulse repetition rates from 1 per hour to 1 per day. Recently LLNL delivered a sub-scale version of an IFE laser concept, for the world's first 10-Hz PW laser system. This laser is supporting HED and discovery science experiments at the ELI-Beamline Facility in the Czech Republic. This investment ($53 million) by the European Union in laser technology developed in the United States illustrates how investments in ICF and IFE laser technology enabled advances in other areas.

There are still clearly challenges in achieving ignition and challenges in developing driver technologies that would be required for an IFE power plant. Even with those challenges, a modest IFE program in the United States would strategically leverage the significant investments made, and to be made, in the mainline HED program. The United States still leads the world in ICF research, high repetition-rate lasers, and pulsed power drivers, all of which are prerequisites for an IFE program. Maintaining a modest IFE program would open the way for partnering with the private sector as is now occurring in magnetic fusion energy (MFE). Industrial engagement has been very helpful for MFE. Such engagement for IFE would help build the knowledge base for IFE and, more broadly enhance the HED infrastructure. Pursuing ICF ignition is an extremely important goal, even without the current prospect of commercial energy. The pursuit of ICF ignition enables plasma studies at conditions relevant for nuclear weapons stockpile stewardship and other HED science applications.

The importance of HED science for the stewardship of the nation's nuclear stockpile was clearly stated in the *NNSA 2018 Stockpile Stewardship and Management Plan*. In order to fulfill its stewardship mission, NNSA listed strategic objectives of the Science Program. Specific objectives relevant to HED science for stockpile stewardship include:

- Enhanced capabilities will need to be developed to recreate more weapon-like conditions in experimental facilities;
- Focused experiments such as material characterization at HED conditions will be needed to support annual assessments;
- HED conditions will be needed to understand the impacts on performance of aging and of new materials and processes, and
- Promote academic alliances to recruit and train new generations of scientists.
- Evaluating the HED plasma environment requires innovative, sophisticated diagnostics.

ICF ignition and gain, important for the future of inertial fusion energy, are also important for stockpile stewardship. The degree of relevance to stockpile stewardship is to some degree correlated with the fusion energy yield. With higher energy yield from an ICF capsule, one can gain access to more weapons-relevant physics. For example, the following physics follows from achieving a given fusion yield.

- *Yield = 0.01:* Interplay of thermonuclear fusion burn and mix, nuclear physics data (reaction-in-flight, fission, and radiochemistry). This yield is currently available on the NIF which can provide a maximum yield of ~0.05 MJ.
- *Yield = 0.1 MJ*: Transport of charged particles in plasmas, threshold for fusion-fission physics.
- *Yield ≈ a few MJ*: Threshold for enabling complex mix physics studies, robust radiation and charged particle transport, robust fusion-fission experiments.
- *Yield = 20-30 MJ*: Higher fidelity versions of the above experiments are possible, neutron sources for materials and environmental studies

- *Yield = 500 MJ*: Use of fusion targets to drive complex experiments, use of fusion targets for material properties (EOS, opacity) research, combined neutron and x-ray environments for outputs and effects studies.

The training of scientists through the study of HED physics is an excellent contribution to the STEM workforce. These individuals gain fundamental, interdisciplinary knowledge of extreme states of matter using the most advanced technical systems that exist. For that reason alone, research at universities in HED should be strongly supported. However, the investigation of HED physics at universities also serves a strategic and critical role for national security. Science-based stockpile stewardship requires a uniquely trained and mentored workforce, which is best produced by actually researching HED physics, computationally and experimentally. It is difficult to imagine maintaining the technical expertise required for science-based stockpile stewardship in the absence of university programs in HED physics. To help advance education in the field of HED, and to increase access to HED resources for scientists in the field, the NNSA Stewardship Science Academic Alliances (SSAA) Centers of Excellence were started in the late 1990s. The first was the Institute of Shock Physics at Washington State University, founded in 1997. The funding of these Centers increased after the launch of the NNSA-DOE Office of Science Joint Program in HED Laboratory Plasmas in 2007. Subsequent studies have commended these Centers and recommended increased funding for them. Currently, nine Centers are funded with five focused on HED physics. Center funding has recently been flat with funding per Center decreasing from (typically) $2.5 million per year to $1 million per year, to enable more Centers to be funded. However, a stagnant funding environment has the potential to reduce the number of new facilities, given that operating existing centers is likely to be less expensive than creating a new center, and the overall number of students trained. The viability of stockpile stewardship rests on its scientific workforce, and the Centers are critical to providing that workforce.

Individual investigator support is also extremely important in supporting university research in HED and advancing the training of scientists in HED physics. This need is supported in part by the DOE Office of Science (SC) Fusion Energy Sciences (FES) and the DOE/NNSA/DP Joint Program in High-Energy-Density laboratory plasmas (HEDLP). This program, started in FY2007, remains a major source of funding for individual investigator work in HED. Individual awards range from $50,000 to $250,000 per year for grants from 1 to 3 years. In 2018, the program awarded 26 grants, totaling $13.8 million. However, this funding has been at risk in recent years. The program should be strongly supported as a significant complement to the larger HEDP Centers.

In addition to HEDLP, federal agencies have supported university research in HED science and closely related disciplines, including DOE-NNSA, DOE-SC, NSF, AFOSR, ONR, and DTRA. The major facilities in the NNSA ICF program (NIF, Omega, Z) have university use programs, while LaserNetUS network (launched in 2018 with DOE-SC support) is dedicated to providing “mid-scale” facility access to the HED science community. These efforts have enabled strong university collaborations and significant fundamental scientific discoveries, including helping in developing the future technical workforce. However, there remain significant concerns regarding workforce development. Universities are not provided a sufficient level of resources and attention in several technical areas relevant to ICF and HED physics, making it difficult to provide for future workforce needs, particularly where there are citizenship requirements. One such area is pulsed power-driven HED science and technology.

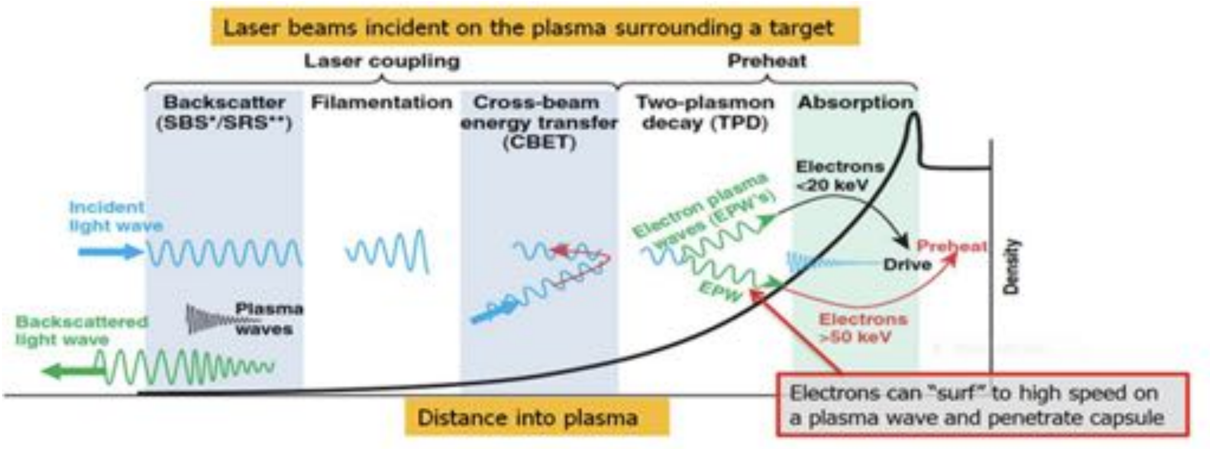


FIGURE 4.6 *Getting Laser Energy Into an ICF Plasma.* Laser driven ICF is challenged by uniformly depositing energy from the laser into the plasma. In many ways, the plasma fights against being uniformly heated by the laser due to a variety of instabilities that occur. Each instability has a threshold energy or power at which it is launched. In this image, the plasma density is shown by the black line, and increases towards the right. At the lowest density the laser may drive ion-acoustic waves in the plasma, reflecting light backwards, creating filamentation in the plasma, or transferring energy from one laser beam to another. Any of these will affect how the laser couples to the plasma. At higher densities, the laser may couple to the electrons and drive electron plasma waves, creating high energy electrons. These energetic electrons can penetrate into the unablated, dense target and raise its temperature and entropy. Laser plasma instabilities present challenges for the ICF community, but may represent opportunities as a way to create plasma optics. SOURCE: D.H. Froula, et al., Plasma Phys. Control. Fusion 54, 124016 (2012).

HED AND ICF ACHIEVEMENTS

In the past decade, the fields of HED physics and ICF have flourished. The following sections summarize some of these accomplishments.

Laser Driven ICF

ICF ignition designs, whether driven by x-rays, magnetized liners, or directly by lasers, attempt to compress DT fuel to high enough densities to ignite fusion reactions. The DT fuel is initially heated by the work done in compressing the fuel. This, in principle, is accomplished by assembling DT fuel in a small, dense, hot region at the center of the target ("hot spot"), which is surrounded by dense, cold, DT fuel. After ignition of the hot spot, a burn wave of fusion reactions propagates into the cold fuel, greatly increasing the yield. During fusion reactions, energetic helium nuclei (α-particles) are produced. Two threshold definitions are common in ICF: (1) A burning plasma is achieved when the energy deposition by the fusion-produced α-particles contributes more than 50% of the heating of the fuel in a capsule; and (2) Ignition occurs when the α-energy deposited in the hot spot is equal to the energy losses due to emitted x-rays and electron heat conduction.

The laser energy delivered by NIF to the target is at its maximum achievable level with the present design. This new capability brought research for laser indirect drive ICF to scales and conditions for ignition. (In laser indirect drive, LID, laser illumination of a small cavity holding the target, the hohlraum, produces short wavelength radiation that heats the target.) However, currently laser plasma instabilities and hydrodynamic instabilities are limiting indirect drive target performance. LPI occur when the lasers interact with the plasma inside the hohlraum, consisting of a combination of low atomic weight (low-Z) atoms ablated from the hydrocarbon capsule containing the DT fuel and high atomic weight atoms ablated from the hohlraum, typically coated with gold. LPI of various kinds can change the direction of laser beams (affecting symmetry of illumination of the target), transfer energy into electrons rather than ions (making the energy transfer less efficient and preheating the low-Z capsule), and reflect the laser energy back up the laser amplification chain (possibly damaging optics).

The laser direct drive (LDD) approach to ICF also has the potential to provide the high fusion yield required both for stockpile stewardship and for IFE. In LDD approaches laser beams are focused onto the surface of the target, possibly seeding hydrodynamic instabilities. LDD thus requires particularly uniform illumination to prevent instabilities. Both hydrodynamic and laser-plasma instabilities (LPI) similar to those occurring with indirectly driven capsules are expected as laser direct drive targets approach ignition. For example, complex hydrodynamic flows similar to those simulated for the indirectly driven capsule are predicted to occur for directly driven capsules. Although within directly driven targets the plasma consists of only low-Z atoms, LPI can still distort the incoming laser beams and produce high energy electrons which preheat the target. The main advantage of LDD is the higher coupling efficiency of laser energy into the kinetic energy of the shell (by a factor of 3 to 5 compared to LID). This higher efficiency results in less stringent ignition requirements for the maximum pressure at the hot-spot in the center of the target and by how much the shell of the target must be compressed. (This compression is measured by the convergence ratio, CR, the ratio of the hot spot radius to the initial capsule radius.) At LLE. where most direct-drive ICF implosions are performed, progress in diagnostics and modeling over the last decade have resulted in significant improvements in predicting the properties of a compressed target using hydrodynamic codes, enabling significant improvements in capsule performance.

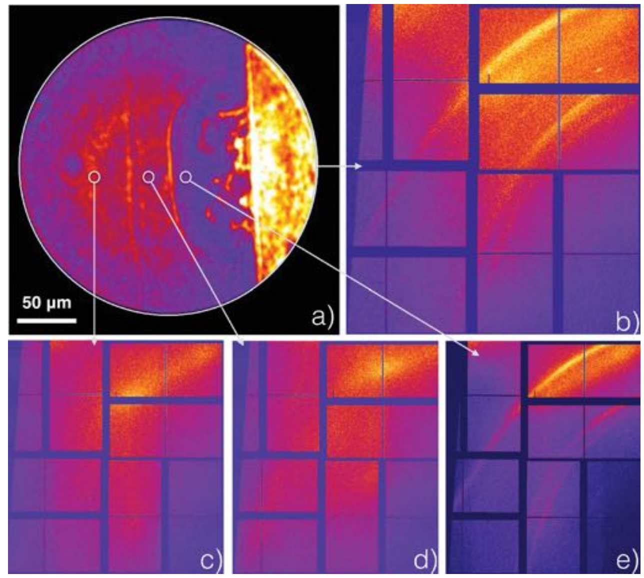


FIGURE 4.7 *Very High Intensity Laser Interactions with Materials.* The Matter at Extreme Conditions (MEC) end station at the Linac Coherent Light Source (LCLS) at SLAC uses the LCLS x-ray source to probe material in HED states. Here a sample of single-crystal silicon is shocked by the MEC short pulse laser, and the shock is imaged at high resolution by a phase contrast imager. An elastic wave and a plastic deformation wave can be seen, with clear increases in density and phase transition to polycrystalline Si. The x-ray beam is also diffracted (b) This image shows the diffraction patter from the entire image. By narrowing the field of view of the optics, the diffraction patterns can be sampled at different locations: (c) in the unshocked single crystal, (d) behind the elastic wave, and € behind the plastic wave). SOURCE: Review of Scientific Instruments 87, 103701 (2016), https://doi.org/10.1063/1.4963906.

Magnetically Driven ICF

In magnetically driven ICF, the inwardly pointing J × B forces that occur in, for example, high current discharges such as a z-pinch are used to compress a plasma to fusion densities. Some of the earliest concepts for laboratory fusion, dating from the 1940s, were magnetically driven. Unfortunately, due to challenges in overcoming instabilities, magnetically driven ICF fell out of favor. In fact, the field was not reviewed in the Plasma 2010 study, as there was little relevant research at the time. However, in the intervening years, a class of magnetized ICF known as magneto-inertial fusion has attracted more interest. At SNL's Z-machine, integrated experiments using magnetized targets preheated by a kilojoule laser source ("MagLIF") have demonstrated significant neutron yields. The strong magnetic fields decrease the plasma density required to stop α-particles so that they heat the fuel more efficiently, reducing the convergence ratio required to produce fusion from a DT target. Thus, the mix of cold ablator material into the fuel introduced in high-convergence, high velocity implosions (such as those in laser direct or indirect drive) may be mitigated. In addition to reducing the range of α-particles, the magnetic field reduces the thermal conductivity and keeps the fuel hot. The high efficiency of pulsed-power machines such as z-pinches makes them an attractive candidate for IFE drivers.

MagLIF and its targets, unlike the spherical targets in LDD, operate in a cylindrical geometry. The target DT fuel is first magnetized by an external magnetic field and then preheated to about 500 eV by an external laser. Finally, the target liner is imploded by the high MA currents produced by the Z-machine, compressing the DT fuel. Successful MagLIF experiments on the Z-machine showed significant thermonuclear yield in 2014 and helped invigorate research efforts in magnetized target fusion. In addition to SNL, the Alpha program in DoE's ARPA-E has provided funding to universities to perform fundamental research applicable to MagLIF fusion as an alternative energy concept.

User Access to HED Facilities

Since the Plasma 2010 report, LLNL and SNL have established external user programs whereby scientists outside the NNSA laboratories are granted access to the NIF and Z-machine HED facilities. The programs offer opportunities for a broad range of users to perform experiments in HED science, including laboratory astrophysics, planetary science, high pressure materials science, unique regimes of plasma physics, nuclear science, and particle acceleration. These regimes are found in planets, stars, galaxies, supernova dynamics, astrophysical shocks, and accreting massive black holes. Since the inception of the Z Fundamental Science Programs (ZFSP), major discoveries have been made in the areas of matter at extreme conditions and laboratory astrophysics. As one example, researchers have been able to achieve very high pressure, high density conditions that are relevant to planetary interiors. Solid state samples are being studied at pressures matching the interior and formative conditions of terrestrial planets, and at even higher pressures to match the interior conditions of gas giant planets, exoplanets, and the outer regions of brown dwarfs. Other experiments have measured opacity at stellar interior conditions in the laboratory (e.g., the opacity of iron). These experiments, performed on the Z-machine, produced opacities higher than theoretically expected, showing that the standard opacity models used by astrophysicists may need to be revisited. Although these programs provide excellent opportunities for external users, the community would benefit from there being a lower barrier for entry and support for the LLNL and SNL scientists who help external users navigate the system to gain access.

High Brightness Sources

The brightest free electron laser x-ray source, Linac Coherent Light Source (LCLS) at the SLAC National Accelerator Laboratory is enabling new investigations of HED plasmas. Studies using the Matter in Extreme Conditions (MEC) facility at LCLS have explored HED plasmas generated by long and short pulse lasers, using the femtosecond x-ray pulse from the LCLS. This has allowed, for example, investigations of warm dense matter structures and properties, nanometer-scale plasma features, dynamic phase transitions and lattice dislocations, and shock waves in materials. Diagnostics at the MEC allow direct measurements of material properties on each shot. The MEC is a major DOE/OFES investment in HED science and a major facility completely devoted to HED basic science.

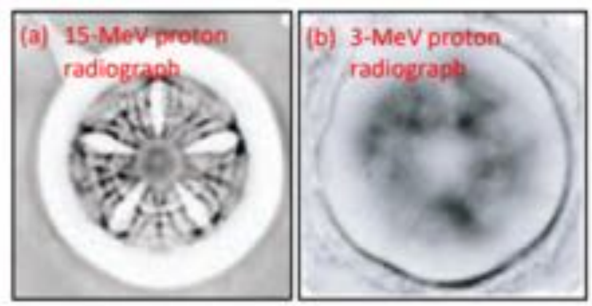


FIGURE 4.8 *An Experimental Setup.* While the strong electric and magnetic fields created in hohlraums (typically ~10^8 V/cm and ~100 T) have long been expected, calculating the formation and effects of such fields is an ongoing area of research for indirectly driven ICF. High energy protons are now being used to diagnose these very strong fields, but multiple ion species and energies are probably required to constrain the analysis. Two experimental radiographs show the deflection of 15-MeV protons (left) and 3-MeV protons (right) passing through a gold hohlraum driven by the Omega laser at the Laboratory for Laser Energetics. The protons are deflected by the strong electric fields generated by the hohlraum (the 3-MeV protons more than the 15-MeV protons). The five-fold symmetry is due to the laser irradiation symmetry, as the strong fields are produced at the collisions of expanding gold bubbles from the capsule. SOURCE: Science 2010: 1185747 doi: 10.1126/science.1185747.

Diagnostics and Simulations

A wealth of new results has emerged from ICF experiments over the past decade, enabled by diagnostics improvements, and have led to significant improvements in our scientific understanding. After the first set of ignition experiments on NIF (known as the National Ignition Campaign, NIC), it was recognized that hydrodynamic instabilities were degrading the quality of the implosions. Reducing instability growth (at the expense of hydrodynamic efficiency) improved target yield by an order of magnitude. The ability to model targets at high resolution in three dimensions has led to a better understanding of the impact of capsule “engineering features” such as fill tubes and mounts. By improving these features, target performance has also improved. Understanding the impact and control of the x-ray drive on the capsules has also improved. For example, the emerging field of plasma optics plays a role by using laser-plasma instabilities to create plasma gratings, in order to steer the laser beams in NIF hohlraum and improve capsule implosion symmetry. Implementation of many lines of sight for neutron detectors has given a clearer picture of the symmetry of neutron production in the hot spot, with asymmetry in drive linked to motion in the hot spot.

These new diagnostic-enabled results have motivated a complementary improvement in our ability to analyze, simulate, and deal with unprecedented volumes of data. Increases in computer power combined with improved algorithms have considerably improved the ability of simulations to model plasma experiments. Higher fidelity simulations with more fundamental physics and better resolution have improved our understanding of the physics controlling the performance of these experiments. For example, ICF simulations of indirect drive ignition targets and capsules can now include a broad range of perturbation sources such as surface imperfections, engineering features and drive asymmetries in a fully 3D geometry. These new capabilities have significantly improved the ability of simulations to match a suite of experimental observations across a range of targets. Simulations of direct drive targets and magnetically driven targets have also increased in fidelity and realism. The United States leads the field of ICF plasma simulations. This leadership has important implications for national security as well as future energy security and economic competitiveness.

Diagnostics on the major ICF facilities are proposed, prioritized, and scheduled (depending on funding) by the ICF National Diagnostic Leadership Group, based on input from the ICF National Diagnostics Working Group. As described in the "Energy and Water Development Appropriations for 2011 Hearings", the mission of the working group was to support the development of radiation hardened diagnostics for use on NIF after ignition was achieved. Its mission now encompasses diagnostics for the three major U.S. ICF facilities: NIF, LLE, and Z. NNSA sponsors workshops that are open to all technically qualified participants (the most recent was held in 2017, with 105 participants). Based on the outstanding results from diagnostics fielded in those three facilities over the last decade, this model works well. The National Diagnostic Working Group could be expanded to officially encompass diagnostic specific to HED, technology transfer to and from mid-scale facilities, and data analysis and data mining techniques.

Plasma Optics

Since the Plasma 2010 report, plasma optics has emerged fully as a field of research. Interactions of beams in plasmas have the potential to produce plasma-based optics that are capable of supporting much higher intensities and fluences than is possible in solids. Plasma mirrors, starting in the early 1990s, have been used to improve the contrast of short pulses and as a final focusing mirror for short pulse systems. In the past decade, several other plasma components, while still in the nascent stages of development, have been successfully demonstrated in experiments: lenses, waveplates, q-plates (which transfer angular momentum of photons between spin and orbital angular momentum), beam-combiners, compressors, and amplifiers.

SCIENCE CHALLENGES IN HED AND ICF PHYSICS

There are many science challenges unique to HED and ICF physics. In particular, it is clear that fusion ignition remains a grand challenge. Initial indirectly driven ICF experiments on NIF were strongly affected by implosion asymmetries and perturbations. Significant improvements in target engineering reduced perturbations seeded by capsule roughness, bettered hohlraum design to reduce asymmetries driven by LPI, and refined capsule design to reduce geometrically seeded asymmetries. The end result is that experiments on NIF achieved as much as a factor of three higher yield than that calculated without α-particle heating, near the threshold of a burning plasma. However, even with these successes, the cold fuel around the hot spot is not measured to be as dense nor as uniform as simulated, and laser-plasma instabilities remain a challenge that limits the maximum usable laser intensity. NNSA has a milestone for 2020 to identify and quantify the improvements needed to obtain ignition on the NIF, if it has not been achieved, and to determine the scaling to multi-megajoule yields.

Ignition may represent the most visible challenge, but it is far from the only one. As the HED field evolves to address the fundamental questions listed above, other challenges will arise to address the needs for the next generation of facilities, requirements for diagnostics in completely new regimes, and advances in computational techniques. These challenges include:

1. Further investigations into the astrophysical, opacity, and material science questions described above will require a new generation of drivers—lasers or pulsed power. Higher energy densities are needed to reach more relevant plasma regimes. These plasmas will need to be larger in spatial scale and more uniform to improve the quality of measurements.

2. Investigating those same fundamental questions will also require the brightest possible x-ray sources coupled to high-resolution diagnostics capable of interrogating higher energy densities. The paradox is that in creating larger, more uniform plasmas at higher energy density with more energetic drivers, the currently available x-ray sources (such as the SNL Beamlet backlighter and NIF's ARC petawatt laser) will be insufficient to diagnose density, temperature, ionization, and other required plasma parameters. Brighter sources, more like that currently available at LCLS, will be required for diagnostics. The requirements for better diagnostic resolution also increase requirements for source brightness.
3. Diagnosing exotic quantum materials likely means investigating the plasma conditions created by the highest intensity lasers at ever shorter time scales. Higher repetition rates (on the order of MHz proposed for LCLS II and a proposed upgrade to MEC) will achieve unprecedented precision and produced unprecedented amounts of data. Advances in computational capabilities for data mining and machine learning will be needed to deal with the large volumes of data produced.
4. While the existing major facilities are expected to continue to produce scientific return for at least the next decade, planning for successor facilities (both laser driven and pulsed power driven, for both ICF and HED) has started. The construction of LCLS II is underway, and proposals to upgrade the MEC facility are in progress. To continue the United States lead in ICF will eventually require the next facility intended for high gain ICF to be designed and built. Given recent discoveries, whether pulsed power or laser driven, the current HED facilities and technologies are likely be inadequate to achieve high gain ICF. Developing the driver technology to meet this goal will require early investment in design and proof of principle prototyping. The lead time is long and postponing such fundamental science and technology investigations until a funding decision is made to construct the next facility would result in significant delays. A Next Generation Pulsed Power Facility (NGPPF) based on linear transformer driver technology is a leading candidate to replace today's Z-machine. Understanding the low-density plasmas in the anode-cathode gaps of large pulsed power machines is important not only for electrical power transmission in such a high gain facility, but also for target implosion dynamics and overall target performance. These investigations can be done now to prepare for the next generation of machine.
5. *Computations and fundamental Data:* Computational advances will certainly be necessary to design, diagnose, and understand HED and experiments. Precise, ab initio simulations of materials in the plasma state are required to predict material properties such as opacity and equations of state. These simulations will need to be validated by focused and perhaps dedicated experiments designed for validation. Kinetic effects, magnetic and electric fields, and other detailed physics models must be improved from the current approximations. These will require significant improvements in current computational capability. Given these validated codes, simulations of the response of an integrated system such as an imploding ICF capsule, a supernova, or the interior of a giant planet will be possible.

   These first-principles simulations will need fundamental data such as cross sections for electronic and nuclear interactions, opacities, transport coefficients and oscillator strengths. Although generation of this data is generally thought to be the realm of AMOP (atomic molecular and optical physics) and NP (nuclear physics), it is nearly impossible to separate these disciplines from HEDP. The ability to simulate HEDP systems and interpret HEDP diagnostics critically depends on the availability of fundamental data. The HED/ICF computational and diagnostic goals can only be met by a synergistic relationship with a well funded AMOP/NP community in which fundamental data is produced and tested.

6. *Uncertainty quantification, artificial intelligence, and machine learning*: The large datasets beginning to be produced in HED/ICF facilities will need the same computational techniques for data analysis, uncertainty quantification, artificial intelligence (AI) and machine learning (ML) currently being implemented in other fields of science and engineering, though likely modified to the specialized types of data produced by these experiments. There is certainly a role for conventional methods of AI and ML which are in large part based on pattern recognition and optimization. However, there are also great opportunities to develop physics-based machine learning algorithms so that fundamental parameters can be derived, which can then be used as input to advance simulations. For example, currently the MEC operates at a maximum of about 5 Hz. A proposed upgrade will increase the data rate to 120 Hz. Future upgrades are planned for a 1 MHz repetition rate. This increases by orders of magnitude the volume of data produced, and this will need far more sophisticated data analysis tools. Modeling NIF cryogenic implosions requires ensembles of 10^4 to 10^5 simulations to cover the appropriate range of uncertainty in inputs. Storing, processing, and mining these ensembles requires ever improving data analysis techniques.

The need for improved, more sophisticated data analysis and uncertainty quantification is being recognized by the community. In 2014, there were only two talks at the APS Division of Plasma Physics Annual Meeting that dealt with either uncertainty quantification or data mining for HEDP. That number increased to ~10 in 2018 and 2019 (with a mini-conference in 2018). However, HEDP generally lags behind other branches of plasma physics in these areas. Of the mini-conference talks in 2018, less than a third were from an HEDP/ICF perspective (6 of 22 talks), although contributed oral talks from HEDP/ICF made up more than half of the conference (22 of 42 sessions).

In addition to laser and pulse-power technologies, advances in diagnostics and computations will be broadly applicable to other areas of plasma physics and even beyond plasma physics. For example, diagnostics necessary to understand (and advance) ICF/HED science will find application in nuclear physics, space physics, optical science and pulsed power development.

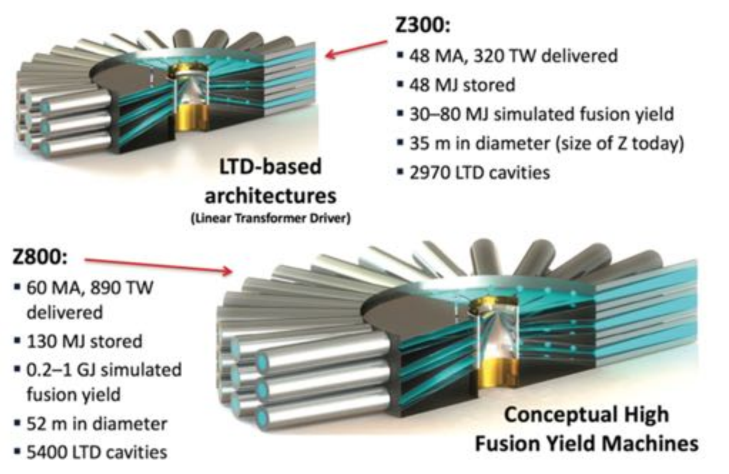


FIGURE 4.9 *The Future of Pulsed Power for HED*. Concepts for future high fusion yield pulsed power machines are based on the Linear Transformer Driver architecture. This architecture, conceived of in Russia at the High Current Electrons Institute in the 1990s, has been developed into fast single cavities which are shown here implemented in a modular design for future facilities. Another possible technology is based on the Marx generator (used by the existing Z facility at Sandia). However, for either type of device, the multiscale plasma physics required to understand and design the power coupling in a next generation machine remains a challenge to the HED physics community. Mid-scale (> 1 MA) pulsed power facilities are almost nonexistent and there is a need for such a facility to support progress in the pulsed power field. SOURCE: W.A. Stygar et al., Phys. Rev. ST Accel. Beams 18, 110401 (2015), Creative Commons Attribution 3.0 License.

FUTURE OPPORTUNITIES FOR HED AND ICF PLASMA PHYSICS

Addressing the science challenges above represents an opportunity to increase the relevance and impact of HEDP and ICF, and to empower other disciplines. Plasma physics is intrinsically interdisciplinary, and HEDP/ICF is no exception. Addressing fundamental plasma physics challenges requires discipline-centric investigations of the unique conditions of HEDP, yet those same investigations rely on advances in fundamental AMO/NP data, diagnostics, optics, electronics, computations (e.g., AI/ML). At the same time, the science and technologies produced by investments in HEDP/ICF have huge impact on other disciplines and national priorities, from studying supernovae to stewarding our nuclear stockpile.

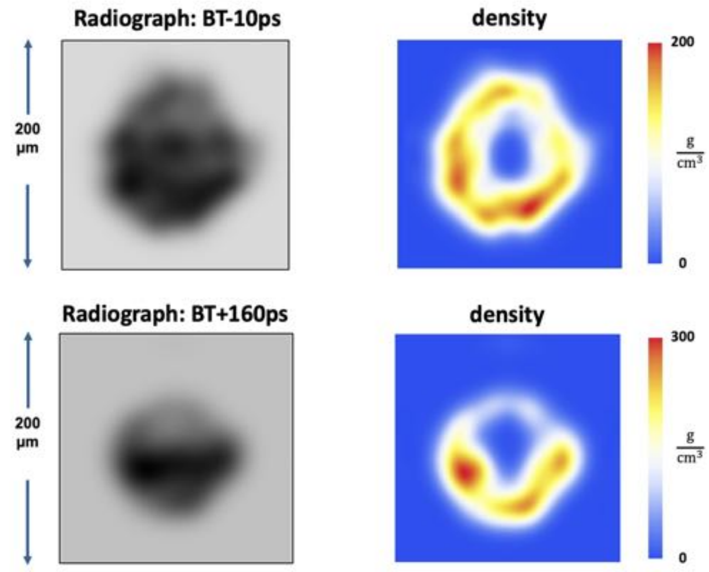


FIGURE 4.10 *Looking into the "Unseeable."* Left: Compton radiographs of a 3-shock HDC THD layered implosion recorded 10ps before and 160ps after bang-time (BT) at the NIF, using >50keV point projection backlighters generated by irradiating a 25µm-diameter Au wire with 30ps-long ARC pulses. Right: Reconstructed density distributions of fuel and remaining ablator showing significant 3D structure and top-down asymmetry. SOURCE: Courtesy of Riccardo Tommasini, Lawrence Livermore National Laboratory from Tommasini, R., Landen, O. L., Hopkins, L. B., Hatchett, S. P., Kalantar, D. H., Hsing, W. W., et al. (2020). "Time resolved fuel density profiles of the stagnation phase of indirect-drive Inertial Confinement implosions." Manuscript submitted for publication.

Ultra-Broadband Laser Technologies

One such example is the development of ultra-broadband laser technology. ICF designs are limited to intensities below the threshold of common laser-plasma instabilities. LPIs inhibit the deposition of energy in the ablator and risk damaging the laser by scattering light back up the optical chain. These instabilities can also generate super-thermal electrons that preheat the fusion fuel which reduces its compressibility. For LDD schemes, any non-uniformity in the illumination of the target—the so-called laser imprint—can produce instabilities. When using nearly monochromatic lasers, speckle can appear on the surface of the capsule, seeding a Rayleigh-Taylor instability which can cause the capsule to break up during compression.

Ultra-broadband lasers are a technology that may significantly mitigate the energy lost to laser-plasma instabilities in ICF, enabling more efficient use of laser energy with better coupling to the targets, whether directly or indirectly driven. (Ultra-broadband lasers would be an order of magnitude larger bandwidth than that produced by chirping techniques to generate femto-picosecond pulses.) This capability could dramatically expand the design space available for HED and ICF experiments. Techniques have been proposed for both gas (ArF and KrF) and solid state lasers. Optical parametric amplifiers create high power, broad bandwidth light that can be seeded with a variety of temporal formats. Preliminary experiments have demonstrated that another technique, using stimulated rotational Raman scattering, can broaden the spectrum of solid state and KrF laser pulses to multi-terahertz bandwidths.

Time compressing an ultra-broadband laser pulse (amplified to ~ kJ levels) could result in pulses in the range of tens to hundreds of petawatts. Such high-power lasers would provide access to completely new physics regimes such as ultrahigh field physics and relativistic astrophysics. In this field too, the United States is uniquely poised to make significant advances in laser technology, with impact well beyond ICF and HED physics.

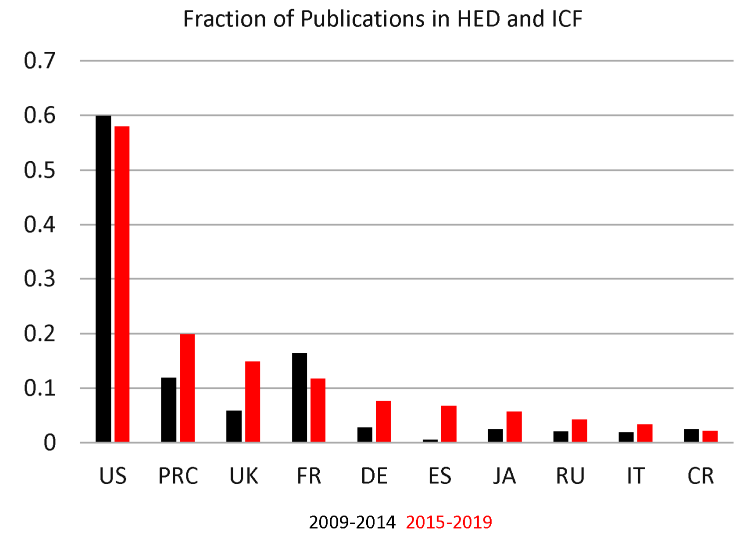


FIGURE 4.11 *Publications in HED and ICF*. International collaborations are crucial to the current vibrant state of HED plasma science. More than half the HED publications in high-impact journals are multi-national collaborations. The United States remains the leader in HED and ICF research, as measured by publications. The chart shows the fraction of publications relevant to HED science that have an author from the country shown. Over half of these publications had scientists from U.S. institutions among the authors during 2009-2014 and 2015-2019. However, if publications on ICF are not included, there appears to be a downward trend for the United States. Over the last 5 years, U.S. participation has dropped from 62% to 50%. The trend is consistent with the recent flourishing of high intensity laser facilities outside the United States. (This is a major topic of the 2018 NAS report *Opportunities in Intense Ultra-Fast Lasers: Reaching for the Brightest Light*.) Collaborations at large U.S. facilities are frequently multinational; for example, about 20-30% of basic science efforts at the National Ignition Facility and the Laboratory for Laser Energetics include non-U.S. researchers. SOURCE: Courtesy of Gail Glendinning, Lawrence Livermore National Laboratory.

Laser Plasma Optics for ICF

Ultimately, advances in laser-plasma interactions will require laser pulse repetition rates or intensities that exceed the damage limits of solid-state optical components. Even with improvements in optical coatings that are less damage prone to high intensities, the size the optical components would likely need to increase to keep energy fluences below tolerable levels. Aside from the increasing cost of such large optics, this approach will eventually become counterproductive. Larger optics can transmit higher total laser power, but their fabrication introduces surface aberrations that reduce the ability to focus the laser beam and, as a result, reduces the peak intensity.

Although mediating laser-plasma instabilities is one of the greatest challenges in achieving ignition in ICF, leveraging these instabilities also represents an opportunity to address the limitations of solid state optics. With a deep understanding of the physics of LPI, one could establish and control efficient interactions between electromagnetic fields and charged particle motion. This capability would enable researchers to harness the LPI to create plasma optics for a range of light manipulation applications. For example, energy transfer from one laser beam propagating through a plasma to another (cross-beam energy transfer or CBET) has been controlled on the NIF by adjusting the difference in laser frequency between the two beams. In principle, with a robust and accurate predictive capability for LPI, a plasma could be designed to provide optical dispersion, refraction, or frequency conversion to mimic any solid-state optical components. In recent NIF experiments, multiple laser pump beams were shown to interact in a preformed plasma with a seed beam, which was amplified by a factor of about 5.7, an energy higher than the energy of any of the individual beams. The fluence of the amplified beam was about 4 kJ/mm^2, or about 300 times the damage threshold of Nd:glass in a laser amplifier.

Computational HEDP and ICF

The United States is a leader in the field of computational plasma physics, however the majority of that capability lies in the computational tools that are not broadly available. Unlike many other areas of plasma physics, advances in HEDP and ICF have national security implications, and that is nowhere more true than with computations. Having said that, there are opportunities to create shared, open source codes in the HED/ICF fields that are focused on the fundamental physics of HED/ICF. As discussed in the 2018 JASON report *Prospects for Low Cost Fusion Development*, on the ARPA-E Alpha initiative on magneto-inertial fusion, "The National Laboratories should contribute their unclassified state-of-the-art simulation codes to collaborations with academic and commercial efforts, and support training of qualified users." The committee adds that this recommendation should include unclassified codes for data analysis, uncertainty quantification, and data mining (machine learning).

X-Ray Sources and Diagnostics

The new capabilities in x-ray sources arising in the laser-accelerator field hold great potential for advancing HEDP. Perhaps the greatest potential is in the use of these x-ray sources as imaging diagnostics. However, these sources first need to be coupled to the systems where they are most needed—the largest-scale drivers for HED/ICF experiments. Recently, 30 ps duration radiographic snapshots were produced on the NIF from ~100 keV radiation generated by a 4 kJ, laser. These images tracked the time evolution of density in the imploded core of a NIF implosion. With multiple bright, small, short pulse, high repetition rate x-ray sources, a fully three-dimensional evolution of the hot spot can be imaged.

Another need for advanced x-ray imaging is the study of hydrodynamic instabilities in HED plasmas. For example, a uniform, large spatial scale and long temporal scale drive is needed to push hydrodynamic instabilities from the linear regime to fully turbulent mix. (Such drives are now only available at NIF and on the Z-machine.) To better understand such hydrodynamic instabilities, imaging of the evolution of materials in the mixing region is required. This imaging could be accomplished with the high-repetition-rate, bright X-ray sources currently only available at the LCLS. A proposed upgrade at the Matter at Extreme Conditions (MEC) end station at LCLS would add high repetition rate petawatt class and long pulse drive lasers. This would complement the ongoing upgrade of LCLS to a 25 keV X-ray free electron laser (FEL) beam. If the proposed upgrade is implemented, the improved facility would enable a significant step forward in understanding hydrodynamic instabilities in HED plasmas, and in fundamental processes of HEDP and ICF such as new superconducting and quantum materials and dynamic phase transitions. Co-location of coherent and/or brilliant mono-energetic X-ray sources, produced using conventional or new plasma based methods, with mid-scale or NIF or Z-machine scale facilities would enable significant advances in imaging these fundamental processes.

Matter-Electromagnetic Coupling

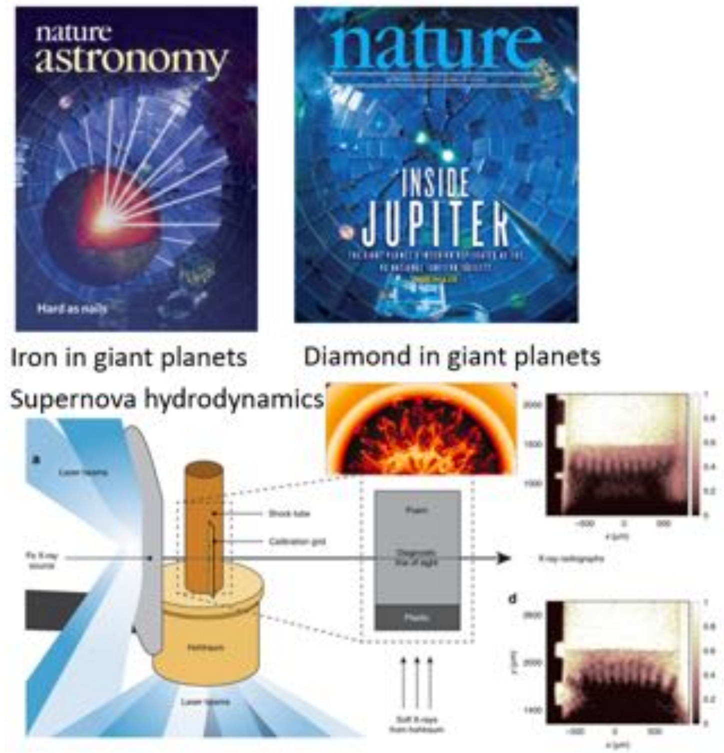


FIGURE 4.12 *The Impact of Discovery Science on the National Ignition Facility.* The Discovery Science program at NIF has resulted in U.S. and international researchers having access to the NIF laser. Their experiments span a wide breadth of topics in HED science. Many have direct relevance to fundamental astrophysical and material science questions. About eight percent of the experimental time on NIF is devoted to Discovery Science projects. SOURCE: Top: Courtesy of Lawrence Livermore National Laboratory. Bottom: Nature Communications 9:1564 (2018).

While the plasma physics relevant to breakdown of a plasma in an intense electric field does not occur in the HED regime, the process is central to understanding, predicting, and designing the next generation of pulsed power machines. A higher priority must be placed on electromagnetic field-matter coupling throughout the HED community in order to better understand the low-density plasmas and plasma breakdown in pulsed power machines. These processes include the study of intense electric and magnetic fields in vacuum interacting with dense metal and dielectric surfaces as well as bulk materials. Such a fundamentals focused program would include the development of new models and computational algorithms that are capable of handling the multi-scale physics encountered as electric and magnetic fields terminate abruptly across very steep density gradients (such as across a vacuum-metal or vacuum-plasma interface).

A need that transcends plasma physics in general, and not limited to HED regime, is an improved understanding of plasma emissions. All plasmas produce and absorb radiation in some manner, and those processes can dominate power transfer. This is another example of where advances in understanding fundamental processes in HEDP are closely linked to AMOP to provide the needed data for modeling and interpreting diagnostics. In the HED and WDM regimes, methods developed in the condensed matter community are able to predict spectral structure appropriate to high plasma densities and low temperatures. However, these methods are not likely to be applicable to the WDM regime now being produced using X-ray free-electron lasers (XFELs). The critical need for consistency between the fundamental data and the resulting plasma transport is highlighted by model discrepancies with experiments in the quasi-continuum of the L-shell iron opacity. This inconsistency may be the result of a weakness in the theory (e.g., continuum resonances in partially bound states) or another as yet not understood atomic processes acting within a plasma environment. A multi-laboratory effort was launched to reproduce the results on the NIF to address the discrepancy. Resolving this opacity inconsistency by refining our understanding of this fundamental matter-field coupling will impact not just HED plasmas but also the astrophysical problem of stellar structure.

Opportunities to leverage the many linkages between HED plasma physics and other branches of physics will continue. For example, high-energy-density plasmas can produce, via nuclear fusion reactions, significant yields of MeV neutrons, protons, and other ions, and facilitate the ponderomotive acceleration of protons and light ions in laser-irradiated foils, as well as electron wakefield acceleration. These accelerated particles can be used to initiate reactions in a range of nuclear physics experiments.

The conditions found in stellar interiors and stagnated ICF targets share unique conditions perhaps not found elsewhere. Nuclei in stellar interiors are immersed in a degenerate electron continuum whereas nuclei in conventional matter are surrounded by bound electrons. These differences can significantly affect the screening of nuclear interactions triggered by charged particles. HED plasmas can populate low-lying excited nuclear states, which, in turn, would affect the neutron-induced reaction rates. The physical similarity between the stellar interior conditions and the laboratory HED plasma environments opens new opportunities for experiments relevant both for nuclear physics and astrophysics.

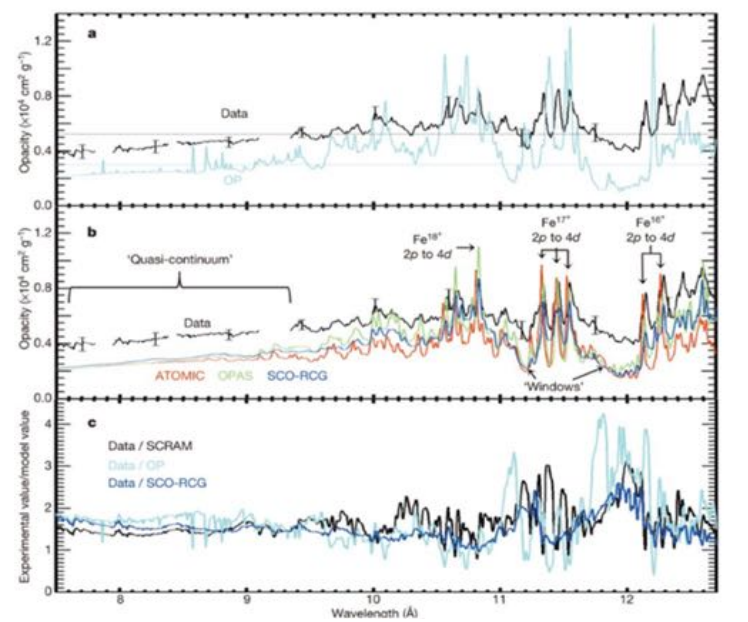


FIGURE 4.13 *Radiation Transport in HED*. Radiation absorption by stellar material helps determine the internal temperatures of stars. This absorption is determined by the radiation mean free path, or opacity × density, of the material near the radiation/convection boundary (much of which is iron). When this measurement of iron opacity was published in 2015, it was the first measurement of opacity under star-like conditions in the laboratory. The difference between measured and calculated opacity, shown as a ratio in the bottom plot as a function of radiation wavelength, is as large as a factor of four at some energies. Replication of this measurement (from the Z Fundamental Science Program on the Z machine) is the subject of a significant effort using the NIF laser to achieve similar star-like conditions.
SOURCE: Bailey, J., Nagayama, T., Loisel, G. et al. A higher-than-predicted measurement of iron opacity at solar interior temperatures. Nature 517, 56–59 (2015). https://doi.org/10.1038/nature14048.

THE U.S. ROLE IN THE INTERNATIONAL HED PHYSICS AND ICF FIELDS

The United States is the international leader in HED research by many metrics, including the number of publications. Over the last 5 years, 50% of publications in HED are attributed to the United States. The next largest contribution is from the People's Republic of China with about 15% of the publications. However, there are interesting trends in the publication statistics for HED research.

1. High impact journal publications in the HED field are more likely to be international collaborations. About 60% of the publications during 2018-2019 were multi-national collaborations. Although this is a from a fairly small sample size, it is clear that international collaborations are vital to producing high-impact work in HED physics.
2. Over the last 5 years the number of non-U.S. publications in HED has risen faster than the number of U.S. publications. In 2009-2014, the number of publications with U.S. authors was about 62% of the total, compared with the 50% during 2014-2019. The largest increase has been by authors from European countries, with France rising from 10 to 15% of the total, Germany rising from 9 to 13%, and Russia increasing from 7 to 10%. The number of publications in this time increased from 167 to 316 in the Web of Science analysis. Many of the new publications are tied to high-intensity, short

pulse lasers, where the United States has not maintained its original lead in facilities (as described in the Brightest Light report).

Many international collaborations are in progress at the large U.S. facilities. For example, in the National Laser User Facility (NLUF) program to use the Omega laser at LLE, all proposals must have a U.S. principal investigator (PI). Of those investigators, ~50% have international collaborators and ~25% have multiple international collaborators. In NIF's Discovery Science program, 2 of the 10 proposals approved in 2019 have a non-U.S. PI and three others are multinational collaborations. Although the United States is an international leader in certain aspects of HED facilities (e.g., NIF, Z-machine), that is not the case across the spectrum of HED and WDM physics. Experiments that require single or multiple beams of ultrafast multi-PW (10 PW-scale) lasers for advanced laser plasma-based particle acceleration or study of collective plasma effects with extreme fields must be performed outside the United States. As noted in the Brightest Light Study, the United States is falling behind both Europe and Asia in PW laser capabilities.

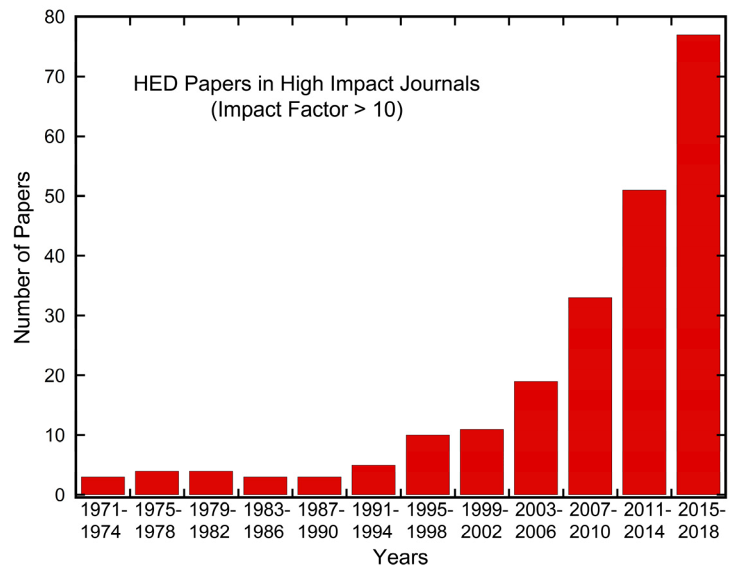


FIGURE 4.14 *The Expanding Field of HED*. The number of publications on HED and ICF appearing in high impact (impact factor > 10) journals has greatly increased since the early 2000s. This significant change is correlated with the commissioning and operation of several major new facilities since 2007 (Omega EP, NIF, and Z Refurbishment.) In addition, there were recommendations in the Plasma 2000 (1995), Plasma 2010 (2007), and Frontiers in High Energy Density Science (2007) reports that basic research be supported in HED at the major facilities. In the Plasma 2010 report, one conclusion was that "User programs on the major NNSA facilities at the national laboratories that provide a significant amount of facility time for investigator-driven research are lacking." All of the major facilities now devote some fraction of the facility time to basic research, accessible to outside users through proposal processes. SOURCE: Courtesy of Rulon Linford of Lawrence Livermore National Laboratory.

HED FACILITIES AND MAJOR PROGRAMS

The largest HED/ICF facility is the National Ignition Facility (NIF), which came online in 2009. The 192 beams of NIF routinely deliver 1.8 MJ of laser energy at a peak power of 500 TW at a wavelength of 0.351 μm. In 2018, in support of a milestone to reach 2.1 MJ, NIF delivered 2.15 MJ. Currently there are about 60 diagnostic instruments. Depending on the complexity of the shot, one shot is fired about every eight hours. NIF currently produces 400 shots/year (although some of these are facility shots rather than for physics experiments).

The Discovery Science program at NIF allocates about 8% of the shots to investigators to conduct fundamental HED experiments that are not necessarily closely aligned with the NNSA mission. These shots are awarded through a competitive proposal process. In the last call, there were 25 proposals, of which 10 were selected. Typically, a Discovery Science proposal is awarded 1-3 days of shot time.

The Laboratory for Laser Energetics (LLE) at the University of Rochester is home to both the Omega laser and the Omega EP laser. Omega is a 60-beam Nd:glass laser, operating since 1995, routinely delivering 30 kJ at a peak power of 100 TW at a wavelength of 0.351 μm. Omega EP, completed in 2008, has four NIF-like beams. These deliver, as on NIF, about 10 kJ at 0.351 μm, or, after compression and expansion, in a short pulse mode with a peak power ~1 PW at a wavelength of 1.05 μm. The two lasers beams may be propagated to the same target chamber for experiments requiring both high energy, uniform illumination and short pulse, high intensity illumination. About 35-40% of the shot time is allocated to ignition, 30-35% to HED studies, and 25-30% to fundamental science. The fundamental science allocation is divided between the Laboratory Basic Science program (for LANL, LLNL, NRL, SNL, and LLE scientists) and the NLUF program for scientists from academia or industry. Many diagnostics designed for the NIF are first fielded and demonstrated on Omega.

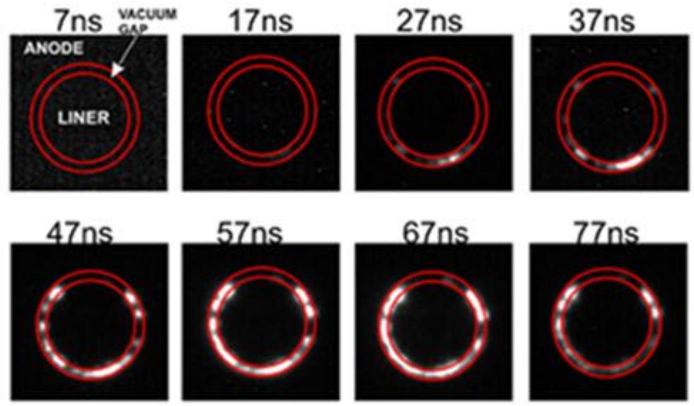


FIGURE 4.15 *Breakdown in Pulsed Power Devices and Midscale Facilities*. Breakdown is the process of creating plasma from a non-plasmas state. Breakdown is a necessary and desired process if you want plasma. However, when you want gaps to be free of plasma, as in the circuitry of pulse power devices, breakdown is something to avoid. These optical images show emission from breakdown and plasma formation in a 200 μm gap between two Al cylinders (shown by the red circles) in the COBRA pulsed power device at Cornell University. The bright spots show non-uniformity in the azimuthal distribution of breakdown. COBRA one of a group of university pulsed power machines used for basic research and training students in HED physics. Several such facilities are described in Table 4.2. However, there are essentially no mid-scale (current >1 MA) facilities available for researchers in the United States. The lack of such facilities is a disadvantage, as is the lack of a coordinated network to support science, applications, and technology of pulsed power machines, similar to LaserNetUS. SOURCE: Physics of Plasmas **23** 092711 (2016).

The Z-machine at Sandia National Laboratory can deliver over 2 MJ of radiation with a spectrum that is comparable to that of the interior of the Sun. The Z-machine produces currents exceeding 26 MA in 100 ns to 1 μs long pulses and voltages exceeding 5 MV. High currents also allow the Z-machine to generate up to 8 Mbar (million atmospheres) pressure from magnetic fields, and flyer plate velocities exceeding 40 km/s. Work on Z-machine is funded by NNSA for defense and related applications. These include producing intense UV and x-ray radiation for a variety of applications, intense magnetic fields and pressures for dynamic materials properties measurements, ICF research, stockpile stewardship, and the creation of extreme environments for astronomy experiments. Like LLNL and LLE, SNLA supports use of the Z-machine by the broader science community for fundamental basic science experiments. This program is the Z Fundamental Science Program (ZFSP). The first call for proposals under the ZFSP was in 2010. A second call for proposals was issued in 2017, and 10 teams from 9 institutions were awarded time. A third call was issued 17 June 2019. The ZFSP has executed 107 shots on the Z-machine since 2010. The scientific impact of the program has been notable with many publications in high impact journals.

The Linear Coherent Light Source (LCLS) at SLAC National Accelerator Laboratory began operation in 2009. Since coming online in 2010, the Matter in Extreme Conditions (MEC) end-station at

LCLS has been a state-of-the-art user facility for studying laser-plasma interactions, warm dense matter, and dense material physics. Its ability to diagnose wide-angle x-ray scattering of the LCLS source enables the entire angular distribution of scattering vectors to be captured in a single shot. This capability has produced new insights into the atomic structure of materials in compressed or heated states while the material is dynamically evolving.

In addition to these major, world class HED facilities there are many mid-scale facilities in the United States. One of the recommendations for HED science from the Plasma 2010 report was that mid-scale facilities needed to be maintained, expanded, and utilized as effectively as possible. Table 4.1 describes the high intensity laser facilities, many of which are linked through LaserNetUS.

LaserNetUS is an advance in support for users of mid-scale, high-intensity laser facilities. LaserNetUS was established in August 2018 to help restore U.S. dominance in high-intensity laser research, and to specifically address some of the recommendations of the NAS Brightest Light report. The report recommended that the DOE create a broad network of lasers to support the science, applications and technology of intense, ultrafast lasers. LaserNetUS is intended to provide institutions and single scientists access to PW-class laser systems. Most facilities enable active participation by the users and so provide an ideal training ground for students and early career scientists in state-of-the-art laser technology. Given its short operating record at the time of this report, its long-term effectiveness cannot yet be assessed. However, in 2019 LaserNetUS provided experimental access to 200 researchers from dozens of institutions in the U.S. and abroad. An important role fulfilled by LaserNetUS is the training of students and postdoctoral researchers. Well over 100 students and postdoctoral researchers have already participated in LaserNetUS experiments.

TABLE 4.1 U.S. Mid-Scale Laser Facilities

Location	Laser	Properties
Colorado State University*	Advanced Beam Laboratory	Petawatt class, femtosecond pulses, intensities 0.6–10^{22} W/cm^2
Lawrence Berkeley National Laboratory (LBNL)*	Berkeley Lab Laser Accelerator (BELLA)	Dual beam (1) PW class, 30 fs, 40 J, 1 Hz; (2) 10–50 TW, 40 fs
Lawrence Livermore National Laboratory (LLNL), Jupiter Laser Facility*	Janus	Dual beam, 1–15 ns, ~1 kJ
	Titan	Dual beam, one Janus beam and one short pulse (0.7–40 fs), 10^{19}–10^{20} W/cm^2
	Comet	0.5 ps to 2 ns, 10 J
Naval Research Laboratory	Nike	248 nm, 4–5 kJ, 4 ns
	Electra	193 nm, 700 J, 1–5 Hz, 50 ns
Ohio State University*	Scarlet	30 fs, 10 J, 5×10^{21} W/cm^2

SLAC National Accelerator Laboratory, Linac Coherent Light Source (LCLS)*	Matter at Extreme Conditions (MEC) (laser only)	10 ns, 60 J 50 fs, 5 J
University of Michigan, Center for Ultrafast Optical Science (CUOS)*	Hercules	30 fs, 300 TW, 1e22 W/cm^2
	T-cubed Laser (TTT)*	400 fs, 8J, 3e19 W/cm^2
University of Nebraska, Extreme Light Laboratory*	Diocles	0.2–0.7 PW, 0.1 Hz
	Diocles HRR	100 TW at 10 Hz
	Archimedes	10 TW at 10 Hz
University of Rochester, Laboratory for Laser Energetics (LLE)*	Omega EP	Short pulse—2 beams 0.7–100 ps, 0.5–2.3 kJ Long pulse—2 beams, 5 kJ/beam, ns pulses
University of Texas at Austin, Center for High Energy Density Science*	Texas Petawatt Laser	140 J at 140 fs, 2×10^{22} W/cm^2

* = Member of LasernetUS.

There are several small scale (1–3 MA) pulsed power facilities at U.S. universities. However, these generally do not meet the requirement of mid-scale facilities accessible to users, (with capability between 1 MA and 20 MA). These facilities are summarized in Table 4.2. Several of the university pulsed power systems are used for technology development and not HED/ICF experiments. There is no equivalent to LaserNetUS for pulsed-power facilities. However, the first “ZNetUS” workshop, hosted by The Center for Energy Research at UC San Diego, is planned for January, 2020. The organizers intend to discuss recent developments in Z-pinches, focusing on several specific topics. Among these is the need for a mid-scale user facility.

The availability of mid-scale pulsed power facilities is clearly less than that for mid-scale laser facilities. As described above, a Next Generation Pulsed Power Facility (NGPPF) based on improved linear transformer driver (LTD) technology is a leading candidate to replace today’s Z-machine, which uses the older, more mature but less efficient Marx generator/water pulse-forming lines technology. The LTD technology offers an opportunity to address the dearth of mid-scale facilities, providing a lower cost path to achieving significantly higher pulsed power performance. Mid-scale facilities (5-15 MA) could be built with LTDs to provide facilities for investigating HEDP and technology concepts in the gap between the majority of university facilities and national laboratory facilities. The LaserNetUS concept has been embraced by the pulsed power community. At community forums held for this report, a similar network for access to mid-scale pulsed power facilities was proposed on several occasions.

TABLE 4.2 Small-Scale Pulsed Power Facilities

Location	Facility	Properties
Cornell University	COBRA	1 MA Marx-pulse forming line
Naval Research Laboratory*	Hawk	800 kA Marx
	Mercury	300 kA Insulated Voltage Adder (IVA)
Sandia National Laboratory*	Mykonos	1-MA, 5-cavity LTD
University of California, San Diego	GenASIS	250-kA LTD
University of California, San Diego	LTD-III	~1-MA LTD
University of Michigan	MAIZE	100 ns, 1-MA single cavity LTD
	BLUE	150 kA, 4 cavity LTD
University of Nevada, Reno	Zebra	1-MA Marx-pulse forming line
University of New Mexico	LOBO	200 kA LTD
University of Rochester	HADES	~1 MA, 6-cavity LTD
University of Washington	ZaP-HD	450 kA, 1-2 Tesla, 30-70 μs
	FuZE	200 kA, 1-9 Tesla, 20-40 μs

*While the NRL Hawk and Mercury, and the SNL Mykonos machines, are not user facilities, scientists from outside NRL and SNL collaborate in many of the research projects on these machines.
NOTE: LTD = linear transformer drive, Marx = Marx Bank.

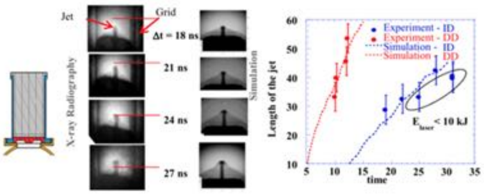


FIGURE 4.16 *The PETAL, LMJ and Jets*. The Laser MegaJoule (LMJ) in France has been operational since 2014, beginning with 8 of its eventual 176 beams, and performing experiments with 40 beams (150 kJ) since 2017. The petawatt laser PETAL was added to the LMJ facility in 2017. Currently about 20-30% of the operating time is accessible to academic researchers. The images shown are from one of the first of a series of hydrodynamic instabililty experiments, showing the evolution of a hydrodynamic jet. Initially the jet is a small surface perturbation on the target shown at left. When a shock launched by an x-ray drive incident from the bottom crosses the interface between high density (red) and low density (gray) material, the perturbation introduced by the surface shape forms a rapidly growing jet, as seen in the x-ray radiographs. Simulations accurately capture the size of the jet as a function of time, as seen in the plot on the right. SOURCE: Jean-Luc Miquel and Emmanuelle Prene 2019 Nucl. Fusion 59 032005.

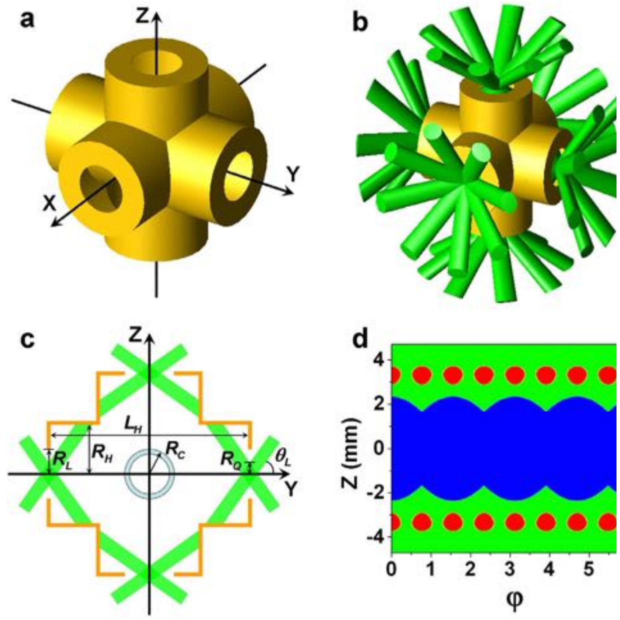


FIGURE 4.17 *A Different Approach to Hohlraums*. The ShenGuang III laser is currently operational in China. It has 48 beams, operates (as do NIF and Laser Magajoule LMJ) at 351 nm, and has a designed maxim um energy of 180 kJ. Optimized for a hohlraum geometry, experiments at the facility are exploring novel hohlraum geometries such as spherical hohlraums, and, shown here, a novel shape called "TACH". This design uses six small hohlraums open at one end to drive a central cavity. In this way, all the laser beams are incident at the optimum 50° angle, and the symmetry is inherently spherical, thus greatly reducing the effects of the cross-beam energy transfer laser instability and improving drive uniformity. SOURCE: Kuang, L., Li, H., Jing, L. et al. A novel three-axis cylindrical hohlraum designed for inertial confinement fusion ignition. Sci Rep 6, 34636 (2016). https://doi.org/10.1038/srep34636.

The next generation of large-scale facilities should be able to achieve high gain in order to further both IFE and stockpile stewardship goals. It is now premature to select one type of driver over another. What is clear is that fundamental research on the science and technology of new pulsed power and laser drives must be sustained so that wise choices can be made in defining the next generation large facilities. The current low level of support for mid-scale pulsed power facilities with access to university researchers works against having a robust community developing a diversity of options for the next ICF facility.

There are three existing or planned NIF-class laser facilities outside the United States. The Laser Megajoule (LMJ) in France currently has 40 NIF-like beams, eventually to be 176. It is intended to provide about 1.4 MJ at 351 nm wavelength. Like NIF, it has a petawatt-class laser (PETAL, currently 1 kJ at 570 fs, eventually reaching 3.5 kJ at 10 ps) that is integrated with the longer pulse drive beams and can be used for high-energy backlighting and HED experiments. It is configured much like NIF, with beams oriented for indirect laser drive (in a cylindrical geometry rather than uniformly distributed around a sphere). The current hohlraum design is a rounded cylindrical ("rugby") shape, rather than the right circular cylinder used on NIF. LMJ and PETAL are available for national and international collaborations through the Institute Lasers and Plasmas. Four experiments were selected from the 16 applications in the first call (2014). Two experiments selected from the second call are to be fielded in 2019, using PETAL, 56 LMJ beams, and 16 diagnostics.

A second currently operating major facility is the Shenguang III laser in China. With 48 beams, it is designed to have a maximum energy of 180 kJ at 351 nm wavelength. It too uses a hohlraum to drive a capsule for ICF studies, but there are multiple hohlraum designs being explored. These include spherical hohlraums and a novel "TACH" shape, shown in Figure 4.18. This design uses only laser beams incident at large (~50 degrees) angles. This larger angle of incidence is predicted to reduce backscatter, crossed-beam energy transfer, and symmetry degradations due to expanding hohlraum walls, all of which result in implosion degradations seen on NIF experiments.

FIGURE 4.18 *Pulsed Power in China*. The 8 MA, 8 MJ pulsed power facility Primary Test Stand (PTS) in China is currently the largest operational pulsed power machine outside the United States. PTS has been used since 2016 to study (among other important high energy density phenomena) imploding liners (both wire arrays and solid), shock compressed materials, and behavior of a conductor under pulsed megagauss magnetic fields. PTS is about 1/3 the energy and current of Sandia's Z machine.
SOURCE: Matter and Radiation at Extremes, Volume 1, Issue 1, January 2016, Pages 48-58.

The third international NIF-class laser is under construction—the UFL-2M laser in Russia. It is designed to have 192 beams (the same as NIF) but will irradiate the target at 531 nm instead of the 351 nm used by NIF and LMJ. Due to the more efficient frequency conversion of the Nd:glass produced 1053 nm to 531 nm. and higher damage threshold for optics at the longer wavelength, its energy is designed to reach 2.8 MJ. The irradiation geometry is spherically rather than cylindrically symmetric, in order to optimize the symmetry for laser direct drive.

In 2018 the NAS report "Opportunities in Intense Ultra-Fast Lasers: Reaching for the Brightest Light" (referred to here as the "Brightest Light report") was published. As described in the report, most of the high intensity lasers in the world have been (or are being) built outside the United States. It is now the case that U.S. scientists studying HED at very high electric field strengths (for example, nonperturbative quantum electrodynamics effects) are not able to perform research in the United States.

Major pulsed power facilities outside the United States are beginning to compete with U.S. capabilities. The Primary Test Stand in China (PTS), currently operating, is an 8 MA, 8 MJ Z-pinch facility (about 1/3 the power and energy of Sandia's Z-machine). Similar to the Z-machine, the PTS has a 1 kJ laser for backlighting experiments. It is an important part of the Chinese Academy of Engineering Physics roadmap for Z-pinch fusion. The proposed Baikal facility in Russia is intended to be a 50 MA, 100 MJ Z-pinch machine, or nearly 4 times the energy of the current Sandia Z-machine. Baikal has a stated goal of 25 MJ Z-pinch fusion energy. Approximately 5 years ago, however, this project was postponed due to funding issues.

RELATIONS TO AND PERSPECTIVES OF INDUSTRY

In the 2018 Brightest Light report, possible industrial applications of ultrafast lasers were described, with a focus on medical applications. In order to understand, predict, and improve these possible applications, the HED physics of the interactions of the high-intensity lasers with their targets must be better understood. While materials processing with ultra-intense lasers is already employed in manufacturing processes, the plasmas produced are typically not in the HED regime. The goal of the process is usually to affect a small volume of a solid material (without, for example, creating shocks and cracks). However, in many other applications the goal is to produce a brightly radiating plasma, or to accelerate particles to high energy. In this case the plasmas would likely be in the HED regime. Summarized here are some of the possible industrial and medical applications of intense lasers, described in more detail in the Brightest Light study, where HED plasma physics understanding plays a role.

1. *Ultrafast X-ray radiography in medicine and industry*. Ultra-intense (typically petawatt-class lasers) are used to produce bright x-ray backlighters as described in Chapter 3 and have great utility for performing radiography of imploding ICF capsules. These bright sources have been demonstrated to produce high resolution and high contrast images, with the potential to allow 3D reconstruction of images. The sources are sufficiently coherent to create enhanced signals around density discontinuities (phase contrast imaging), allowing discrimination of various tissues (or other samples). This is not a feature of radiation from conventional medical x-ray sources from x-ray tubes. Simulation capabilities to quantitatively predict the x-ray characteristics of such sources would aid in optimizing and designing these sources.
2. *Electron beams for cancer therapy.* As described in Chapter 3, intense lasers may be used to accelerate particles. High-energy electrons, whether from cyclotrons, linear accelerators, or lasers, may be a better choice for tumor therapy than x-rays, as they are more easily focused and targeted on the tumor. High energy ions also have advantages over x-ray therapy, particularly the ability to minimize damage to surrounding tissue. Laser-based accelerators may offer cheaper, smaller electron sources than other options.
3. *Laser-produced isotopes for positron emission tomography*. PET requires positron-emitting radioactive sources. Production of the positron-emitting isotope ^{11}C was estimated to be 4200 kBq (on

the LLNL Titan laser) via the $^{10}B(d, n)^{11}C$ reaction, with an illumination intensity of 9×10^{19} W/cm^2. However, this is still much less than the required 800 MBq for PET. Higher repetition rate lasers such as ELI at 10 Hz will clearly be a large step towards feasible production of PET isotopes.

These possible applications all have documented proof-of-principle experiments, as described in many references in the Brightest Light report and may be ready for implementation over the next decade.

The field of high energy density physics is not limited to national laboratories and large companies. The High Energy Density Science Association (HEDSA) was founded in 2005 to enable academic and small business high energy density researchers to advocate for HED physics research. HEDSA facilitates increased communication and collaboration between smaller research programs and businesses and larger ones. Most of the small business members of HEDSA focus on software activities, including experimental design, plasma simulation, and computational physics.

In addition, large companies are closely involved in supporting HED/ICF experiments. General Atomics, for example, conducts research and development in ICF/HED targets, and supplies a significant fraction of targets at the major ICF/HED facilities in the United States.

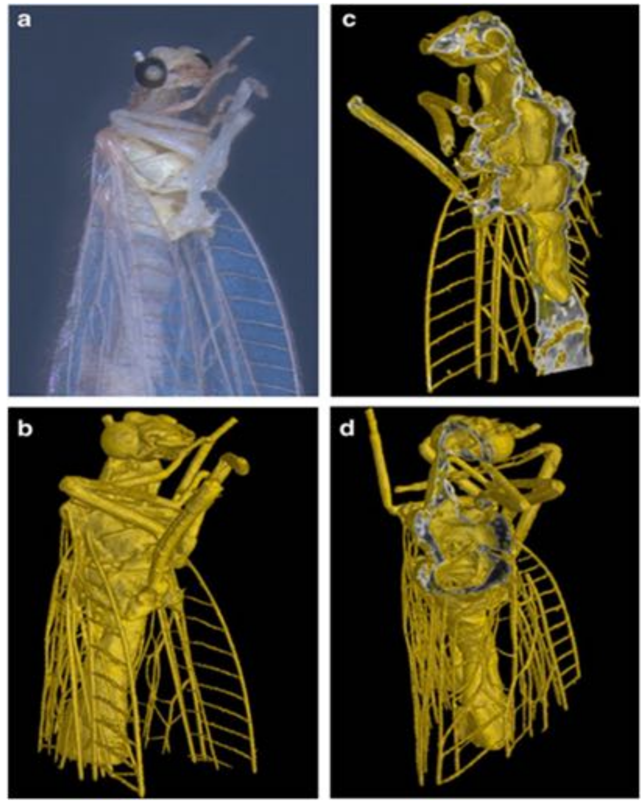


FIGURE 4.19 *3-dimensional X-ray Imaging.* Imaging small details in biological tissue is a major challenge for medical applications, requiring bright, coherent, and small x-ray sources. These sources can be produced by irradiating a solid with a high-intensity laser. The level of detail obtained in the radiographs shown above and produced by such an x-ray source is due to the phenomenon of phase contrast imaging. In this technique, a density gradient creates interference fringes in a coherent x-ray source which can then be use to perform 3-dimensional reconstruction of the target. Quantitative understanding of the HED physics involved in the production of x-ray sources would improve the design and optimization of such biological and medical imaging systems. SOURCE: Relations to and Perspectives of Industry, Nature Communications volume 6, Article number: 7568 (2015).

FINDINGS AND RECOMMENDATIONS

HED is a field with broad, cross-cutting applications in plasma physics. The field has flourished for the past 10 years. There are numerous results from many institutions and facilities that have had a large impact. The emergence of new major facilities has greatly expanded HED capabilities and has resulted in significant data for stockpile stewardship and national security. The ICF community is (and should continue to be) pursuing multiple options for inertial confinement fusion, including direct magnetic drive, direct laser drive, and indirect laser drive. In the last decade, major facilities have made important contributions to all approaches. There is now greatly improved understanding of the physics required for ignition due to experiments performed on the NIF, even without ignition.

Finding: Innovative diagnostics and diagnostic techniques have enabled developing a detailed picture of ICF plasmas and imploded target cores with unprecedented precision, and enabled the investigation of HED matter at previously unattainable conditions.

Finding: Diagnostic innovation is an ongoing need.

Finding: While significant progress in HED science has been made in the last decade, more advances are needed to improve predictive capability.

Recommendation: The DOE-NNSA, DOE-FES, and NSF-MPS should increase resources for development of new diagnostics and analysis methodologies to address needs for ongoing innovation in HED physics.

Recommendation: The current NNSA ICF *National Diagnostics Working Group* charter and workshops should be expanded to explicitly include HED diagnostics, interaction with mid-scale facilities, and data analysis and data mining techniques.

There exist opportunities to improve the fundamental science basis in plasma simulation codes, as well as to incorporate uncertainty quantification and machine learning techniques. The understanding of laser-plasma instabilities (LPIs) and their mitigation, and incorporation of the physics of LPIs into simulations, will benefit HEDP and all approaches to ICF.

Finding: Improving our understanding of LPI is essential for continued progress toward validated predictive capabilities, which are necessary for ignition and gain.

Recommendation: To achieve the goal of ignition and improve the quality of HED science, DOE-NNSA, DOE-FES, and NSF-MPS should expand and strengthen numerical simulation capability, focusing in particular on improved atomic and kinetic modeling (including equation of state), improved radiation transfer (including opacity), improved LPI (laser-plasma-instability) understanding, uncertainty quantification and machine learning.

Recommendation: Where possible the National Laboratories should contribute their unclassified state-of-the-art simulations codes to collaborations with academic and commercial efforts, and support training of qualified users.

Finding: Federal support of HED sciences at universities is essential to the health of HED science.

The university centers established by federal funding have seeded growth in HEDP at universities, have been instrumental in achieving the current vibrant state of the field and in providing the needed workforce for federal priorities.

Finding: The current paucity of mid-scale pulsed power facilities is a potential danger for the field.

Recommendation: Federal support of HED at universities and mid-scale laser facilities should continue to expand, not only to benefit HED physics but also to maintain the critically needed HED workforce.

Recommendation: Mid-scale pulsed-power facilities accessible to universities should be established, with leadership of these new facilities drawn from university researchers and the national laboratories.

Finding: The basic science programs at NIF, Omega, and Z-machine have resulted in significant scientific results despite having a small fraction of the available facility time.

Finding: The high visibility of these basic science HED experiments increases the ability to recruit new talent while improving the understanding of the universe and the science underpinnings of other HED/ICF research.

Finding: Guidance is required for how best to leverage and expand the basic science programs. This guidance could come from a new HEDP Basic Research Needs report.

Recommendation: DOE-NNSA, DOE-FES, and NSF-MPS should continue and increase support for basic HED science programs at large facilities in collaboration with universities.

Recommendation: The science program direction and the appropriate level of funding and facility support should be guided by the DOE-NNSA, DOE-FES and NSF-MPS collaboratively commissioning a new HEDP Basic Research Needs report for the HEDP community.

5

Low-Temperature Plasmas: A Unique State of Matter for Addressing Societal Needs

LOW-TEMPERATURE PLASMAS—SCIENCE ENABLING SOCIETAL BENEFIT

The ability of low temperature plasmas (LTPs) to produce desired chemically reactive environments in gases, on surfaces and in liquids has already made society-wide transformations in our quality of life—from lighting, materials synthesis and water purification, to enabling the information technology revolution through plasma-enabled fabrication of microelectronics devices. Those plasma-enabled societal transformations will continue into the future. A strategic and new opportunity for LTP science and technology is to help enable the electrification of the chemical industry—that is, to drive chemical processing by electrical means facilitated by plasmas. The critical enabling science is controlling the flow of energy through LTPs to produce predictable chemical transformations in gases, on solids, and in liquids. The electrification of the chemical industry is a grand science and engineering challenge that will enable an economically viable and sustainable future based on renewable electricity.

This chapter presents the case that improving our understanding of the fundamental processes in LTPs will lead to translational research benefiting nearly every sector of society.

Unique Features of Low-Temperature Plasma Physics

Low temperature plasmas are a unique state of matter composed of neutral atoms, molecules, radicals, excited states, ions and electrons. LTPs represents a distinct and, in many ways, unique form of plasma. Most of the plasmas in the universe, including other areas of plasmas discussed in this report, are fully ionized, often magnetized and have average temperatures much higher than ambient. In most LTPs, only a small fraction of the gas is ionized while the mean energy of electrons (a few to 10 eV) is much larger than the temperature of heavy particles (ions and neutrals) that can be as low as room temperature. So even with energetic electrons, the average temperature of an LTP is low enough that these plasmas can be in contact with heat sensitive surfaces, including living tissue, an ability that has enabled the field of plasma agriculture and medicine. Maintaining this non-equilibrium state is possible because energy transfer from electric fields to the electrons is generally much faster and more efficient than the subsequent collisional energy transfer between electrons and heavy particles. A large fraction of the electron energy can then be channeled into the production of electronically excited states, and, in molecular gases, vibrationally excited species and short-lived radicals. The generation of chemically reactive environments at low gas temperature is a defining property of LTPs that enables their use in so many beneficial technologies.

In spite of the unique nature of LTPs, there are common features with other ionized gases. For example, dust in LTPs can behave similarly to dusty plasmas in space. When high energy density plasma comes into contact with cold walls—for example, in fusion devices—the plasma in the boundary layer cools and shares many characteristics with LTPs. The interaction of electromagnetic radiation with LTPs is similar to phenomena in other types of plasma. Some of the instabilities and waves found in higher energy density plasmas also occur in LTPs.

One feature of LTPs, shared with plasmas in fusion devices, is that nearly all LTPs interact with surfaces that bound the plasma, either by the need to confine the plasma or intentionally to change the characteristics of those surfaces. In LTPs, the neutral gas temperature is near ambient while the electron temperature is elevated, resulting in the ability to produce controllable fluxes of reactive species onto surfaces without excessively heating the surface. The relatively high electron temperature and low electron mass leads to the formation of thin space charge regions—sheaths—at boundaries. The electric fields in the sheaths accelerate positive ions to surfaces which then provide activation energy for material changing reactions on surfaces. Low temperature radical generation coupled with normal incidence positive ion bombardment at surfaces has enabled a tremendous range of industrial applications based on LTP processing of material surfaces and thin films; and in particular has enabled industrial scale fabrication of microelectronics.

PROGRESS IN LTPS SINCE PLASMA 2010

The field of LTPs is exceedingly broad and so the review of progress since the Plasma 2010 report is grouped into four representative application areas: aerospace, life sciences, materials interactions, and environment and sustainability.

Aerospace

During the past decade there have been significant advances in the science and technology of Hall thrusters. The Hall thruster (HT) is one of the mainline architectures for plasma propulsion, devices used to accelerate and control the trajectories of spacecraft in earth orbit, geosynchronous orbit and in missions to the planets. In a HT, ions are accelerated to high energies, and emitted as plume of exhaust that pushes the spacecraft in the opposite direction—akin to the exhaust of chemical rockets. This acceleration of spacecraft is very efficient but produces low thrust, thereby requiring long periods of operation for the spacecraft to reach the desired speed. The development of magnetic shielding has greatly reduced the ion-induced sputtering of the HT chamber walls. This has extended the life of HTs from nominally about 1 year to as long as 5 to 10 years, enabling their use in long duration deep space missions. NASA is developing the Power and Propulsion Element (PPE) for the Lunar Gateway human exploration program, which will use 12.5 kW magnetically shielded HTs to move cargo from Earth to lunar orbits (and eventually Mars). HTs (3–4.5 kW) have been flown on commercial communications satellites in the past decade, significantly reducing the propellant needed for orbit raising and station keeping, and similar thrusters are planned for upcoming deep space missions. In the past 5 years low power HTs, compatible with CubeSat architectures have achieved >50% efficiencies (conversion of input power to thrust) and long lifetimes both enabled by magnetic shielding.

Other advances have been made in the past decade include nested HTs, devices having multiple annular channels to accelerate ions, which have been demonstrated in powers up to 100 kW with >50% efficiency. However, erosion of electrodes and plasma-facing surfaces is increasingly problematic and the topic of continuing research. Investigations of the physics of the cathodes used in HTs have revealed low frequency plasma oscillations and turbulent ion acoustic waves that contribute to transport and energetic ion generation. Electrodeless thruster concepts such as magnetic nozzles and Field Reversed Configuration (FRC) thrusters have been proposed and investigated, concepts that may reduce erosion to that required for multi-year operation at high powers. However, the efficiencies of these concepts are not now competitive with state-of-the-art ion and Hall thrusters.

Life Science Applications

There has been impressive progress in applying LTPs to biology and life sciences in the last decade. For example, there have been many demonstrations of LTPs in selectively destroying microbes in diverse environments, ranging from inanimate surfaces to living tissue, from plants to biofilms. Advances have been made in direct therapeutic applications of LTP in both animal models as well as human subjects. There have been investigations in using LTPs in treating cancer (see Figure 5.1); in healing and disinfecting wounds; for dermatological treatments; and in dentistry, among others. The use of LTP to reduce anti-bacterially resistant bacteria strains in wounds has shown promise in many studies.

A major advance came when the first three LTP sources were approved for human testing in the European Union in 2013. Extensive studies on possible dangers to patients were conducted on these devices and treatment protocols were developed before the approvals for human testing were granted. The available clinical studies generally concluded that LTP treatment causes few or no significant side effects or complications. There has been considerable progress in identifying some of the mechanisms through which LTP acts therapeutically. LTP has been shown to stimulate sub-cutaneous blood flow and blood O_2 content; cell-cell communication; and elements of both innate and adaptive immunity. Another important LTP-associated mechanism is the biological effects of pulsed electric fields.

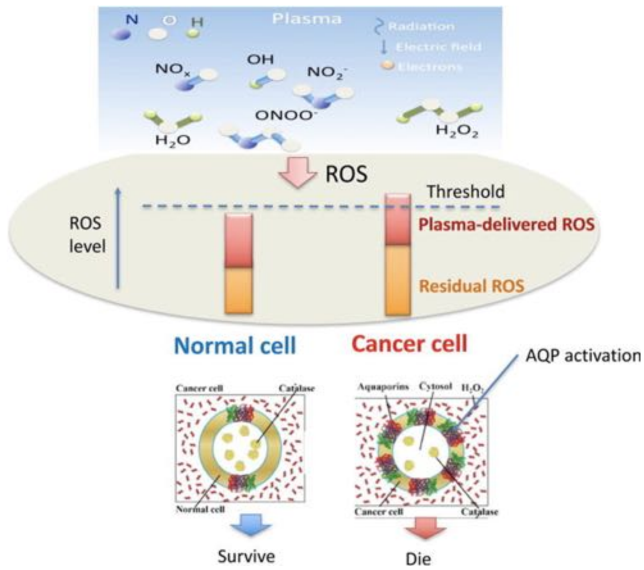


FIGURE 5.1 *LTP for cancer treatment* – A major challenge of plasma-based medical treatment is selectivity – eliminate the bad cells while not harming healthy cells. Here is shown a possible mechanism of selective LTP treatment of cancer cells thereby enabling its application for a novel cancer therapies. Plasmas produce reactive oxygen species (ROS). As cancer cells have larger concentrations of ROS than normal cells, a well-dosed plasma treatment is able to increase the ROS level in cancer cells above the threshold for cell death while healthy cells remain below the threshold. This dose requirement corresponds to a narrow treatment window requiring a detailed understanding of the plasma-bio interaction process. SOURCE: Physics of Plasmas 25, 083504 (2018); https://doi.org/10.1063/1.5034355.

Since most biological systems of interest involve aqueous solutions, studies of LTP interacting with biological targets and liquids have been closely linked. Many studies in the field have addressed the role of reactive chemical species produced by plasma in contact with air adjacent to aqueous solutions. These synergistic studies have led to a broader understanding of the effects of different types of LTP sources on biological targets and how LTPs can chemically activate liquids. For example, LTP treatment of aqueous solutions (including water) produces a liquid that can remain anti-microbial for many days.

In addition to biomedical effects, progress has been made in agricultural and food-related applications of LTPs. LTP have been shown to promote seed germination and disinfect seeds, and to enhance the growth of plants. Agricultural water treatment for both biocidal and nutrition production has been demonstrated. Food and food container disinfection by use of LTP is being investigated and in demonstration trials. Finally, nitrogen fixation (e.g., production of fertilizer) have advanced over the past decade.

Plasma-Materials Interactions

Major developments in plasma materials processing have included the continuing progress in applying LTPs to manufacturing of integrated circuits. During the last decade, microelectronics devices have shrunk to the point that atomic layer control of plasma etching and deposition is required—a requirement that will extend to new quantum devices. Since it is extremely challenging to control plasma to interact with only a single layer of atoms, self-limited processes and ultra-high materials selectivity are needed for both deposition and etching reactions. Plasma-enhanced atomic layer deposition (ALD) and atomic layer etching (ALE) processes have been developed to meet these needs (see Figure 5.2). These goals were met by enhanced control of the interaction of electrons, ions, radicals, excited neutrals and photons with surfaces in LTP environments. When conventional continuous (steady state) plasma-materials processes proved not to be adequate, techniques using pulsing were developed—pulsing of the plasma source power, substrate bias, input gases, substrate temperature, and other process parameters. The development of plasma-materials processes consisting of sequences of individual, self-limited surface reaction steps, where the total deposition thickness or etched depth is controlled by the number of process cycles, has been a successful approach to meet the technological requirements. Device structures continue to get taller (larger aspect ratio), more complex (3-dimensional memory) and with new materials. Plasma technology has, to date, met these multiple challenges.

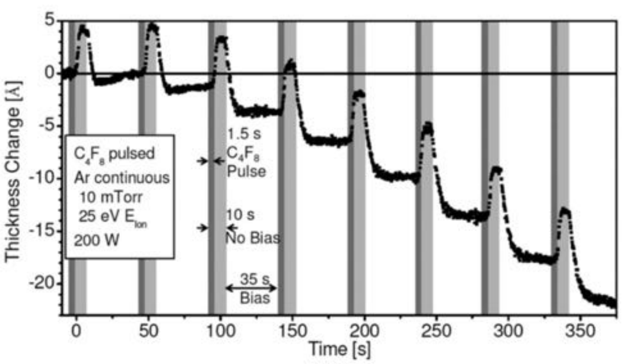


FIGURE 5.2 *Atomic layer etching* – Example of thickness evolution during eight cycles of an SiO_2 atomic layer etching (ALE) process. Self-limited etching of SiO_2 is realized by a number of individual reaction steps in the plasma environment, including surface modification followed by low energy ion bombardment for removal of reacted products from the modified surface. The overall etch depth is controlled by the number of ALE cycles.
SOURCE: Journal of Vacuum Science & Technology A 32, 020603 (2014); https://avs.scitation.org/doi/10.1116/1.4843575

During the last decade there has been wide penetration of plasma surface engineering (PSE) into other industries including etching, smoothing, precision free-forming, patterning, hardening, and coating of surfaces. There has been increasing use of atmospheric pressure plasmas for materials treatment, with extension from inorganic to organic surfaces (such as polymers) and biological tissue (skin, wound treatment). These advances have utilized new methods of excitation. Although historically PSE has been quite empirical, the science of PSE has greatly advanced, through use of modern plasma diagnostics techniques. These diagnostics have led to the discovery plasma instabilities, turbulence and chaos, in what had been considered quiescent devices. Self-organization in process plasmas has also been discovered, most vividly illustrated by instabilities in sputtering magnetrons. The development and application of simulation tools have greatly improved our understanding of PSE systems. Plasmas have also been extensively investigated for synthesis of new materials and structures. Major advancements have been made in the plasma synthesis of nanoparticles and nanostructured materials including 1D and 2D materials.

Thermal plasmas are also intensively used for material processing including welding, cutting and deposition of thermal barrier coatings. In the last decade, a detailed understanding of the influence of metal vapor, particularly in welding arcs, has been developed. 3-dimensional time-dependents models and spatially resolved time-dependent measurements have clarified the mechanisms driving metal vapor transport, and the influence of metal vapor on arc properties, droplet detachment and weld pool depth.

This societal benefit of this scientific advance will come with improved welding processes and wire-arc additive manufacturing.

Sustainability and Environmental Applications

In the last decade, impressive progress has been made in understanding plasma assisted ignition and combustion (PAIC). The motivation of PAIC is to improve conventional combustion processes by enabling lean combustion and ignition under conditions that improve efficiency and reduce the environmental impact of combustion processes. Localized heating and radicals produced by nanosecond pulsed plasmas were found to be effective for triggering combustion processes. Nanosecond pulsed plasmas that produce high electric fields efficiently channel energy deposition into electronically excited states of the molecules in air-fuel mixtures, resulting in rapid oxygen dissociation by electron impact and in excitation transfer from other electronically excited atoms and molecules. The majority of these studies have been performed at or below 1 atmosphere, whereas in many engines, the gas is compressed to high pressures. At high pressures, discharge instabilities and self-organization might affect power deposition, induce hydrodynamic effects and alter dominant plasma kinetics—processes that require further investigation.

The treatment of water contaminated with toxic matter by plasmas has been a strong focus of the LTP community and the effectiveness of plasma in mitigating different pollutants has been investigated. Recently plasma has emerged as a unique technology that is able to decompose carcinogenic species like perfluoroalkyl acids (PFAAs) with energy efficiencies better than competing technologies, as shown in Figure 5.3.

The combination of plasma with catalysts has been extensively studied in the context of environmental remediation during the past decades. Catalysts combined with plasma have shown increased selectivity to remove pollutants from exhaust gases and also increase catalyst lifetime due to in situ plasma-based regeneration of the catalyst. In recent years there has been an increased interest in using the combination of plasmas and catalysts to increase selectivity and yield of chemical conversions, with the main motivation being energy conversion. That is, use plasmas to convert low value materials to high values materials as a form of energy storage. Examples include partial oxidation of methane to make alcohols and ammonia synthesis. The fundamental processes of plasma-catalysis are not well understood. The majority of research has involved performing optimization studies assessing the consequences of varying input parameters (e.g., voltage, flowrate) on the output while not necessarily addressing fundamental processes.

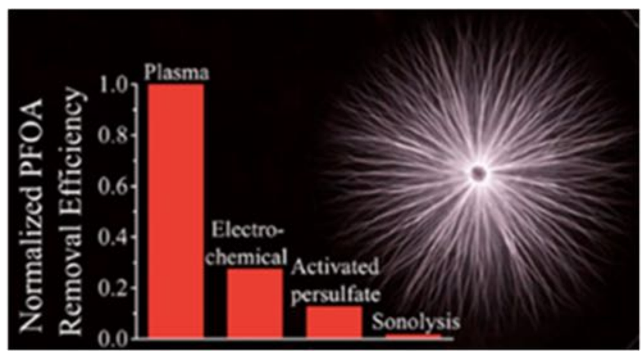


FIGURE 5.3 *Plasma-based water treatment* – There is a growing concern about perfluoroalkyl acids (PFAAs) in water due to their toxicity for humans and wildlife. Conventional water treatment is not effective for the removal of PFAAs. Recently efficient transformation of perfluoroalkyl substances contaminated groundwater by plasma has been demonstrated. Interestingly, the research showed that hydroxyl, often considered the key reactive species in water treatment, plays no significant role and the efficiency is ascribed to plasma-induced reactions with electrons and ions. SOURCE: Environ. Sci. Technol. 2017, 51, 3, 1643-1648, https://pubs.acs.org/doi/pdf/10.1021/acs.est.6b04215

Societal Benefits of Advances in the Science of LTPs

An improved ability to control chemical transformations through electricity-driven LTP has tremendous potential in a wide range of current and future societal challenges, including enabling the transformation of the chemical industry from being fossil-fuel driven to being electricity-driven (see Figure 5.4). This enhanced capability in LTP will benefit multiple sectors of society. Controlling plasma-surface interactions at the atomic level will enable the next generation of materials for quantum computing, combating anti-microbial resistance, improving agriculture efficiencies and food safety, enabling new energy storage technologies and developing plasma-based propulsion capable of taking mankind to Mars and beyond.

THE ECOSYSTEM OF LTP SCIENCE AND TECHNOLOGY

Funding sources for LTP research in the United States are as diverse as its scope. Currently, fundamental research in LTP is focused on plasma generation, non-equilibrium kinetics and plasma chemistry; plasma interaction with solid and liquid surfaces, and near surface (sheath) properties; self-organization, magnetized plasmas and plasma-wave interactions. Funding for fundamental research in LTP science is mainly by U.S. government agencies, including NSF, DOE-FES, AFOSR, ONR, DARPA and NASA. As an example, the NSF-DOE Partnership in Basic Plasma Science and Engineering (PBPSE) LTP-focused research (including topics such as dusty plasmas) on the order of $3 million per year. The DOE FES supported the Center for Predictive Control of Plasma Kinetics for 10 years (2009-2019) with an annual budget of approximately $1.8 million per year and additionally supported DOE laboratory efforts in LTPs at a level of $0.6 million to $1 million per year. In 2019, this program transitioned into support of smaller centers and distributed user facilities for LTP at the level of approximately $4 million per year.

The Air Force Office of Scientific Research (AFOSR) has been a major sponsor for electric propulsion. In addition, many agencies including ARO, DARPA, DOE-BES, NSF (Engineering, Materials), USDA, and NIH support LTP projects that are mainly focused on the utilization of plasmas for specific applications of interest for these agencies. For example, ARO and AFOSR have sponsored several MURI (Multidisciplinary University Research Initiatives) that have funding of about $1 million per year, focused on specific LTP enabled applications such as nanoparticle synthesis and control of electromagnetic radiation. The funding landscape is therefore highly dispersed and with a primary focus on applications and translational research. There is relatively little inter-agency coordination of LTP research with the exception of the NSF/DOE Partnership in Basic Plasma Science and Engineering.

Funding for applied research in LTP in the United States includes both government

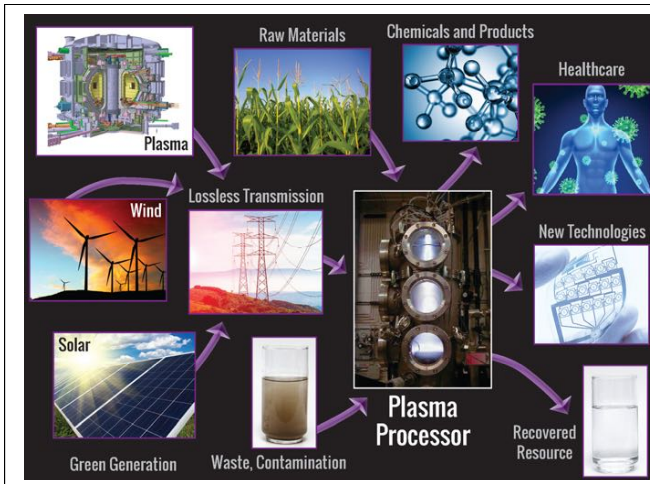


FIGURE 5.4 *Enabling a future based on electricity through non-equilibrium plasma chemistry* – An exciting new vision for LTPs is its use as a processer to use renewable resources and waste, convert them into valuable products. This vision leads to electrification of the chemical industry as plasmas are ideally suited to be driven by electricity produced by renewable energy sources (including fusion in the future) and can be used for point of use technologies. SOURCE: Courtesy Mark Kushner, University of Michigan, https://arxiv.org/abs/1911.07076.

and industrial support. The Small Business Innovation Research (SBIR) and the Small Business Technology Transfer (STTR) programs fund a wide variety of projects that use LTPs for a specialized and applied outcome, but typically do not emphasize fundamental research. That is particularly the case for SBIR. STTR requires the small business to collaborate with a research institution, typically a university, and so those programs tend to have a more fundamental component. Each year, federal agencies with extramural research and development (R&D) budgets that exceed $100 million are required to allocate 3.2% (e.g. for FY 2017) of their R&D budget to SBIR and 0.45% to STTR awards. To estimate the amount of funding that involves LTPs in some manner, even if approximate, the SBIR/STTR grants database over the past 5 years was searched for the term “plasma”, which would include projects that, for example, simply used a plasma tool to coat a surface but was exclusively focused on other topics, to more plasma focused work. Projects referring to biological plasma were excluded. The results were $20 million to $40 million per year. The majority of these projects involving LTP are likely using the plasma as a tool and not investigating plasma properties.

Industry funding is focused nearly exclusively on applications. Obtaining precise numbers for this effort is difficult since companies are not required to publish these data and LTP applications in industry are invariably coupled with other sub-fields of science and technology. One sector that utilizes LTP extensively is the semiconductor equipment industry. For example, one leading U.S.-based semiconductor equipment company (Lam Research, Fremont, California) that uses plasma extensively in their equipment reports an R&D expenditure of about $1.2 billion in fiscal year 2018. Other U.S. semiconductor equipment companies such as Applied Materials (Sunnyvale, California) probably spend a comparable amount on their LTP-based equipment development. The chip manufacturing companies also support internal R&D in their plasma-related activities but no data are publicly available. Given the range and scope of using LTPs in industry (i.e., semiconductor, defense, aerospace, automotive, biotechnology, materials, environmental), there are no doubt many other companies that support LTP R&D.

In summary, U.S. funding for fundamental LTP science is no more than about $10 million per year. By contrast, corporate R&D funding for the development of LTP industrial applications probably exceeds many $1 billion per year. Industrial estimates of total federal funding investments in LTP related to semiconductor manufacturing, a part of all LTP research, is only 0.01% of the plasma processing market—a small fraction for such a strategically important technology. The proper ratio is certainly debatable. However, given that fundamental LTP research underpins several industries that are critically to our national economy and national security, the applied-to-fundamental research ratio appears to be a significantly out of imbalance.

The central role of LTP is often hidden from public view, creating *hidden value* to the United States and world economy. The hidden value of plasma technology and the unquestionable value of the underlying basic science have led to inconsistent research funding for the field. In the absence of consistent and reliable funding, it is impossible to sustain a sufficient number of world-class research groups in in the United States in LTP science to maintain long term leadership in the LTP field. LTP research is carried out at universities and research institutes in multiple departments. The field is truly cross disciplinary. However, this interdisciplinary strength has, to date, been a liability rather than an asset in securing research funding for the field. Most funding agencies and funding mechanisms continue to be strongly compartmentalized and discipline specific. Agency statements in support of cross disciplinary research do not often translate into actual funding programs for cross disciplinary research, which is a severe problem for LTP in the United States. The impact of the already small amount of government funding for LTP fundamental science is further reduced by being highly dispersed with very little coordination between funding agencies.

Level of Effort

An estimate of the number of faculty and senior researchers active in low temperature plasmas in U.S. academic institutions can be made from a community-generated white paper submitted to the APS Community Planning Process in 2019. The white paper had 157 co-signers from 74 institutions (universities, national laboratories, companies). Of these co-signers, 136 had academic appointments from 58 universities and colleges. Many of these colleagues are also involved in other research areas and many focus on applications. This count is known to be an undercount, and so to be optimistic, the committee estimated 175 academic researchers. This is significantly fewer than corresponding numbers in countries such as France. Colleagues in France estimate that between 240 and 350 researchers are involved in LTP within CNRS (the French National Center for Scientific Research) and in French academic institutions. Using the low-high estimates for both countries, on a per capita basis France (population 67 million) has 3.6-5.2 LTP academic researchers/million population. The United States (population 329 million) has 0.41-0.53 LTP academic researchers/million population. On a per capita basis, France has 9-10 more LTP academic researchers than the United States. The committee concedes that these figures are estimates. As the LTP field is exceedingly broad and many researchers use plasmas as part of their research, it is difficult to provide exact figures.

Another estimate of the size of the U.S. LTP community can be made from the number of PhD and MSc theses published, available from the *Proquest* database for dissertations and thesis. This database lists most, but not all, theses from U.S. educational institutions. Searches in this database over the last 10 years, using the key words “low temperature plasma”, yield an average of about 75 theses/year. However, typically fewer than 10% of these theses involve fundamental plasma studies. It is important to note that whereas LTP research involving applications continues to grow, fundamental research in LTP appears to be declining. There is concern that if this trend continues, within the next 10 years, fundamental research in LTP that has historically been the basis of the development of LTP applications will, with a few exceptions, no longer be practiced in the United States.

The demographics in the LTP field will result in a leadership class retiring within the next decade. Plasma research is a multidisciplinary field and recent university faculty hiring has not produced early career faculty with a focus on the fundamentals of LTP science. There are simply too few early career LTP-oriented faculty for the United States to continue to be an international leader when the current leadership class retires.

The establishment of the Low Temperature Plasma Science Center program at DOE since the 2010 Decadal study has benefited fundamental LTP research. LTP research at U.S. universities remains highly dispersed and it is not uncommon that only one faculty member to be involved in LTP research at an entire university. This underlines the need for a coordinated funding model for LTP and the need to stimulate and support inter-university collaborative efforts. The DOE Plasma Science Center Program has served this role.

RELEVANCE AND BENEFITS OF LTP

In most LTP applications, control of the plasma to achieve the desired effects is the ultimate goal. Designing the plasma device entails making decisions on particulars of the power supply (e.g., radio frequency, pulsed), method of excitation (inductively coupled, dielectric-barrier-discharge, capacitively coupled) geometry, pressure and composition and rates of gas flow. Proper choices depend on the details of the application. In addition to design variables, the process parameters must be selected and optimized for each application. The challenge of this task is, in many cases, difficult to exaggerate. For example, in modern plasma etching applications in the semiconductor industry, it has been estimated that there can be as many as 15 different control parameters, leading to an astonishing 10^{15} different process recipes that could be used. This huge number results from the multiple film materials are typically etched, with many different gas compositions, coupled with many different possible operating parameters such as gas flows, pressure, multiple power supplies and control of wafer temperatures. Each of these parameters can and often are altered as a function of time, with time variations that range from slow ramps to abrupt pulsing. Controlling such a process is a major challenge. In spite of this huge set of possible parameters, industry is very good at finding a solution that satisfy their needs. That solution is not necessarily the best solution—it is the solution that time and budget allowed.

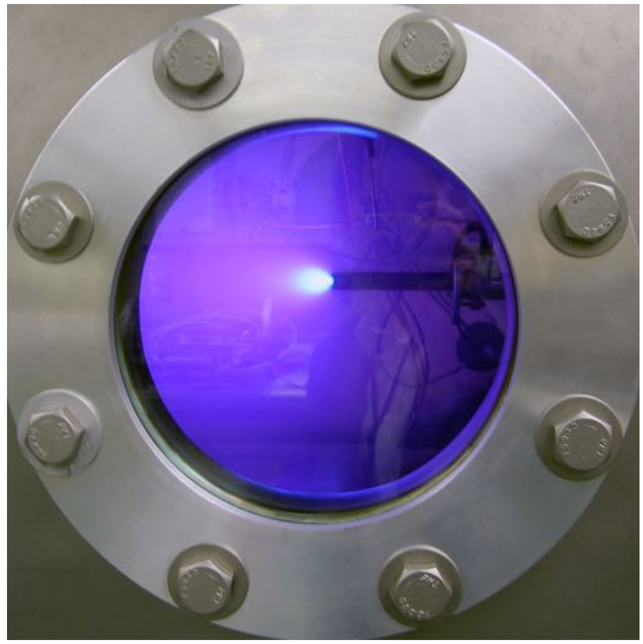


FIGURE 5.5 *Plasma contactors*. The environment surrounding the International Space Station (ISS) is hazardous to astronauts for many reasons. One major issue is electrons from the sun and local space plasma charging up the structure. The ISS stores charge like a capacitor, which can then discharge as electrical arcs hazardous to space-walking astronauts. This hazard can occur in all human exploration missions and can occur in robotic missions where docking to other spacecraft is used. The charge buildup is neutralized (and astronauts protected) by “plasma contactors,” which spray electrons into the surrounding ionosphere using hollow cathode discharges to maintain the electrical ground of the space at the same electrical potential as the surrounding ionosphere. SOURCE: NASA/JPL.

Other applications may not have quite as large a parameter space, but similar challenges do exist. How does one design and control the plasma to achieve a desired outcome? LTP is a highly non-linear and complex physical system, including its interactions with its environment, and having more degrees of freedom than any other plasma discussed in this report. The fundamental research questions in LTP are often oriented towards this complex optimization and control problem. To deal with this complexity, an understanding of the dominant physical and chemical processes are necessary to build models that are by necessity less complex but represent system well enough to enable predictive capabilities.

TECHNOLOGY AND SOCIETAL BENEFITS FROM ADVANCES IN LTP SCIENCE

Plasma-Assisted Propulsion in Space Science and Exploration

Propulsion systems based on plasma, typically called electric propulsion thrusters or electric rockets, are an established technology used to keep communications satellites in their desired orbits against gravitational and solar-flux disturbances that perturb their trajectories. Electric propulsion is also emerging as the system of choice for deep space science missions. Gridded ion thrusters were used by NASA on the Deep Space 1 and Dawn missions to visit asteroids and were used by the Japanese Space Agency JAXA to return samples from a near-Earth asteroid. The European Space Agency (ESA) mission BepiColombo is now using ion thrusters to propel the spacecraft to planet Mercury. The Hall thruster was used by the ESA to propel the SMART mission to the moon. Hall thrusters are also planned for the upcoming NASA science mission to the asteroid Psyche.

LTP Enabling Long-Mission Human Space Science and Exploration

One of the unsolved challenges for long mission human space flight is life-support-systems. This challenge extends to long-term habitation on the moon and planets. Life-support requires energy efficient sources of food, water and oxygen, and recycling of waste products. Plasma-liquid interactions and plasma chemical conversion represent a potential solution for all of these areas. Beyond water treatment, plasma-technologies can address a wide range of space habitat challenges. Space agriculture would benefit from the plasma treatment of seeds to reduce microbial load and improve water uptake to enhance yield and the direct application of nutrients to plants via plasma-activated water.

Plasma-based subsystems are potentially components of life support systems. Unlike conventional systems, which require high temperatures for chemical conversion, in LTPs chemical conversion occurs largely at room temperature. LTPs can support atmosphere control through the decomposition of carbon dioxide into by-products such as CO and oxygen. The potential for a plasma-based life support system has yet to be explored, and would be paradigm shift, enabling for essentially complete recycling of waste-water and gases in the spacecraft. LTP is also key to the safety of spacecraft and astronauts enabling the alleviation of charging. (See Figure 5.5.)

LTP in Advanced Microelectronic Devices Enables Many Other Areas of Science

The recent detection of colliding black holes by LIGO and the imaging of a black hole by the Event Horizon telescope simply would not have occurred in the absence of modern microelectronics devices. Gene sequencing, simulations of weapons, remote sensing, satellite communications, 3D manufacturing, the display with which the reader is likely viewing this report, are all enabled by microelectronics devices. The essential role played by LTPs in this enormous advance in human capability enabled by microelectronics is in the manufacture of those microelectronics devices.

A recent report (April 2019) from the U.S. Semiconductor Industry Association entitled *Winning the Future. A Blueprint for Sustained U.S. Leadership in Semiconductor Technology* addresses semiconductor-related research support in the United States. This report notes the importance of semiconductors in emerging areas of advanced scientific exploration such as artificial intelligence, quantum computing, and advanced wireless networks. The fact that LTP is enabling the modern semiconductor industry illustrates that LTP enables most of modern scientific discovery and technological advances that create a major impact.

Atmospheric Electricity

Physics of lightning has long been considered as prohibitively difficult to understand from first principles, and so lightning research focused either on observations of the macroscopic phenomena (lightning occurrence and properties) or on lightning protection based on engineering models. Lightning protection remains a topic of growing importance, particularly given the trend toward composites in the aerospace industry. However, the discovery of transient luminous events (TLEs) between clouds and ionosphere in 1989, and the discovery of terrestrial gamma-ray flashes (TGFs) and other high energy phenomena from active thunderstorms in 1994 have stimulated new plasma physics research on atmospheric electricity. A new community has developed that is making new observations, undertaking microphysics-based modeling and simulations and analogous lab experiments.

LTP research will play a crucial role in some of the key science challenges in this area including:

- *Lightning inception:* It is now roughly understood how a lightning discharge can start near one graupel particle (soft hail or snow pellets) due to the local enhancement of the rather low background electric field in the cloud. The manner how lightning grows to tens of meters and more is not known.
- *Polarity dependent lightning propagation and stepping:* Our understanding of how space charge dominated streamer discharges propagate is improving, and this understanding also applies to their larger relatives, sprite discharges in the thin upper atmosphere. However, when additional effects like plasma heating and plasma chemistry start to play important roles on larger scales of space and time, our understanding is still quite limited. This increased understanding is necessary to explain polarity dependent lightning propagation and stepping.
- *Lightning attachment:* Where and how does a lightning leader attach to a structure (on land or an aircraft) leading to lightning damage? Recent optical observations show how counter-leaders emerge from tall objects (like apartment buildings) and approach lightning leaders growing downwards from the cloud. A better understanding of this process would lead to new lightning protection schemes.

Plasmas in Hypersonics

Hypersonics is the field of fluid dynamics for speeds greater than Mach 5 (five times the speed of sound). Bodies moving at hypersonic speed through gas will produce an enveloping plasma due to heating by the shock waves at the leading edge of the body. Understanding these plasma dynamics is critical for the design of efficient, reliable and safe hypersonic platforms—for space access and return, planetary entry, defense applications, and high-speed civil transport. Understanding these LTP dynamics is also of importance in predicting meteor penetration through the atmosphere and the associated risks that a meteor impact might have to civilization. The plasma surrounding a body entering into the atmosphere at high velocity produces tremendous heat loads and a communication blackout. These particular phenomena have been long known, but poorly characterized. However, for vehicles that have more lift, the leading edges are sharper and heating is much more severe, exceeding many kW/cm^2. Methods to reduce the heating and accurately predict the heat loads are needed to improve the safety of the crew and reduce the weight of thermal protection system. As the plasma passes around the hypersonic body, expansion and recombination processes become important. Research on plasma produced radiation and recombination mechanisms is needed to predict heat loading and to develop methods to minimize it. The conductivity of the plasma is also of interest for the development of advanced control and power extraction methods. For example, a magnetic field may be used to force the leading edge away from the surface, controlling the drag and reducing the heat load. Magnetic fields may also enable MHD type power extraction methods. Injection or ablation of easily ionized species may be used to enhance the conductivity for some applications.

High-Power Microwave Generation

Advances in high power microwave (HPM) generation over frequencies of ~0.1–1,000 GHz are needed for applications such as accelerators, fusion plasma heating, new materials development, advanced radar, remote threat detection, and the transmission of massive volumes of data over long distances. Producing high microwave-energy-density systems requires addressing issues of intense beam generation, dense charged-particle confinement, extreme-environment-compatible materials, intense radiation and particle diagnostic development, and the development of compact pulsed power. HPM research and development requires advances in plasma physics theory, computation, experimental diagnostics, and the integration of advanced electronics (sensors, system control, pulsed power) and signal processing.

Extending conventional magnetron oscillators to GW power and kJ pulse levels requires better understanding of beam-plasma interactions, plasma-induced pulse shortening, plasma-enhanced mode competition, and scalability. Future opportunities include development of time-domain sources, where HPM radiation is emitted from single-shot (ultrawideband pulses) or periodic-pulse-trains of plasmas generated by ultra-short-pulsed lasers. There is both a need and opportunity for research of higher power, compact (portable) sources of mm-wave and THz-regime radiation.

New materials are both the enabler and a research frontier for advances in HPM science. Advances in predictive computational algorithms, computational materials by design, hardware, and physical models are leading to new electromagnetic materials (especially plasmonic and metamaterials), new extreme-energy-tolerant refractory materials (for low-outgassing anodes) and new cathode materials for thermionic, photo- and field emission. Frontiers in cathode physics include understanding how interfaces, morphology, microstructural heterogeneity, bipolar flows and space charge effects, including nanoscale charge transport, determine emittance, brightness, and cathode lifetime, especially in cold (field emission) cathodes.

Understanding and controlling interactions between localized, dense plasmas and strong EM fields is critically important to HPM sources. Multipactor avalanche (where electrons are scattered and multiply along a microwave window) on conducting and dielectric surfaces by HPM fields can lead to a localized plasma discharge. Controlling surface breakdown of both distributed and spatially periodic discharges would enable longer HPM pulses.

Plasmas for Optics and Wave Manipulation

The field of "plasma metamaterials and plasma photonic crystals" involves LTP science in which plasma elements (individual plasmas, plasma gratings or plasma arrays) serve as, or are integrated into, electromagnetically active artificial materials to produce desired response to electromagnetic (EM) waves. "Plasma metamaterials" act as a filter that will pass or reflect only certain wavelengths due to there being resonances of the EM wave with the plasma array. "Plasma photonic crystals" and gratings relay on EM wave interactions with repeating plasma structures comparable, leading to Bragg interferences, that will reflect only selected wavelengths.

Plasma integration into Metamaterials (MMs) and photonic crystals (PCs) have already proven important in a wide range of applications in microwave, mm-wave, and optical-wave photonics—applications important to communications systems. These devices are typically "static" systems. The potential of plasma-based MMs and PCs is the ability to rapidly reconfigure these structures by changing the properties of the plasma. Plasmas can be used to more effectively focus and shape the radiation field of antennas or reflectors, be used as invisibility cloaks, provide improved impedance matching, and they can spectrally filter, guide, and confine EM waves with high quality factors. The plasma introduces a degree of reconfigurability at potentially high bandwidths. In communications applications, several of these features relate to the improvement or enhancement of speed and bandwidth (the amount of information that can be communicated). An example of a plasma photonic crystal is illustrated in Figure 5.6.

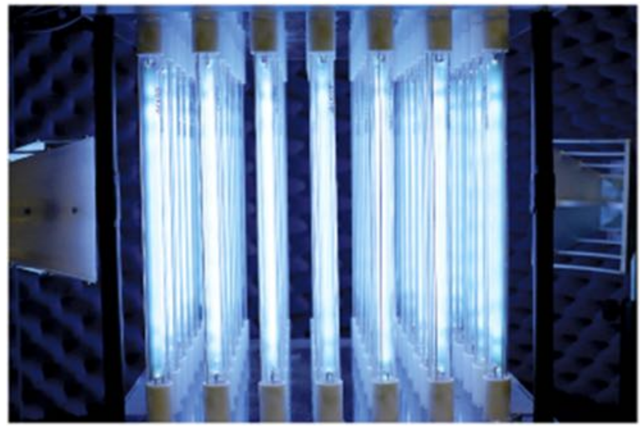


FIGURE 5.6 *Plasma wave interactions* – A photonic crystal is a structure that enables the manipulation of light and can for example be used as an optical modulator. Plasma devices can be used to actively tune the properties of the photonic crystal by changing the electron density as their operation frequencies are controlled by the plasma frequency. A key advantage is that the tunability can be achieved at relatively high rates as it is only limited by the ionization or recombination times of the plasma which can be significantly faster than typically mechanical, thermal, or fluidic time scales used in conventional devices. The image shows an example of a plasma photonic crystal setup that is completely formed by plasma elements that are individually controllable.
SOURCE: https://doi.org/10.1063/1.4946805

LTP Benefits to the Environmental and Sustainability

Water purification: LTP processes help mitigate environmental hazards and processes that contribute to man-made climate change. For example, LTPs as ozone generators have long served as the basis of water purification in municipal water systems. Water is commonly polluted by pharmaceutical wastes, organic compounds, odor, NO_x, SO_x , viruses, agricultural runoff and other waste products, including fracking effluent and industrial waste water with persistent pollutants. Cleaning water in an efficient and scalable manner challenges traditional means of water purification. A relatively new approach utilizes *advanced oxidation processes* (AOP). These methods use the oxidizing potential of the hydroxyl radical (•OH) which is more reactive than ozone (O_3) and hydrogen peroxide (H_2O_2). LTPs are emerging as a strategic technology that can provide the reactants in AOP treatment of water. LTPs are being investigated as in-water sources of oxidizing species such •OH, O• and H•, and for the emission of UV light for disinfection. Plasma based water treatment is especially attractive since there is no input required other than electricity. The radicals required to remove contamination, pollutants and organic matter are derived from the water itself (or air in contact with the water), requiring no additional chemicals.

Closed carbon and sustainable energy cycles: Of all the environmental and sustainability issues that must be addressed, CO_2 engineering is perhaps the most pressing. There is currently no technology available to economically and permanently remove CO_2 from the environment, or to capture and recirculate the carbon in a carbon neutral manner. LTPs represent a science able to address many of these needs. Current research is addressing plasma conversion of CO_2 to CO for syngas (a mixture of CO and H_2) to recirculate the carbon for carbon-neutral combustion. Similar LTP processes are being investigated for plasma conversion of CH_4 to hydrogen (the second component of syngas) and to higher value hydrocarbons. The ultimate closed carbon cycle may involve bio-based carbon raw materials to replace currently manufactured petro-chemicals. Recent research indicates LTPs may play a key role in this effort.

Utilizing plasmas in energy applications already has a record of success. Thin film solar cells are economically viable due to the efficiency and selectivity of plasma-assisted deposition and thin-film etching in industrial scale fabrication processes. LTPs for pollutant mitigation and waste treatment have potential applications across the industrial and municipal landscape. Pilot plants use plasma torches for converting municipal solid waste to syngas and minimizing the need to dispose of solids. The syngas can then be used to sustainably produce electricity. Plasma based systems are used to treat contaminants in industrial gases, to treat SO_x/NO_x emission from power plants and to remediate medical waste.

Fossil fuel combustion will likely play a significant role in modern society for the next several decades. Using those precious resources more efficiently positively impacts every measure of environmental stewardship. As discussed above, plasma-aided ignition and combustion (PAIC) is a highly promising technology to address some of those needs.

SF_6 replacement gases in high-voltage switchgear in electricity distribution systems: SF_6 has several favorable properties that have led to its use in high-voltage circuit breakers—it is non-toxic, stable, is gaseous even under pressures of the several atmospheres that are typically used, it has excellent insulating properties and, since it has lower energy than any of its decomposition products and is thus reformed after an arcing event. However, because of its high global warming potential, it is scheduled to be replaced. CO_2 is now being used in some installations but has poorer insulating properties and is also a global warming gas. New gases, in particular C_4F_7N and C_3F_8O, show strong promise; however, they have relatively high boiling points and therefore have to be mixed with CO_2 or other gases. They are also gradually decomposed after arcing events. Research into the decomposition pathways of these gases under typical operating conditions, their reactions with metals and vapors ablated by the arc, and computational modelling of the arcing process are all required to optimize the design of circuit breakers that use such gases.

LTP in Education and Workforce Development

LTP is intrinsically multidisciplinary, with investigations extending to other research fields from material science to medicine. As a result, students pursuing LTP topics in their graduate studies receive an interdisciplinary education. The research in these allied fields similarly has far-reaching educational impact, helping to train the next-generation of investigators in both the application area and in plasma physics. Graduates from LTP programs begin their careers in a wide range of science and engineering disciplines in industry, national laboratories, and academia.

LTP IN ECONOMIC DEVELOPMENT

LTP science and technology have long addressed critical societal problems and have created significant economic impact through the interplay between basic science, applied science, and technological challenges. Since plasma technologies are primarily enabling technologies, their contribution to a specific product or method often remains hidden or even unknown and their direct impact, especially their economic impact, is often difficult to assess. Success of LTP in advanced applications has been the result of a significant and sustained investment in basic and applied plasma research in North America, Asia and Europe over many years. This critical support enabled the plasma community to (1) leverage basic plasma science breakthroughs for the development of strategic applications (e.g., integrated circuits in microelectronics) and to (2) use the success of plasma applications to challenge basic plasma science to thoroughly investigate these new phenomena and provide a scientific underpinning.

Materials Processing: Semiconductor and Related Industries

As one of the top 10 industries in the United States, the semiconductor industry is a strategic asset to the U.S. economy and national security. Semiconductor chips are the fundamental technology that enables computers of all types (laptops, mobile phones, data centers, and supercomputers) and their applications, from medicine to national defense. Microelectronic chips enable the rapidly expanding world of artificial intelligence (AI), where state-of-the-art chips are increasingly embedded into products such as autonomous vehicles, web commerce sites, industrial manufacturing plants, and ultimately supporting the growing sophistication of our national security infrastructure.

The chemically reacting environment capable of delivering highly controlled activation energy to wafers enabled by LTPs is absolutely essential to the manufacture of these devices. Of the 400-950 processing steps required to manufacture leading integrated circuit (IC) chips, 40-45% are plasma based. It is no exaggeration to say that virtually every chip in circulation today has been touched by plasma. If there was a better, cheaper, more reliable method for microelectronics manufacturing than use of LTPs, the committee believes the industry would have gone in that direction. The reality is, that after decades of exponential semiconductor scaling, advances in new technologies depend more than ever on plasma-based processing. Plasma etching, alone ("trimming"), or in conjunction with atomic layer deposition (ALD) has recently been used to create mask features with widths of tens of nm to < 10 nm. This "disruptive" technology may obviate the need for extreme UV lithography in many applications.

The economic impact of LTPs is enormous and can be quantified in the microelectronics industry. Currently, the United States leads that industry with close to half of the global IC market worth nearly $500 billion, which serves a roughly $2,000 billion electronics market. Estimates of future growth in the IC industry based on current trends suggest that a 5-year doubling in revenues is likely. To manufacture the microchips that enable this market, the global IC industry purchases $50 billion (2018) of wafer fabrication equipment per year, of which approximately $15 billion to $20 billion is plasma based.

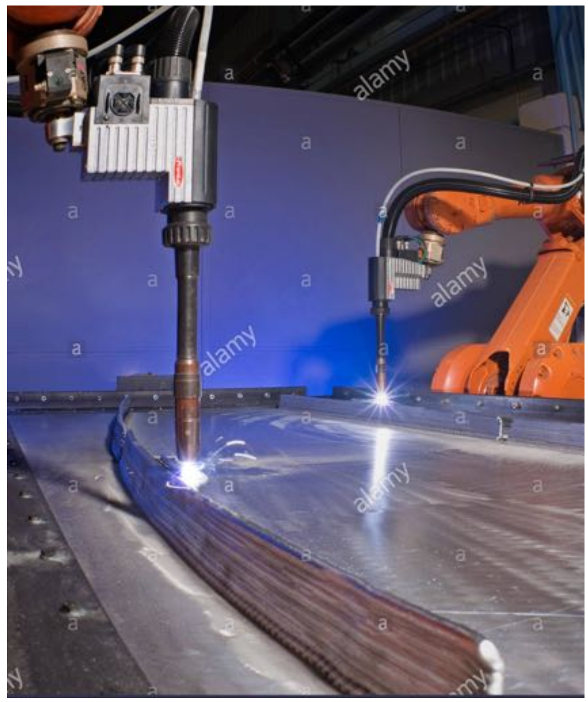


FIGURE 5.7 *Plasma additive manufacturing* – Two robotic welding machines are fabricating steel-aluminum aircraft wing ribs using a wire + arc additive manufacturing process (WAAM) which deposits layers of metal from a wire in a technique derived from welding. WAAM fabrication of pieces from metals, alloys and composite materials is significantly shorter than using conventional methods, with considerable cost savings. The concept has long been pursued, but recent developments in LTP arc technologies and robotic control are increasing WAAMs importance in the manufacture of, for instance, aircraft parts which are conventionally machined from solid blocks of metal. SOURCE: https://www.alamy.com/stock-photo-wire-arc-additive-manufacturing-at-cranfield-university-147641206.html.

Materials Processing: Polymers

The use of LTPs in materials processing beyond microelectronics fabrication has and continues to have a huge impact. LTPs for functionalization of polymers for wettability and adhesion is the basis of large industries as well as emerging applications. Commodity polymers such as polypropylene, polyethylene and polystyrene are treated with plasmas to produce hydrophilic surfaces that will wet and adhere to other materials. These techniques are now being applied to high value materials such as metals, carbon fiber laminates, 3D-manufactured parts to remove contaminants and to improve adhesion. The development of plasma processing techniques for biotechnology is also an established industry with emerging applications. LTPs are used for biocompatibility (e.g., cell adhesion, specificity) and sterilization, and is now finding new markets in treating medical polymers to enable more precise and reproducible medical studies.

In 2018, the worldwide production value of polymer films and sheets was $120 billion, growing at 5 to 6% annually, of which 70% involves forms of polyethylene and polypropylene films, virtually all of which require some form of surface modification. The products using these films and sheets have a market value of over $330 billion. The majority of *all* products utilizing polymer films require LTP (corona) treatment to enable acceptable final product performance.

Materials Processing: Coatings

LTP sputtering processes are extensively used in industry for coatings and functional films. The cathodic arc deposition has remained a base technology for high-rate coatings on tools and automotive parts and gained new importance in deposition of thick thermal barrier and erosion protection coatings such as on turbine parts. At the same time alternative technologies such as HiPIMS (high power impulse magnetron sputtering) are becoming established in segments of the industry, especially the high-end tooling industry. Another major application includes plasma deposition on glass substrates for reflection and antireflection coatings.

Additive Manufacturing

Metallic additive manufacturing is an increasingly important process, enabling prototyping, production of custom-designed parts and production of complex structures not possible using traditional methods. Many metallic additive manufacturing processes use metal powder as the precursor (e.g., powder-bed approaches such as selective laser melting and selective electron-beam melting, blown-powder approaches). Thermal plasma processes, including spheroidization using inductively coupled thermal plasma and wire-to-powder using thermal plasma jets, have proven ideal for production of such powders.

Wire-arc additive manufacturing (WAAM) is an emerging additive manufacturing approach. In this process, a wire is fed into a high intensity plasma arc, which rapidly melts the wire to redeposit on an adjacent surface. WAAM is well suited to the production of large components, since it is fast and relatively inexpensive (metal wire is much cheaper than powder). There are several challenges that have to be overcome. These include improved resolution and control, which requires control of the arc and ideally a spatially confined arc, separate control over the wire feed rate and the arc current, methods to reduce residual stress and distortion (which occurs due to the repeated heating and cooling cycles), and methods to control the microstructure of the deposited metal, which determines the mechanical properties of the component. An example is shown in Figure 5.7.

LTP Applied to Lighting

Plasma lighting sources have dominated commercial, industrial and public lighting needs for 150 years. In spite of this longevity, plasma-based lighting has made progress in the development of compact fluorescent lamps and back-lighting for flat panel displays, both of which have extensive commercial, industrial and residential use. In the 2010 Decadal Survey, it was reported that plasma light sources—fluorescent bulbs and high-intensity-discharge lamps—produced 80% of all the light used in general lighting. While consumers were switching to more efficient plasma (fluorescent) lighting at that time due to improvements in the quality of the light and the life expectancy of the lamp compared to incandescent bulbs, lighting still accounted for 22 percent of all electricity produced in the United States. Plasma-display panels and televisions, also controlled a significant amount of the display market in family households at that time.

That dominance of plasma lighting is beginning to erode with the development of solid-state lighting sources (e.g., light-emitting-diodes and laser-diodes) and flat panel displays. However, the essential role of LTPs in lighting has actually increased in the transition to solid state light sources. The high-volume manufacturing of these devices requires the controllable chemical reactivity produced by LTPs in the same manner as microelectronics fabrication. Essentially all solid-state lighting and flat panel displays use plasma deposition, etching, cleaning and implantation steps in their manufacturing. While plasma may no longer be the main source of the light, it is the source of the higher efficiency and lower cost electronic devices that make and control the light today. The U.S. Energy Information Administration (EIA) estimated that in 2018, only about 8% of the total electricity consumed by the combined residential and commercial sectors was used for lighting. Advances in plasma processing in the last decade directly resulted in significant reductions in the amount of electricity required for lighting in the U.S.

FIGURE 5.8 *From fundamental micro-plasma research to ozone production for rural point-of-use water purification* – Fundamental research into the generation of plasmas in micrometer sized channels has led to the development of stackable modules of microplasma channels for efficient low energy ozone production for rural water purification. The sources can be powered by solar cells and have proven their value in developing countries and for disaster areas. SOURCE: Photo courtesy of J.G. Eden.

LTP Applied to Flow Control

Plasma-based flow control actuators have seen major advancements that improve the operation of aircraft. For example, if efficient arrays of LTP can be applied for on-demand vortex generation during takeoff and landing of aircraft, and be deactivated during the cruise phase, there is the possibility of significant fuel savings during the overall flight. This technology would eliminate the drag penalties associated with conventional vortex generation in the cruise phase. Alternative opportunities may also exist for drag reduction by generating plasma at other positions on the aircraft to reduce drag, reduce noise, or eliminate instabilities.

Ozone Generation

LTPs, as ozone generators, have for many decades served as the basis of water purification in municipal water systems. The global ozone generation market was valued at $880 million in 2016 and is expected to reach $1.5 billion by 2023. To be economical, ozone generation systems typically need to be on the scale suitable for municipal water treatment. This discourages their use for rural point-of-use water treatment far from municipal systems. A recent development is using microplasmas for rural point-of-use water treatment (see Figure 5.8). (A microplasma is a plasma confined to less than 1 mm dimension.) Using modular arrays of microplasmas powered by solar cells, ozone-based water treatment has been made available to “off grid” villages. While ozone generation processes are well known, technological advances continue to be made in the field and are often highly focused on engineering. At the same time, science challenges do remain. For example, the ozone zero phenomenon (where ozone production ceases) in pure O_2 is not well-understood. This is of significant relevance for applications requiring pure ozone as in some semiconductor processing applications.

CURRENT AND FUTURE SCIENCE CHALLENGES OF LTP

Kinetics and Collisional Processes in a Highly Nonequilibrium Regime

The key distinctive feature of LTPs is that power transfer to gases, solids and liquids occurs through energizing electrons (and ions in sheath regions) followed by collisions of those particles with gases, solids and liquids. This leads to highly non-equilibrium plasma kinetics. The LTP field is often driven by applications with plasmas in complex molecular gas mixtures and operating over a wide range of gas pressures. The fundamentals of plasma kinetics have been studied in atomic low-pressure plasmas. The investigation of plasma kinetics in complex molecular plasmas and at higher pressures (often atmospheric pressure and above) and even in liquids has received far less attention, yet applications of these systems are where future opportunities lie. The analysis of molecular plasmas often suffers from a lack of fundamental data, ranging from electron impact cross sections to ion mobilities. At the interface between plasma and liquids, such as water, electron and ion solvation play a dominant role, a topic that is only beginning to be understood.

The driving focus for LTP science is: *Controlling the non-equilibrium energy deposition and dissipation in collisional LTPs to enable plasma-produced selectivity.* This is an extremely challenging topic that has a common science base—that being plasma kinetics and collision physics. However, even fundamental plasma science investigations will have system and application specific solutions. (See Chapter 2.) This specificity is due to the large number of reactions and species, and the wide range of plasma conditions, for example, nearly 9 orders of magnitude difference in pressure between microelectronics processing and plasma-in-water treatment. Bridging this large gap and exploring selectivity for a broad range of applications places great emphasis addressing fundamentals that will scale and the development of predictive modeling.

Plasmas generate infrared, optical, UV and VUV radiation—this is the basis of plasma lighting sources. The consequences of the production and transport of radiation, and particularly UV/VUV radiation, is perhaps one of the greater unknowns in generation and propagation of LTPs and in plasma material processing.

Scaling, Instabilities, and High-Pressure Regimes

The high rate of electron- and ion-neutral collisions at atmospheric pressure not only leads to increased gas heating but also enhances the tendency to develop spatio-temporal instabilities, and self-organization. This increased sensitivity stems from fundamental scaling laws and plasma kinetics. To first order, maintaining constant E/N (electric field divided by gas number density) in many LTPs typically produces similar electron temperatures. At constant E/N, an important scaling law is $pd \approx$ constant, where p is the gas pressure and d the plasma scale length. The higher the pressure p, the smaller the plasma scale length d. In a typical glow-discharge plasma, $pd \approx 1$ Torr-cm. Spatially dependent plasma phenomena that occur over many cm in a 10 mTorr plasma occur over a few microns at atmospheric pressure. This scaling has enabled an entirely new field of microplasmas, which tends to produce filamentary behavior and self-organization. In addition, the larger range of length scales down to the micrometer level provides unique challenges for diagnostics and modeling.

Plasma sustained at high neutral gas density experiences correspondingly higher collision frequencies of electrons and ions with neutral species compared to lower pressure plasmas. At constant E/N, another important scaling law is $p\tau \approx$ constant. The higher the pressure, the shorter the time τ over which a collective plasma process (e.g., ionization wave) occurs. Plasma phenomena that occur over μs to ms in a 10 mTorr plasma tend to occur over ps to ns timescales at atmospheric pressure. These shorter time scales significantly increase the complexity of controlling plasma kinetics at atmospheric pressure. Under these conditions, plasma phenomena that need to be time-resolved create unprecedented challenges for both diagnostics and modeling. Several strategies have been developed to minimize gas heating and the associated development of plasma instabilities. These include nanosecond pulsed plasma excitation to produce the plasma on time scales shorter than the time for an instability to grow. Such fast excitation approaches with large amplitude voltages have enabled the production of novel, highly energetic neutral species as well as *run-away* electrons. Similar phenomena are thought to occur in poorly understood upper atmospheric plasma phenomena such as *sprites* and *elves*.

An example of a new plasma regime is transient plasmas in atmospheric pressure plasmas and liquids with high ionization degrees (more than 10%) generated by nanosecond voltage pulses. These unique conditions, particularly at such short time scales, enable the gas temperature to remain relatively low. Phenomena associated with strongly coupled plasmas start to become important under these conditions, offering many opportunities to explore novel low temperature plasma with analogs to warm dense matter as well as non-neutral and dusty plasmas.

Crossed Electric and Magnetic Fields Transport

Anomalously high transport of plasma across magnetic field lines is pervasive, spanning many branches of plasma physics from fusion to astrophysical plasmas. In LTPs, crossed electric and magnetic fields, E×B, transport is most commonly associated with magnetrons used to sputter in materials fabrication and in electric propulsion (EP) devices. In these E×B systems, instabilities and waves often occur. The lack of understanding of transport in crossed electric and magnetic fields has precluded the development of the types of predictive, numerical models that are highly desirable for both analysis and design. An emerging consensus is that these instabilities can be attributed to non-classical effects such as self-organized oscillations and micro-scale turbulence.

There are a number of remaining knowledge gaps about transport process in EP systems such as Hall effect thrusters (HTs) which are **E**×**B** devices. For example, there are discrepancies between modeling results and experimental measurements related to the shape, dominant energy modes, direction of propagation, and influence of micro-turbulence on plasma transport. Recent particle-in-cell simulations have shown that fast moving electron waves drive coherent, large amplitude, ion acoustic waves. When coupled with local ionization, these waves can produce the cross-field transport and acceleration potential profiles observed in HTs. (Another form of EP the magnetic nozzle, have similar unresolved issues.)

In magnetrons, an array of magnets and a high voltage applied to a cathode produces a closed loop of electron motion adjacent to the cathode. The plasma in the closed loop can be highly ionized, producing a large flux back to the cathode to sputter atoms. Magnetrons are geometrically similar to HTs in having an **E**×**B** structure that is prone to instabilities and waves, which can lead to reproducibility problems in industry.

In an effort to address open questions in **E**×**B** transport, on-going modeling efforts are focusing both on building direct numerical simulations enabled by increased computational capabilities as well as physics-based fluid/hybrid models that can approximate non-classical transport. Expanded experimental efforts combined with new diagnostics will need to be able to measure energy coupling across several scale lengths, the phase relation between microscale electric field and density, and particle distributions.

Plasma Surface Interactions

In most cases, LTPs are bounded and the bounding interface dominates plasma properties. Interactions of plasma with interfaces are also recognized as a major challenge in other plasma disciplines. Examples include the interaction of fusion plasmas with the diverter wall and interactions of interplanetary dust with space plasmas.

Plasma-interfacial interactions can be highly complex due to strong coupling between the plasma properties and the interfacing material surface properties. This interaction can be due to surface charging, electron generation, local field enhancement, sputtering or evaporation of surface material into the plasma, surface deformation, plasma-induced surface property changes and surface reactions in reactive plasmas. Many of these important interfacial processes are not well understood particularly for complex surfaces like volatile liquids and surfaces with complex nanometer to micrometer scale surface morphology such as catalysts. Understanding plasma interactions with complex surfaces will ultimately require developing a broader range of *in situ* surface diagnostics and multiphase modeling leveraging knowledge from different communities. For example, understanding and capitalizing on the synergism between catalysts and plasma remains a major challenge and topic for future intensive fundamental and highly interdisciplinary research. (See also Chapter 2.)

As noted above, low pressure LTPs are used to alter surfaces and thin films for semiconductor device fabrication. For example, progress in maintaining accurate control of ion energies and angles at surfaces in plasma etching is an enabling technology in the semiconductor industry (see Figure 5.9). The materials challenges in the semiconductor industry have been and will continue to be significant. A new group of materials are becoming more important in this industry, including graphene and other 2D materials, III-V compound semiconductors, ultra-high dielectric constant materials, complex oxides and nanoparticles, among others. Control of plasma-surface interactions will become ever more important, and new experimental and theoretical approaches will be needed.

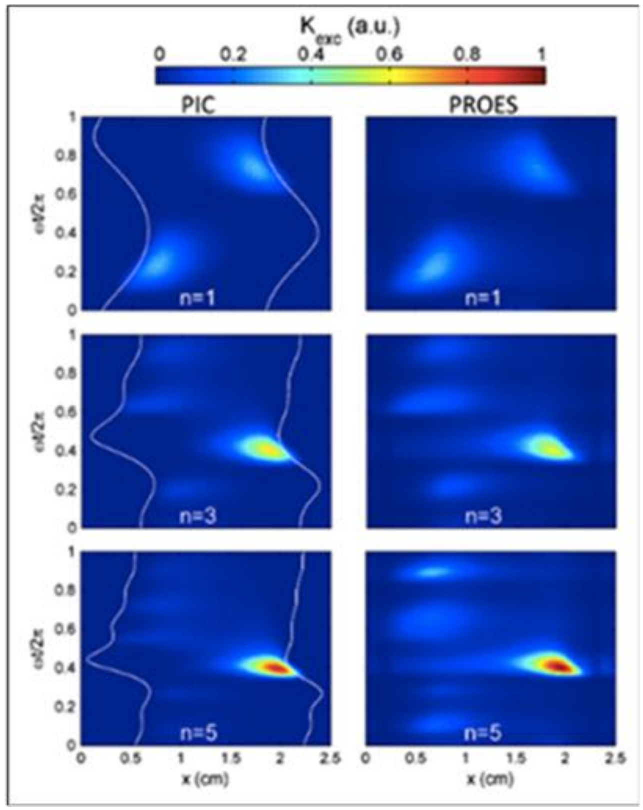


FIGURE 5.9 *Tailored voltage waveforms* – A major goal in low-pressure capacitively coupled plasmas (CPP) of the type used for microelectronic processing, is independent control of the flux and the energy of ions impinging on a substrate. This implies a requirement of direct control of the spatial distribution of plasma properties and ionization. Several techniques have been explored including exploiting dual-frequency plasma generation, nonlinear plasma dynamics by tailored voltage waveform engineering and the electrical asymmetry effect. The figure shows the effect of the spatiotemporal excitation rates as obtained by phase resolved optical emission spectroscopy (PROES) and particle in cell (PIC) simulations while changing from a sinusoidal driven CPP (n=1) to a sawtooth waveform (n=5).
SOURCE: B. Bruneau, T. Gans, D. O'Connell, A. Greb, E.V. Johnson, and J.-P. Booth, Phys. Rev. Lett. 114, 125002, doi:10.1103/PhysRevLett.114.125002.

Self-Organization

Self-organization is an often-observed phenomenon in LTPs. Self-organization can occur in the bulk plasma or in the anode or cathode layer at the interface between a plasma and a resistive or dielectric medium. For example, a resistive or dielectric medium can stabilize the plasma into an array of spots. In glow-discharges interacting with liquids, and typically when the water is the anode, self-organization occurs on the surface with visible patterns ranging from circular to star-like shapes. When ionization fronts propagating through the plasma impinge on a dielectric surface the discharge tends to spread as a surface ionization wave that can display self-organization. The self-organization is thought to result from 'memory' effects associated with surface charge patterns or through non-linear streamer-streamer interactions. Three dimensional simulations of ionization waves and streamers have been performed in the gas phase whereas surface ionization waves have only been recently modeled and intrinsic 3D phenomena have not yet been addressed. We currently do not have a general understanding of the mechanisms responsible for self-organization in atmospheric pressure plasmas interacting with surfaces. (See also Chapter 2.)

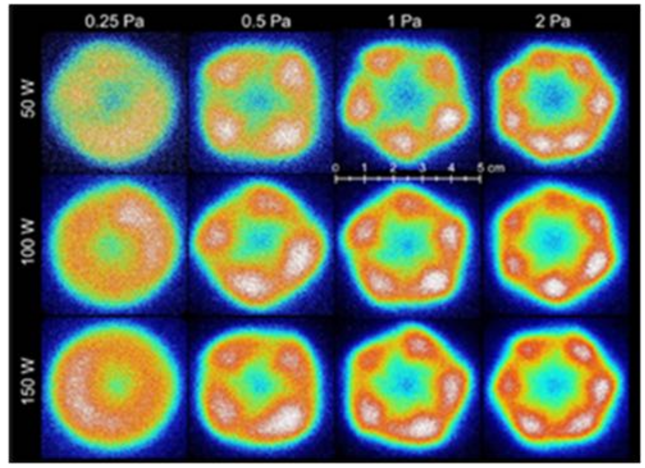


FIGURE 5.10 *Self-organization in high power magnetron sputtering* –Magnetron sputtering is used extensively for the deposition of coatings. The plasma dynamics, including self-organizing phenomena such as spokes, can have a significant impact on the properties of the coatings. In this figure, spoke patterns in a Radio Frequency Magnetron Sputtering regime for different discharge powers and working gas pressures are shown. The light intensity is displayed in a color scale. SOURCE: Journal of Applied Physics 125, 203303 (2019), https://aip.scitation.org/doi/10.1063/1.5094240.

Self-organization can also occur in the bulk plasma. These patterns can arise from non-linear electron kinetics, memory effects and plasma-wave interactions in magnetized plasmas. Examples including striations in non-magnetized glow discharges for a wide range of pressures, filament patterns in dielectric barrier discharges, spokes in magnetron E×B discharges (see Figure 5.10) and in Hall effect thrusters. While specific models have been able to reproduce some observations, a general scientific understanding is still emerging for many of these self-organized processes. To gain a better understanding of self-organization the community needs to answer questions related to the role of gradients, electron kinetics, and the coupling between large- and small-scale plasma structures (energy cascade).

FROM SCIENCE TO IMPLEMENTATION

Due to the close coupling of fundamental science and motivating applications in LTP, the research is nearly always in a state of translation. (Translational research refers to a smooth continuum that begins with fundamental studies and leads to applications.) The translational nature of LTP science is a tremendous strength, but it also places an implied obligation on LTP science to perform that science in regimes that will produce results that quickly convert to applications. An ever-present theme and challenge to LTP science is how to bridge the gap between science discoveries and technologies developed in the laboratory and products that benefit society. Laboratory developed technologies typically require a combination of advanced testing and predictive modeling to understand how they may perform beyond controlled laboratory environments. Two representative examples that highlight the critical challenges faced in implementing LTP technologies for electric propulsion and energy, material, life and agricultural science are highlighted below.

LTP for electric propulsion (EP):

- Challenges arise in the ground testing of thrusters—"facility effects." Thrusters in space emit plasma into nearly perfect vacuum, conditions that are difficult to replicate on Earth in large enough volumes and for long enough to conduct life testing.
- High-power, special purpose facilities can address some of the "facility effects." However improved understanding of EP physics would also enable alternative, cost-effective tests based on numerical models or accelerated wear tests. High fidelity, experimentally validated models are need to understand EP physics and mitigate life-limiting mechanisms.

LTP for energy, material, life and agricultural applications:

- While there are many different surfaces and structures that are treated with diverse goals and objectives, there is a common challenge. Little is understood about how to couple plasma source design and operation to specific applications for chemical, biological and material systems. Translating fundamental studies of particle distributions to activating a desired surface modality is at the forefront of LTP science.
- There remain significant theoretical and experimental challenges to understanding the correlation between a plasma treatment "dose" (the sum of all reactant species incident on the target) and the subsequent biological effect for biomedical applications.
- There are extreme challenges due to coupling of phenomena at vastly different time scales. For example, plasma-tissue or plasma-cell culture exposures usually last from seconds to minutes whereas the biological responses occur over minutes to days, or even longer in some cases. Similarly, plasma produced radicals in the gas phase evolve over much shorter times (microseconds to milliseconds) compared to surface catalytic reaction time scales in plasma catalysis (seconds to minutes). Plasma can induce liquid phase convection over similar long time scales, all of which impact plasma-liquid treatment.
- The central challenge in many of the proposed applications of LTP activated processes to energy, water, food and agriculture is in scaling. Even if plasma can be shown to be effective on small laboratory scales, the process must be scaled sufficiently to make it useful in an industrial setting, whether in the factory or the corporate farm. One exception might be plasma medicine applications since the focus is on safety rather than scale-up.
- It is highly likely that scale-up will take a modular approach—arrays of highly efficient plasma modules that are combined for higher throughput. The modular nature of the technology then enables off-grid point-of-use applications. These would be, for example, small farms or shops using locally generated solar or wind power.

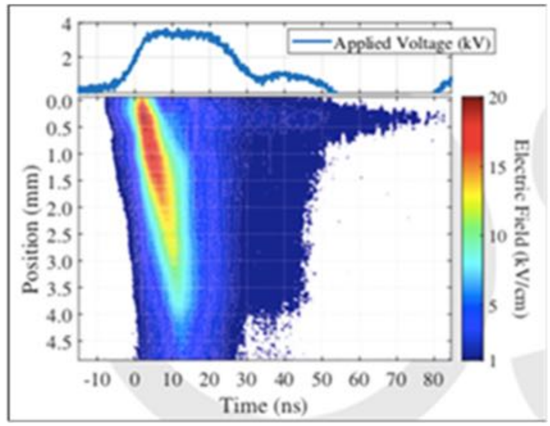


FIGURE 5.11 *Plasma diagnostics developments* – Diagnostics, critical to advancing LTP science, are particularly challenging in multi-species, chemically reacting environments. New diagnostics are being enabled by advancements in laser and detector capabilities. A recently implemented diagnostic, electric field induced second harmonic generation (EFISH), enables electric field measurements with sub-nanosecond resolution, and unlike previous methods, is nearly independent of the species in the plasma. The only requirement is that the gas has a reasonable polarizability and can be used in most high-pressure plasmas. The example shows 1-D measurements of an ionization front in a high pressure LTPs. SOURCE: Reprinted with permission from Goldberg et al., 1D time evolving electric field profile measurements with sub-ns resolution using the E-FISH method, Opt. Lett. 44:3853-3856 (2019), © The Optical Society.

- For many anticipated applications in medicine, and agriculture, the intended users (e.g. physicians and farmers) are unlikely to be trained in the complex field of LTP science and technology. This is particularly the case of off-grid point of use, but also true for medical professionals. There may be a need for LTP source autonomy where the plasma source is intelligent enough to adapt to changes in the surface being treated (every patient and plant is different), perhaps borrowing technologies from machine learning and artificial intelligence driven autonomous vehicles. The concept is 'one doctor, one button' or 'one farmer, one button.'

Diagnostic Development

Recent developments in LTP diagnostics have leveraged laser-based techniques to produce high spatial and temporally resolved measurements. Laser induced fluorescence (LIF) is a widely used diagnostic that can probe species-specific density and velocity distribution functions (VDFs). Since laser diagnostics typically involve the absorption and emission of photons, the collisional nature of most LTPs requires new insights into the consequences of collisions on the measurement. Close collaboration with the atomic, molecular and optics (AMO) community is needed to fully exploit these new laser diagnostics. New diagnostics have been developed based on femtosecond and picosecond pulsed lasers. These short timescale probes, only recently applied to atmospheric pressure collisionally dominated plasmas, can make measurements between collisions. These techniques hold great promise for future investigations. The implementation of Electric Field Induced Second Harmonic (EFISH) diagnostics has enabled, for the first time, measurement of electric fields in a plasma with sub-nanosecond time resolution (see Figure 5.11).

While traditionally reserved for higher temperature and density plasmas, recent advances in laser Thomson scattering (LTS) have opened the door to more extensive use of this diagnostic in low plasma density (e.g., plasma materials processing systems, EP) and atmospheric pressure LTP research. For more compact LTS setups, the use of volume Bragg gratings (in place of triple grating spectrometers) has been demonstrated. Development of laser-based techniques with improved spatial resolution that can be used near surfaces, remains a major challenge.

While the sophistication of experimental techniques continues to progress, there are several critical aspects of low pressure LTPs that to date have not been experimentally accessible. These include non-invasive measurements of high frequency (> 1 MHz), mid-wavelength plasma oscillations (e.g. the relationship between density and potential fluctuations). Direct, non-intrusive measurements of the most fundamental plasma properties (electron densities and temperatures, and electric fields) also continues to be challenging at atmospheric pressure. Extending diagnostics originally developed for low pressure (e.g., laser collisional induced fluorescence and microwave scattering) to higher pressures continue to hold great promise. At the same time, diagnostics that take advantage of high pressure should also be pursued.

The complexity of reactions and range of species in non-equilibrium molecular plasmas provide major challenges for diagnostics. A large variety of diagnostics are available including molecular beam mass spectrometry, LIF, laser scattering techniques, and a range of absorption techniques including broadband absorption, cavity ring down spectroscopy, tunable diode laser absorption. However, each of these diagnostics, powerful in their own right, have limitations on pressure, species, spatial resolution and timescale. Further developments to increase the capabilities of these techniques, and to broaden the types of species that can be measured, should be a key priority, together with exploring new approaches such as the recent development of frequency comb spectroscopy.

Diagnostics tools are available for material surface characterization and measuring active species in liquids. However, the majority of such diagnostics are focused on *ex situ* characterization. An increased understanding of the coupled physico-chemical processes at plasma-solid and plasma-liquid interfaces requires further development of *in situ* diagnostics amenable to a harsh and complex plasma environment. The development and implementation of new *in situ* diagnostics to probe changes in surface properties (solid, liquid and soft organic surfaces) and structure during plasma exposure is a critical priority for the

LTP field. This could be accomplished by developing new surface diagnostics or adapting, where possible, surface science techniques.

Modeling and Simulation

Predictive computational modeling capabilities are critically important in advancing LTP science and technologies. There are three main physics-based approaches employed to model LTP devices: fluid, particle kinetic and grid-based direct kinetic methods. Hybrid models, where fluid and kinetic methods are combined for different species and conditions, are also widely used. Despite significant advances in the field in the past decade, modeling LTP remains challenging due to the multi-physics and multi-scale nature of the discharge phenomena.

While fluid models are inherently computationally less expensive, they have limited capability in representing the detailed aspects of kinetic-based processes. Examples include instabilities found in E×B devices, turbulence in low pressure systems, the dynamics of double-layers and in high electric field regions as in sheaths and near ionization fronts of atmospheric pressure streamers. The challenge for these models is to develop time-dependent, physics-based equations and closures that account for these kinetic effects. For kinetic models, which in principle have the highest fidelity, computational time is a major limitation. For example, current simulations are limited at best to two-dimensional phenomena up to a few tens of microseconds using explicit particle methods. This is too short with insufficient dimensional fidelity to resolve or understand, for example, interplay between collisionless phenomena (beam-bulk instabilities) and three-dimensional collisional phenomena (e.g. plasma wall interactions and intermolecular collisions). Three-dimensional models have been increasingly exploited in the last few years to tackle the intrinsic 3D phenomena of self-organization and inhomogeneous nature of atmospheric pressure plasmas (see example in Figure 5.12).

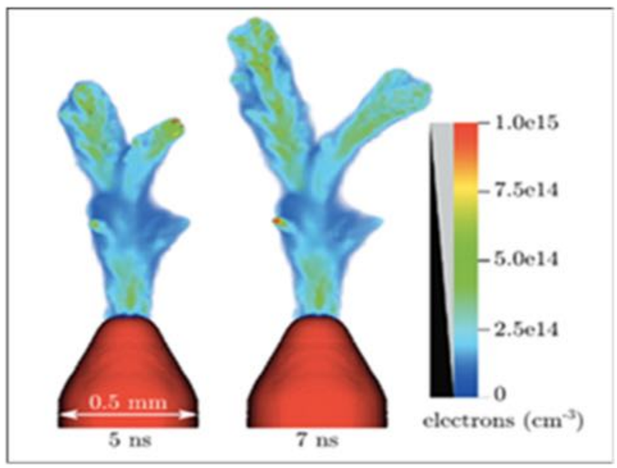


FIGURE 5.12 *Three-Dimensional LTP Simulations.* Simulation of LTPs is typically highly computational expensive and the majority of simulations to date have been performed by 0, 1 or 2D models. In the last decade, 3D simulations have been developed to address many important intrinsically multidimensional phenomena in LTPs. The figure shows an example of a 3D particle-in-cell Monte Carlo collision model with adaptive mesh refinement of the inception of a nanosecond pulsed atmospheric discharge near an electrode. This approach is able to address the highly irregular and inhomogeneous discharge inception – often called branching. SOURCE: Jannis Teunissen and Ute Ebert 2016 Plasma Sources Sci. Technol. 25 044005.

The ultimate LTP challenge is achieving predictive control of the plasma activated chemical processes. This is particularly complex due to the sensitive two-way coupling between the electron energy distribution (EED) and the gas composition, including the species produced through collision processes. Given the translational nature of LTP research, models are required that are fully fundamentally physics based, but also have the robustness to be used for design and optimization of devices. For example, complex plasma chemistries may include a hundred individual gas phase species (ions and neutrals), a thousand reactions, and similar complexity in plasma-surface interactions needing resolution from microns to tens of cm. High-performance computing is required for

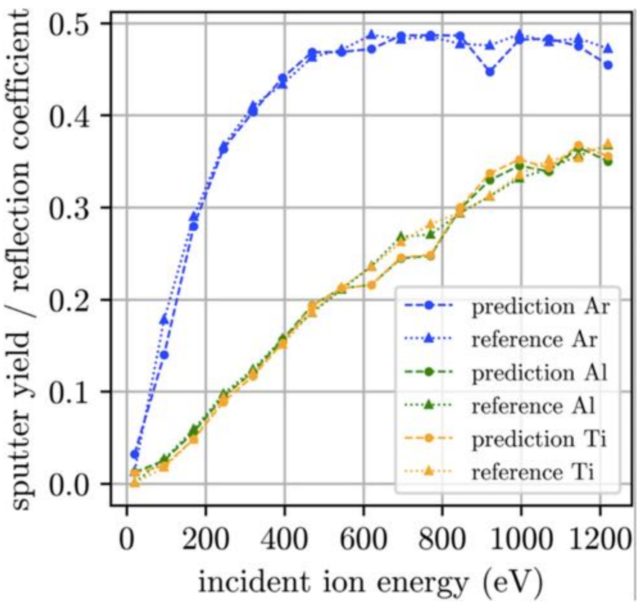


FIGURE 5.13 *Machine learning in LTP* – Big data and machine learning are now emerging in LTP science. Supervised learning might provide unique capabilities for LTPs in process control. The image shows an example of machine learning enabling the construction of computationally efficient surrogate models for thin film deposition produced by ion sputtering of a surface. The algorithms predict sputtered particle distributions (yield Al/Ti and reflection coefficients Ar) for unknown, arbitrary shaped ion energy distributions in multi-scale modeling of plasma-surface interactions across multiple length- and time-scales. SOURCE: Plasma Sources Sci. Technol. 28 (2019), https://doi.org/10.1088/1361-6595/ab0246.

models that contain the needed physics and reaction complexity while also representing the geometries of interest for LTPs on timescales of interest.

Significant progress has been made in plasma-surface interaction modeling for both non-thermal and thermal plasmas. Nonetheless comprehensive models with a two-way coupling of non-equilibrium plasma kinetics in plasmas intersecting with complex interfaces such as liquids, including evaporation, charging, deformation, liquid interface dynamics and liquid phase convection, continue to be a challenge. While models of thermal plasmas have made major progress in the last few years, such as that gained in the detailed understanding of the influence of metal vapor in welding arcs, for example, no self-consistent physically based models of arc-electrode interaction exist for many situations of practical interest. Similarly, models that resolve nano-scale features at plasma interfaces and evaluate their impact on the plasma properties have yet to be fully developed. In large part, these challenges are due to the enormous range of coupled length scales and timescales that must be included in such comprehensive models.

Developing standards for verification, validation, and benchmarking of new and existing models will continue to be extremely important. Validation of models and reaction sets is increasingly important as a comprehensive understanding of LTP phenomena requires coupling diagnostics with validated models. The development of validated predictive capabilities requires a large team and long-term efforts that are currently not in place for the U.S. LTP community. Such efforts to date have focused mainly on gas phase kinetics. Model validation including interaction of LTPs with interfaces has yet to be systematically addressed. Chemical reaction sets are, in some cases, available for both gas and liquid phase plasma models. However, plasma-surface interaction models generally do not match the rigor associated with models of multiphase phenomena characteristic in fields such as atmospheric aerosol models. Descriptions of plasma-surface interactions developed for low-pressure etching and deposition plasmas will need to be extended and adapted to include important processes relevant for a broader class of material properties and plasma conditions.

The purpose of modeling is to better understand the current state of experiments and to predict well beyond the current state of the art—new systems, new excitations schemes, new configurations, new applications, new physic for which experimental data for validation might not exist. The required precision for computationally analyzing well characterized benchmarking experiments is greater than the precision required for exploratory, first of their kind simulations beyond the current state of the art.

Data Science, Machine Learning, and Artificial Intelligence

Machine learning (ML) is a branch of artificial intelligence (AI) that seeks to find patterns from statistical or probabilistic analysis of large amounts of data. ML is attractive for multiple applications in not LTP but in all systems involving plasma. ML involves training a computer algorithm to predict the behavior of a complex system by collecting many examples of input-output behavior. ML methods can be significantly simpler than using exclusively physics-based models. Fundamentals of ML were developed over the last several decades, but only recently has it become practical to obtain and analyze the enormous quantities of data needed for the schemes to work. Learning-based control approaches can potentially transform LTP control, enhancing plasma reliability, flexibility, and effectiveness. ML has already had a large impact for HVM (high volume manufacturing) using plasma processing in the semiconductor industry where very large datasets are available. However, in laboratory scale experimental LTP, in most cases, ML will not have true "big data" to work with. The data sets will be relatively small and incomplete. For big data approach to be useful in LTP, it should be well coupled with our prior knowledge of underlying physics and chemistry—that is, physics or algorithmically based ML. This is a new unique challenge for the LTP field.

Even with its challenges, ML holds the promise to transform LTP modeling, diagnostics, and control. ML and AI could lead to the development of self-aware and self-correcting LTP systems, as will likely be needed in LTP applications where the target varies from case to case (e.g., medicine, biotechnology, agriculture). ML is rapidly expanding into many novel applications, typically driven by practical applications. It is expected that LTP will be not be an exception in the next decade. However, LTP applications are unique challenges to ML methods due in part to the intrinsically strong non-linear coupling of multiple parameters for most LTP systems and processes.

FUTURE OPPORTUNITIES IN LTP SCIENCE—STRATEGIC CHALLENGES

Given the great diversity of science areas and applications in LTPs, future opportunities that cross the area may best be expressed in terms of high-level Strategic Challenges. Here are four strategic challenges that, while not exhaustive, encompass the breadth of the field.

Developing Plasma-Based Tools for Future Health Care and Food Cycle Needs

LTP is a unique state of matter with characteristics that have, until recently, been exploited mainly for non-living materials processing and chemical applications. Recent advances have shown that LTP can be used to decontaminate both inanimate and living material surfaces through a range of physico-chemical mechanisms. LTP has demonstrated human therapeutic benefits for applications that include promoting wound healing and cancer treatment. The fact that LTP can influence biological systems through multiple pathways and mechanisms suggests LTP can be used for many different biological applications as well.

For example, over the last several decades, antimicrobial resistance (AR) has reached nearly crisis proportions. (AR is where microbes, bacteria and viruses, become immune to drugs, rendering those drugs ineffective or useless for treating infections.) All reports indicate that AR will continue to become more severe for the foreseeable future. It is well known that the development of systemic antimicrobial drugs has slowed down and some knowledgeable observers predict a *post-antimicrobial world* where drugs are no longer effective against major infections. Plasma disinfection and sterilization tools would certainly not solve all problems associated with AR, but they could be powerful tools in localized, resistance-free, selective disinfection devices. Many bacterial infections in humans and on medical devices occur in the form of biofilms. The highlight in Figure 5.14 illustrates one field of active research in applying LTP to biofilms.

There are many other potential LTP applications in healthcare. LTP has been shown to stimulate immune systems in animal models, promising for many medical conditions. A relatively unexplored area is use of LTP devices for cosmetics applications and skin treatment. The field of LTP therapeutics is just beginning to indicate its potential.

Promising LTP applications in agriculture could greatly impact the food cycle, from plant growth to food safety. Food, food system, and water disinfection are possible applications of LTP, although costs and scaling issues represent additional challenges. Other potential applications would use LTP to reduce or minimize the use of pesticides or herbicides.

The field of 'bioprocessing' in which biological processes are conducted on a large scale to create or alter some chemical species, could benefit from LTP treatment or enhancement. Recent advances include using LTP to treat organic waste to improve its fertilizer characteristics. This technique uses the plume from air plasma interacting with biologically decomposing waste in bioreactors. This concept could be extended to other bioprocesses.

In each of the potential applications listed above, there is are corresponding challenges, opportunities and need to expand and extend LTP science.

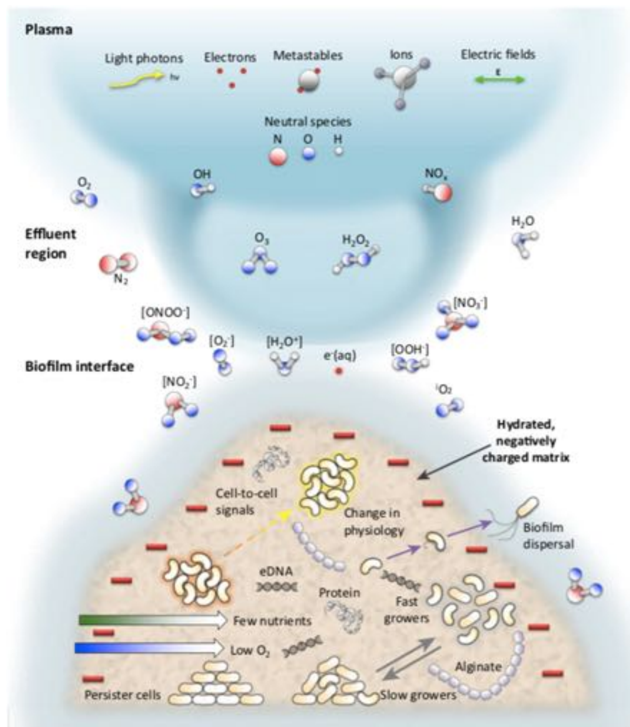


FIGURE 5.14 *Plasma-biofilm interaction* – A biofilm is a community of microorganisms attached to a living or inanimate substrate and are the dominant mode of growth of bacteria. The majority of chronic human bacterial infections are caused by bacterial biofilms. The methicillin-resistant S. aureus (MRSA) bacteria forms biofilms and is one of the most common source of biofilm-associated infections. Plasma has been shown to effectively inactivate biofilms including MRSA. The figure illustrates the active plasma components possibly involved in the inactivation and the complex structure of the biofilm. The interface between the multi-component plasma and the biological interface which has an order of magnitude higher complexity than traditional plasma-solid interactions provide profound intellectual challenges for the field. SOURCE: B.F. Gilmore et al., Cold plasmas for biofilm control: Opportunities and challenges, Trends in Biotechnology, 36(6):627 – 638, https://www.cell.com/trends/biotechnology/fulltext/S0167-7799(18)30091-X.

Challenge 1: Controlling plasma-surface interactions at the atomic level to enable the next generation of materials for quantum computing, new communication, sensor, energy storage and harvesting technologies.

Advances in plasma-materials processing are challenged by the need to choose operating conditions and plasma devices from and enormous parameter space. There is a serious need for a more detailed understanding of the fundamental processes underpinning plasma-surface interactions to enable us to develop predictive modeling capabilities. A huge victory would be predictive modeling that can a priori specify the optimum operating conditions and plasma device architectures. From practical perspective, having modeling reduces the enormous parameter space would enable more productive experiments. The implementation of advanced plasma materials processing may require advanced control schemes, which in turn require better control-oriented mathematical models as well as better *in-situ*, real time plasma diagnostics that are compatible with ultra-clean processing. This offers also opportunities for ML techniques. Major opportunities in plasma materials processing include controlling surface texture at the nanometer scale and controlling interfaces between atomically defined material layers.

Many novel opportunities will no doubt present themselves as the semiconductor integrated circuit device industry continues to grow. Advances in device architectures are now exploiting the 3rd dimension, increasing capability with layers of layers of devices. Memory devices now under development use 256–512 layers each of which need to be deposited followed by etching with aspect ratios (height to width ratio) of on the order of 200. These are major plasma processing challenges.

One example in this area of forward-looking research needs involves *post-silicon materials*. Many post-silicon materials will consist only of a single atomic layer (e.g., 2D materials) or require atomic level precision in their processing. It is clear that plasma etching and deposition of post-silicon materials presents challenges much different than those encountered for silicon. These challenges in turn pose new plasma science questions, including unprecedented control of ion energies (<10 eV) near the chemical sputtering threshold. Precursor gases for post-silicon materials processing are much more complex than in silicon processing. Properties of atomically thin post-silicon materials will be crucially affected by defects created by the interactions of plasma ions, radicals, and photons. Plasma-surface interaction control will be paramount for defect-free plasma processing of post-silicon materials. Achieving atomic-scale control over surfaces and structures for multiple new materials and devices requires a significant increase in understanding of plasma-surface interaction mechanisms and the development of advanced diagnostics and predictive modeling.

Challenge 2: Electrification of the chemical industry based on renewable electricity to enable a sustainable society.

LTP science could be crucially important to enable the vision of a future based on renewable electricity. In this vision, electrification of the chemical industry utilizing plasma will convert electricity into chemical transformation in an environmentally friendly way. The key enabling science will be controlling the flow of energy through LTPs to produce predictable chemical transformations in gases, on solids, and in liquids. Liquid phase electrochemistry and photochemistry - both utilizing catalysis - are generally thought to be the only ways to directly convert electricity into chemical transformation. However, plasma acts as gas-phase electrochemistry, a capability that has been greatly underutilized. Renewable energy sources such as solar, wind, water and hopefully fusion energy will continue to lead to a more abundant availability of cheap electricity that will gradually lead to the electrification of the chemical industry.

In addition to energy costs, the other major challenge with using plasma for large scale chemical conversion is lack of selectivity. Plasma tends to create a wide range of different products with a limited ability to control which are created. One obvious strategy to improve plasma chemical selectivity is to combine plasma with catalysis, a topic addressed in the example in Figure 5.15.

The trend towards chemical industry electrification will coincide with a gradual replacement of chemical feedstocks that originate from fossil fuels to feedstocks produced from renewably sourced raw materials such as biomaterials. The challenge to developing this potential application of LTP is to better understand and control the flow of energy from the electrical power supply to the catalytic surface through key intermediate chemical species. This challenge will require detailed studies to enhance our current understanding of kinetic and collisional processes, plasma self-organization, transport and plasma-surface interactions under highly non-equilibrium conditions. Only an improved fundamental understanding of plasma-chemical species-surface dynamics will make this possible.

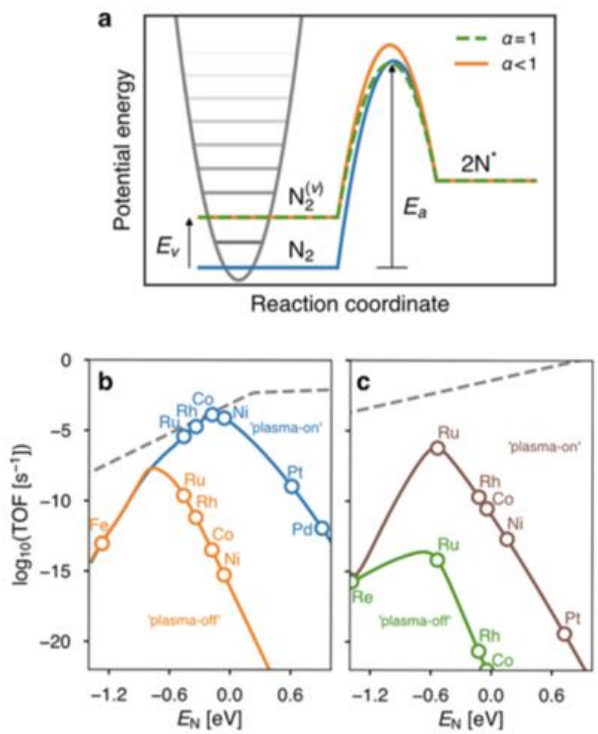


FIGURE 5.15 *Plasma catalysis* – Plasma catalysis provides possible new exciting opportunities for selective and enhanced chemical transformations, however, the underlying mechanisms are not clear. The figure illustrates the anticipated effect of vibrational excitation as one of the possible sources of catalytic enhancement by plasmas. The upper figure shows a reduction of the energy barrier by vibrational excitation. The lower figures shows the enhancement of catalytic site-specific rates by several orders of magnitude over thermal rates as obtained by calculations. The development of an in depth understanding of all possible plasma-induced enhancement mechanisms and their relative importance is of key importance for further progress in this field. SOURCE: Mehta, P., Barboun, P., Herrera, F.A. et al. Overcoming ammonia synthesis scaling relations with plasma-enabled catalysis. Nat Catal 1, 269–275 (2018), https://doi.org/10.1038/s41929-018-0045-1.

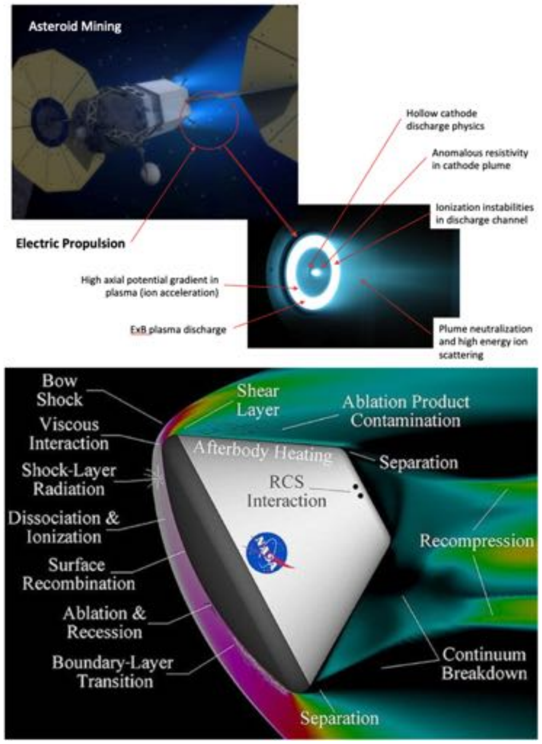


FIGURE 5.16 *Plasma Physics Enabling Space Missions* – Electric thrusters greatly expand our ability to propel spacecraft through the solar system. Missions are planned for probes and manned missions using high power Hall thrusters (HT) to deliver more mass in a shorter period of time than conventional systems. HT use a cross field E×B plasma to ionize and accelerate gaseous propellant. When spacecraft re-enter the atmosphere at hypersonic speeds, an enveloping plasma produces a complex chemically reacting LTP. Detailed modeling and experiments are needed to better understand HTs and to provide guidance for scaling to high powers and lifetimes, and to better understand the interaction of hypersonic vehicles and plasmas. SOURCE: NASA/JPL.

Challenge 3: Enabling space exploration and safeguarding communication infrastructure

Low temperature plasma physics research is crucially important to the future of propulsion used for electric rockets, for in-space propulsion on communications satellites, for NASA science missions, and for the development of advanced electric propulsion (EP) systems that are emerging as a critically needed component of human space flight to the moon and Mars. Industry projections suggest that half of all commercial spacecraft in the next 10 years will have EP onboard. Plasma-based thrusters are highly efficient and can reduce propellant fuel requirements by one to two orders of magnitude over chemical propulsion. This is critically important for commercial applications, and will likely be enabling for human exploration missions that require the transport of large amounts of cargo and even people through space. Fundamental plasma physics investigations on electric thrusters are essential to improve the thruster performance and increase the lifetime. An example of key plasma science challenges linked to Hall thrusters is illustrated in Figure 5.16.

LTP SCIENCE FROM AN INTERNATIONAL PERSPECTIVE

Due to the breadth of applications enabled by low temperature plasmas, there is a diverse international community of researchers. To assess the state of international research, this committee reached out to research leaders in LTP science around the world to solicit their input on their own programs and to provide their opinions on the state of the U.S. LTP program. Since this is not a fully comprehensive survey, the committee has limited the reporting of specific numerical data. Nonetheless, the committee believe that there is a level of consistency among the responses that allows us to make reasonably informed statements about the state of international LTP research.

Distribution of Worldwide Effort in Low-Temperature Plasmas

Much of worldwide research and technology development in LTP is concentrated in Europe and Asia. From Europe, the committee received input on the status of LTP research in Germany, Belgium, France and the Netherlands. From Asia, the committee received input from South Korea, Japan, and China. Among the white papers submitted to this study, the authorship included researchers from France, Germany, India, Italy, Mexico, Slovakia, Spain, United Kingdom, and Ukraine. Research topics mentioned by these researchers match many of the topics that are being pursued in the United States. In those nations with reasonably mature LTP research activities, governments generally provide support for both translational research activities and to support new initiatives, for example, the recent expansion into plasma agriculture. A key difference between the United States and several other countries is that LTP research in U.S. institutions is often based on single-PI activities. By contrast, countries such as Germany, the Netherlands, France and China have clusters of faculty or tenured researchers forming research teams and group.

Self-Assessment of International Research Activities

In Europe, the LTP community is very active, but the level of activity varies among the different countries. Across Europe, the total number of researchers involved in LTP research activities seems to have remained relatively constant in the last 10 years with fluctuations across the different countries: Germany reports relatively stable numbers, while the Netherlands is experiencing a slight increase, but France and Belgium are possibly experiencing a slight decrease. According to our data sources, funding is generally provided via two mechanisms—by national governments and the European Union—but the majority of the funding generally is at the national level. Because of differences in how funding is provided, it is difficult to assess precisely how much research funding is devoted to LTP research. Estimates from European colleagues suggest tens of millions of Euros per year are being provided to support research in LTP active countries. On a per-capita basis, this would appear to be substantially larger than the funding provided by U.S. funding agencies to support LTP research. It should be noted that some countries—notably Germany, France, and the Netherlands—have active programs from government-based Ministries that promote “translational” activities to bring technologies from universities to industry. Many of these are in the form of center-like activities that include European training and networking grants with multi-year programs that advance a particular topic and stimulate multi-institutional collaborations. Regardless of the mechanism, in Europe, it is reported that there has been a substantial conversion of LTP research into new companies.

In Asia, the state of LTP research is more complex. The major programs in this area are based in South Korea and Japan, but China is emerging rapidly as a significant competitor, as are developing programs in Singapore and Taiwan. State support of LTP research varies widely among these locations. In South Korea and in Japan, where the application of LTP technologies is a large and significant industrial driver, both nations provide active support for LTP research, reportedly ~$10 million per year. In both of these countries, state-sponsored funding is available to support translational activities that bring university and national laboratory ideas to the marketplace. Although much more difficult to quantify, China heavily invests in translational LTP research.

In comparison to overseas investments, U.S. industrial leaders specifically cite the Chinese *National Guideline for the Development and Promotion of the IC Industry*. The goal of this program is to develop Chinese capabilities in wafer equipment processing to support China's burgeoning IC device manufacturing industry, and large component of which is plasma equipment. There is nothing analogous in the United States. China is not alone in support of this critical industry. In South Korea, the government funds major university research partnerships with large companies such as Samsung and SK Hynix, both major IC manufacturers. Other governments around the world have clearly recognized the need to fund enabling and breakthrough technology for plasma-based wafer equipment processing. However, the United States significantly lags in this regard.

U.S. Research Activities in LTP in the Context of the World Program

Data shows that over the last decade, the U.S. publication rate (as a percentage of first authorship) has generally remained stable around 25% in a selection of journals publishing LTP research, including the *Journal of Applied Physics*, *Plasma Sources Science and Technology*, and *Journal of Physics D: Applied Physics*. Nonetheless, the submission of papers from Asia and particularly China is growing and although no exact data is made available, Chinese contributions dominate the LTP section of *Physics of Plasmas*.

Europe, Japan, and South Korea are already making significant investments at the national level to advance their LTP industries. China and India are poised to advance their own LTP research and industries. In areas, such as plasma medicine, the United States has fallen behind its competitors in both basic and applied studies due to a lack of substantial and stable funding. This situation is in stark contrast to Germany, The Netherlands, France, Belgium, Italy, Japan, and South Korea, who have had and continue to have major initiatives in these areas. In newly emergent areas, such as plasma agriculture, there are already substantial international investments and the United States is in danger of falling behind in this area as well.

Importance of the United States to Current International Collaborations

Many informal collaborations between U.S.-based researchers and their European and Asian colleagues exist. This is reflected in the significant number of co-authored peer reviewed articles of U.S. researchers with European or Asian colleagues. However, these are often one-on-one collaborations and, in many cases, no structural (i.e. agency-related) funding is available. This is in contrast to the highly collaborative international research facilitated by the EU, as well as several formal 1-on-1 international collaborations (e.g., Russia-France, Japan-Australia). Many leading research groups in the United States often host international scholars from both Asia and Europe as visiting researchers however even those visits are now being limited by visa restrictions and universities imposing fees to cover federally mandated security investigations. The U.S. LTP community has benefited considerably from the existing, limited, degree of international collaboration. However, the U.S. LTP community could greatly benefit from increased interactions with their European and Asian counterparts.

Given that LTP science is closely linked to applications, many potential international collaborations are restricted by ITAR (International Traffic in Arms Regulations) considerations. This is particularly the case in electric propulsion. The committee respects the need for national security oversight of international collaborations. However, a review and update of ITAR classifications would benefit international collaborations and also benefit U.S. science.

FACILITIES, MAJOR INSTRUMENTATION, MAJOR PROGRAMS

The last decade of research in low temperature plasmas has seen significant technological advances in the various ways in which LTP is produced. At the start of the decade, the majority of the research and applications were performed in low-pressure vacuum systems in highly controlled environments and most applications at atmospheric pressure involved high temperatures (e.g., arcs). This has rapidly evolved over the last decade with the development of non-equilibrium atmospheric pressure plasma sources that aim to produce large volumes of plasma without a vacuum chamber. A further development has seen the shift of research in LTP processing from semiconductor materials to “soft” materials such as liquids, biomaterials, and even agricultural products. This evolution in the operating conditions has necessitated the development of a new generation of complex diagnostics that require unprecedented time and spatial resolution to resolve exceptionally large gradients and changes in plasma properties.

The vast majority of laboratory facilities for the study of low pressure to atmospheric pressure LTPs are in the *tabletop* scale of devices—often surrounded by a suite of advanced diagnostic tools. The major investments for a typical LTP laboratory are often complex power supplies including nanosecond pulsed power capabilities and modulated multi-frequency RF plasma sources, coupled with various probe, optical, surface and mass spectrometry-based diagnostics. Within the United States, each laboratory is effectively an independent facility that is generally responsible for its own development of plasma sources and plasma diagnostic tools. While the last decade has seen some sharing of resources among researchers, the operation of individual laboratory facilities remains the dominant research model. This model provides an excellent training ground for students and seamlessly integrates with the LTP practices in industry.

While LTP facilities are focused on small-scale experiments, the facilities needed for LTPs applied to space systems can be very different. LTPs for in-space propulsion requires facilities on the ground that simulate the space environment in with the electric propulsion (EP) device will actually operate in. These facilities have vacuum vessels capable of reaching low enough pressures to relevant to space research and large enough to contain the EP device and its plasma plume, while also having the appropriate diagnostics. These facilities are scattered throughout the United States at NASA and Air Force facilities, universities, and commercial companies, and internationally at locations in Europe, Asia and Russia. Unfortunately, these large facilities are barrier to entry to the EP due to the high capital and operating costs. This has driven many companies and universities to investigate smaller thrusters with smaller facility needs. Investments over many years to install and upgrade test facilities for higher pumping speeds and higher power levels are typically made to achieve the desired capabilities. As EP power levels increase, especially to support human exploration missions, large pumping and power upgrades, and new larger facilities, will need to be brought online.

Needs and Opportunities

Most of the U.S. LTP research community does not utilize the kind of centralized facilities that are more common in other areas of plasma physics—facilities that are few in number, high in cost, and take years to plan and build. LTP facilities are much more commonly associated with individual PIs, typically in universities, but also at a few National Laboratories (e.g. Sandia National Laboratory in Albuquerque (SNLA) and Princeton Plasma Physics Laboratory (PPPL)). There has been some discussion within the U.S. LTP community of establishing a federally funded user facility with plasma-, surface- and materials-related instrumentation. By coupling plasma and plasma-surface interaction investigations, an opportunity for new fundamental knowledge would be created. One challenge is that the widely different applications of LTP require significant differences in facilities, instruments, and associated expertise in personnel. For example, low pressure plasma studies suitable for semiconductor-related studies would be quite different from atmospheric pressure plasma interactions with biological cells in liquid medium. Nevertheless, this potentially attractive option should receive further examination and discussion. At the time of writing this report, the DOE Office of Fusion Energy Sciences established two modest LTP user facilities at SNLA and PPPL to pilot the concept and gauge use response. The results of these pilot operations will be used in future facility funding decisions.

International collaborations

There appear to be no significant, federally funded international collaborations at present involving U.S. LTP researchers.

RELATION OF LTP TO INDUSTRY

LTP science and technology has been of significant industrial importance for more than 150 years. In the section, the committee focus on the role of LTPS in the manufacture of integrated circuits (ICs) and semiconductor devices. This focus is an example to highlight the LTP relation to industry, with the lessons and outcomes being relevant to other industries as well.

The IC industry plays a key role in the U.S. economy and national security as described above. Advanced ICs are essential for defense systems, computers and phones. Cloud computing is growing. Applications in artificial intelligence (AI) are growing rapidly, especially for autonomous vehicles, web commerce sites and numerous commercial and industrial applications. These future technologies will depend on ICs and the technology to manufacture them. U.S. plasma technology industry leaders express concern regarding federal U.S. research funding relevant plasma processes for semiconductors. Many federal initiatives include DoD's quantum computing, DARPA's electronics resurgence, and DOE's Exascale computing project, with a budget of $4 billion spread over 5 years, critically depend on ICs without there being commensurate investments in the plasma processing required to produce those ICs.

Future IC device technologies will depend more than ever on plasma-based processing. The IC industry needs advances in LTP science to meet their diverse and extreme challenges, demanding a deeper understanding of the physics, chemistry and materials-modifying characteristics of LTP used in IC manufacturing as described above.

The opportunities and benefits of closer connection between the LTP research community and industry are clear. By investigating in the complex underlying plasma science and establishing basic scientific principles, these insights and associated experimental and modeling tools can be translated into industrial practice.

In LTP applications to IC manufacture, one possible suggested strategy is to establish technology incubators to fund collaborative ventures comprising academia, start-ups, and an established company to enable translational research and eventual commercialization of innovations. Such a program would focus on applications of LTP to semiconductors with a goal of developing breakthroughs on a 5-10 year timescale. The federal funding would focus on fundamental research and disruptive breakthroughs that can be transferred quickly to industry. The established companies would support the more translational and applied areas of research. In this vision, research in commercial applications of LTP will encourage U.S. leadership in this crucially important LTP enabled technology. Strengthening university-based research in this area by sponsoring graduate students will simultaneously contribute to the development of the highly skilled workforce needed for that industry as well.

FINDINGS AND RECOMMENDATIONS

The science of chemically reactive environments in gases, on surfaces and in liquids has already made society-wide transformations in our quality of life—from lighting, materials synthesis and water purification, to enabling the information technology revolution through plasma-enabled fabrication. The strong track record of low temperature plasma research impacting a broad range of applications demonstrates exceptional interdisciplinary and translational success. The research performed in the LTP field overlaps with physics, chemistry, propulsion, energy and materials, with recent extension to biology, agriculture and medicine. U.S. funding agencies have not embraced this trend, which has led to a loss of U.S. leadership in some specific areas of LTP. For example, U.S. researchers led the field of plasma medicine at its birth more than a decade ago. However, in the last few years, the U.S. leading position has been overtaken by researchers in Europe and Asia. A similar situation is now occurring in plasma chemical conversion and plasma catalysis.

The extremely successful Low Temperature Plasma Science Center program supported by the DOE Office of Fusion Energy Science has had a tremendous impact.

> **Finding:** The success of the DOE Low Temperature Plasma Science Center program underlines that there is a need to sustain LTP research directions for a sufficient period of time (5 to 10 years) and size with support on the level of ~$2 million per year to enable scientific impact and translation of research into society benefiting applications.

> **Finding:** The increasing scope of the LTP field into new materials and biotechnology requires full participation of researchers that are traditionally funded by different agencies not focused on plasma science. This is particularly the case for electrification of the chemical industry.

> **Finding:** U.S. funding agencies are often ill prepared to support initiatives that overlap multiple agencies and should actively pursue synergistic opportunities between agencies to maintain U.S. leadership in LTP in line with the recommendation in Chapter 1.

Recommendation: DOE-FES should establish and coordinate a multi-agency Low Temperature Plasma Science Center Program to support multidisciplinary research teams and to establish the scientific basis of emerging application areas of low temperature plasma science.

Finding: Based on the funding level for the LTP science center program, a possible minimum level of support of $20 million over 5 to 10 years for each topical initiative would be appropriate.

An example of a first initiative could be LTPs aimed at the electrification of the chemical industry and associated sustainability initiatives overlapping with research priorities of ONR, ARPA-E, DOE and NSF.

Finding: Advances in plasma-materials processing are challenged by the need to choose operating and plasma device designs from the enormous set of possible operating and design conditions.

Finding: There is a serious need for a more detailed understanding of the fundamental processes underpinning plasma-surface interactions that will enable us to develop predictive capabilities.

Finding: Advances in our understanding of LTP interactions with materials will enable the control of plasma-surface interactions at the atomic level which in turn will enable the next generation of materials for quantum computing, new communication and sensor technologies, and energy storage and harvesting.

Recommendation: DOE-FES and DOE-BES should develop a synergistic collaborative program to focus on the intersection of plasma and materials.

In addition to FES and BES, initiatives could be coordinated and funded between plasma-focused and materials-focused programs in federal agencies that would lead to advances in the science and technology of both fields.

Industry support could also be leveraged to stimulate fundamental research through public - private partnerships e.g. with the semiconductor industry. This public-private partnership could take the form of the federal government supporting more fundamental interdisciplinary research and industry co-funding more translational research.

Finding: The fundamental research performed in LTP is intrinsically interdisciplinary with societal benefits occurring most rapidly when that fundamental research is guided by applications.

Finding: Although the NSF/DOE Partnership in Basic Plasma Science and Engineering is a strong supporter of LTP research, the translational and convergent nature of LTP research often transcends the scope of the NSF/DOE partnership.

Finding: Support for translational and convergent research in LTP by the NSF Engineering directorate has not been consistent, has not been long term and has not kept pace with the opportunities described in this report. Deliberate actions are needed to empower these interdisciplinary opportunities.

An additional level of support of $3 million per year for fundamental research in LTP, similar to the current support from the NSF/DOE partnership, coupled with a similar budget from the application areas, would enable collaborations between, for example, biologists and plasma physicist. These collaborations would produce convergent research and translational research opportunities.

Recommendation: NSF-MPS and NSF-ENG and funded at a level of $6 million per year, should establish interdisciplinary and inter-directorate support for emerging LTP science topics that lead to translational research.

The rationale for this funding level is to enable a critical number of projects focusing on a breadth of application areas, while including researchers from the allied sciences who are critical to translational success.

The establishment of the Low Temperature Plasma Science Center program at DOE since the 2010 Decadal study has benefited fundamental LTP research.

> **Finding:** Continuing initiatives like the DOE Low Temperature Plasma Science Center program will help sustain an internationally competitive LTP community in the United States.

> **Finding:** LTP research at U.S. universities remains highly dispersed and it is not uncommon to find only one faculty member involved in LTP research in an entire university. This situation underlines the need for research networks and student training opportunities.

One model is provided by the European Union. The EU has invested heavily in research networks (e.g., *COST Action* programs) and collaborative research training programs (e.g., *Marie-Skłodowska-Curie Innovative Training Network*). Enhanced support to enable mobility of promising early-career researchers between different laboratories in the United States and abroad would be extremely valuable for the field. These initiatives initiate and encourage large-scale collaborative efforts and develop and strengthen emerging research areas.

> **Finding:** There are no multi-institutional, networking programs in the United States focused on LTPs. Training of a new generation of scientists in fundamental LTP science, including diagnostics and modeling, is a critical need for the coming 10 years, and would benefit from such programs.

> **Finding:** Many U.S. PhD students working in the LTP field are trained with an exclusively application perspective. To sustain the field, more fundamental LTP science training opportunities for early career researchers are needed.

Taking the EU again as an example, the annual International Low Temperature Plasma Physics school has provided effective training for the next generation of PhD students in LTP science. There is no long-term support for such an initiative in the United States.

> **Recommendation: NSF should support LTP research networks in the United States by providing funding for graduate students and postdoctoral researchers to participate in exchanges between U.S. universities, and for international research experiences for junior scientists.**

> **Finding:** Fundamental research in LTP has declined in the United States over the last decade.

There is a concern that if this trend continues foundational research in LTP will, with a few exceptions, disappear from the United States.

> **Finding:** The demographics in the LTP field show that the leadership class will retire within the next decade with an insufficient number of early career faculty available to assume leadership positions.

LTP research is multidisciplinary and the model for hiring university faculty in multidisciplinary fields has produced too few early career faculty with a focus on the fundamentals of LTP science.

> **Finding:** There are currently too few early career LTP-oriented faculty in the United States. The hiring of faculty within universities in the 21st century needs to be viewed from an interdisciplinary perspective that recognizes the intellectual diversity of a field that spans multiple colleges and departments and would benefit from investment by federal agencies.

Recommendation: To strengthen LTP research at universities, NSF and DOE should establish specific programs that fund the creation of faculty positions similar to the NSF Faculty Development in Space Sciences program to address the urgency of losing key expertise and leadership in low temperature plasma science over the next decade.

Finding: The vast majority of laboratories for the study of low temperature plasmas consist of tabletop scale devices—often surrounded by a suite of diagnostic tools.

While the last decade has seen some sharing of resources among researchers and use of national facilities (e.g., synchrotron sources for VUV diagnostics), the operation of individual laboratory facilities remains the dominant research model. Because of the cost and technical expertise associated with advanced LTP diagnostic development, there have been discussions about the need for a centralized set of diagnostic tools for the LTP community. That discussion is ongoing and is being put to the test with the recent establishment of two LTP user facilities.

Finding: Based on its established track record, it is clear that the LTP community does not generally require nor is there demand for large, single purpose centralized user facilities having a single plasma source to make societal impact.

Finding: Leveraging the flexibility and interdisciplinarity of individual laboratories should be considered a valuable asset of LTP community, rather than comparing that style of research to large facilities in other areas of plasma science and declaring that mode of operation a weakness.

Finding: There is a need to support the flexibility and interdisciplinarity of individual LTP laboratories perhaps through a mix of user facilities concentrating on diagnostics and improving diagnostic and source capabilities in individual laboratories that could form a distributed user facility.

Recommendation: NSF and DOE should expand opportunities to develop and acquire diagnostics, plasma sources, numerical models and reaction mechanisms in support of low temperature plasmas science, perhaps through the NSF/DOE Partnership in Basic Plasma Science.

This effort could be configured similarly to LasernetUS, with support for both equipment and use of the diagnostics, sources, numerical codes and reaction mechanisms.

6

Magnetic Confinement Fusion Energy: Bringing Stars to Earth

A MAGNETIC BOTTLE TO CONFINE A BURNING PLASMA

The driving force behind research in magnetic confinement fusion energy (MFE) is harnessing nuclear fusion reactions to produce carbon-free energy for large scale societal benefit, from generating electricity to providing process heat for industry. In fusion, positively charged nuclei of lighter atoms are *fused* together to make heavier nuclei. The fusion reaction that is easiest to achieve in the laboratory (having the largest "cross-section" or probability of occurrence) is between two isotopes of hydrogen: deuterium (hydrogen with an extra neutron, abundant in water) and tritium (hydrogen with two extra neutrons, radioactive but can be made from lithium). (See Figure 6.1.) During this D-T reaction, deuterium and tritium fuse to produce a helium nuclei (alpha particle), a neutron and a release of energy in the form of the kinetic energy of the alpha particle and neutron. Since the deuterium and tritium nuclei are both positively charged, these initial particles must be given enough energy to overcome their mutual electrostatic repulsion and get close enough for fusion to occur (releasing more than 100 times the energy given to the initial particles). While fusion reactions can be generated by firing beams of energetic deuterium and tritium at each other, the probability for the particles to scatter off each other is far higher than the probability for a fusion reaction to occur. Only a small fraction of the colliding beam particles will undergo fusion reactions. As a result, it is nearly impossible to produce net energy by this approach (although similar schemes can be useful in using fusion to produce neutrons for other applications, including the generation of medically relevant isotopes).

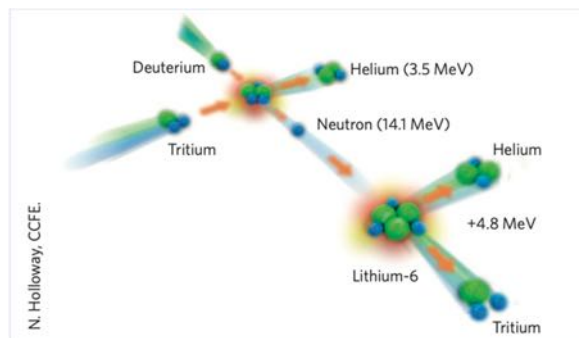


FIGURE 6.1 *Fusion Basics*. The deuterium-tritium (D-T) fusion reaction will be the basis of future fusion reactors. The fuel for the D-T reaction is deuterium (plentiful in seawater) and lithium (which can be converted to tritium fuel through capturing the neutron produced by the D-T reaction). SOURCE: Courtesy Nick Halloway, Culham Centre for Fusion Energy.

To produce net energy through fusion, the D-T particles must be confined in a region of space long enough to undergo many, many scattering interactions before finally fusing and releasing energy. The goal is then to efficiently confine a hot soup of charged particles, a plasma, with a temperature around 100 million K to enable the average particle to have enough energy to overcome the electrostatic repulsion between nuclei and produce fusion reactions. The fusion reactions can be self-sustaining if some of the energy released can be captured by the plasma and used to heat additional deuterium and tritium nuclei to fusion temperatures. Energy production above that required to sustain the fusion reactions, can be utilized for other purposes including generation of electricity.

Stars, including the Sun, are powered by fusion. By virtue of its large mass, the Sun confines hot plasma very efficiently by gravitation. Stars are usually powered by fusion of normal hydrogen nuclei (protons). This is a very low probability (small cross-section) reaction and a typical proton survives in the core of the Sun for billions of years before fusing. Fortunately, gravitational confinement is exceptionally good. The excess energy of these fusion reactions creates the sunlight that enables life on earth. Gravitational confinement of plasmas for fusion energy production unfortunately cannot be accomplished on Earth. To produce steady state fusion reactions on earth, another means of confinement must be devised.

In MFE, magnetic fields are used to confine a sufficiently hot and dense plasma so that fusion reactions can occur. Magnetic forces can limit the motion of and confine charged particles in directions perpendicular to the magnetic field. Charged particles move along magnetic field lines much like beads

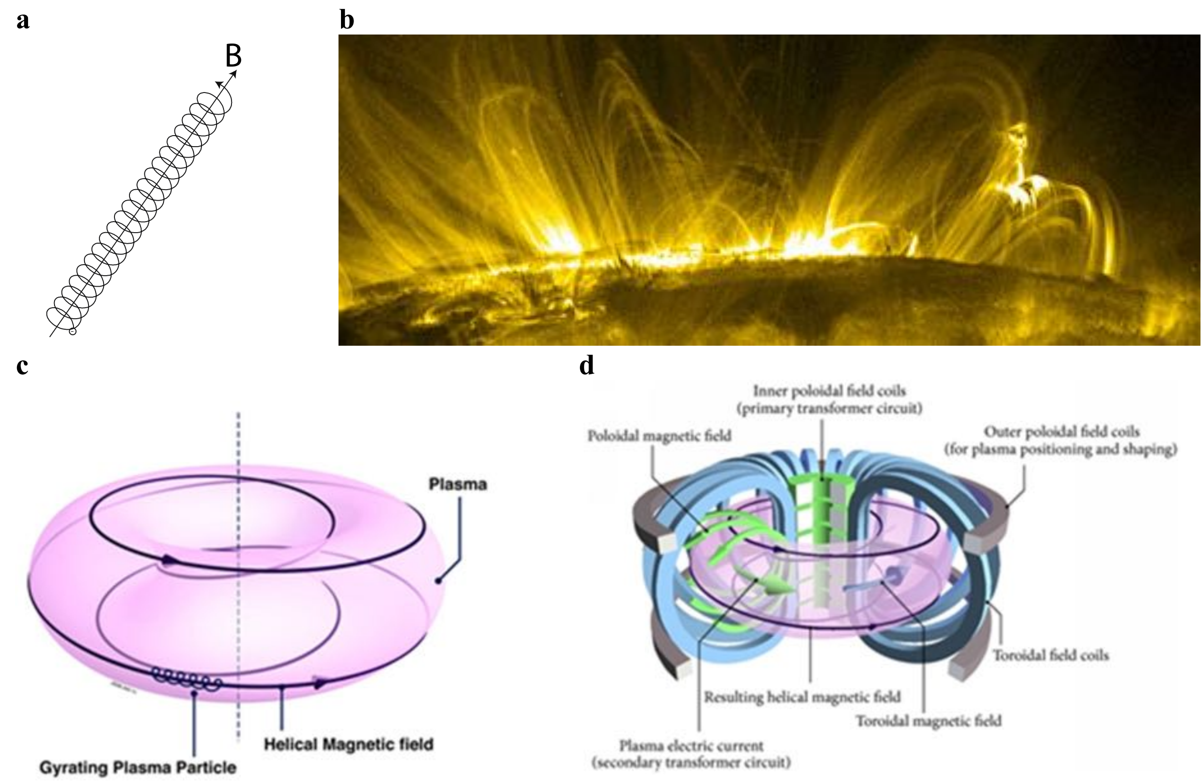


FIGURE 6.2 *Magnetic confinement*. (a) Charged particles execute helical orbits in the presence of a magnetic field - free to move along the field line, but constrained in the directions perpendicular to the field. (b) Natural magnetic confinement occurs where hot plasma is trapped on magnetic fields emerging from the surface of the Sun. . (c) Toroidal confinement uses magnetic field lines that wind around in a torus or doughnut shaped region. Pure toroidal (circular) field lines do not confine particles due to slow vertical drifts, but helical field lines that wind around the torus will confine charged particles. (d) A tokamak produces helical magnetic field lines using external coils to generate circular (toroidal) magnetic field and produces poloidal magnetic field (wrapping the short way around the doughnut) by driving current in the plasma itself. SOURCE: (a) Courtesy Troy Carter, University of California Los Angeles; (b) NASA TRACE Satellite; (c-d) EFD-R(07)01 *Focus on: JET*, The European Centre for Fusion Research (2007).

on a wire. (See Figure 6.2.) While a range of magnetic confinement schemes have been studied, the most successful so far is toroidal confinement. Using this scheme, confinement in the third direction (along the magnetic field) is provided by producing magnetic field lines that wind around in a toroidal (doughnut-shaped) region. The simplest example of such a magnetic field is produced by a toroidal solenoid. In this case magnetic field lines are circular and close on themselves. However, due to gradients in the strength of the magnetic field, charged particles are not confined by a purely toroidal field. The particles will slowly drift out (upward or downward, depending on the sign of the charge) and be lost to the walls of the confinement chamber. The magnetic field must be made helical to achieve confinement of a charged particle. In a helical magnetic field, the charged particle is still always slowly drifting, for example, upward. However, since the particle follows the helical magnetic field line and spends some time on the underside of the torus, for part of the time drifting upward means drifting back up into the magnetic field trap. In a tokamak, the additional magnetic field (called the poloidal field) necessary to produce the helical field structure is generated by running a current through the plasma itself. In a stellarator, external magnetic coils are utilized to produce the twisted field structure and it is not necessary to drive current in the plasma. Tokamaks have, to date, achieved the best fusion performance, including the generation of several megawatts of fusion power in the Tokamak Fusion Test Reactor (TFTR, 10 MW) at Princeton Plasma Physics Laboratory (PPPL) in the United States, and the Joint European Torus (JET, 16 MW) at Culham Laboratory in the UK.

The international fusion community is working toward the creation of the first magnetically confined burning plasma in the laboratory. A plasma is said to be burning when energy released by fusion reactions is the dominant source of heating in the plasma. In a magnetically confined fusion plasma, the goal is to magnetically trap the energetic alpha particles produced by fusion reactions. These alpha particles then slow down and release their energy to the plasma, heating it to reach and maintain a temperature sufficient for fusion to occur. The neutron released by the D-T reaction is not confined by the magnetic field and does not contribute to heating the plasma. Instead, the goal is to capture this neutron and its energy in a material structure surrounding the plasma where it can be used to generate tritium from absorption by lithium atoms and its energy can be captured for generation of electricity. ITER, based on the tokamak concept, is under construction in Cadarache, France with the goals of producing a burning plasma in the laboratory and producing more energy from fusion reactions than is required to heat the plasma to fusion temperatures. The ITER project has the goal of producing ~500 MW of power from fusion while utilizing 50 MW of power to heat the plasma, a fusion gain or ‘Q’ of 10. ITER construction is more than 60% complete at the time of the writing of this report and first plasma is scheduled for 2026.

A recent National Academies study, *A Strategic Plan for U.S. Burning Plasma Research (BPR)* endorsed U.S. participation in the ITER project, citing it as the best path currently available to achieving a burning plasma, a critical step in commercializing fusion energy. That study made an important second recommendation about the U.S. program beyond ITER. Recognizing that while ITER is a sound and low-risk path toward achieving the important milestone of a burning plasma and together with the knowledge gained about burning plasmas, the design is very conservative. Projections using that design extrapolate to an extremely large and costly fusion electrical power plant. Instead of only following that path, the *BPR* recommended that the U.S. program also focus on investigating more economic solutions for fusion energy and pursue the development of a compact fusion pilot plant. These compact fusion concepts will use technologies that were not available at the time that ITER was designed and carry additional risk. Following the path of compact fusion reactors would uniquely position the United States in the international pursuit of fusion power, leveraging recent advances in our understanding of fusion plasmas and new developments in technology. The *BPR r*ecommendations set the stage for a focused plasma science and engineering research program needed to enable a compact fusion pilot plant.

This proposed path forward for the U.S. MFE program is enabled by recent technological breakthroughs. In 2017, the DOE Fusion Energy Sciences Advisory Committee (FESAC) was charged “to identify the most promising transformative enabling capabilities (TEC) for the United States to pursue that could promote efficient advance toward fusion energy, building on burning plasma science and technology.” The resulting report outlined a number of recent technological developments that could lead to more rapid progress or enable new promising directions in the quest for fusion energy. Highlighted were: (1) Advanced algorithms for computation and control, including machine learning and artificial intelligence; (2) new superconductor magnet technology, in particular high-temperature superconductors (HTS) using rare-earth barium copper oxide (REBCO) materials; (3) advanced manufacturing techniques including additive manufacturing; and (4) novel new technologies for production, extraction and control of tritium fuel. Magnets based on REBCO HTS in particular could enable more compact fusion reactors.

REBCO conductors can carry an order of magnitude more current density than low-temperature superconductors currently in use such as niobium-tin. This higher current density allows much higher field strengths to be reached (REBCO-based solenoids have produced 40 T magnetic fields) and also allows magnets to reach the same field strength as current low temperature superconductor solutions while having smaller physical size.

MFE research has and will continue to be at the frontier of plasma science and engineering. MFE requires understanding and controlling very hot, collisionless magnetized plasmas far from thermal equilibrium with their surroundings. This endeavor includes plasma physics that spans a tremendous range of phenomena that must be understood (and controlled) to achieve a burning plasma. Global plasma instabilities can ultimately limit the pressure and fusion power that can generated while microinstabilities can lead to turbulence and transport of heat, limiting the efficiency of magnetic confinement. Wave-particle interactions underlie interaction of energetic particles with the plasma and schemes for heating and driving current. The interaction of hot plasmas with the material surroundings must be controlled to prevent damaging those materials. Engineering is as important, if not more so, than the plasma physics for fusion to be ultimately successful. Solutions are needed for confining materials that can withstand the high fluxes of heat and neutrons and maintain their integrity, for efficiently breeding tritium fuel from fusion neutrons, and for robust, capable and cost-effective magnet technologies. This report will focus on issues centered on plasma science and engineering while recognizing the importance of materials science, mechanical engineering and nuclear engineering in achieving the goal of commercial fusion power.

At the time this report was being written, the Department of Energy was executing a strategic planning process for MFE activities within DOE Fusion Energy Sciences (FES) to identify and prioritize the research required to advance both the scientific foundation needed to develop a fusion energy source, as well as the broader FES mission in plasma science. The process included a community-driven discussion, led by the American Physical Society Division of Plasma Physics (DPP) call the Community Planning Process (CPP). The CPP provided input to FESAC whose task was to produce a strategic plan for fusion research for FES that will include both fusion plasma science and fusion engineering and technology. With this study and the CPP being performed at the same time, much of the data and community input from both studies was shared. At CPP workshops, consensus was found in having the output of the CPP be broadly consistent with the first two recommendations of the *BPR*—continue to support ITER and to start on a path towards a compact fusion pilot plant. In particular, the CPP will utilize the second recommendation, the goal of a compact fusion pilot plant, as the basis of its strategic plan.

THE PROMISE OF MFE: CARBON-FREE, SUSTAINABLE ELECTRICITY AND THE SCIENCE AND TECHNOLOGY OF HOT PLASMAS

The societal benefit of MFE research is clear and enormous—fusion energy can provide a carbon-free source of power for generating electricity or process heat, utilizing an abundant and essentially limitless source of fuel. The fusion process that most MFE research focuses on is the D-T reaction. Tritium is radioactive with a short (13.6 year) half-life and so is not naturally available in sufficient quantities for commercial power production. However, tritium can be produced from lithium by absorption of a neutron. (See Figure 6.1.) Both deuterium and lithium are abundant in seawater (and lithium can also be mined), suggesting that there is a sufficient supply of both to use fusion power to provide the energy needs of our planet for many hundreds of thousands of years. (See Figure 6.3.) Besides providing energy and process heat, fusion reactions can be used to provide a source of neutrons for the generation of radioisotopes (e.g., for medical applications) and for transmuting waste produced by fission reactors into safer by-products.

FIGURE 6.3 The fusion fuel needed to provide energy for one family for one year is about 0.08g of deuterium and 0.02g of lithium. This amount of deuterium can be mined from only 2.5 liters of seawater, which contains 1 atom of deuterium for every 6240 atoms of hydrogen. SOURCE: By Jyi1693, CC BY 2.5, https://commons.wikimedia.org/w/index.php?curid=10443013.

MFE research has many links to other areas of plasma science and technology, advancing other areas of plasma science and vice versa. The collisionless, magnetized plasmas studied in fusion research exhibit phenomena that are also important in near-earth and interplanetary space plasmas and in astrophysical plasmas. Examples of synergies include wave-particle interactions, magnetic reconnection, and turbulence driven by spatial inhomogeneities. Energetic particles are often present in fusion experiments, either generated by heating (e.g., direct injection of energetic particles by neutral beams or with radiofrequency power), as a result of fusion reactions (helium nuclei, called alpha particles, from D-T fusion) or by disruption of the plasma current in a tokamak (producing *runaway* electrons). These energetic particles can excite waves that in turn scatter, de-energize and eject particles from the magnetic trap. The same processes occur in Earth's radiation belts and magnetosphere, where energetic protons and relativistic electrons are trapped and similar types of waves (Alfvén and whistler) can both energize and scatter these particles. Magnetic reconnection (where magnetic field lines are broken and, reconnect, producing large releases of energy—see Chapter 2) is ubiquitous in space and astrophysical plasmas, leading to stellar flares and perhaps gamma ray bursts (see Chapter 7). This same process occurs in fusion plasmas in fast nonlinear tearing modes that limit their performance. Turbulence in fusion plasmas is often driven by strong spatial inhomogeneities in plasma current or pressure, as is turbulence in Earth's ionosphere and planetary magnetospheres. Interactions between fusion, and the basic and space and astrophysical plasma communities have steadily grown in ways that have benefitted all participants. For example, the gyrokinetic computer codes created to understand and predict turbulence and transport in fusion plasmas are used to investigate turbulence in the solar wind and in stellar accretion disks, contributing to our understanding of how electron and ion heating works in these settings.

FIGURE 6.4 Edge Localized Modes or ELMs are plasma filaments that erupt from the edge of the tokamak as a result of the growth of the peeling-ballooning instability. This image shows filaments during an ELM event in the MAST spherical torus. SOURCE: © ITER Organization, http://www.iter.org/, https://www.iter.org/newsline/229/1229

There are also links of fusion to the low temperature plasma community. All fusion plasmas ultimately involve interactions with material surfaces. These plasma material interactions (PMI) can erode plasma facing components and introduce impurities into the core fusion plasma, potentially degrading confinement by processes including radiation. Similar plasma material interactions occur in plasma processing equipment used to create semiconductors and in plasma-based thrusters.

PROGRESS IN MFE RESEARCH SINCE PLASMA 2010

Since the *Plasma 2010 Decadal Survey* was published, significant progress has been made on the underlying science of magnetically confined plasmas for fusion energy research. A number of highlights are provided below.

Understanding and Controlling the H-Mode Edge

The advances in MFE science in heating and confinement achieved using tokamaks is in large part linked to the discovery of the high-confinement mode or "H-Mode." This operational mode can be accessed through exceeding an empirical threshold in heating power and leads to an edge transport barrier where strongly sheared radial electric fields suppress turbulent transport. This edge transport barrier is known as the "pedestal," which has a very large gradient in plasma pressure, much larger than the pressure gradient in the core region of the plasma inside the pedestal. The pedestal's formation, height, and stability are therefore key drivers of overall fusion performance, since fusion power scales with the square of the plasma pressure. Numerous mechanisms, including collisional "neoclassical" transport and electron scale turbulence, can drive heat and particle transport across the pedestal. However, due to very strong sheared plasma flow, electromagnetic effects, and the presence of large heat and particle sources, the pedestal is often limited by electromagnetic instabilities driven by pressure and current gradients. These instability producing processes are known as kinetic ballooning modes (KBM) and peeling-ballooning (P-B) modes. (See Figure 6.4.) A simple model, EPED, has had significant success in predicting the pedestal pressure and width, the outcomes of which are particularly important to both KBM and P-B. (See Figure 6.5.) The model predicts that when the plasma has a highly triangular plasma shape and a particular range of densities, the pedestal can bifurcate into the usual "H-Mode" and a higher pressure "Super H-Mode".

Motivated by theoretical predictions, recent experiments have explored the Super H-Mode regime. A record pedestal pressure of 80 kPa was obtained in the Alcator C-Mod Tokamak at the Massachusetts Institute of Technology. A record fusion gain for a medium scale (major radius $R < 2$ m) tokamak was obtained in pure deuterium experiments on the DIII-D National Fusion Facility tokamak at General Atomics. Deuterium-deuterium fusion reactions have a lower cross-section than D-T reactions. If

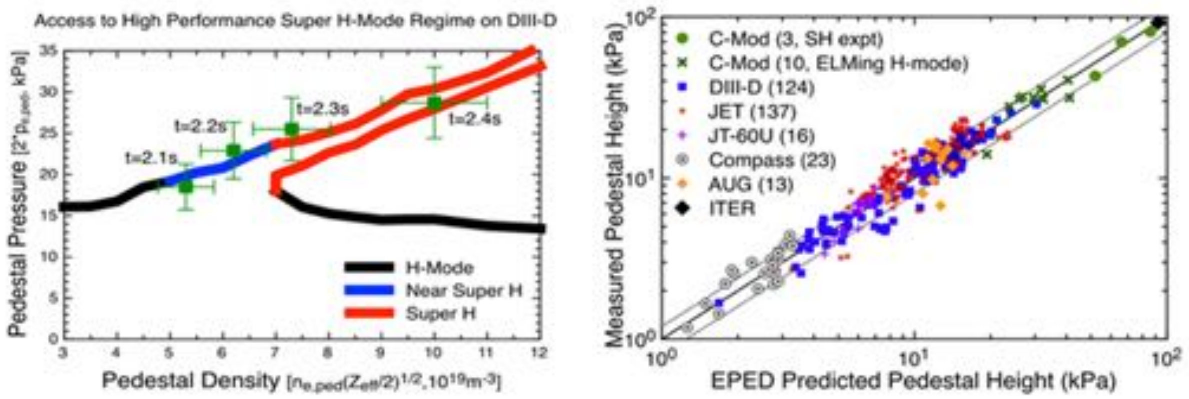


FIGURE 6.5 *Collaborative computations and experiments* (right) EPED code predictions for the H-Mode (black line), Near Super H-Mode (blue line) and Super H-Mode (red lines) regime are compared to measurements from an experiment on the DIII-D tokamak (green squares) which accessed very high pedestal pressure, and high fusion performance. (left) EPED predicted pedestal pressure compared to observations on 6 devices across a wide range of size, shape, magnetic field and plasma current find good agreement. The highest pressure cases shown (green circles) were obtained in Super H mode experiments on the Alcator C-Mod tokamak, reaching pedestal pressure (~80 kPa) near the value predicted for ITER (black diamond). SOURCE: Snyder et al, Nuclear Fusion 59, 086017 (2019).

D-T had been used in these experiments a fusion gain (ratio of fusion power produced to heating power input) of ~0.5 would have resulted.

Operation in H-mode produces significant increases in confinement time and performance over L-mode (or "low-confinement" mode, without an edge transport barrier). It is expected that ITER will access H-mode to achieve the goal of producing a burning plasma. There is a risk, however, since the H-mode pedestal can suffer instabilities that leads to edge localized modes (ELMs). These instabilities cause a fraction of the core plasma pressure to be abruptly lost, producing significant heat and particle loads on the plasma-material interface, especially at the divertor plates where the plasma is exhausted from the system. (See Figure 6.3.) Although ELM-induced particle transport has a beneficial effect in allowing density and impurity control within the core plasma, the pulsed heat load can cause rapid erosion of these divertor plates. This instability is a major risk to the ITER device and its operation. Either ELM mitigation or, preferably, operation without ELMs, is necessary while still maintaining H-mode levels of energy confinement combined with adequate particle transport for helium ash removal and impurity control.

A significant breakthrough over the last 10 years is the use of small, non-axisymmetric, three-dimensional (3D) magnetic fields called Resonant Magnetic Perturbations (RMP) to mitigate or eliminate ELMs. Experiments on the DIII-D tokamak[1] were the first to demonstrate that ELMs can be completely eliminated through application of RMP while maintaining high-performance H-mode transport barriers. Based on the initial success of 3D magnetic field control research in DIII-D, many of the major international tokamaks, including MAST, ASDEX-U, KSTAR, EAST, HL-2A, J-TEXT and COMPASS have installed similar capabilities, and have contributed to our physics understanding of the interaction of these small non-axisymmetric magnetic fields with the nominally axisymmetric tokamak magnetic equilibrium. Improved theoretical and computational capabilities have accompanied experimental progress using a variety of MHD (magneto-hydrodynamic) codes (e.g., M3D-C1, NIMROD, MARS, JOREK, VMEC, TM-1, IPEC/GPEC). These codes have been generalized to include the plasma response

[1] A table of fusion facilities appears later in the chapter, providing more information on the devices cited here.

to imposed non-axisymmetric magnetic fields. They have been able to explain many, but not yet all, of the experimental observations. For example, explanations of observed multimode responses, ELM-suppression bifurcations, rotation thresholds for suppression and density pump-out, have given increased confidence in use of such techniques on ITER. (Density pump-out is a local reduction in plasma density due to increased transport associated with the imposed RMP.) Nevertheless, a number of phenomena are still not yet fully understood, including the exact mechanism of ELM suppression and the robustness of the temperature pedestal despite density pump-out. Based on the success of RMP ELM suppression, a set of 3D magnetic field coils has been incorporated into the ITER design. (See Figure 6.6.)

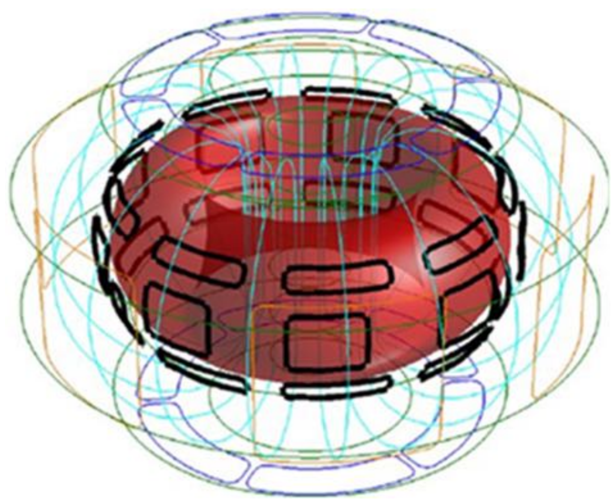


FIGURE 6.6 *3D stabilization of Tokamaks*. Coil sets for the ITER experiment will enable introduction of 3D magnetic perturbations and allow for resonant magnetic perturbation (RMP) edge localized mode (ELM) control. SOURCE: Lazerson Plasma Physics and Controlled Fusion 56, 095006 (2014).

While progress in ELM mitigation has been impressive, the effectiveness of these mitigation strategies is often limited to particular operational regimes. Identifying a general path to ELM-free, high performance operation is a major goal. Over the last 10 years, two possible operational regimes have been identified and their operational space expanded, these being the intermediate-mode or "I-mode" and the quiescent-H-Mode or "QH-Mode".

The I-mode is a stationary operating regime with improved thermal confinement but unaltered (and favorable) particle confinement which occurs at input powers below those required for the L- to H-mode transition. The I-mode has the following characteristics: 1) formation of ion and electron temperature pedestals, 2) increase in stored energy relative to L-mode, 3) little or no change in density relative to L-mode, 4) flow shear in the edge pedestal region which is intermediate between that found in L-mode and H-mode, 5) usually no ELMs and 6) changes in the edge turbulence with decreases in some frequency ranges and increases in others. Operation with increased energy confinement but unchanged particle confinement is particularly relevant for future reactors, since fusion power would be enhanced while impurity and ash removal would be facilitated. (Ash refers to the fusion alpha-particles that have given up their energy to the plasma and must be removed from the plasma.) What is now recognized as the I-mode was first seen in Alcator C-MOD and ASDEX-U in the late 1990s but its significance was not apparent at that time and work on this regime was dormant for about 10 years. I-mode experiments resumed in C-MOD prior to its decommissioning and the significance of I-mode as a stationary regime was recognized. Since the mid-2000s, considerable work on the I-mode has been done on Alcator C-MOD, ASDEX-U, and DIII-D and EAST.

The QH-mode, a stationary H-mode without ELMs, was first discovered in DIII-D and was subsequently investigated on ASDEX-U, JET and JT60-U. The initial discovery resulted from operating in lower density plasmas and forcing the plasma to rotate in a direction opposite to the direction of the plasma current. This was accomplished by driving plasma rotation using neutral beam injection (called counter-NBI). Experiments over the last 10 years have broadened the range of QH-mode operation to include plasma rotation in the current direction (co-NBI) and to operate with balanced (no torque) NBI but using magnetic perturbations from external coils to drive flows. This result makes QH-mode operation on ITER possible as NBI torque will be limited due to the large size of the ITER plasma and limited penetration of neutral beams. The key to standard QH-mode operation is the excitation of the edge

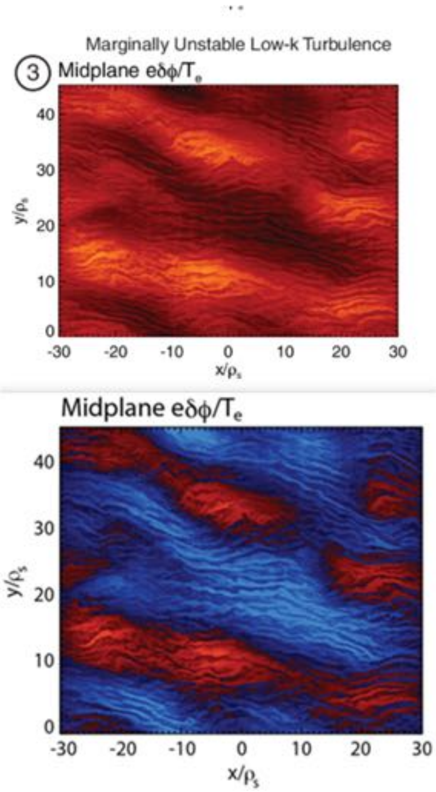


FIGURE 6.7 Fluctuations in electrostatic potential in a tokamak plasma from a multiscale simulation demonstrating the coexistence of (and interaction among) large scale (ion scale) and small scale (electron scale) structures. SOURCE: Howard et al., Nuclear Fusion 56, 014004 (2015).

harmonic oscillation (EHO), which is a coherent edge electromagnetic mode. The EHO provides extra edge transport and prevents the edge pressure gradient from reaching the stability boundary for ELMs.

The standard QH-mode operates at edge conditions, matching those in future devices such as ITER. However, to achieve the predictive understanding needed for use in future fusion reactors, we need a detailed, validated theory of the EHO. Although results from linear stability analysis have provided a significant understanding of the mode, we need a complete theory of the saturated, nonlinear state and how the EHO drives cross magnetic field transport. Some promising initial modeling of the EHO has been performed but much remains to be done.

Multiscale Processes in MFE Plasmas

Processes in magnetized plasmas span a huge range of spatial and temporal scales. For example, the timescales in a tokamak plasma range from rapid Langmuir plasma oscillations, ~0.1 ns, to slow global current diffusion, ~10 s. The Plasma 2010 report recognized the importance of and scientific opportunity to study "multiscale" processes in magnetized plasmas. These include dynamics with strong coupling between, for example, large and small spatial scales. Gaining insight into such processes is demanding. Substantial resources in massively parallel simulations are required to simultaneously resolve both the small and large spatial or temporal scales. Important progress in this regard has been made over the last 10 years. Two examples are in the multiscale interaction between ion and electron scale turbulence and in the interaction between global MHD instabilities and microturbulence.

Decades of experimental and theoretical plasma physics research has shown that turbulence is driven by unstable gradients in plasma properties (electron density and temperature, n_e, T_e; and ion temperature T_i). This turbulence is likely to be responsible for the 'anomalous' transport observed in the core of many fusion devices. (Anomalous transport refers to movement of plasma that proceeds faster than classical, linear scaling laws would predict.) Long wavelength turbulence, present at the ion-scale, is defined as turbulence with a poloidal wavenumber less than the ion Larmor radius ($k_\theta\rho_i < 1.0$). (The poloidal wavenumber, k_θ, is the inverse of the typical scale size of the turbulent structures.) At this scale the ion temperature gradient (ITG) and trapped electron mode (TEM) turbulence are thought to be important in explaining experimentally observed transport. The analog of ITG turbulence is known to exist at the shorter electron scale. Electron temperature gradient (ETG) turbulence is found at short wavelengths, with poloidal wavenumbers less than the electron Larmor radius ($k_\theta\rho_e < 1.0$). Historically, the role of ETG turbulence has generally been thought to be limited due to their presumed small eddy size. However, early numerical simulations indicated that ETG turbulence could form radially elongated "streamers" that increase the transport associated with ETG and could lead to experimentally relevant

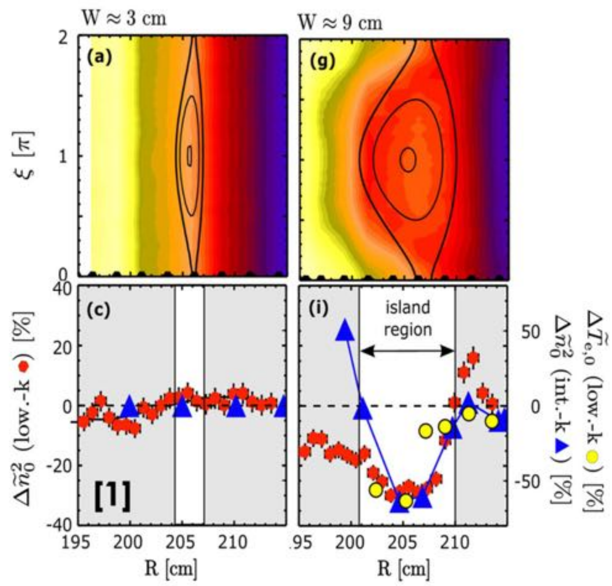


FIGURE 6.8 (top) Measured temperature profile around a small (left) and large (right) Neoclassical Tearing Mode (NTM) island. (bottom) Measured fluctuation amplitude change in the presence of small and large islands. With a large enough island, turbulence in reduced substantially inside the island and increased outside. SOURCE: Physics of Plasmas 24, 056106 (2017); https://doi.org/10.1063/1.4977533.

heat flux levels in conditions without long wavelength turbulence. Despite this finding, it was believed that in the presence of long wavelength turbulence, streamers would likely be sheared apart by the long wavelength turbulence leading to a reduced impact of the ETG.

The evolution of modern supercomputing platforms has enabled a new type of gyrokinetic simulation that is able to capture the spatial and temporal scales of ion and electron-scale turbulence simultaneously. (See Figure 6.7.) (Gyrokinetic models average over the rapid charged particle motion in orbits around the magnetic field to focus on slower, lower frequency processes including slow particle drifts and low-frequency turbulence.) Early attempts at these multi-scale simulations used artificially heavy electrons to slow their motion to better match that of the ions, and simplified plasma geometry and profiles to reduce the range of scales and lessen the computational demands. As a result, these studies generally concluded that electron temperature gradients (ETG) would likely play a minor role in heat transport. However, comparisons of model results showed notable disagreements with experimentally measured levels of electron heat flux. The origin of these disagreements was not clear.

Steady advances in computing have enabled the first multi-scale simulation of experiments to be performed with actual electron mass and all experimental inputs. Motivated by the disagreement in electron heat flux between ion-scale gyrokinetic simulation and experiment, realistic multi-scale simulations in the core of the Alcator C-Mod tokamak were performed. These simulations pushed the limits of supercomputing, requiring ~20 million CPU hours per case. Their outcomes showed that ITG turbulence could, in fact, coexist with ETG streamers. Complicated cross-scale interactions were observed in these simulations. Through modification of the zonal flows and cross-scale energy transfer it was found that short wavelength turbulence actually increased the heat flux driven at long wavelengths. An extensive validation of multi-scale simulations with comparisons to experiments demonstrated that only multi-scale simulations capable of capturing cross-scale interactions could reproduce the observed heat fluxes found in experiment. These efforts produced a likely explanation for the origin of electron heat flux in the core of tokamaks. Further simulation studies showed that cross-scale coupling is likely important in the core of high performance conditions, like those projected for the operation of ITER and future fusion devices. The importance of multi-scale turbulence remains an active area of investigation with important implications for the model fidelity needed for prediction and interpretation of fusion devices.

Progress has also been made in understanding the multi-scale interaction between global modes and microturbulence in confinement devices. Neoclassical Tearing Modes (NTMs) are a major impediment to the development of operational scenarios for tokamaks as they can limit plasma pressure and can lead to plasma termination—called a disruption. NTMs produce magnetic islands that lead to flattening of the pressure profile within the island. (See Figure 6.8.) This is caused by rapid transport

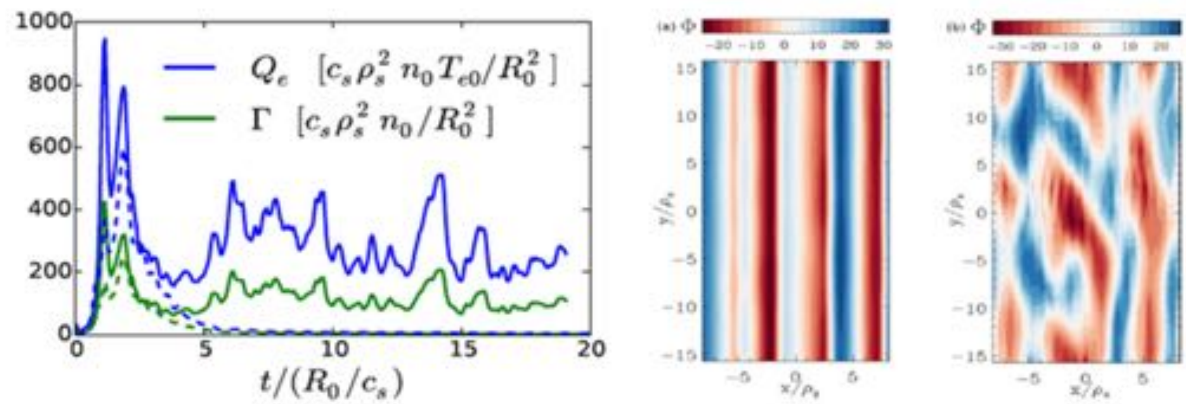


FIGURE 6.9 (left) The heat and particles fluxes from a gyrokinetic simulation of a discharge in the Madison Symmetric Torus (MST) Reversed Field Pinch (RFP). The equilibrium is unstable to trapped electron mode turbulence. However, if the magnetic fluctuations of global tearing modes are not included in the simulation the fluxes are nearly zero after an initial transient (dashed lines). When tearing mode fluctuations match the experimental tearing-mode level, the fluxes become finite and their level matches the fluxes inferred in experiment (solid lines). (right) Without the external magnetic field perturbation there are strong zonal flows (a) that quench the turbulence; with the magnetic perturbation the zonal flows are markedly reduced (b) in accordance with theoretical predictions, and fluxes rise to experimental levels. SOURCE: Left: Physics of Plasmas 22, 012504 (2015); https://doi.org/10.1063/1.4905709; right: Williams et al. Physics of Plasmas 24,122309 (2017). https://doi.org/10.1063/1.5000252.

(parallel to the magnetic field) within the island. In toroidal plasmas with large enough pressure a self-generated 'bootstrap' current arises that is proportional to the gradient of the pressure associated with trapped particles. (Bootstrap current is a toroidal current produced in the presence of a pressure gradient.) The pressure flattening in an NTM acts to reduce the pressure gradient at the island and hence removes bootstrap current from that region. This reinforces the island and causes it to grow in size. Turbulent transport around the island can prevent or reduce this pressure flattening and affect the dynamics of the NTM island. At the same time, pressure flattening by the NTM also removes the source of turbulence, leading to a complex nonlinear and multiscale interaction between microturbulence and the NTM. The first direct measurements of this interaction were made on the DIII-D tokamak

In the reversed field pinch (RFP) unstable global tearing modes drive a cascade spanning multiple scales which has been compared to the magnetic turbulence spectrum of the interstellar medium. Measurements show that the cascade acquires features at small scale associated with disparate microscale physics. Gyrokinetic simulations demonstrate that the global and microscales couple through zonal flows. (Zonal flow refers to plasma flowing within a magnetic surface primarily in the poloidal direction.) These regulate small-scale turbulence while being regulated themselves by large-scale magnetic fluctuations. The role played by zonal flows makes this phenomenon potentially relevant to the most important types of instabilities in magnetic confinement fusion. Recent experimental measurements and modeling show that this physics also arises in DIII-D tokamak plasmas, where resonant magnetic perturbations (RMPs) raise fluctuation levels and reduce zonal flows. This has been tested in DIII-D using an RMP whose magnitude is varied to test the response of turbulent fluctuations. The frequency spectrum of density fluctuations from beam emission spectroscopy for four different values of the RMP coil current is shown in Figure 6.9. Increasing coil current uniformly increases the fluctuation level over the frequency range of microturbulent fluctuations (40–120 kHz).

FIGURE 6.10 Physics Today Cover, October 2015.

Energetic Particle Driven Modes

Energetic particles (EP) such as the 3.5 MeV alpha particles generated by D-T fusion reactions, fast beam ions from neutral beam injection and high energy tail ions generated by radio frequency (RF) heating play critical roles in heating, current drive, and momentum input. The confinement of these EP is essential in future fusion reactors. Confinement of these particles, however, faces several challenges. The most significant is that these particles can excite a variety of instabilities, which in turn lead to EP transport or loss. This interplay between EPs and instabilities is a fundamental wave-particle interaction problem that spans all areas of plasma physics from the interstellar medium to tokamaks. Since the Plasma 2010 report, research on EP interactions with instabilities has progressed rapidly due in large part to advances in diagnostics for both fast ions and the instabilities themselves (see Figure 6.10). For example, measurements of the confined fast ion profile are available (using Fast Ion D-Alpha (FIDA) spectroscopy) and structures are routinely measured using electron cyclotron emission. A decade ago, measurements of ion transport in the presence of Alfven eigenmodes (a type of EP driven instability) was an unresolved issue. Research in the last decade has resolved this issue and revealed the key underlying physics of the measured fast ion transport. This effort utilized detailed experimental data coupled with theory and simulation. This was accomplished first by tracking energetic particle orbits through magnetic perturbations consistent with measurements and second by using massively parallel computation to self-consistently evaluate the interaction between energetic particles and MHD modes. The primary factor causing the transport was found to be the overlap of many wave-particle resonances. Comprehensive simulations are now able to identify not only the basic properties of EP driven but the feedback that impacts the EP profile.

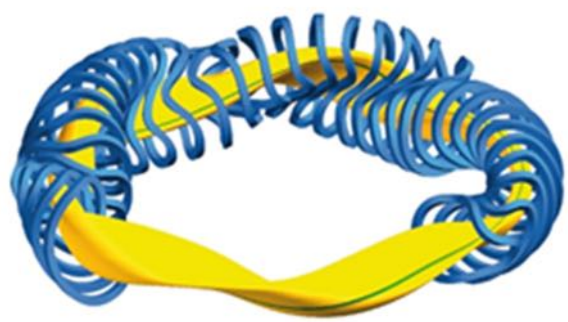


FIGURE 6.11 A stellarator uses purely external coils to produce a helical field line (green in figure) and does not require plasma current to be driven, a significant advantage over the tokamak. SOURCE: Max-Planck Institut für Plasmaphysik.

Optimized Stellarators and Wendelstein 7-X

As discussed earlier, plasmas cannot be confined with purely toroidal (circular) magnetic fields due to drifts caused by gradients in the magnetic field. Instead the magnetic field must have some “rotational transform,” meaning the magnetic field line must be helical rather than circular. In tokamaks, external current coils produce a purely toroidal field. In a stellarator, the helical magnetic field is produced entirely by specially designed external coils, and no plasma current is required. (See Figure 6.11.) To generate the helical field, the coils cannot be axisymmetric and the resulting magnetic field pattern is three-dimensional and not rotationally symmetric as in a tokamak. In the past decade, a significant advance in 3D plasma confinement has been the Wendelstein 7-X (W7-X) stellarator at the Max Planck Institute for Plasma Physics in Greifswald which began plasma operations in 2015. W7-X, the largest stellarator in the world, is an optimized stellarator, designed with a magnetic geometry intended to reduce neoclassical transport (losses of heat and particles due to collisions between particles that are in a special class of orbits called trapped orbits). W7-X, achieved the record fusion triple product (nTτ - density × temperature × confinement time) for stellarators.

The United States supplied a "trim" coil system for WX-7 that was utilized in conjunction with the flux surface measurement diagnostics to confirm the accuracy with which the 70 superconducting magnetic field coils were placed, an accuracy necessary to produce the complex array of magnetic fields. (See Figure 6.12.) Initial operation also enabled the very first assessment of neoclassical transport behavior including bootstrap current. In a tokamak, bootstrap currents are beneficial as they reduce the amount of plasma current that must be driven by external means. However, in a stellarator, bootstrap currents can potentially modify the magnetic field structure being imposed externally which can lead to degraded performance. Hence, in stellerators, one seeks to minimize bootstrap currents. W7-X experiments further validated theories for the radial electric field and bootstrap current in stellarators, showing that the device's optimization for minimal plasma current was successful. Operation of WX-7 with pulse lengths in excess of 30 s (much longer than the "energy confinement time" defined as the stored thermal energy in the plasma divided by the heating power) confirmed neoclassical bootstrap currents in line with optimization criterion.

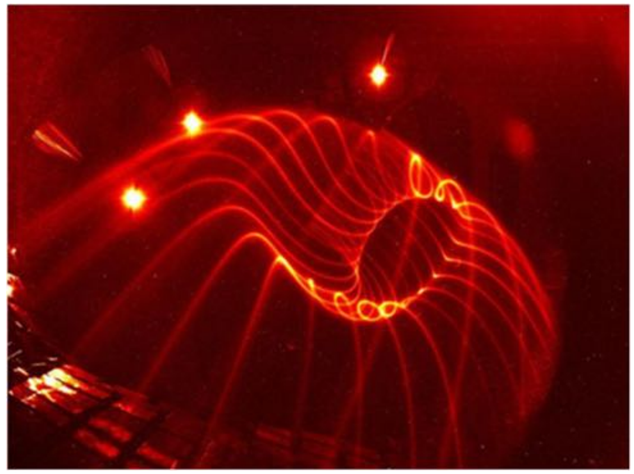


FIGURE 6.12 Image of light emitted as an electron beam follows the magnetic field lines through a neutral gas in Wendelstein 7-X, demonstrating good magnetic surfaces in the device. SOURCE: "Confirmation of the topology of the Wendelstein 7-X magnetic field to better than 1:100,000". Nature Communications 7: 13493. Figure 2.

Toroidal confinement devices utilize a magnetic geometry that directs heat and particles exhausted from the core plasma to a material surface designed to handle this power exhaust. This magnetic geometry and material surface is called a divertor. Installation of uncooled divertor elements during a second commissioning campaign in W7-X enabled experiments demonstrating the island diverter concept (a special magnetic geometry for a stellarator divertor), assessing diverter protection elements, and achieving current pulse lengths of up to 100 s. A set of U.S. supplied diverter overload protection elements ("scraper elements") were installed and successfully assessed. Edge spectroscopic measurements enabled assessment of impurities in W7-X and the ability of the island divertor to prevent impurities from the edge region from propagating into the core plasma. A desirable mode of divertor operation, demonstrated on W7-X, is called a "detached" divertor, where power exhausted from the core plasma is absorbed and re-radiated by a buffer gas before hitting material surfaces. In addition, operation of electron cyclotron resonance heating (ECRH) and frozen hydrogen pellet injection for fueling led to high performance discharges. Experiments using edge gas puffing confirmed that not only was diverted operation possible in steady-state scenarios, but that it resulted in no significant impact on confinement or impurity screening

At the time of this report, W7-X is finishing installation of water cooled in-vessel components that will enable it to run for 1800 s with 10 MW of injected ECRH power. In 2021, the device will resume operation with a fully cooled divertor which has been qualified for up to 10 MW/m^2 steady-state operation (20 MW/m^2 transient). The completed device will enable scientists to address plasma physics related to energetic particles, turbulence, plasma stability, magnetic island physics, and plasma material interactions. A 7 MW neutral beam system and 1 MW ion cyclotron resonance heating system will enable investigations of energetic particles in three dimensional magnetic fields. Fluctuation diagnostics will be

Configuration	Near-Unity Beta	Increased Compactness	Reduced Field at Magnet	No Auxiliary Heating	Simply- Connected Geometry	Advanced Fusion Fuels	Steady State (S) Pulsed (P)
Gas Dynamic Trap (GDT)	◆				◆		S
Centrifugal Mirror		◆			◆		S
Reversed Field Pinch (RFP)		◆	◆	◆			S
Spheromak		◆	◆	◆	◆		S
Field-Reversed Configuration (FRC)	◆	◆	◆		◆	◆	S
Levitated Dipole	◆				◆	◆	S
Flow Z-pinch	◆	◆	◆	◆	◆	◆	P
Magneto-Inertial Fusion (MIF)	◆	◆	◆	◆	◆	◆	P

TABLE 6.1 Advantages of non-tokamak, non-stellarator magnetic fusion configurations. The last column identifies inherently pulsed (P) or a steady-state sustainment scenario that is identified (S).

used to investigate how both magnetic fields and plasma gradients influence turbulence. Stability limits and the physics of magnetic islands can be studied through the device's flexible magnetic configurations. For the first time, scientists will have access to heat fluxes up to 10 MW/m^2 for up to 1800 s, facilitating world leading plasma material science.

Alternative Magnetic Configurations

While the tokamak and stellarator magnetic configurations have demonstrated performance closest to those needed for a fusion reactor, these concepts have appreciable engineering complexity. Tokamaks require plasma current to be sustained, and stellarators, while inherently steady state, require complex non-planar magnetic coils. Other magnetic configurations, often called "alternate concepts", offer the potential for significant reduction in engineering complexity while also being challenged in confinement and stability. The main alternate concepts include:

- Open magnetic field topologies, for example, the centrifugally confined mirror, the gas dynamic trap (axisymmetric mirror), and the flow-stabilized Z-pinch;
- Closed magnetic fields topologies. Those concepts having a moderate toroidal field include the reversed field pinch and spheromak. Those with no toroidal field include field reversed configuration and levitated dipole;
- Pulsed concepts that rely on magnetic insulation or imploding liners such as magneto-inertial fusion (a.k.a. magnetized target fusion).

Key potential advantages for non-tokamak, non-stellarator configurations are listed in Table 6.1. There has been progress in developing each of these configurations, but DOE-FES support for alternate concepts has been greatly curtailed in the last decade.

Much of the recent progress on alternate concepts has been supported by private industry and DOE ARPA-E. As one example, the Z pinch provides a simple magnetic confinement configuration for plasma and has many advantages as a compact fusion reactor, such as an order unity plasma beta and no magnetic field coils. (The plasma beta is the ratio of plasma pressure to magnetic pressure.) Equilibrium in Z-pinches is ideally produced by the radial force resulting from the azimuthal magnetic field that is generated by the directly driven axial current. MHD plasma instabilities, well known theoretically and experimentally, have largely precluded achieving long-lived high-performance Z-pinch plasmas. Sheared axial flows, where flows along the magnetic field are different at different radii, were theorized to stabilize these troublesome MHD modes. Unlike the addition of axial magnetic fields, equilibrium axial flows do not alter the radial force balance, thereby preserving the Z-pinch scaling relations. Separating the plasma properties that determine stability from those that specify the equilibrium makes the shear flow stabilized (SFS) Z-pinch appealing as a thermonuclear fusion device and as a research platform for high performance plasmas.

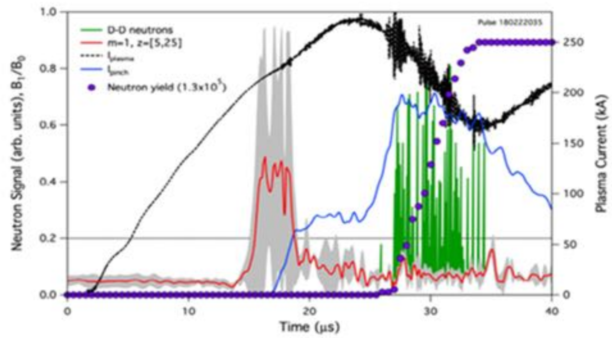


FIGURE 6.13 Experimental data from the FuZE SFS Z-pinch experimental device showing a sustained fusion neutron production (green) when operated with deuterium. Neutron production is coincident with high pinch current (blue) and with the plasma quiescent period indicated by low magnetic fluctuations (red, with gray shading indicating variation along the axis [5, 15, 25] cm). Total plasma current (dashed black) is included for reference. Measurements of neutron yield indicate a steady emission to within statistical expectations. SOURCE: Courtesy Uri Shumlak, University of Washington.

Experimental measurements coupled with numerical simulations confirmed a correlation between flow shear and plasma stability. These shear flows produced stable plasmas with ion temperatures over 1 keV in a 0.3 cm radius 50 cm long Z-pinch. A collaboration between the University of Washington and Lawrence Livermore National Laboratory has been exploring the possibility of using the SFS Z-pinch as a compact fusion device. With a more robust experimental configuration and improved pulsed power and gas injection, the SFS Z-pinch, FuZE (Fusion Z-pinch Experiment), has demonstrated sustained steady fusion from a quiescent plasma when the pinch current is high. Experimental data are presented in Figure 6.13 that demonstrate sustained fusion neutron production when a H_2–D_2 mixture was used in the FuZE device. Neutrons are observed to be produced at a constant rate when magnetic fluctuations are low and pinch current is high.

Scintillator detectors used to image the neutron emission volume on FuZe show that the neutrons emitted uniformly along a 34 cm long section of the 50 cm Z-pinch can be attributed to a thermonuclear process. Numerical fluid and kinetic simulations have been tightly coupled with the experimental investigation and have been instrumental in developing physical insight into the SFS Z-pinch operation. High-fidelity kinetic simulations demonstrate the effectiveness of sheared flow stabilization and find a flow shear required for stability that is approximately equal to the value from linear theory.

Progress Toward a Burning Plasma: ITER

Successful fusion concepts require a core plasma that is “burning” i.e., the absorption of energy released by fusion reactions is the dominant source of heating within the plasma. In particular, this heating is dominated by energetic alpha particles born in fusion reactions. These energetic particles slow down by collisions with bulk electrons and ions, and in the process transfer energy to them, resulting in plasma heating. However, a significant population of energetic alpha particles can lead to instabilities—

FIGURE 6.14 ITER site in Cadarache, France in February 2020. Construction required for first plasma was 69% complete as of March 31, 2020. SOURCE: © ITER Organization, http://www.iter.org .

plasma waves can be resonantly excited through interaction with the alpha particles. In turn, these plasma waves can cause scattering and loss of the alpha particles from the magnetic trap and can also cause unwanted transport and loss of the bulk D-T plasma. In current tokamak experiments, plasma heating can be controlled and localized in space in order to achieve desired plasma profiles and improve plasma performance. In a burning plasma, there is a strong feedback mechanism between the plasma profiles and fusion heating—more fusion will occur in the hottest and densest region of the plasma, which provides positive feedback by providing more heating locally. The burning plasma can therefore "self-organize" and the ability to use external heating to control plasma profiles is diminished. Studying this self-organized state with dominant alpha-particle heating is critically important to successfully designing and operating a fusion power plant. The study of burning plasmas was raised as a key scientific challenge for MFE research in Plasma 2010 and will continue to be a focus of the field for the next decade.

To perform critical studies of a burning plasma in the laboratory, the United States has been a partner in the international ITER project since 2003. ITER is being built in Cadarache, France by a collaboration of 35 nations. The United States is a 9% partner in the ITER construction project. The ITER project is one of the most complicated and largest scientific experiments ever constructed. The project has unfortunately suffered from significant delays over the last decade. The original plan for first plasma was 2018 but that has now slipped to 2026. In part because of these delays, some concerns were raised by Congress and DOE leadership over whether remaining a partner in ITER is the right strategy for the U.S. program. As a result, the NAS Burning Plasma Committee was charged to evaluate U.S. participation in ITER in 2015. Around the same time, a change in management occurred within the ITER Organization with Dr. Bernard Bigot taking over as director. Dr. Bigot's new management produced a more realistic timeline and costing for the project; and has kept to the project cost and schedule. At the time of this writing (end of 2019), the ITER construction project is over 65% complete (Figure 6.14).

SCIENTIFIC OPPORTUNITIES FOR MFE RESEARCH

Future science challenges and opportunities in MFE are being strongly driven by the NAS Burning Plasma study recommendations. The first recommendation from that report, that the United States remain a partner in the ITER project, represents the lowest risk route to studying the physics of a burning plasma. The NAS Burning Plasma Committee released an interim report which states: "burning plasma research is essential to the development of magnetic fusion energy and contributes to advancements in plasma science, materials science, and the nation's industrial capacity to deliver high-technology components." Further, the report states that "any strategy to develop magnetic fusion energy requires study of a burning plasma." Active participation in the ITER project is necessary for the United States to derive full benefit from the ITER project in its quest for a domestic fusion power plant. Effective participation in ITER requires that the United States continue to invest in domestic tokamak facilities and research to address operational issues for ITER and prepare the physics and fusion technology needed to

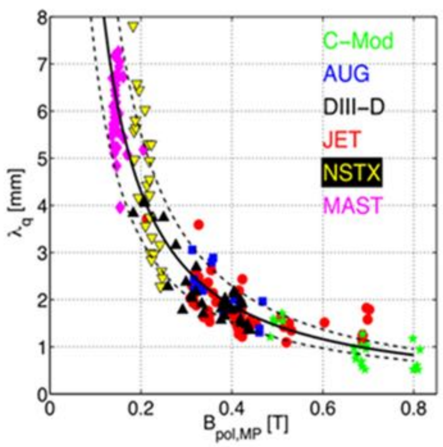


FIGURE 6.15 Dependence of the width of the region carrying heat flux from the scrape-off-layer to the divertor region as a function of poloidal magnetic field strength in several tokamaks SOURCE: Eich et al., Nuclear Fusion 53 09301 (2013).

enable next step devices. Such an active domestic experimental program would ensure that the United States gains maximum benefit from a successful ITER project along with a strong research and development program that:

- Provides solutions and technical support for successful preparation and operation of the ITER facility. In some areas the United States is world-leading and is providing contributions essential to ITER.
- Prepares and provides a team of talented and experienced researchers to participate in the ITER program and bring its results back to the domestic program.
- Develops the physics basis and tools to take ITER's results and make use of them to take the next steps on the path to developing cost-effective fusion reactors.

By supporting strong U.S. participation in ITER, including continued strength in these three areas, the United States will be positioned to build on ITER's accomplishments to move toward the ultimate goal of fusion powered electricity generation.

The second recommendation of the Burning Plasma Report is that the U.S. program pursue science and engineering activities leading to the development of a compact fusion pilot plant, representing a more economical approach to fusion power. More compact reactors require improved performance of the core plasma, likely enabled by the increased magnetic field, but also exacerbate the challenge of handling the power exhaust from the device by shrinking the surface area over which heat can be exhausted. Tokamaks must show a route toward high performance, sustained discharges with a solution for maintaining the plasma current required for confinement. In addition, unplanned plasma terminations or disruptions and ELMs must be avoided or mitigated to prevent damage to the plasma facing components and structural components.

Stellarators provide an attractive alternative route to a fusion pilot plant that does not need plasma current sustainment, so the recirculating power fraction can be reduced and reactor economics improved absent the requirement for current drive. They are also inherently steady state and do not suffer from current disruptions. Stellarator research must address core thermal and energetic particle confinement, which are deficiencies relative to the tokamak, and identify a divertor solution for power handling. Reactor concepts based on alternate concepts could also reduce cost and complexity by mitigating other fundamental challenges, like auxiliary heating. Collaboration between private industry, DOE ARPA-E, and DOE-FES offers the most expedient path forward for the development of these alternatives. Developing validated predictive capability for core plasma behavior and for plasma material interactions remains an essential challenge to achieving fusion energy. Multi-configuration research (exploring alternates to the tokamak and stellarator) has been and can continue to be part of the strategy to test fundamental plasma models and inject innovation.

Taming the Plasma Edge: Solving the Power Exhaust Problem

The MFE research program must establish the scientific and technological basis for ensuring adequate power handling in a compact fusion pilot plant (CFPP). The region surrounding the core plasma from which heat flows to the divertor is called the scrape-off layer or SOL. Designing a power exhaust solution (divertor geometry and materials) for a fusion reactor requires confident projections of the expected heat flux in the SOL and the conditions that will result in its mitigation to stay below material limits. Recent empirical and model-based projections of the heat flux in next-step devices indicate a very strong scaling with the magnet field. (See Figure 6.15.) For tokamak concepts that rely on increasing the magnetic field, this scaling implies extremely large fluxes that could exceed material limits. This heat flux can be mitigated by injecting higher mass impurities into the divertor region, with the goal of absorbing and re-radiating the exhausted power (which will be spread over a much larger surface area). This scheme can lead to a so-called "detached" divertor, where the majority of the heat flux is radiated away before reaching the material surface. Investigations of the impurity fraction required for radiative flux to disperse the exhaust heat in high-field devices suggest that the impurity fractions are manageable for next-step devices. These scalings require validation and more comprehensive models. Current projections and models rely on assumptions for impurity transport that require more theoretical and experimental corroboration. Confirmation of the predictions for the impurity requirements are essential. There is an upper limit to the impurity content that can be tolerated in tokamaks related to the ability to screen these impurities from the core plasma and induce further compression in the boundary plasma.

Solutions for the power exhaust problem should not sacrifice high-performance in the core plasma. The high neutral density needed to enhance radiation in the divertor region and reduce heat fluxes to material surfaces can have a negative impact in the region of the H-mode pedestal and core plasma. Research is needed to explore how the divertor geometry can be optimized, leveraging advanced magnetic configurations or physical design, to limit the negative impacts on the edge/pedestal often seen during detachment. There is a key capability gap that the United States could fill through a new facility focused on testing power exhaust solutions together with a high performance core plasma.

In the plasma core, well-defined dimensionless parameters are expected to govern the plasma physics. Extending this analysis to the divertor is complicated due to the importance of atomic physics, non-standard geometries, and the need to maintain absolute limits on density and temperature to prevent damage of the divertor. Ultimately this analysis, from dimensionless parameters to full scale computations, must address reactor-scale relevant conditions. Validation of these analyses needs data from reactor-scale devices. Fortunately, the operation of such near-reactor tokamaks lies in the foreseeable future, with ITER to begin operations within the decade, and the newly formed private company Commonwealth Fusion Systems aiming for operations of their SPARC D-T device in the mid-2020s.

Although ITER and SPARC will enable essential studies of core-edge integration, the requirements on the divertor of these machines are not the same as those for a CFPP. It is possible, and even expected, that these experiments will show that their baseline divertor scenarios are inadequate for follow-on facilities. For this

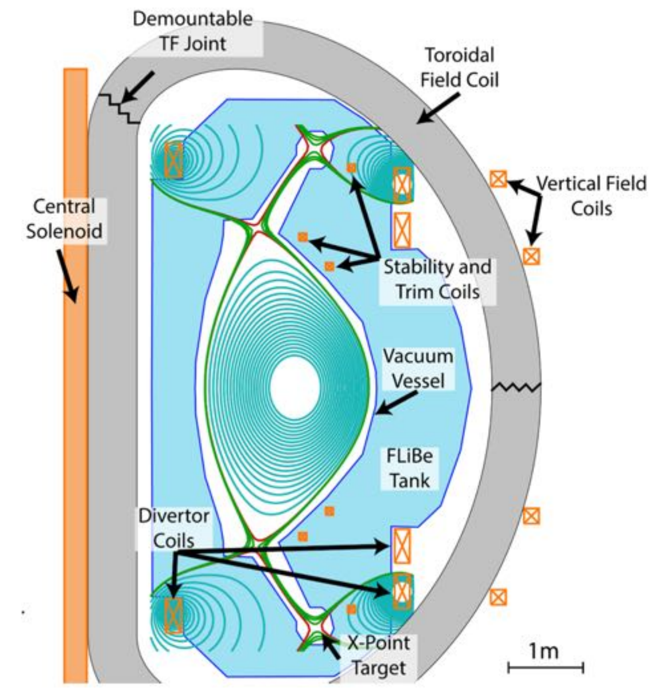


FIGURE 6.16 Example of a "long-legged" divertor design, an "X-point target" divertor for the ARC tokamak being designed by Commonwealth Fusion Systems (CFS). SOURCE: © 2018. This manuscript version is made available under the CC-BYNC-ND 4.0 license http://creativecommons.org/licenses/by-ncnd/4.0 , https://arxiv.org/ftp/arxiv/papers/1809/1809.10555.pdf.

reason, the world program is actively developing advanced divertor scenarios to reduce risk and to ensure that a solution is in hand for the post-ITER era. These efforts include the construction of new facilities dedicated to this task. However, the worldwide power exhaust research program lacks the capability to properly study the unique physics of a long-legged divertor—divertors that utilize a magnetic geometry with a long path from the edge of the plasma to the divertor surface to allow magnetic expansion of exhaust plasmas lowering the heat flux at the target. (See Figure 6.16.) Long-legged divertors must be studied at high exhaust parameters as part of this risk mitigation strategy. Predictions for this class of advanced divertors, in particular the United States developed Super-X and X-point Target concepts, indicate that they will both mitigate heat flux and potentially increase the isolation of the divertor from the core plasma. Recent predictions have also highlighted enhanced cross-field transport driven by turbulence in the long-legged divertors. There are clearly challenges with utilizing this concept in a reactor, which further emphasizes the need to better understand the physics and to gain experience in long-legged divertor engineering in a more forgiving environment. Establishing the capability to explore these concepts is essential to fully exploring options for power handling in CFPP.

A key technical and engineering challenge for the development of a working fusion energy system is developing plasma-facing materials that can survive the intense thermonuclear environment inside the plasma. Indeed, a detailed discussion of these issues was presented in the 2019 NAS report on a *Strategic Plan for U.S. Burning Plasma Research*. Some of the key findings are noted here. The essential properties of the plasma-facing "first wall" materials are that their structural properties should remain stable under thermal loads that may exceed 1 MW/m^2 and subject to neutron fluxes that lead to displacement events (atoms moved from their natural positions in the material) that can be 50 to 100 times higher than in fission reactors. These materials must be able to survive continuous operation of fusion systems in order to satisfy the requirements of tritium retention, safety, structural integrity, lifetime, and plasma compatibility. Because of these unique operational conditions, the development of plasma simulators that can operate under steady-state conditions that approximate fusion level particle and energy fluxes are critically needed. In the United States, devices such as the PISCES facility at University of California, San Diego, the Tritium Plasma Experiment at Idaho National Laboratory (INL), and the Material Plasma Exposure Experiment being developed at Oak Ridge National Laboratory (ONRL) are providing the testbed infrastructure for evaluating the performance of materials. The development of resilient, next-generation materials for the fusion environment is a critical need regardless of the architecture of the final fusion device. Investing in this materials development before the decision is made on the architecture of the next generation fusion device would be a highly strategic move. Doing so requires close collaborations between plasma physics, nuclear engineering, and materials science research, and should involve more collaborative activities that link the Department of Energy's Basic Energy Sciences and Fusion Energy Sciences programs. The 2019 NAS Decadal Survey on Materials Science *Frontiers of Materials Research* called out "Materials for Extreme Environments," including for fusion energy systems, as a frontier opportunity for the field.

Achieving Steady-State, High-Performance, Disruption-Free Core Tokamak Plasmas

The development of a plasma that self-organizes its state to not only heat itself, but also sustain its own current and thus confinement, represents a fascinating and fundamental challenge in plasma physics. Previous experiment and theory work have demonstrated that toroidal plasmas self-generate a ‘bootstrap’ current due to collisional spreading of net currents arising from ion orbit trajectories. Theory suggests that such currents lead to plasma configurations that can reach the very high pressures required for fusion and suppress turbulent fluctuations that would otherwise diffuse fusion heat. However, understanding how to realize this vision rests on a number of foundational physics mechanisms for which fundamental understanding must be developed.

Achieving high performance tokamak plasmas means optimizing the configuration (current, flow, pressure profile) to limit transport losses due to turbulence. This turbulence can be substantially stabilized by plasma flow and through the radial variation in the magnetic field line pitch that is established by the plasma current profile. Variation in flow and magnetic field line pitch can “tear apart” the turbulent eddies and twist them magnetically. Significant progress has been made over the last decade in understanding and exploiting this stabilization process. However, the high pressures and densities in a fusion reactor will lead to the increasing importance of electromagnetic effects in edge turbulence, and our understanding needs to be extended to this regime to project advanced tokamak scenarios to reactor relevant conditions.

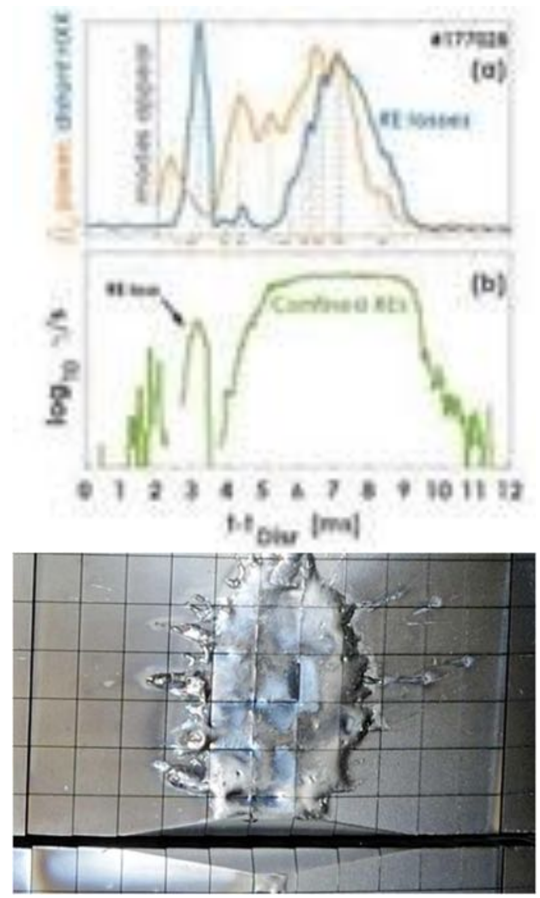


FIGURE 6.17 (top) Runaway electrons produced by a disruption stimulated by massive injection of Argon in DIII-D create hard x-rays and excite and interact with kinetic instabilities (observed on external pick-up loops). (bottom) Melted plasma facing tiles due to runaway electron damage in JET. SOURCE: Top: Lvovskiy et al 2018 Plasma Phys. Control. Fusion 60 124003; © ITER Organization, http://www.iter.org.

Operating at high performance and high plasma pressure also means operating near global instability limits. Instabilities such as NTMs and other magnetohydrodynamic (MHD) modes can arise at high pressure and lead to enhanced transport or plasma termination (disruption). Much has been learned about these global modes, but work remains including studying electromagnetic effects and wave-particle resonances that can modify stability limits and mode behavior. Projection to a reactor rests on understanding these mechanisms and developing quantitative predictive simulation tools.

Understanding global instabilities is important, in particular where that understanding enables one to avoid those instabilities. However, learning to control these instabilities when they do arise is also extremely important. ELMs occur in the steep pressure gradients associated with the H-mode edge in a tokamak. During ELM events, large filaments can form that reconnect as they are ejected, carrying with them a substantial fraction of the plasma energy in the edge region. In current devices ELMs are tolerable. However, in ITER and future reactors, one ELM could lead to significant damage to materials surrounding the plasma. Several techniques have been developed to suppress or minimize the size of ELM events including use of 3D magnetic coils to enhance transport and prevent the pressure from rising to the stability limit (RMP suppression). However, RMP is not effective under all plasma conditions. More work needs to be done to develop full confidence in techniques for controlling ELMs. This will necessitate both theoretical and experimental efforts. The experimental work would be best done in devices with reactor relevant edge conditions (e.g. relevant absolute pressure so that effects like neutral penetration are properly addressed). The theoretical work requires extension of the MHD and turbulence formalisms to new regimes where conventional models break down.

Global instabilities can lead to unplanned plasma termination or "disruption." Finding ways to avoid or mitigate disruptions is a major challenge for the tokamak concept. Disruptions result in sudden loss of plasma thermal energy to the first wall, which can cause substantial damage to plasma facing components. In addition, there is significant magnetic stored energy associated with the plasma current in a tokamak. Sudden disruption of this current causes very large inductive electric fields that can induce currents in conducting structures around the tokamak and accelerate plasma electrons to very high energies. Induced currents in the tokamak structure (e.g. vacuum vessel) can lead to strong magnetic forces. In existing tokamaks these forces have been strong enough to move the entire tokamak structure vertically. (These are impressive forces. The JET tokamak weighs more than 2000 tons and disruptions have created forces up to 5 MegaNewtons. This is equivalent to the peak thrust of the main engines of the space shuttle). The large inductive electric fields can also accelerate electrons to very high energies within the tokamak. These electrons, called "runaway electrons," can reach energies of 10's of MeV and can carry currents equivalent to the original plasma current (which could be several MegaAmperes of current). The impact of such an electron beam on material components can cause substantial damage. (See Figure 6.17.) In current experiments, stored energies are in the range of 10's of MegaJoules. ITER will have roughly 1 GigaJoule of stored energy, split roughly equally between thermal and magnetic energy associated with the plasma current.

The primary strategy to maintain stability and prevent disruptions is to design and sustain an intrinsically stable configuration. This will be achieved by exploiting fundamental understanding of the source of instabilities, combined with real time diagnostics, calculations, or machine learning prediction. If an onset of a disruption can be detected or predicted, preventive measures can, in principle. be rapidly implemented. However, it is always possible that a fault such as a power supply failure or a structure failure that may inject solid material into the plasma leading to large scale distortion, loss of confinement and a rapid disruption. Safe means of quenching such a fault are needed, which requires solving the triple challenge of high heat (energy) flux, induced device forces (as current rapidly quenches magnetic forces arise) and induced runaway electron beams. Proposed strategies to deal with disruptions include avoidance (staying away from instability) and mitigation (intentional plasma termination ahead of disruption). Both approaches require developing understanding of global instabilities including their non-linear evolution. Mitigation schemes include the injection of large amounts of neutral gas (massive gas injection) or frozen pellets (single pellets or "shattered" pellet injection) with the goal of controlled plasma termination ahead of an anticipated disruption. The dynamics of runaway electrons are particularly challenging, as they create their own confined plasma, which can undergo dissipative interaction with waves, or become unstable directly.

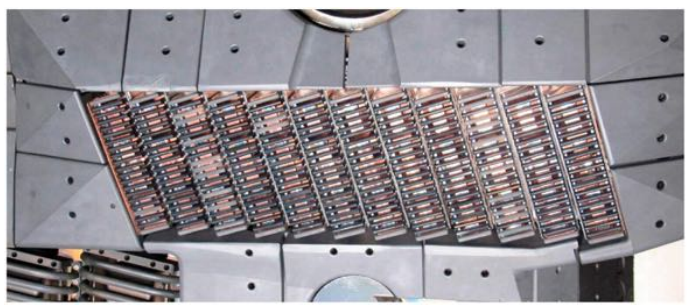


FIGURE 6.18 Antenna structure installed in the DIII-D tokamak to excite "helicon" fast waves to drive plasma current non-inductively. SOURCE: J.F. Tooker, A. Nagy, J. deGrassie, C. Moeller, M. Hansink, B. Fishler, C. Murphy, J. Anderson, H. Torreblanca, Development of a high power Helicon system for DIII-D, Fusion Engineering and Design, 123, 2017, 228-231, https://doi.org/10.1016/j.fusengdes.2017.03.055.

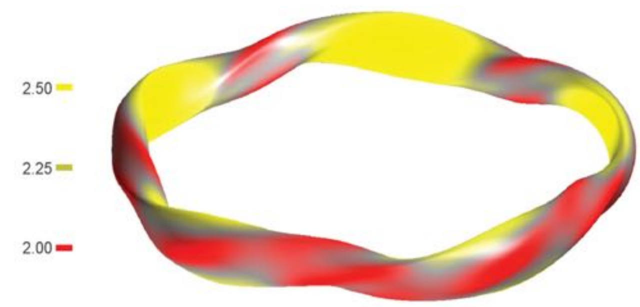


FIGURE 6.19 Magnetic surface rendering (with magnetic field strength in color in Tesla) of a stellarator magnetic geometry designed by optimization to minimize turbulence and turbulent transport. SOURCE: Xanthopoulos, et al., Phys. Rev. Lett. 113, 155001 (2014).

A key challenge in achieving a steady-state tokamak plasma is to find a way to sustain the plasma current that is needed. In shorter pulse experiments, inductive techniques can be used. A solenoid is threaded through the "hole" in the tokamak and rising currents in this solenoid induces a toroidal electric field inside the tokamak plasma, driving a current. In this arrangement the tokamak is like a transformer with the plasma acting as the secondary. Such inductive drive cannot continue indefinitely as there are limits on how long the current in the solenoid can be steadily increased. ITER will use a solenoid to inductively drive current for 400 s. To achieve a steady state burning plasma, auxiliary means to drive current are needed to operate for longer times in order to maintain the desired, self-stained configuration of current and magnetic fields. Radiofrequency waves can be injected into the plasma to directly drive currents, either by injecting momentum and "pushing" particles in a particular direction or by introducing collisional asymmetries, making it easier to push particles in one particular direction. Promising techniques include electron cyclotron resonance, ultra-high harmonic 'helicon' fast wave (see Figure 6.18) and lower hybrid resonances. These techniques need to be demonstrated with appropriate efficiency in reactor conditions.

Using Three-Dimensional Magnetic Fields to Resolve Major Challenges

For optimal plasma confinement, many critical obstacles can be addressed using magnetic fields that are non-axisymmetric, that is, without continuous rotational symmetry as is the case in the standard tokamak. As described above in our discussion of the W7-X, stellarators naturally provide stable, steady-state confinement with no disruptions, no runaway electrons, no Greenwald density limit (an operational limit for the density in magnetic confinement devices), and no need for current drive. Since stellarators can confine plasma with negligible internal current, they can be used to confine low-density non-neutral plasmas and pair plasmas (made of electrons and positrons) for basic physics studies, in addition to high-temperature plasmas relevant to fusion. Nonaxisymmetric or '3D' effects are also important in nominally axisymmetric confinement concepts such as the tokamak, which have small unavoidable departures from symmetry. Symmetry in tokamaks is sometimes also intentionally broken by nonaxisymmetric magnetic fields to control edge instabilities. Nonaxisymmetric plasma states can also arise spontaneously in reversed field pinches, and differences between 2D and 3D geometries are significant in other plasma phenomena such as reconnection. However, challenges remain to fully realize the potential of 3D shaping of magnetic fields to optimize plasma confinement. Creating the "perfect magnetic bottle" using 3D magnetic fields is one of the outstanding challenges in plasma physics. The major scientific questions that must be addressed to achieve the perfect magnetic bottle by customizing the 3D magnetic field—also known as 3D shaping—include:

- Optimizing 3D shaping to separately reduce collisional and turbulent transport (see Figure 6.19), improve confinement of fast-particle orbits, and stabilize MHD modes. Can 3D shaping be used to simultaneously optimize all of these processes?
- Is it possible to control turbulence by 3D shaping?
- The confinement of alpha particle orbits in a stellarator fusion reactor—can alpha confinement be optimized 3D shaping?

- What combination of electromagnet topologies, permanent magnets, and diamagnets is best for 3D shaping?
- How can we design stellarators to make the magnets simple, with generous tolerances?
- How can 3D shaping be leveraged to maximize control of the basic properties of the plasma?
- What is the best geometry for a stellarator divertor?
- In tokamaks, what is the mechanism by which ELMs are suppressed or triggered by 3D fields?
- Can ELM control by 3D fields be made reliable and an "every-day" practice?
- How do 3D perturbations in otherwise symmetric magnetic fields affect particle and energy transport?
- How can theory and computations be improved and leveraged to optimize and understand 3D shaping, and investigate configurations that are now beyond current experimental capabilities?

As discussed above, the W7-X stellarator has proven many concepts in using 3D shaping to achieve record confinement and plasma times. The LHD (Large Helical Device), a large stellarator in Japan, achieved several milestones such as a 10 keV ion temperature. The CTH (Compact Toroidal Hybrid) stellarator at Auburn University has collected more evidence that moderate nonaxisymmetric shaping can be applied to a tokamak to eliminate disruptions. Significant theoretical advances were made and new codes have been developed for both collisional and turbulent transport, and have demonstrated that 3D shaping can be optimized to reduce turbulent transport. New algorithms and codes have been developed to design stellarator magnets, and new plasma configurations were demonstrated with exceptional alpha confinement. In tokamaks, 3D magnetic perturbations have been explored, demonstrating that 3D field perturbations can suppress ELMs, modify edge profiles, and control many other properties. Theory and simulation of 3D effects in tokamaks have advanced significantly, with multiple codes now available that include the plasma response to external perturbations.

In the next 10 years, significant developments in 3D shaping are on the horizon. W7-X is being upgraded with a cooled divertor to enable 30 minute discharges, and a steady-state pellet injector will enable continuous peaked density profiles. The CFQS (Chinese First Quasi-axisymmetric Stellarator) will begin plasma operations early in the decade, providing the first experimental realization of a quasi-axisymmetric field. The EPOS experiment (Electrons and Positrons in an Optimized Stellarator) has been funded to explore pair plasmas. Other stellarator design activities are underway at the University of Wisconsin, Princeton Plasma Physics Laboratory, and the National Institute for Fusion Science (NIFS) in Japan. The Simons Foundation recently began an interdisciplinary project to improve understanding of 3D MHD equilibria and bring state-of-the-art applied mathematics to bear on stellarator optimization. Adjoint analytical methods are now becoming available to obtain the plasma properties (e.g. confinement quality) with respect to variation in plasma or coil shape. These new techniques could transform stellarator optimization.

Related areas of science, technology, and mathematics are making breakthrough contributions that will advance development of 3D plasma confinement schemes. First, high-temperature superconductors enable new options for electromagnetic coils. While it may be difficult to increase the magnetic field strength in stellarators due to the need to support complicated distributions of electromagnetic forces, reducing conductor thickness and cooling demands would still provide additional flexibility in the design. For example, demountable joints in such superconductors would make different coil topologies feasible. Second, advanced additive manufacturing processes will likely enable here-to-fore unachievable 3D configurations. Third, there is enormous expertise in optimizing complex system design available in other fields that can be leveraged for stellarator designs, for example, learning from the design of advanced aircraft.

The United States plays a leading role in some areas of 3D plasma physics and has a more modest standing in others. The use of 3D perturbations for tokamak control was led by the United States, with related efforts now on many tokamaks abroad. Though the stellarator was invented in the United States, the largest such devices today (W7-X and LHD) are located abroad. The United States has made valuable hardware contributions to W7-X, on which scientists from several U.S. institutions collaborate. There are several small stellarators in the United States, all at universities: the Helically Symmetric Experiment (HSX, University of Wisconsin), CTH (Auburn University), and Columbia Non-Neutral Torus (CNT, Columbia University). In the past decade, many significant theoretical and computational advances in 3D plasmas have come from the United States. Having said that, the U.S. investment in stellarator research is small, only ~1.5% of the DOE FES budget in 2019. With a modest increase in this investment, an opportunity exists to leverage the existing expertise in 3D physics to position the United States as a leader in this area.

Developing Predictive Capability to Enable Design and Control of Fusion Reactors

Experiments have been absolutely essential to progress in MFE research, leading to key discoveries such as the H-mode and edge-localized mode (ELM) suppression using 3D magnetic fields. Experiments are key to developing scientific understanding and validating theory and computation. Moving forward, there will be a greater and more necessary need for theory and computations to lead experiments. The cost of state-of-the-art fusion reactors and the time required to approve, construct and commission systems places a very high premium on having robust, designs from both a physics and engineering perspective. Increasing confidence in the design and construction of new fusion systems will largely come from fundamental theory and computations. Computations that are based on fundamental theories and validated using data from existing systems will be necessary for predictive design that has the confidence of the community. For example, extending the confinement performance from H-mode to the Super H-Mode regime in tokamaks was only possible due to guidance from the EPED model, developed and validated through experimental observation. The design of optimized stellarator experiments was enabled by improved theoretical understanding—the success of W7-X in reducing neoclassical transport was a result of this understanding. As the U.S. MFE program plans for future experimental facilities to lead the international community, there is a need for improved first-principles, validated understanding and predictive capability to help design and then fully exploit these facilities.

Advances in multi-scale, multi-physics theory and modeling capabilities across the MFE discipline are necessary to predict not only the plasma physics of 3D configurations, but also the interaction of plasmas and surrounding materials. Perhaps the highest requirement is validating codes on present experiments to build confidence in predictions of fundamentally new physics regimes typical of a fusion power plant. These physics models must ultimately be integrated into the engineering focused codes to develop designs for future fusion experiments, and in particular a fusion pilot plant. There is a hierarchy of approaches spanning whole-plasma modeling (core to first wall), whole-device modeling (adding the divertor, wall and blankets), and whole-facility (including balance of plant and economics to the site boundary). There is also a hierarchy of types of models needed, from first-principles simulations to reduced models that enable more rapid computation for use in scoping/design and potentially real-time control and feedback of experiments.

To meet these computational goals, the MFE program needs to support (ideally collaboratively with other agencies and offices within DOE) experimental and computational studies on fundamental fusion-relevant plasma and material physics. Continued development of validated predictive models with tight coupling to experiments is necessary to the future of the field. To increase collaboration between theory, computation, and experiment, specific programs aimed at this goal are necessary. The DOE FES and Advanced Scientific Computing Research (ASCR) partnership program Scientific Discovery through Advanced Computing (SciDAC) is one such model that can be expanded, bringing in other partners such as DOE Basic Energy Sciences (BES). These activities would build, refine, and validate predictive models of fusion-relevant plasma and material processes over a range of complexities (first principles to reduced models) and computational cost to meet the need. Validation must be performed with rigorous uncertainty quantification to develop the required confidence in predictive models. Validation should focus on regimes that are relevant to burning plasmas where possible.

Innovations in data analysis and machine learning should be used to complement more conventional model development where appropriate. Investments should be made in computational infrastructure and software engineering to optimally employ current and future high performance computing platforms; and to enable advanced data management and analysis, with the goal of improving the interface between experiments and computation. These advances would be aided by the adoption of data standards and common formats to support benchmarking and accessibility. The MFE program should invest in the processes and infrastructure needed to make the outcomes of large-scale simulations available to the broad community in a way analogous to the distribution of experimental data by major fusion experimental facilities. (For example, MDSplus is a set of data acquisition and software tools widely used by the international fusion community.) Investments should also be made to support software engineers converting legacy production codes to new architectures, and to develop standardized libraries to minimize the overhead of new code development.

FIGURE 6.20 Interior of the DIII-D Tokamak vacuum vessel. SOURCE: Rswilcox, https://commons.wikimedia.org/wiki/File:2017_TOCAMAC_Fusion_Chamber_N0689.jpg.

It is important to have a balanced approach to investing in both developing computing capability (e.g., producing codes that efficiently use the largest supercomputers) and leveraging computing (e.g., performing computations needed to advance physics and engineering). For example, first principles kinetic plasma simulations are essential to investigate the fundamental physics of fusion plasmas, and its related large computational resource needs are a driver in the plasma community for exascale computing. In the past, funding priorities have driven the community more toward capability computing (use as many processors as possible in the largest machines) rather than providing resources to actually use this capability to evaluate experimental results, design new experiments and drive the science of MFE forward. Investing in computations enables both continued use of production codes as well as advancing high-fidelity modeling capabilities.

MFE FACILITIES IN THE UNITED STATES

Here the committee briefly discuss the MFE facilities in the United States that have contributed to our understanding of fusion physics and advanced fusion technologies over the past decade. (See Table 6.2.)

DIII-D

DIII-D is currently the largest magnetic fusion research experiment in the United States, located at the DIII-D National Fusion Facility in San Diego and operated by General Atomics for the DOE. (See Figure 6.20.) DIII-D is a multi-institutional user facility whose primary research goals are to:

- Provide solutions to physics and operational issues critical to the success of ITER;
- Develop the physics basis for steady-state tokamak operation as required for efficient power production;
- Contribute to the technical basis for a fusion nuclear science facility, and

- Advance the fundamental understanding and predictive capability of fusion science.

The DIII-D project began in 1986, and its technical capabilities have continually improved, making it a flexible device that can study confinement, stability and divertor physics with a variety of heating and current drive techniques. This capability, in turn, enables development of high-performance, advanced tokamak concepts having simultaneous control plasma profiles both in the core and at the edge of the tokamak. Near-term research on DIII-D addresses plasma configuration scalable to the high gain fusion that is the goal of ITER. Longer-term research focuses on developing techniques to produce stable, high-performance, steady-state (i.e., non-inductive) operation in ITER and beyond.

DIII-D has a major radius of R = 1.67 m and a minor radius of a = 0.67 with a nominal aspect ratio of R/a = 2.5. (R is the radius of the entire tokamak torus; a is the radius of the tube of the torus). It can operate with a 2.2 T toroidal magnetic field and 3 MA plasma current, although it generally operates at lower currents, ≤ 2 MA. Eighteen magnetic field-shaping coils operated by a plasma control system provide great flexibility in the shape of the plasma, discharge evolution, and divertor configuration. Divertor cryopumps control the plasma density. DIII-D has 26 MW of external heating capability, split between 20 MW of neutral beam injection (NBI) heating and 6 MW of electron cyclotron heating (ECH) and current drive. The neutral beams are configured on- and off-axis, and in the co- and counter-current direction to provide a range of torque and neutral beam driven non-inductive current profiles. A key feature of DIII-D is sets of internal and external coils that provide a wide range of 3D magnetic perturbations for edge-localized mode (ELM) suppression and other edge profile control studies. Shattered pellet injection and argon pellet systems are used to mitigate disruption and runaway electrons. (This is a technique by which frozen pellets of gas, either whole or shattered, are injected into the plasma and then evaporate to increase the local gas density.) A lithium and boron “dropper” (a system that dispenses particles smaller than a few hundred microns) is used for wall-conditioning, and a laser blow-off instrument (where a laser pulse ablates a puff of material into the plasma) is available for impurity transport studies. DIII-D has an outstanding, comprehensive set of core, edge, and divertor diagnostics. A close collaboration between theory, computations and experiment enables the data to be readily used to validate first-principles physics simulations for the development of high-confidence predictive tools.

Organizationally, DIII-D is managed by a private company, General Atomics (GA). Multiple national-laboratory and university, as well as GA employees, constitute the scientific staff. Generally, GA employees operate the major systems. Several major subsystems are the responsibility of national laboratory teams while diagnostic systems are the responsibility of university, national laboratory, and GA personnel. Experiments are selected from proposals submitted to Research Opportunities Forum that is open to all and reviewed by a Research Council with experienced team members from GA, laboratories, and universities. Final allocations for experimental time on DIII-D are made by GA management. Experiments are conducted by multi-institutional teams that often include international visitors. The research program is influential. As a measure of impact, consider the papers selected for oral presentations at the most recent IAEA Fusion Energy Conference (the highest visibility conference in the field). Of 42 experimental magnetic fusion papers, 15 utilized DIII-D data, the most of any facility in the world.

NSTX-U

The National Spherical Torus Experiment-Upgrade (NSTX-U) is one of 17 tokamaks worldwide designed to operate in the low aspect ratio regime. (See Figure 6.21.) It is a high-powered, medium-sized device that is one of the two largest and most capable low aspect ratio tokamaks in the world, the other being MAST-U in the U.K. The mission of NSTX-U is to:

- Advance the spherical tokamak (ST) as a candidate for a Fusion Nuclear Science Facility (FNSF);
- Develop solutions for the plasma-material interface, including the snowflake divertor and lithium/liquid metal plasma facing components (PFCs);
- Advance toroidal confinement physics predictive capabilities for ITER and beyond; and

- Develop the ST for fusion energy production, for example as an ST Pilot Plant.

FIGURE 6.21 The NSTX-U Spherical Torus Experiment. SOURCE: Princeton Plasma Physics Laboratory.

Many of ST physics challenges were investigated in NSTX, the predecessor to NSTX-U. NSTX had an aspect ratio of R/a=0.85/0.68~1.25, operated with plasma currents up to 1.5 MA and with toroidal magnetic fields of up to 0.55 T. NSTX had pulse lengths of up to 1.5 s, and operated with either D^+ or He^{++}. NSTX was equipped with a three-source neutral beam capable of injecting 6 MW of power at 90 keV, and up to 6 MW of High Harmonic Fast Wave RF power for heating and current drive. Co-axial Helicity Injection (CHI) was used for non-inductive plasma startup. Close-fitting passive conductors, coupled with application of active control algorithms using applied 3D magnetic fields as actuators, were used to stabilize MHD instabilities and maintain high-performance operations.

NSTX-U will continue to explore physics issues critical to low aspect ratio tokamaks, but with enhanced capabilities. The toroidal magnetic field will be increased from 0.55–1 T, the plasma current from 1.5–2 MA, and the pulse length from 1–5 s. A second, more tangentially injecting neutral beam was added, doubling the total available power up to 12 MW under normal operating conditions. These additions make NSTX-U the most powerful ST in the world, with the highest toroidal field and highest accessible pressure and plasma β. This will enable NSTX-U to achieve up to 10 times higher fusion triple produce ($nT\boldsymbol{\tau}$) and four times higher divertor heat fluxes, reaching levels expected in ITER.

The increased current, field and power will enable NSTX-U to operate at higher temperature and up to five times lower collisionality than in NSTX. Operation at reduced collisionality is critical to resolving how confinement varies with this parameter. If this favorable confinement trend with reduced collisionality is confirmed, that is, exhibiting a stronger trend than observed in tokamaks with conventional aspect ratios, this would be critical information for optimizing designs of compact tokamak reactors having small aspect ratio, high-β.

While there is significant overlap between the two major ST devices—NSTX-U will focus on core physics, and in a complementary fashion MAST-U will focus on boundary physics. MAST-U is equipped with poloidal field coils that will enable more flexible divertor configurations than those that can be produced in NSTX-U. However, NSTX-U can contribute and, in some instances, lead in power exhaust studies. NSTX-U will be using solid lithium coatings to protect PFCs from high heat fluxes, to improve confinement and to suppress ELMs, as was done in NSTX. Solid lithium injectors on the top and bottom of the vessel will double the lithium deposition over that in NSTX. Long-term plans include the development of liquid metal divertors as a possible transformative wall solution.

NSTX-U operated a 10 weeks productive scientific campaign in 2016. However, by the end of that period, it was discovered that one of the poloidal magnetic field coils failed, necessitating NSTX-U to shut down for an extended repair. The NSTX-U Recovery is ongoing, with numerous design improvements, including modification of the vacuum chamber, in order to support flexible operations and increase reliability to achieve key mission goals. New requirements for the divertor heat fluxes have been defined, based on recent models for the SOL heat flux. New error analysis has been conducted, with the goal of optimizing both the global MHD stability and minimizing PFC heat flux asymmetries. New designs of graphite plasma facing components utilize crafted surfaces to reduce the mechanical stresses, allowing tiles to reach temperature of ~1600 C. Improved divertor coil designs simplify fabrication and facilitate turn-to-turn testing. The NSTX-U Recovery project is on track to enhance reliability and safety and provide the highest performance ST device as a robust user facility. NSTX-U is expected to resume operations during 2021.

Alcator C-Mod

Alcator C-Mod is a compact, high-magnetic field, diverted tokamak that was operated at the MIT Plasma Science and Fusion Center (PSFC) from 1993 until 2016. (See Figure 6.22.) C-Mod has a 0.68 m major radius and 0.22 m minor radius and can operate with up to 8 T magnetic field using liquid nitrogen cooled copper magnets. The high magnetic field enables the small device to create the dense, hot plasmas (> 100 million degrees) of the type expected in a fusion reactor. C-Mod holds the record for the highest volume average plasma pressure in a magnetic confinement device, which is an important metric for fusion performance. The plasma is heated to very high power densities using radio-frequency heating from novel antennae and sustained with microwave current drive. The third in a series of high-magnetic field tokamaks at MIT, C-Mod leveraged PSFC expertise in high-field magnets, high power radio-waves, plasma physics, fusion materials, theory and simulation, and cutting-edge engineering. This experimental device enabled a wealth of new and important results.

C-Mod has contributed data extending physics understanding into new parameter spaces to develop new tokamak operating regimes while demonstrating important technical solutions to fusion problems. The relatively large power in a small device allows for tests of heat exhaust at reactor-relevant heat and particle fluxes in reactor-relevant divertor geometries. To handle these conditions, C-Mod pioneered the use of the vertical target-plate divertor with refractory metals, a design that has been incorporated into other devices including ITER. Studies on C-Mod have clarified the roles of rotation and shear on transport and stability across the plasma and have demonstrated stable operating regimes at high magnetic field that may eliminate explosive instabilities.

Until 2016, C-Mod was one of three domestic tokamaks and a DOE user-facility. C-Mod engaged collaborators from all over the world to plan and execute experiments. The team of over 100 professors, scientists, students, engineers, and technicians made C-Mod the largest experiment at MIT with participation from many MIT academic departments. Following completion of operations, the facility was placed into safe shutdown, with no additional experiments planned at this time. There is a wealth of data archived from the more than 20 years of operations, and the experimental and theoretical teams continue to analyze the results and publish them in the scientific literature.

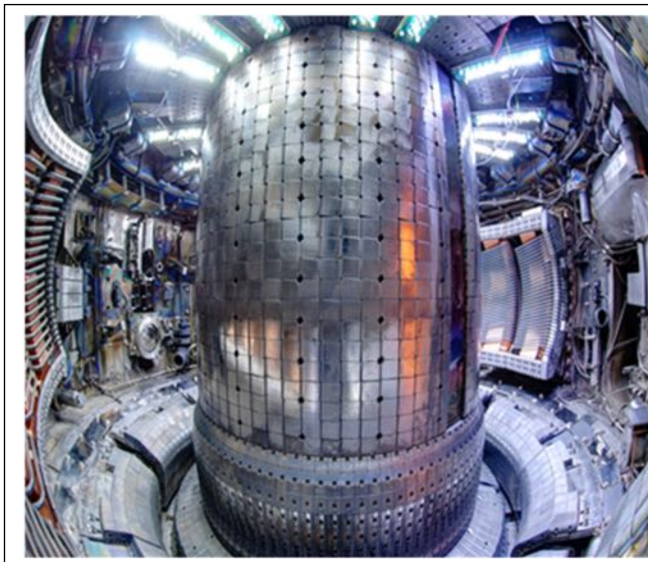


FIGURE 6.22 Interior of the Alcator C-Mod vacuum vessel. SOURCE: Courtesy of Mike Garrett.

Smaller MFE Research Facilities in the United States

Pegasus is an ultra-low aspect ratio tokamak at the University of Wisconsin that operates with a major radius of R~0.35 m, R/a ~1.13–1.3 and a toroidal magnetic field strength of 0.17 T. Its mission is to explore very high-β confinement and stability, and to develop non-inductive discharge start-up techniques. Pegasus has achieved H-mode plasmas, with threshold powers for accessing the H-mode well above (~15x) that predicted for the Pegasus operating parameters with plasma currents up to 100 kA.

Lithium Tokamak Experiment upgrade (LTX-b) is also a low aspect ratio tokamak at Princeton Plasma Physics Laboratory having R=40 cm, R/a~1.55, a toroidal magnetic field of 0.17 T and plasma currents up to 100 kA. The purpose of LTX-b is to develop use of liquid lithium walls to protect plasma facing surfaces, and to study their effect on plasma performance. Its predecessor LTX, used lithium coatings on a high-atomic weight wall, and it exhibited flat electron temperature profiles and enhanced confinement without having the lithium dilute the core plasma or radiate power. LTX-b will extend the capabilities of LTX with 700 kW of NIB heating and fueling, 100 kW of ECH/EBW (electron Bernstein wave) coupling for electron heating, higher magnetic field and current, longer pulse length, and upgraded diagnostics.

The Madison Symmetric Torus (MST) at the University of Wisconsin is a reversed-field pinch (RFP) physics experiment, which relies on a transient burst of current to create the plasma and the confining magnetic fields. In the RFP, the toroidal magnetic field is weaker than the poloidal magnetic field, and it actually reverses direction in the plasma near the edge. The mission of MST, part of the Wisconsin Plasma Physics Laboratory user facility, is to study fusion and astrophysical implications of reconnection, turbulence and dynamo formation. A 1 MW NIB will be used to heat the plasma and enable studies of fast particles and their role in the reconnection process. A wide range of diagnostics is available for characterizing the plasma.

HSX, the Helically Symmetric Experiment Stellarator, also at the University of Wisconsin, is a quasi-helically symmetric (QHS) stellarator with R=1.2 m, a=0.15 m and toroidal magnetic field up to 1.25 T. It has up to 200 kW of electron cyclotron heating, which can energize the electrons up to 2–2.5 keV in the core. By the nature of its QHS design, neoclassical electron thermal transport was reduced. HSX has demonstrated conditions important for reducing turbulence-driven transport, maintaining plasma stability, and for good particle confinement of trapped high-energy electrons. HSX also serves as a flexible divertor test platform, able to produce either an island or non-resonant divertor.

HIDRA (Hybrid Illinois Device for Research and Applications) at the University of Illinois is a classical stellarator with R=0.72 m and a=0.19 m, with magnetic fields up to 0.5 T. The main focus of HIDRA is to study plasma-material interactions, including liquid lithium science and technology. The Compact Toroidal Hybrid (CTH) device at Auburn University is designed to study how MHD stability in a stellarator depends on 3D shaping of the plasma. It has R=0.75 m, a=0.29 m, magnetic field of 0.7 T, and it has independently controlled magnet coils that can produce a wide variety of configurations, enabling conditions appropriate to investigating disruptions.

The mission of the HBT-EP device at Columbia University is to utilize an adjustable close-fitting conducting wall for passive stabilization and applied external magnetic perturbations for active control of MHD modes. It has R=0.92 m, a=0.15 m and toroidal magnetic field of 0.35 T. The Helimac at the University of Texas at Austin (R=1 m, 0.1 T) is a toroidal device that is used to study plasma turbulence at high collisionality. With magnetic field lines having a low pitch, its configuration approximates that of an infinite cylinder. Flow shear is externally applied and can be controlled. The plasma is colder, with T_e ~10 eV and number densities of 10^{11} cm^{-3}.

THE U.S. MFE EFFORT AND ITS INTERNATIONAL CONTEXT

U.S. Leadership in the International Fusion Research Effort

Historically, the United States has been at the forefront of the MFE international research community in virtually all major areas. In large part, this is due to major investments made during 1980–2000, developing a diverse set of research facilities (TFTR, DIII-D, NSTX, Alcator C-Mod), coupled to a strong base program of experiment and theory. A measure of U.S. scientific leadership is reflected in the recipients of significant international research prizes, such as the Nuclear Fusion Award and the Alfven Prize. U.S. scientists constitute a disproportionately large number of winners. Eight out of twelve Nuclear Fusion Awards to-date have recognized work led by U.S. scientists from across the U.S. fusion program. The Alfven Prize of the European Physical Society was established in 2000, and U.S. scientists have been recipients in 8 of the 19 years. Although the prize is for all areas of plasma physics, the U.S. winners have been mostly from the fusion research community.

This recognition of the excellence of U.S. research acknowledges past accomplishments, and is unlikely to continue into the future unless current trends are reversed. Simply stated, U.S. leadership is lagging. The United States is poised to lose research leadership of the world's MFE programs for two coupled reasons. First, there is, and has been for several decades, a lack of major investment in new U.S. facilities and experimental capabilities. Second, there is currently an absence of a U.S. strategic plan for fusion energy. This latter issue is being addressed at the time of this writing by the ongoing CPP (community planning process) for the DOE Fusion Energy Sciences. The committee is hopeful that the resulting plan will be well received, implementable and regularly updated.

While the United States had made significant investment in the international ITER experiment, the lack of major investment in domestic experimental capabilities is startling when compared to investments being made internationally. With a twenty year gap in major investment in new domestic facilities, along with the closure of TFTR and Alcator C-Mod, the United States is left with only two major medium-scale facilities—DIII-D (started in 1986) and NSTX-U (NSTX started in 1999 and was upgraded to NSTX-U in 2012). The contrast internationally is striking, with major investments by our partner nations in new facilities in the European Union (the WEST tokamak and the W7-X stellarator started in 2016), Japan (the JT-60SA tokamak will begin operations in 2021), China (the EAST tokamak started in 2006), and S. Korea (the KSTAR tokamak started in 2008). Substantial upgrades have occurred or are planned for the JET tokamak (UK), the ASDEX-U tokamak (Germany), and the LHD stellarator (Japan). The 2012 Fusion Energy Scientific Advisory Committee (FESAC) report on "Opportunities and Modes of International Collaboration During the ITER Era" states that "the capabilities of new experimental facilities (most with superconducting coils and very long pulse capabilities) in the EU, China, Japan, and Korea would soon rival and in several important areas exceed those of major U.S. fusion facilities."

U.S. Participation in International Facilities

U.S. fusion research strategy has an increasing focus on participation in newer international long-pulse experiments with superconducting magnets including EAST (China), KSTAR (S. Korea), and W7-X (Germany). EAST began operation in 2006 and KSTAR began in 2009. Non-U.S. proposals for new facilities include the superconducting Divertor Tokamak Test facility that would be built by the Italian National Agency for New Technologies, Energy, and Sustainable Economic Development's fusion laboratory in Frascati, Italy, and the China Fusion Engineering Test Reactor (CFETR) is under consideration as a new fusion facility to demonstrate self-sufficient tritium breeding. While researchers in the U.S. fusion community welcome these international opportunities, it is not clear how international cooperation by itself will enable U.S. fusion researchers to maintain a world leadership position without new facility starts in the United States.

The United States has made and continues to make important contributions to the world's largest currently operating fusion device, the Joint European Tours (JET). This includes involvement in testing important auxiliary systems relevant to ITER (e.g., the ITER-like Shattered Pellet Injector), plasma diagnostics, and experimental operating scenarios (e.g., deuterium-tritium scenarios). Additionally, simulation codes (e.g., TRANSP) developed by U.S. scientists have been adopted by international partners and are now routinely used for scenario modeling in the JET program and across EUROfusion ITER-related activities.

For intermediate-sized tokamaks (ASDEX Upgrade, Germany; TCV, Switzerland; MAST Upgrade, UK), many bilateral collaborations exist between the U.S. and EU partners. Prominent recent examples of U.S. contributions include temporarily moving diagnostic devices from U.S. facilities to EU machines, and joint experiments on multiple machines to develop understanding and robust demonstration of control schemes and new plasma scenarios.

An U.S. contribution to fusion research in the EU is participation in the W7-X stellarator project. This includes the construction and operation of five large auxiliary coils and an X-ray spectrometer, as well as the development of fluctuation diagnostics and a pellet injector. This work is carried out at three U.S. national laboratories (Princeton Plasma Physics Laboratory, Oak Ridge National Laboratory, and Los Alamos National Laboratory) and three U.S. universities (Auburn University, University of Wisconsin, Madison, and Massachusetts Institute of Technology), supporting W7-X with equipment that has been funded, designed, and produced in the United States and with related magnetic field and plasma diagnosis and modeling.

The United States is playing a significant role in developing new fusion programs in Asia. Major contributions have been made to new Asian devices, notably in EAST (China), KSTAR (S. Korea), HL-2A (China), and J-TEXT (Japan). A strong relationship continues with smaller spherical tokamaks (QUEST at Kyushu University, Japan; VEST at Seoul National University, S. Korea; SUNIST at Tsinghua University, China). A major focus of an international partnership on QUEST has been in the use of long-pulse superconducting devices to develop steady-state plasma scenarios. Collaborations on EAST have made advances in plasma control and wall conditioning techniques developed collaboratively with and initially demonstrated on DIII-D. Novel computer science hardware and software infrastructure has improved data movement, visualization, and communication and enabled scientists in the United States to remotely conduct experiments using the EAST facility. In July 2017, Chinese researchers using EAST achieved a stable 101 second steady-state high confinement plasma, setting a world record in long-pulse H-mode operation. Similarly, physicists at Princeton Plasma Physics Laboratory have connected remotely to run experiments on KSTAR. U.S.-Asia cooperation aided development of HL-2M under construction in China and in the physics design of the CFETR burning plasma facility under consideration in China, where the United States provides design expertise and simulation codes.

MFE AND THE PRIVATE SECTOR

Since the Plasma 2010 report, the fusion energy landscape has changed significantly with the rapid growth of privately funded fusion companies. The recently formed Fusion Industry Association includes 21 member companies who are working toward commercial fusion energy within the United States and abroad. Around $1 billion of private capital has been invested in these 21 companies over the last 10 years. Prominent examples include:

- *TAE Technologies* (Foothill Ranch, CA) has raised the largest amount of venture capital of any privately funded fusion company to date. (See Figure 6.23.) TAE fusion efforts have focused on a beam-driven field-reversed configuration (FRC) concept. TAE has built a series of devices and is currently operating the C-2W device, 30 m long with a diameter of 0.8 m in the confinement region. Up to 21 MW of neutral beam power is available and has been used to produce FRCs lasting 30 ms with total temperature up to 2 keV (maximum electron temperature of 400 eV). The company has expressed interest in utilizing fusion fuel that does not produce neutrons, in particular the $p\text{-}B^{11}$ reaction.
- *Commonwealth Fusion Systems* (Cambridge, MA), one of the newest fusion companies focused on innovating the tokamak concept using high-temperature superconducting magnets capable of providing very high magnetic field. CFS has attracted major funding from the Italian energy company ENI and subsequent investment from Breakthrough Energy. Near term focus for the company is the development of tokamak magnets based on rare-earth barium copper oxide (REBCO). A first test of

these magnets for CFS would be the SPARC tokamak, which the company plans to use D-T to reach the burning plasma regime. CFS is targeting construction and operation of SPARC in the 2020's.

- *General Fusion* (Burnaby, British Columbia, Canada) has raised substantial capital to develop a fusion reactor based on a magneto-inertial concept. General Fusion's concept is based on utilizing shock waves driven in liquid metal to compress a magnetized plasma target to fusion conditions.
- *Tokamak Energy* **(**Oxfordshire, UK) is focused on the Spherical Tokamak concept as a route to commercial fusion energy. Tokamak Energy is planning to utilize high temperature superconductors to enable high-field, compact spherical tokamak fusion reactors. The company is currently operating the ST40 device which uses a 3T magnetic field and has a major radius of 0.4 m.

FIGURE 6.23 Neutral beam injector on TAE Technology's C-2W. SOURCE: Tri Alpha Energy.

Government investment has both indirectly and directly enabled the growing private fusion industry. The indirect support stems from decades of investment in the federally funded fusion research effort, which has built a knowledge base that underlies all the current privately funded fusion ventures. Direct support for the fusion industry is a recent phenomenon and includes investment in a fusion energy program by the ARPA-E agency within DOE as well as new programs within DOE Fusion Energy Sciences. ARPA-E had a three-year program focused on fusion energy called ALPHA that was announced in 2015. The program was focused on "intermediate density" routes to fusion energy; concepts that fell between lower density MFE approaches and high-density inertial confinement fusion. This program primarily involved researchers interested in magnetized target fusion, an approach that blends MFE and inertial confinement fusion (ICF) approaches. ALPHA program participants included several fusion companies as well as university-based efforts that eventually lead to the formation of new fusion companies, in part due to ARPA-E support. ARPA-E has recently announced a second program in fusion energy research, the BETHE program, which targets lower-cost fusion energy concepts and innovative research that can help lower the cost of mainline fusion devices, including tokamaks and stellarators. DOE Fusion Energy Sciences recently created the INFUSE program as a route to public-private partnership in fusion energy research. INFUSE is modeled after the DOE Office of Nuclear Energy GAIN program and gives companies working on fusion energy access to resources at DOE national laboratories (funds go to the laboratories to support work for the fusion company). A limitation in the current INFUSE program is that it does not allow fusion companies to work with university researchers in the MFE area. There are public-private programs that go beyond the INFUSE model that could be utilized by DOE FES. In particular, NASA's Consumer Orbital Transportation Services (COTS) program was successful in stimulating the development of private solutions to reaching near-Earth orbit. A COTS-like program could also work in the fusion energy space, using milestone reimbursement to incentivize private companies to perform innovative research and development relevant to commercializing fusion energy.

In addition to industry focused on developing fusion reactors, the U.S. MFE program engages other industry partners, in particular as part of the ITER project. As of June 2019, $616 million in contracts has been awarded to U.S. industry to develop components for the ITER project. These components have ranged from superconducting magnet components, to cooling water systems to steady state electrical network components.

TABLE 6.2 MFE Facilities Cited in This Report

Facility	Description		Facility	Description
Alcator C-MOD*	Tokamak, MIT Plasma Science and Fusion Center.		JET	Joint European Torus, Culham Center for Fusion Research, UK.
ASDEX-U	Tokamak, Axially Symmetric Divertor Experiment Upgrade, Max Planck IPP, Garching		J-TEXT	Tokamak, Wuhan, China
CFETR**	China Fusion Engineering Test Reactor, Hefei, China		JT60-U JT60-SA**	Japan Torus 60-Upgrade, Naka Fusion Institute, Ibaraki, Japan
CFQS***	Chinese First Quasi-Axisymmetric Stellarator, Southwest Jiaotong University in China.		KSTAR	Korea Superconducting Tokamak Advanced Research, Daejeon, South Korea
CNT	Columbia Non-Neutral Torus stellarator, Columbia University		LHD	Large Helical Device Stellarator, Toki, Gifu, Japan
COMPASS	Compact Assembly Tokamak, Institute of Physics, Czech Republic		LTX-b	Lithium Tokamak Experiment upgrade, Princeton Plasma Physics Lab
CTH	Compact Toroidal Hybrid stellarator, Auburn University		MAST* MAST-U**	Mega Ampere Spherical Tokamak, Culham Center for Fusion Energy
C-2W (Norman)	TAE Technologies Field Reversed Configuration, Foothill Ranch, CA		MST	Reversed Field Pinch, Madison Symmetric Torus, University of Wisconsin
DIII-D	National Fusion Facility Tokamak, General Atomics, San Diego		NSTX*, NSTX-U**	National Spherical Torus Experiment and NSTX Upgrade, Princeton Plasma Physics Laboratory.
EAST	Experimental Advanced Superconducting Tokamak, Hefei, China.		Pegasus	Pegasus Toroidal Experiment Tokamak, University of Wisconsin
EPOS***	Electrons and Positrons in an Optimized Stellarator, Max Planck IPP, Garching, Germany		QUEST	Tokamak, Kyushu University, Japan
FuZE	Fusion Z-pinch Experiment, University of Washington		SPARC***	Commonwealth Fusion Systems tokamak, Cambridge, MA
HBT-EP	Tokamak, Columbia University		ST-40	Spherical Tokamak, Tokamak Energy, Oxfordshire, UK
Helimakc	Toroidal experiment for studying turbulence, University of Texas		SUNIST	Sino-UNIted Spherical Tokamak, Tsinghua University, China

HIDRA	Hybrid Illinois Device for Research and Application, University of Illinois		TCV	Tokamak à Configuration Variable (Variable Configuration Tokamak), École Polytechnique Fédérale de Lausanne, Switzerland
HL-2A	Tokamak, Chengdu, China		TFTR*	Tokamak Fusion Test Reactor, Princeton Plasma Physics Laboratory
HSX	Helically Symmetric Experiment Stellarator, University of Wisconsin		VEST	Versatile Experiment Spherical Torus, Seoul National University, S. Korea
ITER**	International burning plasma experiment, Cadarache, France		W7-X	Wendelstein 7-X Stellarator, Max Planck IPP, Greifswald, Germany
JET	Joint European Torus, Culham Center for Fusion Research, UK.		WEST	W(Tungsten) Environment in Steady-state Tokamak, Cadarache, France

* Not now operational or decommissioned.
** Under construction, renovation or upgrade.
*** Design phase.

THE MFE WORKFORCE

The workforce for the U.S. MFE research program has been evaluated recently through two processes: (1) a 2014 DOE FESAC subcommittee on MFE Workforce development, and (2) a survey conducted by the University Fusion Association (UFA) that produced a white paper on the "Status of university-based fusion science research" in 2017. Both of these evaluations expressed concerns over the status of university research groups in the MFE area. Survey data indicated an aging faculty and uncertainty on the prospect for future faculty hiring in MFE areas. The reports, and in particular the UFA report, raised concerns over declining University participation in DOE FES research programs. Over the last decade, there has been a major shift in the types of FES programs that engage University researchers. A major university experimental facility, Alcator C-Mod, ceased operations during this period (first slated for shutdown in 2012 but continued operating until 2016). In addition, a program that had supported a number of on-campus experimental facilities, the "Innovative Confinement Concepts" (ICC) program, was discontinued. At the time of these transitions, there were limited funding opportunities, and more importantly, access to intellectual leadership opportunities, for affected university researchers to re-engage with FES-funded MFE research. While funding is certainly important to maintaining healthy university programs, it is intellectual leadership that is often the most important currency in driving decisions for faculty hiring. University administrators and department faculty want to see that new hires have the opportunity to work on the most important research that has the most impact in the field in question and that there is a path to grow into national and international leadership. If it is perceived that such opportunities are not available, it is likely that hiring decisions will favor other fields of science or engineering. The demise of visible on-campus programs and the lack of equivalent opportunities for university researchers contributed directly to the uncertainty in future hiring prospects in MFE.

FES has recently implemented regular funding opportunities for research using the DIII-D tokamak, NSTX-U, and international experiments at facilities including W7-X, MAST-U, KSTAR and EAST. These programs are very welcome and have provided new opportunities to engage university researchers in the program. However, they do represent a shift to a new paradigm of off-campus research and a potentially more difficult path to intellectual leadership in the field. For major user facilities in other areas of science (and plasma science), such as light sources operated by DOE BES and laser facilities utilized in HEDP research, the user is the clear intellectual leader in the science being performed. The operator of the facility is focused on, e.g., providing photons and the high-impact science is tied to the target or sample that the user designs. This clear separation of roles is not present in MFE national facilities. The facility is designed with a particular goal or set of goals in mind and the team operating it is focused on achieving these scientific goals; as such the scientific leadership is generally controlled by that team. For current and past U.S. MFE facilities, the leadership team is a single institution (in contrast with major facilities and missions in other fields, such as major space missions where the team generally has PIs from multiple institutions). This structure does not make it easy for university faculty to see a path to intellectual leadership and to engage in the research program. Credit is due, however, to the institutions that currently operate U.S. MFE national facilities who have attempted to work within the current structure and engage collaborators/users in the scientific leadership. For example, while ultimate authority in setting scientific focus and runtime allocation for the DIII-D tokamak rests with General Atomics (working with DOE FES), the DIII-D program engages collaborators, including university researchers, in leading scientific thrusts and in deciding which proposals get runtime. This structure has led to university researchers growing into intellectual leadership roles and leading visible research programs on DIII-D. This is also true on international facilities, in particular the W7-X stellarator which has adopted a "one team" approach that engages collaborators in W7-X program leadership. U.S. researchers have been able to grow visible programs with leadership on W-7X for this reason, including recently hired faculty at U.S. universities. While it is difficult to change leadership structures of existing facilities, adopting policies like the "one team" approach, coupled with appropriate funding opportunities, could stimulate more engagement of universities in existing MFE programs. New major facilities should consider broader engagement from all stakeholders in the program and might be developed with teams drawn from multiple institutions including labs, universities and industry. The science of MFE can be addressed at facilities at a range of scales; there have been very few opportunities over the last decade for new intermediate scale and small-scale facilities. There are a range of frontier scientific opportunities that could be addressed at both scales. For example, quasi-symmetric stellarator at intermediate scale and a range of MFE technology and engineering issues could be addressed at small-scale. Opportunities to site these kinds of facilities at universities would offer a clear path to scientific leadership and enhanced visibility of MFE research.

These demographic changes and shifts in the types of funding opportunities for universities come at the same time as strong growth in privately funded fusion ventures and also a recent growth in federal funding for fusion research from DOE FES and DOE ARPA-E. There is strong demand for research scientists in the MFE area and in particular a need for a workforce skilled in fusion engineering issues including materials and nuclear technology such as tritium breeding. University programs are a critical source of skilled researchers for the MFE workforce and these programs must be renewed and strengthened to meet these needs.

FINDINGS AND RECOMMENDATIONS

U.S. magnetic fusion energy (MFE) research has long defined the forefront of fusion energy research for the international community.

> **Finding:** While the United States is still a major contributor to international MFE efforts and benefits from these collaborations, the U.S. program has lost ground and is at risk of losing leadership in several areas of MFE research.

Funding for MFE through DOE FES has seen unprecedented growth over the last few years, driven in part by growth in funding for ITER in response to significant progress in and new management of the project. Private investment in fusion energy research has grown substantially and helped boost federal programs through the development of private-public partnerships. At the same time, DOE leadership and Congress have made it clear to the community that continued strong support for the MFE program is contingent on the development of a community-driven, consensus strategic plan for MFE. ..

Finding: The absence of a consensus strategic plan for fusion research in the United States is an important factor in our falling behind on international developments, a situation compounded by the lack of vetted designs for new experimental facilities.

Such a strategic plan for the fusion program will allow DOE and Congress to make informed decisions about the specifics of fusion program funding, will position the community to respond to new opportunities (for example, new major facilities) and be able to prioritize in the event of downward funding pressure. The NAS Burning Plasma report called for regular strategic planning in the U.S. MFE community and called out the need for new experimental facilities, in particular at large scale. At the time of this writing, an FES community planning process is being conducted with the goal of developing a strategic plan. There also are opportunities for U.S. leadership to be re-established through investment in smaller intermediate scale facilities.

Finding: A roadmap is needed that is enabled by new experimental MFE facilities in the United States with opportunities across a range of scales when appropriate,

Finding: To enable proper planning and to enable creation of a roadmap, ongoing feasibility and facility design activities are essential.

Recommendation: DOE FES should undertake regular strategic planning, led by the U.S. MFE community, as recommended in the NAS *Burning Plasma Report*.

Recommendation: Aligning with the *NAS Burning Plasma Report*, DOE FES should develop a roadmap for the development of commercial fusion power in the United States.

Over the last decade, the landscape of MFE research at universities has changed substantially. Programs that had funded large university experimental efforts were terminated and new equivalent opportunities to participate in forefront MFE research were not made available to universities. At the same time, the average age of university faculty and researchers is increasing and new hiring in MFE areas has declined. At some institutions this is reaching a critical point where longstanding MFE programs may cease to exist.

Finding: Declining participation by universities in the MFE program reduces the level of innovation in the program and is a direct threat to the health of the field. It is essential that the MFE program respond to this crisis.

Finding: Renewing and growing new efforts at universities could be enabled by providing university researchers opportunities to participate in and, more importantly, lead the most important research programs in the field.

This opportunity for intellectual leadership is essential to convince university faculty and administrators that hiring in MFE should be prioritized over hiring in other areas of research in science and engineering departments. Creating such opportunities represents an important but indirect way to promote faculty hiring. Other fields of plasma science have used more direct approaches to re-invigorate their fields, for example the NSF Faculty Development Program in Space Sciences provides, along with other resources, funding to pay the salary of a newly hired faculty member until tenure is granted. This has been and continues to be effective in creating new faculty positions at several institutions. The program signals the importance of this area of work to the funding agencies and lowers the cost to the university of bringing in a new faculty member.

Finding: There is a need to grow efforts in fusion engineering and an opportunity exists to stimulate university programs in this area using both the indirect and direct mechanisms discussed above.

Recommendation: DOE FES should structure funding opportunities in MFE to provide leadership opportunities to university researchers and to directly stimulate the hiring of university faculty.

Examples of the above include major new facilities or missions that could be organized with leadership teams that involve university researchers; major activities in the field could be organized around centers that are led by teams including university researchers; and specific programs could be implemented to provide funds or other incentives for the creation of faculty positions (example: NSF Faculty Development Program in Space Sciences).

Finding: A recent Office of Management and Budget decision targeted at limiting duplication in education and outreach programs in funding agencies caused the loss of discipline specific graduate fellowships and outreach programs in DOE Office of Science (SC).

In DOE FES, this resulted in the loss of the Fusion Energy Sciences Graduate Fellowship Program and the National Undergraduate Fellowship (NUF) Program in Fusion. Working within the new rules, SC has attempted to replace these programs. A new Internship program for graduate students has been established that provides short-term funding (< 1 year) for students to spend time at national laboratories working on their thesis project. The NUF program has been merged with the DOE Science Undergraduate Laboratory Internships (SULI) program that provides research opportunities for undergraduates at national laboratories, but the possibility of working on MFE research at universities was eliminated.

Finding: These programs are important but lack the effectiveness of the former graduate fellowship and NUF program in attracting new talent into the MFE field.

The lab internship program is useful for students who have already made the decision to work in MFE but is not as effective as a 3 year graduate fellowship in attracting students to the field.

Finding: The NUF program and the graduate fellowship could be used as a tool to enhance diversity within the MFE research community.

It should further be noted that the removal of student support for university based MFE research further disincentives universities from hiring or retaining faculty engaged in MFE science.

Recommendation: The DOE Office of Science should restore discipline-specific graduate fellowships and undergraduate research programs that support MFE research at U.S. universities as a vehicle for attracting new and diverse talent into mission-specific areas such as MFE, and for maintaining a presence in university science and engineering programs.

Finding: There has been significant growth in non-traditional support of MFE research, i.e., support other than that provided by DOE FES, including privately funded fusion companies, philanthropic organizations, and DOE-ARPA-E.

Most of these efforts are based on non-mainline approaches to magnetic fusion, significantly broadening the range of risk-reward tradeoff with a goal to develop lower cost paths for fusion. The emergence of these efforts has occurred while the DOE FES program has become more concentrated on mainline approaches and ITER. The breadth of the collective MFE portfolio is therefore similar to that when DOE FES funded a wider range of approaches, like the Innovative Confinement Concepts program. However, the structure is complicated in having private investments and federal support in different offices.

Finding: There is a danger that the knowledge base, including that generated by former DOE FES supported research, could become increasingly fragmented. Some challenges, for example the development of key technologies and materials, are similar even if the fusion configurations are distinct. Solving these challenges through separate efforts increases overall cost and timescales.

Recommendation: Federal agencies funding the development of MFE science and technology (DOE-FES and DOE-ARPA-E) should leverage privately and philanthropically supported fusion research and vice versa.

Collaborative programs that bridge the public-private sectors can advance fusion development more effectively if they are adequately coordinated. The new INFUSE program is a step in this direction, however the opportunity to be involved should not be limited to DOE national labs. Many of the privately funded efforts and those being proposed by ARPA-E are closely related to projects that were formerly supported at universities. There are also private entities whose business models are focused on supporting capabilities like computation or technology and not the development of a fusion power source per se. In particular, DOE FES can facilitate a coordinated effort of the combined public-private sectors through leveraged investments that support high-risk, high-reward elements of a balanced portfolio of different approaches and by supporting facilities and capabilities for the development of technologies, materials and computing capabilities that are largely generic to fusion systems.

7

The Cosmic Plasma Frontier

OVERVIEW

Plasma heliophysics and astrophysics have been at the vanguard of extraordinary discoveries in the past decade, exciting worldwide interest from the public and scientists alike. Humanity left our solar system and took the first physical step into the interstellar medium (ISM) plasma with the venerable Voyager 1 and 2 spacecraft, the farthest human-made objects from the Sun. The pioneering Parker Solar Probe (PSP) is plunging repeatedly into the plasma of the solar corona, becoming the closest human-made object to the Sun. The first views of plasma orbiting the innermost neighborhood of a black hole, and of the plasma surrounding two merging neutron stars accompanied by detection of gravitational waves, have shed "light" on the most exotic events and objects in the plasma universe. The plasma environment's role in shaping the habitability of the exploding number of detected exoplanetary systems, ranging from the chemistry of the atmosphere to the development of life forms, is now being explored on many fronts. These discoveries and the promise of breakthroughs to come are fascinating scientists and the general public alike. All this occurred a mere 60 years after the start of the space age. (See Figure 7.1.)

The vast majority of baryonic (non-dark) matter in the Universe is in the form of plasma, spanning a stunning range of physical conditions, spatial scales, and dynamics. Space and astrophysical plasmas (SAPs) reach regimes inaccessible to earthbound laboratory experiments, enabling deep insights into fundamental plasma processes that impact observations and understanding of the formation and evolution of the universe. Some can be sampled directly by spacecraft, while others only reveal their secrets through spectroscopy, imaging, polarimetry, and other remote-sensing techniques. SAPs are also fascinating and exotic—from solar flares to active galactic nuclei to black-hole accretion disks—giving plasma physics high visibility and importance in the quest to understand heliophysics and astrophysics.

To understand and predict how the plasma universe around us operates, the fundamental physical processes responsible for phenomena ranging from electron-scale interactions to galaxy clusters need to be explored. Magnetic fields are paramount in governing the behavior of cosmic plasmas and play a key role in determining the habitability of our planet. Progress has been made, but more is needed, in determining how magnetic fields are generated in planets, stars, and galaxies, and how this magnetic energy is stored and released impulsively in the form of eruptions, geomagnetic storms, and other explosive events. Magnetic reconnection—the breaking and reconfiguring of magnetic fields—is the primary candidate to explain impulsive energy release, yet it is barely understood why it occurs at certain locations and times and how the liberated energy is partitioned among mass motions, particle acceleration, and heating. This ubiquitous mechanism is thought to explain the onset of stellar and accretion-disk flares and mass eruptions, magnetospheric storms on Earth and other planets, and γ-ray flares from the Crab Nebula. New observations and computational methods have revealed much about reconnection in cosmic settings, particularly in collisionless plasmas, but the fundamental processes governing this important phenomenon are still not well understood.

FIGURE 7.1 Space and astrophysical plasmas span an enormous range of scales. (top) The heliosphere encompassing our solar system contains plasmas surrounding current sheets in the Sun's corona (~10^{-5} km), planetary plasmaspheres (thousands to millions of km), and the interplanetary medium (10^{10} km across). (middle) The Voyager spacecraft have already penetrated the limits of our solar system – the heliopause that separates the influence of the Sun from interstellar space – on their way to the Oort cloud (the birthplace of comets) and nearby astrospheres. (bottom) Beyond lies the exotic plasma physics of galaxies (10^{18} km across) and vast clusters of thousands of galaxies. SOURCE: Top: Charles Carter / Keck Institute for Space Studies; middle: NASA/JPL-Caltech; bottom: NRAO.

Eruptive events often drive shocks, which alter plasma properties substantially, generate waves and turbulence, and can accelerate ions and electrons to high energies. Within our heliosphere (the volume occupied by the magnetic field produced by and enveloping the Sun), shock-accelerated particles can endanger astronauts and spacecraft; higher-energy cosmic rays generated by supernova shocks and other sources can cause even more damage and can penetrate far into our atmosphere, perhaps affecting weather and mutating genes. Reconnection, shocks, and waves both generate and are generated by turbulence**,** which redistributes energy from large to small scales while increasing the complexity of the ambient plasma. Turbulence also accelerates and disperses charged particles, and may heat stellar coronae. Not all plasmas in the universe are fully ionized; the solar chromosphere, planetary ionospheres, the outer astrosphere, the ISM, and protoplanetary accretion disks all contain neutral atoms and molecules, which are not tied to the magnetic field as charged particles are. Partial ionization substantially alters the dynamics and energetics of the entire plasma system, through interactions between the charged and neutral particles, different responses to radiative input, and modifying conductivity and dependent processes (e.g., reconnection and turbulence).

The full range of phenomena found in SAPs has counterparts in other areas of plasma physics. This overlap is particularly valuable for advancing our understanding of the underlying fundamental mechanisms. Magnetic reconnection, particle acceleration, turbulence, shocks, and instabilities govern energy release and transport in laboratory devices such as toroidal plasmas and inertial confinement fusion experiments, as well as in stellar eruptions, planetary and pulsar magnetospheres, and galactic winds. The complex dynamics and energetics of partially ionized plasmas and ion-neutral coupling dominate stellar chromospheres, planetary ionospheres, comets, and the ISM, and are the processes in applications of low temperature plasmas for chemical conversion and materials processing (Chapter 5). Fundamental dimensionless parameters such as the ratio of the particle mean free path to the system size, the ratio of thermal to magnetic pressure, the fluid and magnetic Reynolds numbers, and the ratio of the gyroradius to the system size enable advances in apparently unrelated environments to apply elsewhere. For example, collisionless plasmas are found in Earth's magnetosphere, stellar winds, and the diffuse medium permeating galaxy clusters. Fusion devices contain high energy-density plasmas (Chapter 4), as do stellar interiors, black hole inflows, and the cores of super-Earths and hot Jupiters.

The plasma β (ratio of thermal to magnetic pressure) in SAPs varies widely depending on the environment. For example, β is less than 1 in the very local interstellar medium, the solar corona, and the outer regions of molecular clouds, whereas β ≥1 in the solar wind, stellar convective zones, planetary magnetosheaths, and the intracluster medium. Fusion plasmas (Chapter 6) are necessarily low β, and thus have some commonalities with and substantial differences from high-β SAPs. Because of these differences and similarities, we can develop deep insights into different plasma behaviors by studying and comparing both fields.

Advances in observational capabilities, and extensions to new diagnostic regimes, invariably uncover new phenomena, challenge existing theories and spark new ones, and motivate cross-disciplinary collaborations. In the past decade a wealth of new heliophysics missions populated geospace and our heliosphere, complementing continuing missions to form the Heliophysics System Observatory. Breakthrough advances in plasma astrophysics were brought about by data generated by space-based high-energy observatories. The advent of smallsats and cubesats has begun a new era of in-situ multipoint observations, which are essential for understanding the connections between kinetic and global-scale behaviors, and has driven innovative developments in miniaturization of instruments. In parallel, new ground-based facilities have opened new windows on nearby and remote cosmic plasmas.

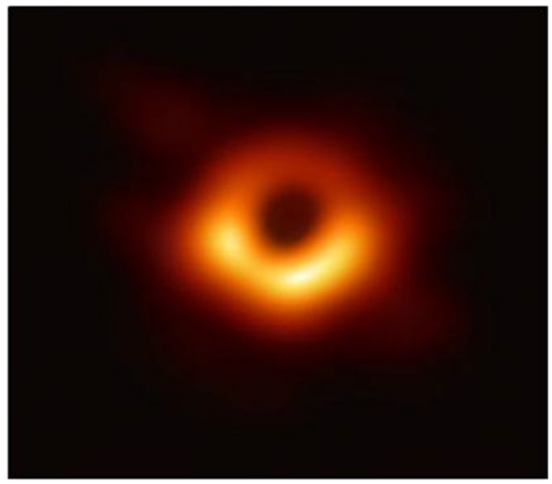


FIGURE 7.2 The first direct image of plasma orbiting a black hole, taken by the Event Horizon Telescope. The radio image shows hot relativistic plasma surrounding the supermassive black hole at the heart of the galaxy M87, orbiting at nearly the speed of light. In the center, the shadow of the black hole is silhouetted against the heated material spinning around it. The appearance of the disk is strongly distorted by the general relativistic effects of light bending. From Event Horizon Telescope Collaboration et al. 2019. SOURCE: The Astrophysical Journal Letters,875:L5, 2019, https://doi.org/10.3847/2041-8213/ab0f43, ©2019.

The high-resolution, high-cadence images of the solar corona obtained by the Interface Region Imaging Spectrograph (IRIS), Hinode, and the Solar Dynamics Observatory (SDO) have revealed distinct prerequisites and signatures of magnetic reconnection in explosive jets, flares, and coronal mass ejections (CMEs): plasma sheets surrounding current sheets, inflows, Alfvénic outflows, and plasmoids. The transition from the magnetically structured solar corona to the more isotropic, turbulent solar wind was seen for the first time in images from the Solar TErrestrial RElations Observatory (STEREO) Heliographic Imager. Quasiperiodic plasma density structures were tracked from the inner heliosphere to their impact on Earth's magnetosphere, by combining data from multiple spacecraft and modeling. These periodic plasma bursts were speculated to be "fossil" markers of structure generated near the Sun. Such structures in the solar wind have long been known to drive compressional oscillations in Earth's magnetosphere, thus affecting particle energization and losses in the radiation belts. Recent investigations by PSP have identified other signatures of this solar wind driving and, most important, established that these pulses originate at the Sun. The mysteries of collisionless reconnection are being unraveled by the Magnetospheric Multiscale (MMS) mission, a 4-spacecraft cluster. By measuring electron distribution functions in a reconnection site in the magnetotail, MMS found strong support for a leading explanation for magnetic field-line breaking. Van Allen Probes discovered a third radiation belt and identified waves in the belts that accelerate particles and those that contribute to particle precipitation. The twin Voyager spacecraft, launched in 1977, have journeyed well past their nominal 5-year missions and are headed into the ISM, revolutionizing our understanding of the interaction of the solar wind with the local interstellar medium (LISM).

An impressive example of exotic plasma physics is the recently imaged supermassive black hole (BH) in the galaxy M87 by the Event Horizon Telescope (Figure 7.2). This image shows the radiation of the hot, dense plasma orbiting the black hole, which emits no radiation. In conjunction with the groundbreaking detection of gravitational waves from cosmic events, electromagnetic emissions from the turbulent plasmas surrounding the BH gave vital clues about the nature and characteristics of the system—information that could not be derived from gravitational radiation alone. The detection of exoplanets (planets orbiting stars other than the Sun) in an extraordinary range of plasma environments has exploded over the past decade. These discoveries challenge our previous understanding of planetary formation and evolution, while illustrating the power, and success, of applying theories and numerical models developed to understand our solar system to investigate exoplanets in the very different environments of distant stars. These observations and insights are being leveraged to answer some of the most fundamental questions about how Earth evolved, and how the radiative output and eruptive activity earlier in our Sun's history affected Earth's atmosphere, oceans, and development of life. Lessons learned from these studies will enable us to look for the markers that may indicate that life is possible on other planets.

New computational techniques and computer architectures (Chapter 2) have emerged to rapidly advance our investigations of SAPs. These advances have enabled massive particle-in-cell (PIC) and gyrokinetic simulations of kinetic-scale instabilities and waves over larger system sizes than ever before. Highly detailed magnetohydrodynamic (MHD), multi-fluid, and hybrid simulations model the initiation and propagation of solar eruptions from the Sun to Earth and beyond, reveal the dynamic evolution of planetary magnetospheres in stellar systems, and capture the relativistic chaos surrounding black holes. (See Figure 7.3.) Substantial progress has been made toward overcoming the challenges of assimilating and leveraging huge amounts of data and using that data to guide complex simulations. Automated feature recognition, machine learning (ML), and artificial intelligence (AI) methods are being introduced for data mining and analysis, to cope with the growth of large datasets that cannot be adequately processed by existing techniques for reducing, calibrating, cleaning, and visualizing these data.

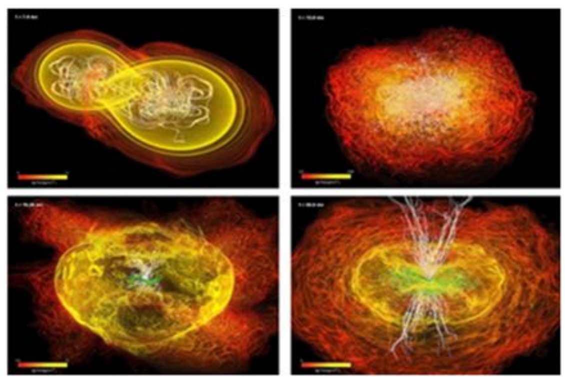


FIGURE 7.3 General relativistic MHD simulation of the evolution of merging neutron stars leading to the formation of a black hole, accretion torus and hot ejecta, and generation of collimated magnetized outflow. The jet produces a short g-ray burst. The color-code map shows the density, with selected magnetic field lines (white) superposed. SOURCE: Rezzolla et al. 2011, ApJL 732 L6, https://iopscience.iop.org/article/10.1088/2041-8205/732/1/L6/meta.

Perhaps the most striking growth area in SAP having direct, on-the-ground societal benefit has been the science of space weather—the causes and consequences of activity generated at the Sun that propagates through the heliosphere toward planetary surfaces, and Earth in particular. Both living organisms and technology can be adversely affected by these solar disturbances that interact with our magnetosphere and ionosphere. Our worldwide dependence on reliable electricity, global-positioning satellites (GPS), and telecommunications relies on stable and quiescent plasmas surrounding Earth and in its ionosphere. Consequently, the disruption of these plasmas by energetic particles and hard radiation from solar eruptions can lead to widespread power and communications outages, and infrastructure damage that could take years to repair. Energetic particles and radiation pose even greater threats to manned space travel and bases on the moon and planets that lack the natural protection that magnetic fields provide. To understand and ultimately predict space weather events, we must develop deep physical insight into all plasma mechanisms that initiate, transport, and transform these energetic storms. Space weather is now recognized by the U.S. government as a natural threat, motivating disaster preparedness as well as investments in basic and applied research. The understanding developed from our knowledge of space weather on Earth also is more broadly applicable to planetary space weather and to the issue of habitability on planets and exoplanets. Water may be necessary for all known instances of life, but it is not sufficient to ensure its survival if extreme space weather events can damage the planet's atmosphere.

Space and astrophysical plasma research in the United States is funded predominantly by NASA, NSF, DoD, and DoE. NASA's Science Mission Directorate funds space missions and instruments, data analysis, theory and numerical simulations, as well as a small amount of funding for ground-based observations and laboratory experiments in support of its missions. The research side of NASA's Human Exploration Mission Directorate supports applied research on solar energetic particles (SEPs), with the aim of protecting astronauts from harmful exposure. NASA's Space Technology Mission Directorate primarily supports development of the crosscutting, pioneering, new technologies and capabilities needed for current and future missions, using high-performance computing and technology demonstrations to test emerging instrument concepts. NSF funds existing and new ground-based facilities, a wide range of research in space, solar physics, astronomy and astrophysics, aeronomy and the plasma physics of the upper atmosphere, the National Center for Atmospheric Research (NCAR) and its subsidiary High Altitude Observatory (HAO), and some cross-disciplinary programs that bring together basic plasma and space/astrophysics research. DoD supports university and commercial SAP research through ONR, DARPA, and AFOSR, and internal (at DoD facilities) research and facilities at the Naval Research Laboratory (NRL) and the Air Force Research Laboratory (AFRL). A modest program of space and astrophysical plasma research by the external community is supported by DoE, along with projects within the agency relevant to DoE needs (e.g., updated atomic physics and opacity tables). Several DoE international (e.g., PPPL-Max Planck) and domestic (e.g., with NSF) collaborative programs touch on SAPs. The highly successful but perpetually underfunded NSF/DOE *Partnership in Basic Plasma Science and Engineering* has been extensively utilized by members of the space plasma physics and plasma astrophysics communities since 1997, often in collaboration with plasma physicists in different subdisciplines. A significant improvement in interagency collaboration between NASA and NSF was announced as this report was being completed. The new program, *Next Generation Software for Data-driven Models of Space Weather with Quantified Uncertainties (SWQU)*, will support teams of researchers to develop comprehensive space-weather models from Sun to ionosphere). This exemplary collaboration will address both fundamental science and translational research.

RELEVANCE AND BENEFITS

Science Advances

Astrophysical Plasmas

The last decade brought us discipline changing discoveries in the field of plasma astrophysics. For the first time, in August 2017 the Laser Interferometer Gravitational-Wave Observatory (LIGO)/Virgo collaboration detected the merger of two neutron stars in the galaxy NGC 4993 by their gravitational wave signatures. Just a few seconds later, the Fermi Gamma-ray Observatory (Fermi) observed a γ-ray burst at the same location. Within hours, intense optical emission was detected from the same region. Ultimately, more than 60 telescopes monitored the electromagnetic counterpart for weeks until its optical and infrared emission decayed. This long-awaited detection ushered in a new era in multi-messenger astronomy (i.e., coordinated observations using different "messenger" signals: electromagnetic radiation, gravitational waves, neutrinos, and cosmic rays.) The observations were consistent with a kilonova—the radioactive-decay–powered ejecta of neutron-rich material—as predicted by state-of-the-art MHD models. Emission during a kilonova can come from multiple plasma sources, and each component can reveal different information about the original neutron stars and their merger.

Much of the excitement surrounding this first detection of merging neutron stars was centered on their role in producing heavy elements. Low-mass elements are produced in low-mass stars and expelled into the ISM late in stars' lives, while heavier elements are produced in supernova ejecta. For heavier, so-called *r*-process (rapid neutron capture) elements, it was postulated as early as 1957 that neutron star mergers would result in neutron-rich ejected plasma that could produce these heavy elements. The detection of a neutron star merger, combined with the first spectroscopic detection of elements heavier than Xe, open up the possibility of probing the formation site of these heavy *r*-process elements. However, interpretation, analysis, and modelling of the observed spectra are severely hindered by the sparsity of atomic opacity data and model predictions for these *r*-process elements under kilonova conditions.

In many astrophysical settings the magnetic field controls the overall dynamics of the plasma, while the dissipation of magnetic energy may power the observed high-energy emission. In the past two decades, magnetars (strongly magnetized neutron stars possessing super-strong magnetic fields), pulsars and pulsar wind nebulae, jets of active galactic nuclei, γ-Ray Bursters, and coronae of accreting black holes have been the subjects of intensive observational studies by X- and γ-ray instruments on several satellites. These objects share one important property: relativistic plasmas that are magnetically dominated—the energy density is mostly contributed by the magnetic field rather than by the rest mass. This exotic, astrophysically relevant plasma regime differs dramatically from laboratory plasmas, planetary magnetospheres, and the interplanetary medium, and hence requires targeted, systematic study.

Other major discoveries in plasma astrophysics since 2010 include: very short and intense fast radio bursts; rapid γ-ray flares at GeV photon energies in the Crab pulsar wind nebula; ultra-rapid (~10 min) TeV flares in blazar jets emanating from active galactic nuclei; giant BHs swallowing stars in tidal disruption events; and the IceCube neutrino observatory detection of a very energetic neutrino coincident with a flaring blazar. The plasma parameters in these events differ substantially from those of traditional laboratory plasmas, planetary magnetospheres, and the IPM, as they include several "exotic" physical processes. The plasma is often relativistic in terms of particle speeds, bulk motions, and characteristic wave speeds. Radiation-reaction effects (e.g., synchrotron or inverse-Compton radiative cooling), electron-positron pair creation, ultra-strong magnetic fields, quantum electrodynamics (QED), and general-relativistic effects are all important.

In the last two decades, exoplanet science has moved rapidly beyond its initial discovery phase. With thousands of exoplanets already confirmed, researchers are now investigating key issues such as planet formation, evolution, structure, and habitability. Understanding the properties of the plasmas deep in planetary interiors and their enveloping atmospheres is essential to all these studies. Understanding the interiors of gas giants and super-Earths requires understanding matter under extreme pressures, introducing new domains of plasma physics. Fortunately, exoplanet observations and interpretations that need knowledge of plasmas under Megabar pressures now can turn to direct laboratory studies of these extreme conditions (see Chapter 4).

The large number of exoplanets already discovered invites questions about whether those planets ever had (or will have) conditions that can support life. Cross-disciplinary studies are applying space-weather theories and models developed for our solar system to answer these questions. With knowledge of the evolution of our own solar system, the models are being used to investigate conditions on hot Jupiters, super Earths, and other previously unexplored exoplanet environments. For example, observations of over 1500 stars by the Kepler space telescope designed to discover exoplanets showed that young, fast-rotating, solar-type stars produce superflares. Simulations of extreme eruptions in such fast-rotator systems, however, found that the tightly wound interplanetary magnetic field complicates and extends the routes taken by the resulting accelerated particles to the exoplanets. Simulations of the possible effect of superflare produced energetic particles on life-enabling conditions on orbiting planets suggest that the conditions that could foster Earth-like living organisms are quite narrow in terms of radiation dose, atmospheric properties and chemical composition and presence of liquid water. Therefore, habitability studies have focused on establishing factors besides simple distance from the star that can push a planet into or out of the "Goldilocks" zone amenable to life. Many factors have been clarified by adapting heliophysical models for exoplanetary and young-Sun conditions: the presence and cyclic nature of a magnetic dynamo, the ability of stellar winds to strip away a planet's atmosphere, the existence of stellar eruptions that are orders of magnitude more energetic than those of our Sun, and the capability of stellar eruptions to change the atmospheric chemistry and irradiate the surface. While our Sun was still "young", for example, solar eruptions (CMEs and eruptive flares) were substantially stronger and more frequent than today, and Earth's atmosphere was more nitrogen-dominated. Recent simulations have shown that energetic particles from those solar eruptions could have changed Earth's atmospheric chemistry sufficiently to warm the early Earth through a greenhouse effect (Figure 7.4). The possibility of life elsewhere in the universe excites both scientists and the public, and plasma science plays a key role in this quest.

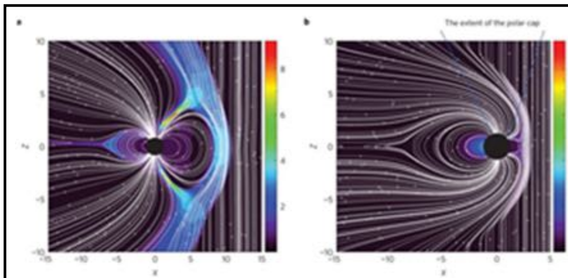


FIGURE 7.4 Two snapshots from a 3D simulation of the impact of a large CME from the young Sun on the magnetosphere and ionosphere surrounding the early Earth. The white lines are magnetic field lines, and the color shading shows plasma pressure. Axes represent distance from the Earth's center in units of Earth radius. (left) Initial conditions at t=0. (right) Two hours after CME launch, when the CME hit the early Earth's magnetosphere. This study assumed a steady-state paleo-solar wind at 0.7 Gyr with a mass loss rate of 1.7×10^{-12} M_{sun} yr^{-1}. SOURCE: https://iopscience.iop.org/article/10.3847/2041-8205/817/2/L24/meta

Heliophysical Plasmas

All solar phenomena include plasma physics. High-resolution, high-cadence imaging of the Sun, by space missions such as the Ramaty High Energy Solar Spectroscopic Imager (RHESSI), SDO, and IRIS, and by ground-based facilities such as the Goode Solar Telescope and the Extended Owens Valley Solar Array (EOVSA), has revealed key small-scale features and transient events. Distinct signatures of magnetic reconnection in eruptive events, from tiny jets to huge coronal mass ejections, and the formation of plasmoids in flare current sheets (Figure 7.5), were detected for the first time, testing long-standing theories and firmly establishing the role of reconnection in impulsive energy release.

An outstanding unsolved problem in solar physics is how the corona is heated—this outermost layer of the Sun is nearly 3 orders of magnitude hotter than the surface. The corona is believed to be heated by nanoflares (small reconnection events), ion cyclotron waves, and/or magnetic turbulence. Observations by IRIS and the rocket-borne EUNIS spectrometer find some evidence for nanoflare heating, including nonthermal electron beams generated by these tiny events, but little agreement yet exists. The committee anticipates that Parker Solar Probe might provide a definitive answer.

The MHD dynamo that generates and recycles the Sun's magnetic field is sustained by the energy of internal plasma motions such as differential rotation, turbulent convection, and meridional circulation. The toroidal magnetic field is generated through the stretching of the poloidal component of the magnetic field by differential rotation (different rotational speeds at different latitudes), and is widely believed to be

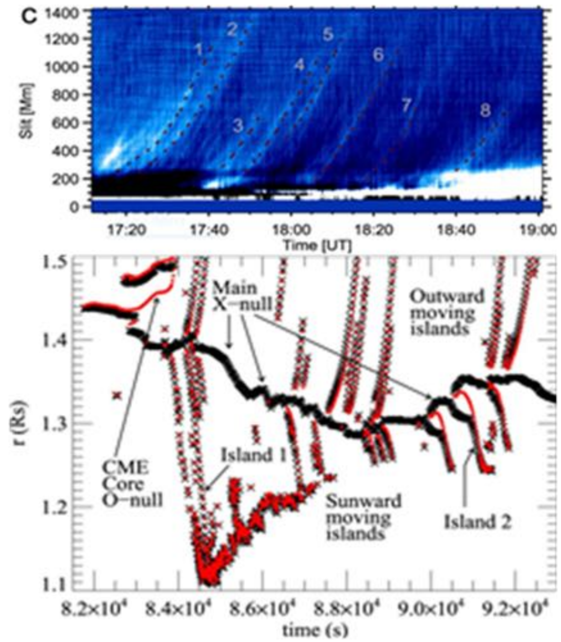


FIGURE 7.5 High-resolution observations and MHD simulations agree that plasmoids form in flare current sheets. (top) Time–distance plots of running-difference K-Cor white-light images along the direction of the flare current sheet behind a CME. The white curved tracks, traced by dashed lines, denote the trajectories of eight anti-sunward moving blobs (from Cheng et al. 2018). (b) Time-distance plots of sunward and anti-sunward O-type nulls (plasmoids) tracked in a high-resolution, adaptively refined, 2.5D MHD simulation of a CME (from Guidoni et al. 2016). Note that the times and heights in the two plots differ, because the simulation has not been scaled to the size and characteristic speeds of the observed CME. SOURCE: Top: X. Cheng et al 2018 ApJ 866 64; bottom: S. E. Guidoni et al 2016 ApJ 820 60.

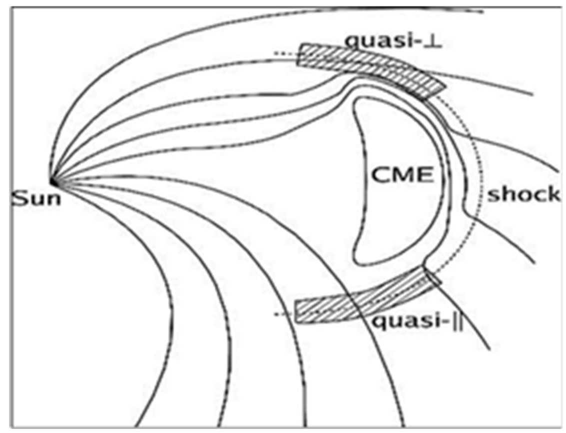


FIGURE 7.6 Schematic of a CME-driven shock (dotted line) in interplanetary space, illustrating the variation in shock obliquity along the front and corresponding regions of high injection-energy thresholds (hatched regions). Curved black lines are magnetic field lines originating at the Sun. Here 'parallel' and 'perpendicular' refer to the angle between the shock normal and the upstream direction of the IMF. SOURCE: G.P. Zank, G. Li, V. Florinski, Q. Hu, D. Lario, and C.W. Smith, 2006, JGR, 111, https://doi.org/10.1029/2005JA011524.

stored and amplified at the tachocline, the thin, highly sheared layer between the Sun's rigidly rotating radiative core and its differentially rotating convective zone. Strong toroidal flux tubes are unstable to magnetic buoyancy and erupt through the surface, producing sunspots that are strongly magnetized and give birth to most fast solar eruptions. The poloidal field is thought to be regenerated through a combination of convection-zone turbulence and the redistribution of the magnetic flux from tilted bipolar sunspot pairs. The dynamo-mediated evolution of solar magnetic fields governs solar irradiance variations and eruption frequency, which affect planetary atmospheres and magnetospheres. A recent breakthrough in dynamo simulations has produced cyclic, solar-like polarity reversals of the large-scale magnetic field. Although advances have been made since Plasma 2010 in understanding the complex, nonlinear dynamo system of our Sun, we are still unable to definitively predict whether the downward trend in the solar magnetic output during the last few sunspot cycles will be a long-term decline, as in the Maunder minimum (1645-1715).

Solar eruptions are the most energetic phenomena in the solar system. Large eruptions release about 10^{24}–10^{25} J and can accelerate particles to energies of several GeV per nucleon. RHESSI has raised new questions about particle acceleration in solar flares: how can electron-associated hard X-rays (HXRs) and ion-associated γ-rays be separated by large distances, and how can relativistic flare electrons persist and produce intense radiation in the corona? Two astrophysics missions also contributed to our understanding of impulsive electron and ion acceleration on the Sun. Fermi observed γ-rays from ions accelerated to at least several GeV, as well as pion decay from accelerated ions in many large eruptions. More puzzling, Fermi detected γ-ray emission coming from various regions of the solar atmosphere, prompting heated debates about how particles gain access to and remain in these regions. At the other extreme, the Nuclear Spectroscopic Telescope Array (NuStar) made great strides in understanding electron acceleration in active-region microflares—the faintest solar flares ever observed in HXRs.

An understanding of energetic particles in SAPs, as well as laboratory plasmas, is closely related to our understanding of collisionless shock waves and turbulence. Shocks are ubiquitous in the heliosphere, ranging from those generated by CMEs (Figure 7.6) to forward and reverse shocks created by interacting solar-wind streams (co-rotating interaction regions (CIRs)), shocks in the distant heliosphere, and the heliospheric termination shock. Collisionless shocks are observed in the heliosphere as interplanetary (IP) shocks, inferred in supernovae and accretion disks, and are often associated with energetic particles, With the increase in computational power, theory and simulation of collisionless shocks have progressed rapidly. Numerous satellites with increasingly resolved plasma and field measurements provide in-situ observations of shocks. NASA's growing Heliophysics System Observatory (Cluster, Time History of Events and Macroscale Interactions during Substorms (THEMIS), the Advanced Composition Explorer, Wind, and STEREO, in particular) provides multipoint shock measurements, yielding global insights into shock dynamics and structure on scales of hundreds to thousands of kilometers. Laser-driven supersonic plasma flows in the laboratory have been used to investigate collisionless shocks in a controlled setting using the Omega laser at the Laboratory for Laser Energetics and the National Ignition Facility (NIF; see Chapter 4). Recent experiments on Omega and NIF indicate that, in astrophysical environments, strong shocks generate and amplify magnetic fields and accelerate cosmic rays.

The Magnetospheric MultiScale (MMS) mission, launched in 2015, is a constellation of four closely spaced satellites that can fly as close together as 5 km. The mission was designed to measure electric currents and particle properties over a range of scales. Besides investigating Earth's bow shock, MMS has enabled new studies of IP shocks near Earth at scales that had previously been the preserve only of bow shock research. However, IP shocks are dynamically and structurally quite different from bow shocks, especially regarding energetic particles and their back reaction on shock structure. Missions such as MMS and PSP will provide unparalleled insights into IP shocks from kinetic to MHD and global scales.

Solar flares and CME-driven shocks are primary sites for accelerating electrons and ions as solar energetic particle (SEP) events, which propagate into the heliosphere along the interplanetary magnetic field (IMF). Predicting SEP impacts at multiple vantage points is of great practical importance in the development of reliable space-weather models capable, for example, of guiding astronaut safety decisions in the new "Moon to Mars" programs. In-situ measurements of charged-particle properties show that impulsive SEP events are primarily associated with solar flares, whereas gradual events correspond to CME-driven shock-accelerated particles. Since Plasma 2010, studies of SEP events have benefited from multi-point observations, revealing that energetic charged particles can diffuse considerable distances longitudinally and latitudinally, contrary to expectations. These investigations have revealed the complexity of energetic charged-particle transport, but many open questions remain: in particular, how particles diffuse transverse to the magnetic field, the precise acceleration mechanism for impulsive events, and. the properties of the "seed" particles before acceleration required to explain the observed fluence and energy.

The most likely acceleration process for gradual SEPs is diffusive shock acceleration (DSA), first proposed to explain the acceleration of galactic cosmic rays at supernova shocks. Gradual SEP and CIR-related events typically present an extended front of particles propagating away from (CME-driven shock) or towards (CIR shock) the Sun. For particles to be efficiently energized at a collisionless quasi-parallel shock (see Figure 7.6), they must be confined so that they diffuse across the shock multiple times. Ahead of the shock, Alfvén waves excited by a streaming instability can scatter some of the accelerated particles back toward the shock. Similarly, downstream turbulence generated and amplified at the shock traps particles in its vicinity. The transport of these energetic particles through the corona and heliosphere with their many shocks remains a difficult problem. Two competing effects influence their propagation: focusing along the IMF due to the decreasing magnetic field strength and pitch-angle scattering by IMF turbulence. Strong scattering allows SEPs to diffuse across the IMF, whereas weak scattering leads to particles streaming freely. Numerical modeling of CME

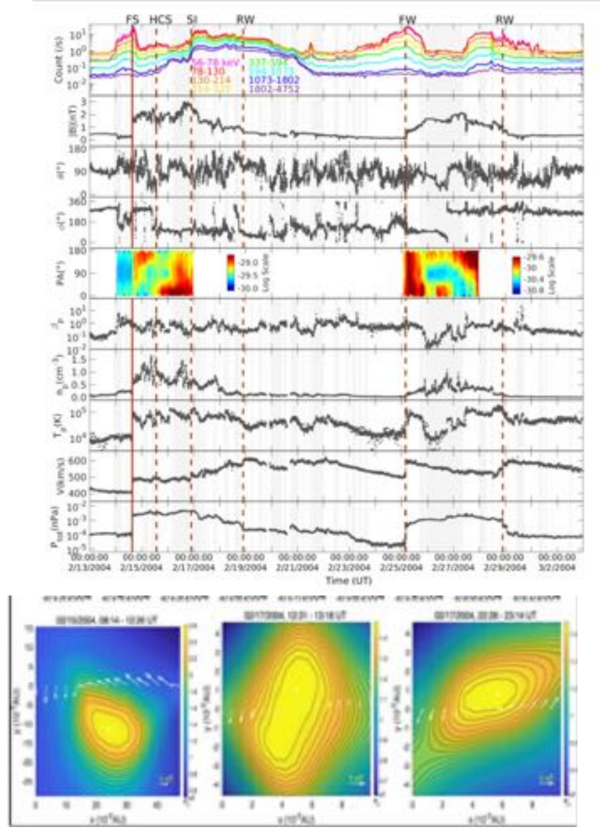


FIGURE 7.7 Ulysses observations of an energetic-particle event downstream of a shock near 5 AU showing evidence for accelerating charged particles in a "sea" of small-scale interacting magnetic flux ropes in the supersonic solar wind. The event characteristics are inconsistent with the predictions of diffusive shock acceleration (DSA), but may be explained by local acceleration in contracting flux ropes. The panels show Ulysses in situ observations from 2004 February 13 to March 3. From top to bottom, the panels are the energetic ion counts, the magnetic field strength (|B|), the elevation and azimuthal angles of the magnetic field direction in the RTN coordinate system, the pitch angle distribution of 116 eV electrons, proton beta, proton density, proton temperature, solar wind speed, and the total plasma pressure. The vertical maroon line shows the observation time of the forward shock (FS). The dashed vertical lines behind the shock identify the location of the heliospheric current sheet (HCS), the stream interface (SI), the first reverse wave (RW), the forward wave (FW), and the second reverse wave (RW), respectively. Shaded areas identify Grad-Shrafnov reconstructed magnetic flux ropes. SOURCE: L.-L. Zhao et al 2019 ApJ 872 4.

shocks and SEP events reached an impressive level of sophistication in the past decade, enabling detailed predictions that compare favorably to observed spectral, energetic, and temporal characteristics of large events.

However, some interplanetary SEP events have been observed that do not fit the DSA model. For example, in-situ particle and field observations by multiple spacecraft near the heliospheric current sheet and in Earth's magnetosphere indicate that SEPs may be associated with dynamically interacting flux ropes (helical magnetic structures that consist of a twist component and an axial field; also see Chapter 2). Theory and simulations demonstrate that flux rope merging and contraction can energize particles locally in the IPM (Figure 7.7) and in solar eruptive flares. Flux-rope contraction and coalescence in reconnecting current sheets therefore appears to be an alternative mechanism for accelerating particles in different SAPs, offering a promising avenue for further exploration in the next decade.

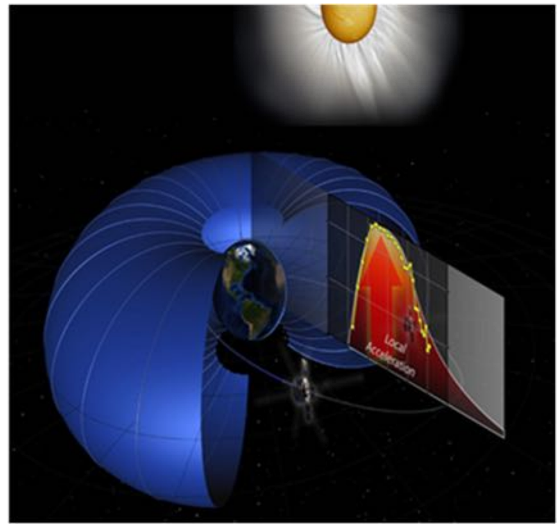


FIGURE 7.8 Data from Van Allen Probes revealed the mechanism that accelerates electrons to relativistic speeds in the Earth's radiation belts—local energy transfer from intense chorus waves excited by a geomagnetic storm. This resolves a long-standing problem in understanding the origin and evolution of the radiation belts, and illustrates the importance of simultaneous in situ measurements of plasma waves and particles in geospace. SOURCE: Science 30 2013: 341, 6149, 991-994, doi: 10.1126/science.1237743.

MMS has probed the inner core of magnetic reconnection sites, where both ions and electrons are decoupled from the magnetic field. This is the actual region where the magnetic field breaks and reconnects. The magnetosphere and many other cosmic plasmas are sufficiently rarefied that collisions between particles are infrequent. In such collisionless plasmas, identifying the mechanism for magnetic flux breaking during reconnection has been a long-standing challenge. For the first time, MMS observations verified a recent theoretical prediction of the underlying process by examining the shape of electron velocity distributions within a reconnection region in the magnetotail. This fundamental discovery illustrates the profound value of combining theory, computation, and state-of-the-art observations.

The recently decommissioned Van Allen Probes (VAP) brought new insights into the source, transport, and loss of charged particles within Earth's radiation belts (Figure 7.8), and the local-global coupling of the magnetosphere and solar wind. The VAP discovered a transient third radiation belt filled with ultra-relativistic electrons, which briefly appeared in September-October 2012 after a geomagnetic storm. Analysis of VAP data identified the long-sought location and source of electron acceleration in the radiation belts. Geomagnetic substorms inject electrons deep into the nightside magnetosphere where they produce chorus waves (a type of whistler wave), which in turn accelerate high-energy radiation-belt electrons to even greater energies. The causes of particle loss from the belts remain a topic of debate, but the likely explanations have been narrowed down by theoretical studies and VAP observations to magnetopause outflow, charge exchange, and precipitation into the ionosphere. In parallel with these observational breakthroughs, laboratory experiments on the Large Area Plasma Device at the University of California at Los Angeles, as discussed in Chapter 7, have contributed to understanding radiation-belt physics by using controlled energetic-electron beams to study the generation of and interaction with whistler waves.

Ionosphere, thermosphere, and mesosphere (ITM) plasma physics has made substantial progress on several fronts. Greater appreciation for lower atmospheric forcing of the ionosphere and thermosphere has emphasized how critical gravity-wave propagation and dissipation are to the thermosphere. Multiinstrument studies by the DoD-NASA C/NOFS (Communications/Navigation Outage Forecasting System) mission, sounding rockets, and ground-based radar facilities, accompanied by numerical modeling, have revealed the complex physics of plasma bubbles and depletions in the ionosphere. These investigations have shown the importance of primary instabilities (e.g., Kelvin Helmholtz) and neutral wind shears in seeding the more slowly growing Rayleigh-Taylor instability. DARPA's new Space Environment Exploitation program aims to accurately predict near-Earth space environment disturbances and perturbations (on scales as small as 100 km) in 1-hour increments extending out 72 hours, through advances in modeling and data collection. Computer simulations that leverage the power of graphics processing units (GPUs) are providing higher-resolution physics-based perspectives than in the recent past (Chapter 2). New sensors and missions are being sought to increase the number of measurements in the greatly undersampled near-Earth space environment, to provide learning sets for advance ML analysis.

The Global-scale Observations of the Limb and Disk (GOLD) mission, launched in January 2018, is now a key tool for ionospheric observations, providing the first day-to-day measurements of the region and its response to forcing by the Sun, the magnetosphere, and the lower atmosphere. GOLD measures the temperature and composition of neutral gases in Earth's thermosphere through full-disk UV imaging spectroscopy of Earth from its geostationary vantage point above the Western Hemisphere. Because the ionized plasma and neutral gases interact in the thermosphere, understanding of plasma processes and computer modeling play critical roles in interpreting GOLD data.

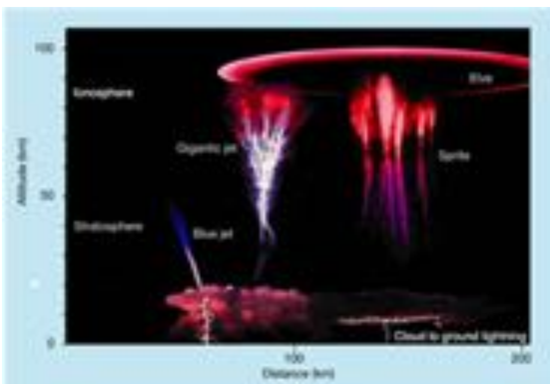


FIGURE 7.9 Illustration of transient luminous events (including elves, sprites, and jets) that occur at stratospheric and mesospheric/lower-ionospheric altitudes and are directly related to electrical activity in underlying thunderstorms. Effects on the upper atmosphere and ionosphere of quasi-static electric fields, electromagnetic waves, and plasmas produced by these events need to be understood, as well as their potential for harming humans and technology exposed to the resulting gamma rays and accelerated particles. SOURCE: Pasko, Nature, 423, 927, 2003.

Even lower in Earth's atmosphere, electrical processes produce lightning flashes that lead to plasma phenomena with measurable effects throughout the atmosphere and beyond. Sensitive photometric and high-speed video records obtained during the last decade indicate that these varied phenomena are dynamically complex. The related plasma processes exhibit a large variety of visual forms, which collectively span the full range of altitudes between the tropopause and the ionosphere. The luminous optical manifestations of these observed events roughly distinguish among the various distinctive classes: sprites, elves, and blue jets (Figure 7.9).

Powerful lightning discharges can directly disturb the lower ionosphere, disrupting very low-frequency radio waves used commonly for communications. Over the last decade, lightning has been found to induce plasma perturbations in the ionosphere that can last tens of minutes. Lightning processes can accelerate electrons to relativistic energies. Terrestrial γ-ray flashes observed from space and from the ground are thought to be bremsstrahlung emission from the deceleration of very energetic (tens of MeV) electrons by collisions with atmospheric molecules. Up to 10^{17} high-energy electrons and fewer positrons are present in a typical event, which can last for fractions of milliseconds and occurs about 50 times per day globally. In addition, lightning can launch strong electromagnetic pulses and create strong quasi-static electric fields, inducing gas discharges in the upper atmosphere (Chapter 5).

NASA's Parker Solar Probe (PSP) is a revolutionary spacecraft designed to approach within 10 R_{sun} (solar radii) of the Sun. PSP is producing unprecedented data on the plasma and energetic-particle properties in the solar wind. For example, PSP magnetic-field and plasma measurements during the first solar encounter at 35.7 R_{sun} identified a slow Alfvénic solar wind emerging from a small equatorial coronal hole, apparently escaping from above low-lying, complex magnetic structures, which exhibited a highly dynamic magnetic field with polarity reversals on timescales from seconds to hours. These varying field structures were associated with clustered radial plasma jets with enhanced energy flux and turbulence. During periods between groups of jets, the sampled solar wind was essentially steady. The combination of PSP with other solar-heliospheric missions and observatories will help answer fundamental questions about the origin of the solar wind, including how the solar corona is heated, and how and where the different types of solar wind are generated.

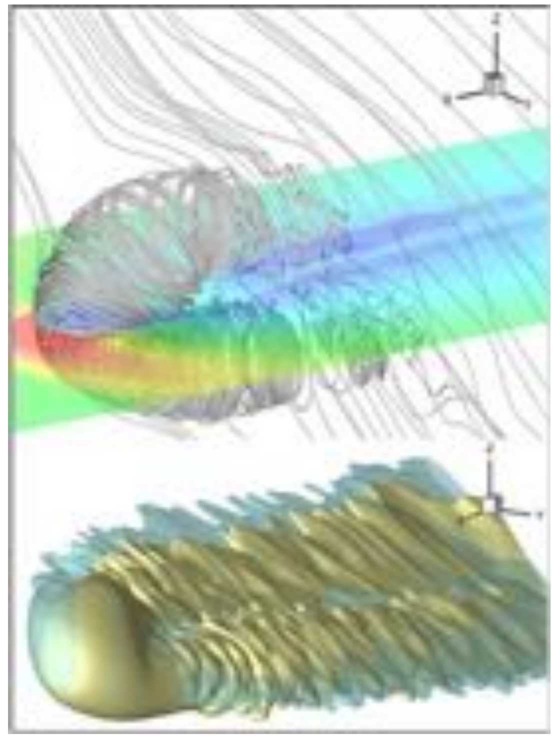


FIGURE 7.10 (Top) 3D MHD simulation of the global heliospheric magnetic field embedded in the interstellar field (white lines), showing signatures of instabilities in the heliotail. The plasma density in the midplane is represented by color shading. The heliopause is at the left, heliotail is extended toward the right. (Bottom) Kelvin-Helmholtz instability of the heliopause increases with increasing interstellar magnetic field strength from 3 microG (yellow color) to 4 microG (blue color). SOURCE: N.V. Pogorelov, S.N. Borovikov, J. Heerikhuisen, M. Zhang, Astrophys. J. Lett. 812, L6 (2015). doi:10.1088/2041-8205/812/1/L6.

Observations by Voyagers 1 and 2, energetic neutral atom (ENA) observations by the Interstellar Boundary Explorer (IBEX), and sophisticated theory and modeling have revolutionized our understanding of the interaction of the solar wind with the partially ionized LISM. The neutral hydrogen component of the ISM profoundly affects the supersonic wind through the creation of pickup ions (PUIs), a suprathermal (~1 keV) plasma component that removes energy and momentum from the solar wind and introduces low-frequency turbulence in the wind beyond ~10 AU (1 astronautical unit (AU) is the distance from the Sun to Earth). Remarkably, the dissipation of this interstellar-driven turbulence gradually heats the distant solar wind, rather than the expected gradual cooling. The PUI population affects the dynamics of all ambient shocks, including the termination shock (where the solar wind transitions from a supersonic to a subsonic flow). Although anomalous cosmic rays (ACRs) were observed to affect the termination shock structure, the Voyagers did not identify the termination shock as the site at which ACRs originate, leaving the debate unresolved. Surprisingly, the inner heliosheath (the region between the termination shock and the heliopause) is far narrower than expected, and is a highly turbulent mix of compressible and incompressible plasma. The heliosheath thermal plasma remains relatively cool because PUIs and ACRs carry much of the thermal energy. The heliopause structure is largely unexplained.

Both Voyager spacecraft have now begun humanity's first in-situ exploration of galactic space, and continue to transform our understanding of cosmic rays. Voyager 1 revealed that the very local interstellar medium (VLISM) is very much influenced by the solar wind. Even at 145 AU, Voyager 1 is still observing interplanetary shocks that have propagated well beyond the heliopause, introducing variations in cosmic ray anisotropies Voyager 1 is measuring the interstellar magnetic field (ISMF) direction and strength, which determines the global shape and nature of the boundary between the solar system and the ISM. Preliminary results from the Voyager 2 crossing of the heliopause suggest that the

ISMF strength exceeds the corresponding measurement made by Voyager 1 at a much higher latitude. These observations have guided 3D MHD simulations of the dynamic magnetic field and plasma structure of the heliosphere, revealing its cometary-like shape embedded in the LISM (Figure 7.10).

IBEX discovered an unexpected "ribbon" of energetic neutral atom (ENA) emission originating from the VLISM. This emission is apparently associated with the orientation of the ISMF (Figure 7.11). The ribbon is thought to be due to the ionization of fast and/or hot solar-wind neutral atoms that propagate from the supersonic solar wind and inner heliosheath into the VLISM, where they are re-ionized to become PUIs gyrating about the ISMF. Re-neutralization of these PUIs by charge-exchange with interstellar hydrogen atoms yields ENAs that can be detected at 1 AU. The ribbon observations of ENAs by IBEX suggests an ISMF strength that is roughly consistent with current Voyager 1 data. Langmuir-wave measurements by Voyager 1 suggest that the heliopause might possess a depletion layer similar to that observed at Earth's magnetopause.

Voyager 1 discovered that shock waves propagating in the low β (dominated by magnetic rather than thermal gas pressure) interstellar space are weak, quasi-perpendicular, unusually smooth and very wide (~10^4 times broader than similar shocks at Earth). The VLISM shocks are IP shocks that propagate through the supersonic solar wind, are transmitted across the heliospheric termination shock, propagate through the heliosheath, and are then partially transmitted into the VLISM at the heliopause. Unlike the heliosphere, the thermal VLISM plasma is collisional with respect to proton–proton collisions that dissipate energy through heat conduction and viscosity. Because the VLISM shocks are weak, this dissipation determines their structure.

Although kinetic approaches are now being used in studies of magnetized plasmas, many such investigations assume that the plasmas are in equilibrium with their magnetic fields. In contrast, most heliophysical plasmas observed since 2010 reveal complex configurations that are not in equilibrium, with signatures of turbulence, strong nonlinearity, and cascade-type processes. High-resolution images (Goode Solar Telescope and SDO), and spectroscopic measurements (Hinode, IRIS, and rocket-borne instruments) show that the entire solar atmosphere exhibits extraordinarily complex, nonlinear magnetic activity. The solar wind contains magnetic and kinetic energy density fluctuations fit by a power law over decades of scale, in addition to persistent, intermittent, and quasi-periodic structures. The magnetosheath and plasma sheet also exhibit noisy, bursty, random structures. Ambient turbulence and its transport and coupling to large-scale flows govern the scattering and transport of energetic charged particles, while coherent structures such as flux ropes can scatter, trap and accelerate particles. Our current inability to predict magnetic fields and particle distributions at specific locations in the heliosphere, as well as uncertainties in space weather prediction, largely stem from our inability to accurately measure or model local turbulent properties. Understanding the basic plasma physics of turbulence and its role in dictating the state of SAPs remains an outstanding problem for the next decade and beyond.

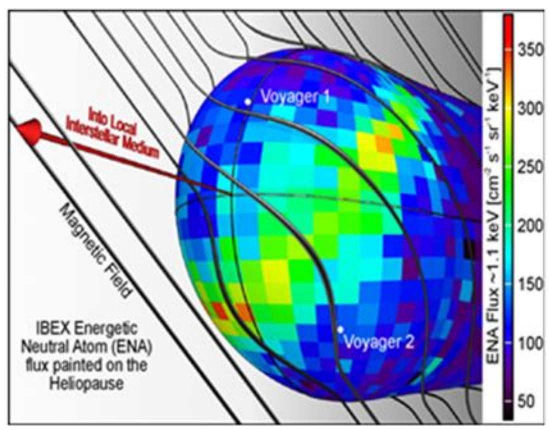


FIGURE 7.11 An illustration of the heliopause ribbon seen in IBEX ENA maps (color shading), showing its relation to the interstellar magnetic field outside the heliosphere (black lines) and the locations of the Voyagers in October 2009. The IMAP mission is expected to answer many questions about the origin of this mysterious feature. SOURCE: Science 13 2009:326, 5955, 959-962, doi: 10.1126/science.1180906.

BENEFITS TO SCIENCE, SOCIETY, INDUSTRY, TECHNOLOGY

Advances in understanding SAPs provide multiple benefits to society and science. The most tangible advantages come from our growing understanding of the causes and consequences of space weather. The most extreme space weather comes from solar eruptions, in particular the fast CMEs that drive shocks, produce SEPs, and smash into our magnetosphere, triggering geomagnetic storms, aurorae, and geomagnetically induced currents that can affect pipelines and the electric power grid. SEPs can directly disrupt onboard computers and other instruments on spacecraft, disable GPS and communication satellites, and induce radiation damage to unshielded humans in space. Geomagnetic storms also cause energetic particles to be ejected from the radiation belts surrounding Earth, potentially damaging spacecraft in low Earth and geostationary orbits. The entire causal chain, from solar eruptions to the impact on the magnetosphere to the space weather effects on our technology, corresponds to a chain of intimately coupled plasma processes. Understanding the entire chain from the Sun to Earth and beyond calls for a systems approach and represents a paradigm shift that has emerged in the past decade. With our critical dependence on technology, PSE is essential for understanding and ultimately predicting space weather, as well as mitigating its effects.

An associated societal and technological benefit of space and astrophysical plasma research is the development of experimental equipment and associated detectors, probes, imaging techniques, and data analysis software. Many techniques initially developed to visualize cosmic phenomena have crossed over to other fields, such as medical imaging, defense, and industrial applications. Large-area astronomical surveys and their catalogued data over the whole electromagnetic spectrum play important roles in developing big data techniques for new discoveries. Numerous important spectroscopic discoveries and methods with practical utility originated in astrophysical investigations, from the discovery of helium to other species in interstellar clouds. The extreme environments of, for example, planetary and stellar interiors, pulsar magnetospheres, and intergalactic filaments offer unparalleled opportunities to explore plasma conditions that cannot be duplicated in laboratories, testing the limits of our theories and models and perhaps leading to new techniques that can be applied to high energy-density investigations and fusion reactors (Chapter 4). The need to understand extreme plasma conditions also drives the development of innovative computational techniques and hardware (see Chapter 2).

Finally, space excites people of all ages, motivating the public to learn more about science and attracting the next generation of space and astrophysical plasma scientists and engineers, and scientists and engineers in nearly all STEM disciplines. Undergraduate research in SAP would expose a more diverse student population to plasma physics, comprising a valuable mechanism to diversify the broader PSE community. Space science and astrophysics can be taught to non-scientists and physics graduate students alike. Space missions and ground-based observatories employ scientists, engineers, and technicians from the earliest design phase through construction to operations, requiring a vast range of skills across the STEM domain. Facilities dedicated to SAP research and technology are found in university departments, private industry, aerospace companies, federal laboratories, and international institutes, all employing the diverse workforce required to keep such organizations thriving. Therefore, the effects of a healthy SAP program extend well beyond the confines of those engaged in research alone.

ECONOMIC DEVELOPMENT/PROGRESS AND ACHIEVEMENTS DURING THE PAST DECADE

The growing awareness of space weather and its consequences has motivated international efforts to create or enhance space-weather forecasting facilities and build physics-based and empirical models to elucidate the underlying processes. These models are enabling increasingly accurate predictions, while the establishment of new facilities and academic programs in this field is actively increasing science capabilities in both developed and developing countries. Summer schools and other educational programs are training the next generation of space-weather researchers. In the United States, agencies such as Department of Homeland Security and the Federal Energy Regulatory Commission began to consider the societal and technological impacts of space weather events, and to include them in disaster planning. Electric power companies, space plasma scientists, and government representatives collectively developed and adopted new reliability standards to mitigate the impacts of geomagnetic disturbances. Several commercial enterprises that supply space weather products, instrumentation, simulations, and predictions were founded in the past decade, creating jobs and serving a diverse base of scientific and operational customers.

The need for high-throughput, high-cadence imaging with ever-increasing spatial and spectral resolution has driven significant advances in instrumentation and image processing that also benefit the broader science community, military, and diverse industries such as commercial earth imaging. For example, recent efforts have focused on developing space-borne photon sieves, hard X-ray spectroscopic imagers, miniaturized plasma instruments and magnetometers, ion-neutral mass spectrometers, and sodium lidar detectors, as well as ground-based adaptive optics telescopes and interferometers with extremely long baselines. Space applications of PSE range from aerospace vehicle construction and spacecraft propulsion to sensors and detectors (see Chapter 5).

Technology Advances

Since the Plasma 2010 report, technological advances in SAPs have improved the plasma instruments and diagnostics used to detect, measure, and record the complex multiscale and multi-messenger phenomena that permeate our universe. Smallsats and cubesats have become favored platforms for obtaining multiple samples and views of localized, transient events in geospace and beyond, driving the development of miniaturized instruments capable of fitting into the highly restrictive size and mass limits of these small spacecraft. Although this rapidly developing technology is still in its infancy, it offers enormous potential for answering many scientific questions about the origins and evolution of space weather effects, from ionospheric disturbances and magnetotail substorms to SEP events. The need for greater sensitivity and higher spatial and temporal resolution motivates a new generation of detectors, materials, and manufacturing techniques.

Several laboratory experiments performed in the past decade were designed to better reproduce important solar and astrophysical conditions and enable comparisons between laboratory experiments and SAP observations (and models). The Line Tied Reconnection Experiment, a basic plasma physics experimental facility at the University of Wisconsin-Madison, was constructed to study ideal and resistive MHD instabilities under variable boundary conditions and equilibria. In particular the line-tied conditions characteristic of the solar atmosphere and the magnetic launching of astrophysical jets were emphasized. The Facility for Laboratory Reconnection Experiments (FLARE) at the Princeton Plasma Physics Laboratory (PPPL) is a new intermediate collaborative user facility constructed by a consortium of five universities (Princeton University, University of California-Berkeley, University of California-Los Angeles, University of Maryland, University of Wisconsin-Madison) and two DoE national laboratories (PPPL and Los Alamos National Laboratory). The goal of FLARE is to provide experimental access to new regimes of the magnetic reconnection process and related phenomena directly relevant to heliophysics, astrophysics, and fusion plasmas. NIF (Chapter 4) also provides new paths to investigate nuclear processes and structural effects in the time, mass and energy density domains relevant to astrophysical plasma phenomena in a controlled terrestrial environment.

The Basic Plasma Science Facility (BAPSF) at UCLA is a national user facility for fundamental plasma science sponsored by DOE and NSF. BaPSF, and its primary experimental device, the Large Plasma Device (LAPD), provides a platform for studying processes relevant to SAP parameter regimes in a reproducible, large volume, magnetized plasma. Examples include the linear and nonlinear physics of plasma waves (e.g., Alfvén waves), collisionless shocks, magnetic reconnection, interaction between energetic particles and waves, and turbulence and transport, over a wide plasma β range.

The Naval Research Laboratory's ground-based Space Physics Simulation Chamber (SPSC), an ONR-sponsored facility, complements theory, modeling, and in-situ measurements with laboratory experiments. SPSC provides a platform to collaboratively investigate the underlying physics of space plasmas under controlled, reproducible, scaled laboratory conditions, particularly those representative of the near-Earth space plasma environment, and a realistic testbed for the development and pre-flight testing of space diagnostics and hardware. The device is used for the study of ionospheric, magnetospheric, and solar wind plasma phenomena; testing/calibration of space-qualified diagnostic instruments for missions; spacecraft charging; large-volume plasma generation; and other investigations requiring a low-pressure environment.

NSF's National Solar Observatory (NSO) operates cutting-edge facilities, develops advanced instrumentation both in-house and through partnerships, conducts solar research, and creates educational and public outreach programs. The NSO Integrated Synoptic Program (NISP), established in 2011, operates two facilities dedicated to long-term full-disk coverage of the Sun: the Global Oscillation Network Group (GONG) and the Synoptic Optical Long-term Investigations of the Sun. Data from the worldwide GONG network has advanced our understanding of the Sun through helioseismology (the study of the Sun's interior using observed oscillations, which explores the internal structure in unprecedented detail) and prominence seismology. NSO's Community Science Program develops analysis and modeling tools that will enhance the value of data taken with NSO's state-of-the-art observing facilities—the Daniel K. Inouye Solar Telescope (DKIST) and NISP—and to train the next generation of solar physicists in the use and development of these tools. Until 2018, NSO also operated telescopes at Kitt Peak and Sacramento Peak Observatories that have been critical to the advancement of the field. NSF's National Center for Atmospheric Research/High Altitude Observatory operates and updates the Mauna Loa Solar Observatory and its two primary instruments, the K-COR Coronagraph and the COronal Multi-channel Polarimeter.

The Center for Solar-Terrestrial Research at New Jersey Institute of Technology operates the Big Bear Solar Observatory (BBSO) and Extended Owens Valley Solar Array (see below), the Automated Geophysical Observatories and other instruments in Antarctica, and geospace observing facilities across South America and the United States, with funding through grants from NSF, NASA, the U.S. Air Force, the Korean National Science Foundation, and other government and private sources. BBSO presently hosts the highest resolution optical solar telescope in the world, the 1.6-m Goode Solar Telescope (GST). Operating since 2009, with adaptive optics installed in 2017, the GST determines the magnetic field and plasma dynamics in the solar chromosphere and photosphere on scales as small as 70 km. This facility also served as a valuable testbed for the adaptive optics and instruments being installed at DKIST.

The Extended Owens Valley Solar Array (EOVSA) is a world-class NSF-funded facility for scientific research at microwave radio frequencies (1-18 GHz) aimed at understanding the Sun and its influence on Earth and near-Earth space environment. EOVSA focuses on studying the magnetic structure of the solar corona, transient phenomena resulting from magnetic interactions (e.g., solar flares and associated particle acceleration and heating), and space weather phenomena. The project has provided solar-dedicated observations since its completion in 2017. EOVSA has yielded groundbreaking observations of some of the most powerful solar eruptions ever measured and provides unique insights into the heating and acceleration of high-energy coronal electrons.

Progress in understanding Earth's ionosphere, thermosphere, and mesosphere (ITM) has long relied on ground-based observations from multiple international facilities. In the ITM, neutral gas motions drive ionospheric density and dynamics, affecting currents, plasma instabilities, and vertical coupling of atmospheric regions. A new class of Incoherent Scatter Radars, including Poker Flat Incoherent Scatter Radar (built during the past decade), RISR-N, and RISR-C, is enabling leaps forward in our understanding of ITM phenomena. T-REX, a network of multispectral all-sky imagers in Canada, is a new capability for comprehensively characterizing the high-latitude thermospheric and ionospheric state and energy inputs. Next-generation scanning Doppler imagers, such as the new facility built by the University of Alaska, are starting to collect detailed ground-based measurements of thermospheric winds. At low latitudes, upgrades and new observational techniques applied in the past decade to the 50-year old Jicamarca Radio Observatory have produced unprecedented images of the electrodynamics of the equatorial ionosphere. Ground-based lidars, which primarily measure temperature, wind speed, and metallicity in the low nightside ITM, have been greatly improved since 2010. These lidars have become more robust and sensitive, covering more species and greater ranges in altitude than ever before. The international proliferation of ground-based GPS receivers, which can measure the total electron content above them, is providing new insights into the temporal and spatial structure of ionospheric variations, traveling disturbances, and other transient phenomena in the upper atmosphere.

Computations, Diagnostics

SAP research has long capitalized on computational advances in hardware, algorithm development, and access to new systems to design new instruments, assimilate data, validate predictive models, probe extreme conditions in cosmic phenomena, and reach for closure between theories and observations. Increasing access to graphical processing units (GPUs) enabled substantial speed-up of select codes, but the need for machine-specific rewriting of programs now limits the potential for widespread GPU usage. Some MHD codes incorporated more relevant physical processes, such as radiative transfer, ionospheric chemistry, and the effects of partial ionization. The use of adaptive mesh refinement to place the highest spatial resolution where it is most needed, such as current sheets, steep density gradients, and boundary layers, became more common for modeling phenomena covering large dynamic ranges.

Because the most interesting physical processes are complex and nonlinear in traditional plasmas, and even more so in extreme plasmas, our ability to understand them greatly benefits from numerical simulations. Computational SAP studies are increasingly important, revolutionizing our understanding of extreme plasmas in exotic astrophysical objects. Particle-in-cell (PIC) codes offer opportunities to understand how exotic/relativistic pair plasma is produced, and how coherent radio and high-energy emissions are generated. These developments are enabling, for the first time, truly ab-initio studies of important phenomena such as Crab Nebula γ-ray flares, pulsed high-energy emission from pulsar magnetospheres, the coronae of accreting BHs, and pair-production cascades in pulsar and BH magnetospheres, as well as basic processes such as magnetic reconnection and particle acceleration in astrophysical plasmas (Figure 7.12). Modeling of extreme plasma physics has been enabled recently by the development of radiative 3D general-relativistic MHD codes and their application to global simulations of accreting BHs and their jets. These pioneering studies clearly demonstrate that rigorous numerical investigation of extreme plasma processes is now feasible and realistic, opening up broad avenues for future exploration.

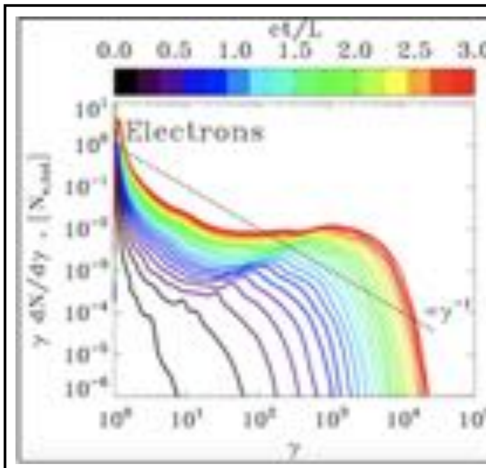


FIGURE 7.12 Evolution of the particle energy spectrum (as a function of Lorentz factor gamma) from a PIC simulation of stressed X-point collapse in a magnetically dominated, relativistic plasma. The results demonstrate that electrons are quickly accelerated to highly relativistic velocities by the reconnection-induced electric field. SOURCE: Lyutikov et al. (2017). Explosive X-point collapse in relativistic magnetically dominated plasma. Journal of Plasma Physics, 83(6), 635830601.

Developing time-dependent simulations with evolving boundary conditions derived from observations is essential to improving the predictive capability of space-weather modeling. For example, AFRL's ADAPT code prepares a time series of magnetograms of the solar photosphere to drive the bottom boundary of coronal and solar wind models. A serious obstacle to this approach is the lack of information about the changeable photospheric magnetic field on the far side of the Sun, which would be best rectified with multiple satellites distributed around the Sun.

New, cutting-edge global modeling techniques are being developed, such as the multiscale plasma Wave-in-Cell (WIC) simulation method that self-consistently tracks wave dynamics. These capabilities can clarify and predict the global magnetospheric impact of microscopic kinetic plasma processes, including wave-particle interactions. Such frontier computational techniques may answer key questions, such as the source of plasmaspheric hiss, the factors determining whether a geomagnetic storm enhances or depletes electrons, the global conditions required to form magnetospheric resonators, and the effectiveness of different radiation-belt remediation techniques.

Novel approaches such as Bayesian analysis, automated feature recognition, and machine learning are extracting valuable science from large data sets. For example, SDO yields 1.5 TB of data daily, necessitating innovative techniques for finding key phenomena or features and interpreting their properties efficiently. Similar approaches are being introduced to interrogate the massive data output from 3D numerical simulations, particularly for ensembles of physics-based space weather simulations. Recent application of machine-learning techniques to IRIS observations has increased the computational efficiency of chromospheric diagnostics one million-fold, compared with physics-based numerical simulations and inversion codes. This approach quickly provides chromospheric researchers with the temperature, velocity, density, and unresolved motions or turbulence as a function of height in the solar atmosphere for every IRIS observation. This new machine-learning based tool, combined with the more than 25,000 IRIS observations of the solar chromosphere since its launch in 2013, will deepen our physical insight into the transfer of energy from the Sun's interior to the corona.

FUTURE CHALLENGES AND OPPORTUNITIES: SCIENCE

The next decade brings exciting opportunities and daunting challenges for space and astrophysical plasma science. Cross-disciplinary collaborations, international cooperation, novel observing platforms, new instruments and diagnostic methods, and targeted combinations of theory, computation, experiments, and data analysis will be crucial for answering the most fundamental questions about the plasma universe.

Astrophysics

Observational advances over the past decade have revolutionized many aspects of astrophysical plasmas, through innovative and exciting ground-based and space-based missions. Ongoing missions such as LIGO (The Laser Interferometer Gravitational-Wave Observatory) and planned or under construction new observational facilities such as ATHENA (Advanced Telescope for High-ENergy Astrophysics, expected to launch in 2028), ETH (Event Horizon Telescope), XRISM (X-Ray Imaging and Spectroscopy Mission), LYNX (Lynx X-ray Observatory), LISA (Laser Interferometer Space Antenna), SKA (Square Kilometre Array), and CTA (Cherenkov Telescope Array) will address major challenges in several sub-areas of plasma astrophysics:

- Extreme plasma physics of multi-messenger cosmic plasmas
- Physics of extremely rarefied/weakly collisional plasmas
- Plasma physics of the early solar system evolution, exoplanets, and the origin of life
- Plasma physics of the interstellar medium

Multi-messenger astrophysics combines information from multiple extrasolar electromagnetic radiation, gravitational waves, neutrinos, and cosmic ray observations. Exploiting these four "messengers" is transforming plasma astrophysics by opening new windows on the universe. The challenges in understanding the extreme plasma physics of multi-messenger cosmic plasmas lies in the fact that energetic plasmas around neutron stars and BHs are under extreme, high-energy-density (HED) physical conditions and are governed by rich physics. These plasmas are often relativistically hot, move at relativistic speeds, and engage strongly with ambient and self-produced radiation fields. The QED interaction of photons with each other and with strong magnetic fields may lead to prolific pair creation (e.g., electrons and positrons). These "exotic" relativistic, radiative, and QED aspects of the basic collective plasma phenomena are novel and do not have analogs in traditional solar, space, and most laboratory plasmas, although recent advances in laser technology are now enabling us to access and study these extreme plasma regimes in the lab. Our understanding of extreme astrophysical and laser-plasma processes (Chapter 3) is incomplete, as classical plasma theory becomes inapplicable. There is a need for a targeted study of kinetic-level collective plasma phenomena that includes laser-plasma and astrophysically relevant physical conditions, relativistic motions, strong interaction of particles with radiation, and QED effects. This requires developing new physical insights and building a rigorous, systematic knowledge base for these extreme plasmas, then applying this new knowledge to uncover the inner workings of the most fascinating and challenging astrophysical objects, including accreting BHs and their jets, pulsars, magnetars, and multi-messenger phenomena such as neutron-star mergers.

The global modeling of astrophysical multi-messenger sources is further complicated by the multi-scale nature of the extreme plasma processes. In many systems of interest, the micro- and macro-scales affect each other in complex ways, so a simple parameterization of a microscopic process may be insufficient, and a true multi-scale problem must be solved. For example, in the context of particle acceleration, the feedback of energetic particles on large scales affects the injection process at small scales, which requires special techniques for modeling. New approaches to multi-scale simulations of astrophysical objects need to be developed, including "hybrid" schemes that combine kinetic particles representing the accelerated component with MHD schemes that can efficiently evolve the background state. In fact, how to connect small and large scales in meaningful ways is a pressing issue for the entire PSE community.

The challenges in understanding extremely rarefied/weakly collisional plasmas around BHs and in clusters of galaxies (inter-cluster medium, ICM) involve a complex mix of rarefied plasma and accelerated particles (and dark matter in the case of ICM). In addition, these plasmas exhibit extreme separation of micro- and macro-scales. Although these plasmas are dominated by thermal rather than magnetic pressure, even weak magnetic fields change the overall dynamics as well as dissipative and transport properties. The dynamics of such plasmas are governed by large-scale bulk motions and complex, multiscale interactions between kinetic phenomena under conditions not in local thermodynamic equilibrium. Key questions include, where is the seed population of charged particles that are accelerated to produce the observed radio emissions, what are the properties of magnetized turbulence in this plasma regime, and what is the source of the additional heating needed to account for the observed X-ray intensity of the deep core of the clusters?

Understanding these interactions presents a challenge for plasma theory, computational studies and experiments. Numerical investigations of weakly collisional SAP plasmas require fully kinetic (PIC) studies to explore microscale physics but will benefit from hybrid-kinetic approaches (with fluid electrons) that address the dynamic range problem. Key areas for study include elucidating the most important kinetic instabilities, particularly in the presence of strong heat fluxes; understanding how kinetic instabilities interact with other plasma processes, such as magnetic reconnection, thermal conduction, and particle acceleration; and understanding the interplay between widely separated fluid macroscales and kinetic microscales.

Partially ionized interstellar plasmas, especially low-ionization plasmas in protostellar cores and protoplanetary disks, present formidable plasma-physics challenges, with important implications for the origin of life in the Universe. Effects of dust formation (and the resulting presence of nearly macroscopic charged particles; see Chapter 2), non-ideal MHD (e.g., resistivity, Hall effect, and ambipolar diffusion), and multi-species plasma components (neutrals, electrons, cosmic rays, molecular and atomic ions, and charged dust grains) collectively comprise a highly complex plasma environment. The interactions among the partially ionized gas component, the charged dust grains, the microscale dynamics of dust coagulation and planetesimal formation, the mesoscale dynamics of the magnetorotational instability in protoplanetary disks, and the macroscale dynamics of outflows and long-term disk evolution are difficult plasma-physical problems. The low temperature plasma community (LTP) has long addressed partially ionized, chemically reactive, and multi-phase plasmas, offering possible strategic opportunities for the SAP and LTP communities to collaborate on low-ionization astrophysical plasmas.

Heliophysics

Space weather is recognized nationally and internationally as a potential threat to our technology-dependent society and to our space programs, including human-flight to the Moon, Mars, and beyond. The complex chain of energy release, transformation, and transport from the Sun to Earth and other sites in the heliosphere encompasses a vast range of interlinked phenomena, all requiring plasma science to achieve understanding, prediction, and mitigation when relevant. One underexplored area of practical interest is extreme events—eruptions at the most energetic end of the scale, on par with or surpassing the so-called Carrington event of 1859. Extreme events challenge our strategic planning, our physical models, and our ability to respond appropriately to loss of communications, electric power, and GPS. Although the basic physical processes associated with geomagnetic storms on our planet's magnetosphere and ITM are understood, our comprehension and ability to model extreme Carrington-scale storms are in their infancy. The "average" solar eruptions cannot be predicted with great accuracy, much less the rare but highly destructive events. By pushing robust first-principles models to their limits and adding key physical processes that are currently missing, however, the impact of weak to extreme eruptions on the near-Earth environment can be assessed to identify the most vulnerable areas and the most likely damaging effects. This will require closer coupling between models of adjacent geospace regions, including the neutral atmosphere beneath the ionosphere. A sufficiently broad dynamic range of scales is needed to capture important local-global interactions, such as large-scale magnetic connectivity changes associated with reconnection, key atmospheric chemistry processes such as nitric oxide enhancements in geomagnetic storms, and kinetic- (e.g., wave-particle interactions) and MHD-scale processes. This area would greatly benefit from joint programs with the LTP community, which possesses expertise in atmospheric plasma chemistry.

Several aspects of space-weather ITM modeling are ripe for improvement. Currently, many global-scale geospace models treat the ionosphere simply as an input boundary condition. This problem is often exacerbated by actual physical gaps between the computational domains being coupled, complicating realistic simulation of the transfer of plasma, electromagnetic energy, and energetic particles between domains. Global models today at best rely on parameterizations of local-scale, kinetic, and/or non-MHD processes such as kinetic instabilities and particle precipitation from the ring current and radiation belts, or neglect these effects entirely. Finally, the high-latitude (open field) and low-latitude (closed field) ionospheres usually are modeled separately, ignoring processes that affect the evolving open-closed boundary. A critical goal is to obtain a global electric-field model that couples these two regions and addresses the impact of large geomagnetic storms on the low- to mid-latitude ionosphere. Efforts to fill in these missing pieces are currently underway. Different combinations of linked models for the ring current, upper ionosphere, and mesosphere are being tested, and key physical processes within this complex system are being added. For example, metal ions that affect conductivity, irregularities, and instabilities are not included in ionospheric models currently, but their effects are being implemented in NRL's SAMI3 ionospheric model. By the next Decadal Survey, the committee anticipate having robust, first-principles models of geospace from the ground to the upper reaches of the exosphere and magnetosphere.

Solar opacity calculations and measurements, especially for iron (Fe), one of the most abundant minor elements by mass, have received renewed interest due to the "solar abundance" conundrum. Analyses of the photospheric composition in the early 2000s found smaller abundances than earlier estimates for many elements. Previously accepted solar abundances were in excellent agreement with helioseismology data. With the new abundances, however, the structure predicted by solar models no longer agrees with that inferred from helioseismic studies. Increased opacities for the key elements under solar conditions would lessen the discrepancies, but there is little justification at present for such an adjustment. The opacities of Fe, Cr, and other elements at the typical electron temperature ($T_e \sim 182$ eV) and density ($n_e \sim 10^{22}$ cm^{-3}) near the solar convective and radiative zone boundary (CZB) were recently measured and systematically studied on the Z-machine at Sandia National Laboratories, and compared to the latest theoretical calculations. The calculated and measured Fe opacities agreed reasonably well at the lowest T_e and n_e, but the models underestimate the opacity as T_e and n_e approach CZB conditions. This finding awaits resolution. Are the opacity theories missing physics, or is there something unique in the experimental iron measurement at $T_e > 180$ eV? To confirm laboratory findings, independent experiments using different platforms, such as NIF, are currently being pursued.

The most fundamental questions concerning particle acceleration on the Sun are: under what circumstances do the relevant acceleration mechanisms trigger and operate, and how do accelerated particles propagate and interact with their environment? Imaging spectroscopy from radio to HXR (hard X-rays with energies > 10 keV) and γ-ray wavelengths have shed some light on these questions in the past decade, but such observations need to be continued and improved over the next decade in order to obtain definitive answers. New radio interferometers such as EOVSA and the proposed Frequency Agile Solar Radiotelescope (FASR) offer new insights into the timing and locations of electron energization and propagation into the corona and heliosphere, and the solar environment in which the eruption energy was stored and released. When the RHESSI mission was retired in 2018, the only source of solar-dedicated high-energy imaging spectroscopy was lost. Astrophysical missions such as Fermi and NuSTAR currently remain the only instruments measuring HXRs from solar flare-accelerated electrons. By ~2025, the STIX instrument on Solar Orbiter will again provide solar-dedicated HXR imaging and will for the first time obtain regular data from non-Earth-view locations, though available observation time will be limited by spacecraft and telemetry constraints. The next generation of instruments designed to study the physics of flare particle acceleration, with sufficient sensitivity and dynamic range to observe faint particle acceleration sites at the same time as bright flare footpoints, urgently seeks launch opportunities in time for the next solar maximum. Instruments such as a γ-ray imager/polarimeter could explain the puzzling separation between electron- and ion-emission source regions, and the existence of long-duration coronal γ-ray sources.

To date, all in-situ observations of solar wind plasmas have been single point measurements or have focused on a narrow range of scales through the use of carefully controlled formations of a few spacecraft. Unfortunately, the dynamics of turbulence depends critically on the orientation of the magnetic and plasma fluctuations relative to the mean magnetic field—a 3D quantity that no single spacecraft can measure. Cluster and MMS, which both consist of four spacecraft in a tetrahedral formation, employ a limited set of spacecraft separations to sample the multi-directional structure of the plasma. Therefore, these missions cannot simultaneously resolve fluctuations on the range of scales needed to understand the nonlinear dynamics of plasma turbulence. The largest and smallest scales sampled by these missions only differ by a factor of 10, which is nowhere near the many orders of magnitude necessary for simultaneously measuring turbulent fluctuations through the inertial and dissipation ranges. Future constellation missions with many spacecraft and variable spacing are needed to unlock the mysteries of solar wind and geospace turbulence.

Two unsolved issues in SEP propagation and acceleration are particularly urgent targets for resolution in the next decade. The recognition that the longitudinal extent of SEP events can vary significantly came with multi-spacecraft observations (e.g., STEREO) of impulsive and gradual SEP events. The surprising longitudinal spread of charged particles during gradual SEP events has been ascribed to cross-field transport in the IPM. Other explanations, such as diverging field lines and longitudinal particle transport in the corona, have not been thoroughly explored yet. Current SEP models typically describe cross-field transport via an ad hoc perpendicular diffusion coefficient, and therefore remains poorly understood. Shock obliquity (the angle between the shock front and the upstream magnetic field; see Figure 7.6) can affect the injection energy and efficiency for shock-accelerated particles, the excited wave intensity at the shock, and the associated parallel diffusion. Consequently, predicting the evolving spectrum of SEPs generated at a particular shock requires detailed knowledge of the shock connectivity to the heliospheric point of interest and a complete description of the competing physical processes affecting their transport. Although progress has been made in the last decade, the current state of observations and modeling falls short of meeting these requirements. In particular, temporal and spatial variations in obliquity along a CME-driven shock, from the flanks to the leading edge, have yet to be incorporated in models of particle acceleration and propagation. The societal quest for accurate prediction of impacts from individual SEP events on spacecraft and humans at specific locations throughout the solar system depends critically on answering these questions.

The 42-year old Voyager Interstellar Mission, migrated from the Grand Tour mission exploring the outer planets, does not have a science payload tailored to exploration of the outer heliosphere and the VLISM. In a few years, this pioneering mission will end as power supplies fall below critical levels and the heaters are turned off. Voyagers 1 and 2 have transformed our knowledge of the outer heliosphere and the LISM plasmas, yet many questions remain unanswered. ACRs do not appear to be accelerated at the heliospheric termination shock, the heliospheric shock is dissipated by reflected PUIs rather than the thermal solar wind, and most of the pressure in the heliosheath apparently resides in heated PUIs. Because the Voyager instrument suite was not designed to measure PUIs, a critical component of this highly non-equilibrated collisionless plasma has been inferred rather than measured directly in situ. Voyager and IBEX observations have challenged and transformed our earlier concepts about the global structure and energetics of the heliosphere, and of the plasma processes acting at its boundary. IMAP, and eventually an Interstellar Probe, will be critical to unraveling the multiple challenges listed above in understanding the interaction of the solar wind with the LISM.

Energetic particles not only are accelerated by shocks, but also play a fundamental role in dissipating shock waves and in determining their structure. Understanding the dynamical effects of energetic and suprathermal particles on heliospheric shocks is receiving increased interest. Numerous observations of shock waves, including some IP shocks within 1 AU, have revealed that the pressure of the energetic-particle component considerably exceeds both the thermal gas pressure and the magnetic field pressure. Because most of the thermal heliospheric and VLISM plasma is not equilibrated with the ubiquitous energetic particles, understanding the structure and dissipation of heliospheric shocks must extend well beyond simple MHD models. Instead, multi-fluid models with appropriate closures are needed, informed by kinetic models of the energetic-particle component and sophisticated PIC and hybrid codes.

The unprecedented detail of measurements by MMS heralds an opportunity over the coming decade to considerably deepen our understanding of Earth's bow shock and nearby IP shocks. The committee anticipate that future MMS studies will analyze electromagnetic waves upstream of and at/within the shock front; examine the evolution of ion and electron distributions from upstream through the shock ramp and into the downstream region; discover PI signatures at the shock; and investigate periodic nonlinear structures, such as double layers and electron holes downstream of collisionless shocks.

Whistler waves are very low frequency electromagnetic waves that can be generated in geospace and other planetary magnetospheres during particle injection events associated with lightning and geomagnetic storms and substorms. Their interactions with both ambient and injected (energetic) electrons have been invoked recently to explain particle acceleration in, and precipitation from, the radiation belts. The resulting "killer" electrons are major threats to spacecraft transiting the magnetosphere. Our ability to predict such space weather effects depends on our understanding of whistler initiation, propagation, and complex interactions with the electron population. Currently, several petabytes of data on whistler waves in the near-Earth environment exists in independent databases across the scientific community. By leveraging modern data mining techniques, trends and features of whistler signals could be extracted on an unprecedented scale. Such techniques will have a tremendous impact on global space-weather prediction and elucidate basic physics of magnetized plasmas.

Future understanding of plasma processes in Earth's ITM layers requires spaceborne and ground-based instrumentation capable collectively of full planet coverage. Ionospheric plasmas vary on wide temporal and spatial scales, so deconvolving the intrinsic evolution requires multipoint spacecraft observations, such as constellations that can observe planetary waves without averaging over a month or more. Multiple smallsats with instrumentation similar to that onboard GOLD could determine the large-scale structure, while widely dispersed ground-based GPS receivers could map the overlying atmospheric properties on finer scales than presently achievable. To probe systematically the bottom of the ITM is particularly challenging with in-situ instruments, because orbits transiting this zone are short-lived unless onboard propulsion is included. As a result, the critical "Atmosphere-Space Transition Region" is largely unexplored, and an important objective for the coming decade.

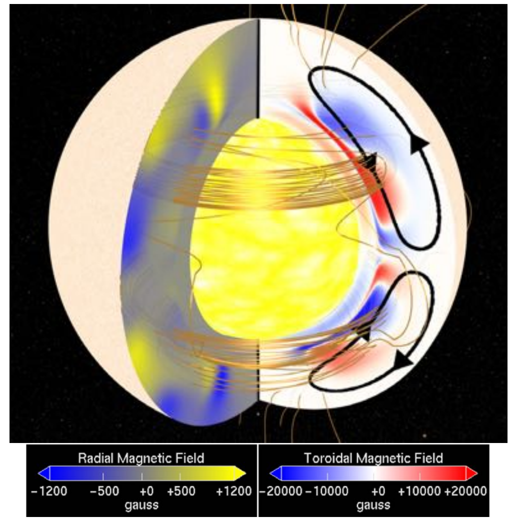


FIGURE 7.13 Illustration of the dynamo process operating in the solar interior close to solar minimum. Meridional flow patterns (black lines with arrows) in a longitudinal plane, magnetic field lines (thin gold lines), the radiative core (inner yellow), toroidal magnetic-field strength (red-blue color shading at right), and radial magnetic-field strength (blue-yellow shading at left) in longitudinal planes are displayed. SOURCE: NASA Goddard Space Flight Center Scientific Visualization Studio.

The atmospheric region where terrestrial lightning generates sprites, elves, and blue jets is a complex interface between the lower atmosphere and the space environment. This region has considerable practical as well as intellectual interest, because most UV-blocking ozone resides there and because local disturbances can disrupt technological systems through their effects on satellite drag, communications, and electrical power distribution systems. Fundamental questions remain about the underlying physics of these events. The close spatial and temporal association observed between lightning and waveguide perturbations implies that the perturbations emanate from plasmas induced by high-altitude discharges, but the mechanisms of these perturbations remain unknown. The seed electrons for these events might be secondary electrons produced by cosmic rays or from compact regions around tips of lightning leaders. The radiation dose to people inside aircraft near a terrestrial γ-ray source could be significant and should be investigated and quantified. While some upper atmospheric effects of lightning have direct societal impact, research on other effects aids in understanding fundamental properties of gas discharges by exploring regimes in which experimental studies are not feasible. Research in the next decade will focus on understanding the initiation of sprites, elves, blue jets, and terrestrial γ-ray flashes, their observable signatures and chemical effects at different altitudes in the atmosphere, the observed gas-discharge features, and their scaling relationships to other discharge forms.

SAP Crosscutting

Understanding plasma conditions common to both astrophysical and heliophysical phenomena poses special challenges to PSE. Although the observational techniques and system dimensions can diverge substantially, the similarities in the underlying physical processes in the examples below call for collaborative efforts to promote advances in understanding.

The origin and evolution of cosmic magnetism remain among the most important outstanding questions of SAP science. We still cannot explain the origin of the first magnetic fields in the universe (magnetogenesis), or how magnetic fields are amplified and sustained by plasma motions (dynamo; Figure 7.13). Observations of radiation from very distant galaxies with the upcoming SKA radiotelescope will shed some light on cosmic magnetism, but a major emphasis should be to further theory, computation, and experiment. Most astrophysical dynamo studies use an MHD model, often further assuming that fields grow without back-reacting on the plasma motions (the "kinematic" approximation), while dynamos affected by kinetic physics are only beginning to be explored. Similarly, although plasma processes and instabilities that can create magnetic fields have been identified, most saturate with weak, tangled fields, and it is unclear whether such fields seeded those observed today. This major gap in basic plasma physics theory simultaneously involves processes such as kinetic turbulence, reconnection, particle acceleration and diffusion, anomalous viscosity and resistivity. In the next decade, progress on cosmic magnetogenesis and dynamos will require the following:

- Formulate MHD-like models that are simple enough to solve in complex, astrophysically relevant geometries, yet detailed enough to capture the multiscale interplay between, for example, kinetic instabilities, bulk fluid motions, reconnection, cosmic-ray diffusion, magnetic-field amplification, and self-organization.
- Develop stable and accurate methods that reduce particle noise and/or computational expense in high plasma β systems, and resolve important electron kinetics without being limited by the speed of light (e.g., implicit PIC).
- Increase availability of mid-range supercomputing options (10–50 M CPU-hour) for routine computational studies involving kinetic methods.
- Develop experimental studies of high-β plasmas while prioritizing a program for funding new university-level plasma experiments and dedicated time on existing devices, accompanied by training of plasma students. Although the high Reynolds number, high-β regime is difficult to produce in the laboratory, there is a large payoff for success.

Understanding how stars cyclically generate and reverse their magnetic fields will not only shed light on our own Sun but is profoundly important for studies of heliospheric structure and evolution, exoplanets and habitability in other stellar systems, and the generation of magnetic fields in more extreme environments. Not understanding the origins of the solar cycle greatly reduces our ability to predict and mitigate adverse space weather. The outstanding questions that confront the community include: are long-term solar cycle predictions at all possible in such systems; if short-term predictions are viable, what is the window of predictability; and how best to transition our physical insights to predictive models? Successful resolution of these fundamental questions requires a combination of new observations, breakthrough theoretical concepts, and state-of-the-art numerical simulations. Analysis of model output can capitalize on machine-learning techniques. For example, observations over a wide range of spatial scales of the magnetic flux balance at the solar poles throughout an entire activity cycle, though technologically challenging, would provide much-needed information on how much flux is carried from lower latitudes, emerges in situ, submerges, and is produced by local, small-scale dynamo action. Key problems that await solutions in the next decade include:

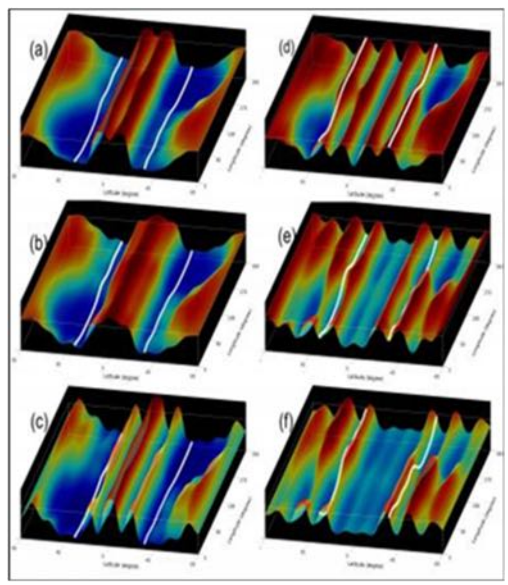


FIGURE 7.14 Tsunamis in the solar interior? Six snapshots of simulated deformations of the top surface of the Sun's tachocline shown at approximately 4-day intervals, illustrating the triggering and development of tsunami-like waves. After reaching the mid-latitudes, these steep waves lift the weak (nonbuoyant) bands of toroidal magnetic flux (white tubes) and help them erupt weeks later as sunspots at the solar surface. SOURCE: Dikpati et al. 2019, Nature Scientific Reports.

- Some evidence points to the tachocline (see Figure 7.14) as an important agent in achieving magnetic self-organization on large spatial scales, while other research indicates that stars without tachoclines can have strong magnetic fields. What is the role of the tachocline in the dynamo process, and in determining its cyclic nature?
- Simple (e.g., kinematic) phenomenological mean-field-like dynamo models nicely reproduce the observed evolution of surface magnetic fields over decadal timescales without turbulent induction. Global MHD models can produce reasonably solar-like large-scale magnetic cycles with decadal polarity reversals, powered by turbulent induction and differential rotation, but do not reproduce the well-observed tilted bipolar pairs on the surface. How can these starkly different modeling frameworks be reconciled?
- Can dynamically consistent MHD simulations of large-scale magnetic cycles produce grand minima (multiple cycles of suppressed magnetic activity)?
- Which aspects of dynamo models are critically dependent on computational details such as subgrid models?

Collisionless shocks can now be generated in the laboratory, positioning us to answer a multitude of basic questions about these important phenomena in the next decade.

- What are the dominant plasma instabilities that mediate the stagnation of the flow in collisionless shocks, and how is the magnetic field amplified?
- What is the effective ion mean free path associated with shock formation?
- How is magnetic turbulence generated at the shock front and how does it decay?
- What is the difference between electron and ion thermalization at the shock?
- What is the injection process for particle acceleration at the shock front, and what is the efficiency?

For SAP applications, experiments capable of exploring both magnetized and relativistic shocks must be developed. To study magnetized shocks requires large volume, high magnetic-field generators, and large phase plates on laser facilities are needed to produce large-scale plasma flows. High-intensity laser systems ($>10^{22}$ W cm^{-2}) are needed to create relativistic flows, and low-energy high-resolution particle spectrometers (<500 keV electrons; <10 MeV ions) to measure the nonthermal component of the accelerated particle spectrum. Shot opportunities in large laser facilities such as NIF are essential for meeting these objectives. Massive multidimensional simulations of the laser-target interaction, employing both radiation hydrodynamics and collisionless PIC approaches, are essential for generating and interpreting collisionless shocks in SAP-relevant laboratory environments. This project would drive fundamental understanding of collisionless shock formation and evolution, shock-associated turbulence, and charged particle acceleration.

Galactic cosmic rays, anomalous cosmic rays, and solar energetic particles are thought to be accelerated by either diffusive shock acceleration (DSA) or some form of stochastic acceleration. Both mechanisms depend fundamentally on turbulence, either by energetic particles generating their own waves/fluctuations or through waves from other sources. However, heliospheric particle observations that are inconsistent with simple DSA indicate that other physical effects must be taken into account, in particular coherent structures (such as magnetic islands) and turbulent electric fields. A key goal for the coming decade is to develop models of these alternative acceleration mechanisms while incorporating numerical representations that capture new understanding of plasma turbulence under relevant conditions.

Turbulence in SAPs can be investigated observationally using ground-based observational platforms, remote sensing spectroscopy, and in situ satellites. Radio observations provide unique insights into the nature of the solar wind and ISM plasmas and their turbulent properties. Radio waves scatter as they propagate through a plasma, allowing a number of plasma properties to be deduced. Observed radio wave scattering, such as interplanetary scintillations, requires suitable background sources such as quasars and pulsars to probe the foreground medium of interest. The number and sensitivity of available radio telescopes (e.g., The Jansky Very Large Array (VLA), Very Long Baseline Array (VLBA), Ooty Radio Telescope) are limited. Hence, the number and angular density of such sources that are effective probes of the solar wind and ISM is not optimal, nor is the distribution of interferometric baselines needed to measure turbulent properties of the medium or its velocity. Recommended observational solutions are discussed in chapter 7.

The exciting new frontier of exoplanetary discovery and the quest for life elsewhere in the universe will continue to advance through observations by new missions and ground-based observatories and innovative computational studies. Broader observational scope and deeper physical understanding are primary goals for the next decade. Because transit observations preferentially select those planets that are close to their stars, the focus to date has largely been on exoplanets whose "Goldilocks" zones are very close to M stars. Late-type M stars are magnetically active, with starspots 10 times larger than sunspots. That and the close proximity of exoplanets to M stars suggests they experience severe space weather as they orbit the outer stellar corona. Energy and radiative input to their atmospheres can be immense, particularly in EUV and X-ray wavelengths, and frequent stellar eruptions can produce a lethal mix of energetic particles, high-energy photons, and magnetic interactions with the planet's magnetic field (if it has one). Moreover, it remains unclear whether planetary magnetic fields mainly shield planets from radiation and direct stripping of the atmosphere or function more like sails, enlarging the planetary cross-section to collect and funnel more stellar-wind energy into the atmosphere. Cross-disciplinary studies have proved highly successful, and should be continued in the next decade. Future studies of stellar eruptions will estimate the plasma and radiation environments of other Earth-like planets orbiting solar-like stars by using data-based MHD models of evolving solar-like stars and their plasma astrospheres, based on observations by missions such as NASA's Transiting Exoplanets Survey Satellite, the Hubble Space Telescope, XMM-Newton, and the upcoming James Webb Space Telescope (JWST). Data-mining and ML techniques will enable efficient extraction of the key structures and properties from the resulting simulation-generated datasets.

PSE and SAP Crosscutting

Multiscale coupling is common to SAPs as well as laboratory plasmas. Bridging the gap between kinetic- and global-scale phenomena has been a long-standing obstacle to advancing our understanding of the energetics and dynamics of activity on the Sun, in planetary magnetospheres and ionospheres, the interplanetary medium, in active galactic nuclei, within accretion disks, and other cosmic plasmas. A primary approach for addressing this problem is numerical simulation, which requires taking full advantage of innovative developments in hardware, algorithms, visualization, and data analysis tools from across the PSE community as well as computational physics.

To capitalize on the great progress and ongoing momentum in understanding reconnection in SAPs, a coordinated program of observations, theory, numerical simulations, and laboratory experiments need to be employed. Many key topics are ripe for breakthroughs—multiscale coupling, 3D geometries, energy conversion and partitioning, onset, partial ionization effects, interplay with ideal instabilities, reconnection in relativistic extreme environments, and connections with turbulence and shocks. Dedicated DOE, NASA, and NSF programs are needed that support the development of next-generation analytical and numerical models and the application of new numerical technology and theoretical understanding to these reconnection challenges. Computational advances require fluid, kinetic, and hybrid models, and multi-fluid models that include kinetic effects through physics-based closure equations. Exascale computing will enable us to finally address these questions in fully 3D systems with increasingly realistic plasma parameters. Over the next decade, unprecedented remote-sensing observations from missions such as SDO, IRIS, and Fermi, as well as exquisite in-situ data from missions such as MMS, PSP, Solar Orbiter, and BepiColombo, will deliver a wealth of critical new insights on magnetic reconnection. An encouraging development is the new NSF/NASA collaborative program, *Next Generation Software for Data-driven Models of Space Weather with Quantified Uncertainties (SWQU)*.

Turbulent cascades culminate at the dissipation scale through kinetic processes that are poorly understood. The physics of dissipation is a fundamental PSE problem, since it involves the irreversible conversion of collective fluid or kinetic-scale motions into internal energy, or "heating." Complicating matters further, intermittency in turbulence can connect dynamically coherent structures (e.g., current sheets), patchy dissipation, and the entire inertial range of turbulence. Because the dissipation scale is generally well below the resolution limit of both observations and numerical simulations, one can only infer its properties in heliophysical and astrophysical objects. For example, the solar corona and wind clearly are heated well above the photospheric temperature, but the manner in which the Sun's magnetic energy is transformed into heat is an open question. Similarly, the cores of galaxy clusters exhibit far less star formation than expected, indicating the presence of an additional heating source that remains a mystery. This major problem in SAPs and laboratory plasmas encompasses turbulence scales that range from fluid to kinetic. Understanding and relating such disparate scales is a challenge for the next decade.

Finite computing resources usually make it difficult to capture the turbulent cascade all the way down to the dissipation scale when simulating high Reynolds number, multiscale turbulent plasmas. Subgrid models bypass this difficulty by parametrizing dissipation at the smallest scales that can be stably resolved on the computational grid, which introduces artificially enhanced dissipation of small-scale structures. When modeling solar/stellar MHD convection, the challenge is to ensure that larger scales remain unaffected by the subgrid model. Therefore, the choice of a subgrid model can strongly influence global characteristics of large-scale dynamo solutions. MHD dynamo simulations with the same code but with different subgrid models have indeed demonstrated that the resulting magnetic self-organization differs substantially. Choosing the appropriate subgrid model is a difficult decision for simulating other turbulent plasmas in their large-scale environments, including the solar wind, astrophysical jets, and the ICM. Consequently, progress in this area will benefit a wide range of SAP investigations.

New facilities investigating the "warm Universe", such as the Stratospheric Observatory for Infrared Astronomy, Atacama Large Millimeter Array, and the upcoming JWST, will study specific plasma environments with low ionization fractions, complicated chemistry, and complex molecular radicals. These observations probe important plasma-physical and chemical processes that lead to the formation of dust and organic molecules. Observations of kilonova emission after neutron-star mergers indicates the presence of plasma dominated by the low ionization stages of heavy elements (lanthanides and actinides). Studies of thermodynamic and radiative properties of such plasmas requires high-resolution spectral information that comes from atomic, molecular, and optical (AMO) theoretical and experimental methods. Collaboration with AMO and low temperature plasma researchers is vital for future progress in this area of SAP physics.

Atomic and molecular opacities are critical for understanding many cosmic phenomena, including the internal structure and evolution of stars, stellar and planetary atmospheres, pulsating stars, and the light curves arising from supernovae. Although the complexity of the problem makes accurate calculations daunting, the advancement of high-performance computing of atomic and molecular data has generated a large amount of more accurate and complete opacity data. Extensive international efforts have calculated massive databases of opacities for plasmas in LTE, but non-LTE opacity data are still sparse. Theoretical opacities can only be validated by comparison with estimates derived from observations of the solar interior, stellar pulsations, and atmospheric spectra of stars and planets, with experimental neutrino-flux measurements, and with predictions from 3D hydrodynamics simulations. Achieving stellar interior conditions in the laboratory is very difficult. Only very recently have laboratory experiments been able to reproduce plasma conditions in the solar convective envelope and approaching the radiative zone.

Dedicated DOE and NSF programs are urgently sought to support the next-generation experimental facilities and diagnostic instrumentation in concert with SAP observations. Spectroscopic diagnostics remain a critical element for determining the physical conditions in SAPs. Models of optically thin radiation (e.g., CHIANTI for calculating spectra from astrophysical plasmas) rely heavily on atomic cross-sections, ionization/recombination rates, electron excitation rates, and radiative decay rates calculated theoretically and validated against laboratory data. Besides CHIANTI, the Atomic Data and Analysis Structure (ADAS) is an interconnected set of computer codes and data collections for modelling the radiative properties of ions and atoms in SAPs, laboratory fusion devices, and technological plasmas. CHIANTI and ADAS are currently the only major resources that are used for space and astrophysical applications. Although many current SAP investigations involve atomic and spectral data for very heavy elements, available databases lack essential data on these elements. Moreover, existing codes are unable to calculate these data, and there has been insufficient funding for new or updated code development. The benchmarking of atomic data models requires new, high-resolution laboratory spectrometers in the UV and X-ray wavelength regions. Furthermore, adequate funding for maintaining and updating production codes and databases, and the workforce for atomic physics calculations, is critically needed.

INFRASTRUCTURE

Research into space and astrophysical plasmas is supported by multiple funding sources, with different requirements, constituents, and goals. Although this situation provides many opportunities and fosters cross-disciplinary studies, it also leaves some crucial areas of SAP science without reliable support. One prominent example is laboratory experiments that approach or reproduce scaled-down versions of plasma conditions in cosmic phenomena. Most facilities capable of performing these experiments are supported by agencies whose missions are not SAPs, while the agencies supporting space research are unlikely or unable to invest the substantial resources that would enable such experiments. Similarly, theory and computation are not well supported in proportion to their importance in designing and utilizing instruments, missions, and observatories. Large disparities exist in this regard between the different parts of PSE, and advances in one sector are not always available to others. Targeted cost-sharing interagency programs would benefit both SAP and basic plasma research (e.g., the recent NSF/NASA *SWQU*), potentially revealing new paths toward the goals of national security, energy independence, and comprehending the universe.

The range of important plasma processes and physical regimes encompassed by the Sun (and other stars) makes it an ideal laboratory for plasma investigations. Similarly, the deep understanding and powerful numerical techniques developed by the basic plasma research community need to be absorbed and applied by SAP researchers. Solar and plasma science have a long history of beneficial exchanges, yet the current level of interaction is not optimal. Focused research programs that target solar phenomena from a plasma-science perspective would enhance cross-fertilization, with joint funding from all stakeholders including NASA. A successful model to emulate is NASA's Living with a Star (LWS) Focused Science Team program, which attacks community-proposed heliophysics problems by assembling teams of small groups that each address some aspect of the problems. Teams that include members from both plasma and solar research communities would ensure effective cross-disciplinary and productive joint research and communication.

Space weather research extends from basic science to operational forecasting. Because different sponsors focus on different aspects of space weather, it is difficult to apply the systems approach needed to make progress on key questions. Recently, a national space weather plan has been formulated that involves all agencies whose purview includes space weather. New opportunities for basic and applied space weather research are being created in partnership with the scientific and end-user communities. This encouraging development should continue with substantial buy-in from all sponsors, with particular emphasis on establishing long-term, stable funding to tackle the most complex problems and to validate and transition the most robust, accurate models to operational use. The NSF/NASA SWQU is an important first step in this direction.

CONNECTION WITH TECHNOLOGY

Better understanding of space weather effects will drive technology development in several directions. Improving the electric power grid to protect against space weather extremes is already underway, and further improvements should be made to prevent massive shut-downs, reduce damage to transformers and other vulnerable equipment, and ensure that repairs or replacements are timely. To predict the impact of space weather events on specific satellites throughout their orbits, models of spacecraft charging and other adverse effects on our assets in space should be linked to models of the space environment. The exploding population of spacecraft and debris in Earth orbit makes it imperative to characterize atmospheric drag as accurately as possible, to better predict satellite lifetimes, avoid collisions, and estimate fuel requirements. Current models are inadequate for calculating changes in drag due to external forcing by solar-wind CIRs, CMEs, and flare radiation, and generally predict time-averaged conditions in specific orbits rather than instantaneous local conditions throughout geospace.

The sustainability and viability of Earth-based SAP observations are threatened by the unprecedented launch of massive constellations of hundreds to thousands of commercial communication and internet-providing satellites. The electromagnetic emissions of these satellites are encroaching on frequencies that are essential to SAP observations. The ubiquitous presence of the satellites is already interfering with optical observations. To date, there has been little discussion of how SAP research and massive satellite-based commercial ventures can co-exist. The penalty for not engaging in discussions and establishing boundaries and processes will be severe limitations on our ability to observe SAPs in future.

FUTURE CHALLENGES AND OPPORTUNITIES: FACILITIES/MISSIONS

Facilities

NSF's Daniel K. Inouye Solar Telescope (DKIST) will be the largest solar telescope in the world, able to view features on the Sun as small as 70 km across. Using adaptive optics technology, DKIST's 4.2-m primary mirror and five major instruments will provide the sharpest views ever taken of the solar surface, with the spatial, temporal, and spectral resolution and dynamic range needed to measure elemental magnetic structures at and above the photosphere. When DKIST is fully operational, there will be unprecedented data revealing the roles played by magnetic fields and the embedding plasma in generating and transporting solar activity. DKIST is ideally suited to studying the transfer of energy from the solar interior to the outer atmosphere, particularly the partially ionized, high-to-low β chromosphere and its magnetic connection to the hot, fully ionized corona. In combination with space missions such as SDO, IRIS, PSP, and Solar Orbiter, DKIST will be a powerful tool for characterizing the Sun's magnetized plasma properties and the physical processes behind coronal heating and eruptive activity. First solar light will be in late 2020. The committee encourages the DKIST team to enable open access to DKIST observations to the greatest possible extent, consistent with U.S. space data practices.

Radio frequency observations have probed the solar wind and the ISM for many years, revealing key properties of turbulence, coherent structures, and waves. However, the lack of a ground-based radio interferometer with the appropriate combination of sensitivity, frequency coverage, and angular resolution has been a barrier to exploiting these phenomena more effectively. NSF's next-generation Very Large Array (ngVLA) will permit pioneering studies of the solar wind and ISM, measuring the solar-wind spatial spectrum from tens of meters to 1,000 km. Intensity scintillation tomography will map fast- and slow-wind velocity fields and their fluctuations in the critical corona-inner heliosphere transition, complementing direct sampling by PSP. Faraday rotation and dispersion-measure observations of polarized background sources and pulsars can reveal the overall density structure and magnetic field of the outer corona and inner heliosphere. By making global measurements of the solar wind properties, turbulence, and transients with radio propagation diagnostics, the ngVLA would be highly complementary to in-situ measurements made by proposed next-generation heliospheric missions such as Helioswarm. For the ISM, the ngVLA will characterize interstellar turbulence, with the same instrument using the same technique (angular broadening), over a wider spectral range than ever before.

Nonetheless, to expand the renaissance that solar radio astronomy has undergone in the past decade, significant observational advances are required. High-cadence microwave imaging, as currently obtained by EOVSA and the JVLA, probes coronal reconnection sites, regions where high-energy electrons are accelerated and propagate, and the elemental structure of the quiet chromosphere. While the JVLA and EOVSA have served as platforms for developing, testing, and demonstrating the potential of broadband imaging spectropolarimetry at radio wavelengths, there is still a need for a high-performance, solar-dedicated radioheliograph designed to fully mine the rich information content of solar radio emission. The high-level requirements for such observations are: extremely broad, continuous coverage from 50 MHz to 20 GHz with high spectral resolution, time resolution as short as 10 ms, full polarimetry, full-disk microwave imaging, a field of view out to several solar radii at lower frequencies, and wide dynamic range (~10^4). These requirements are met by the Frequency Agile Solar Radiotelescope (FASR), a next-generation radioheliograph recommended as a priority by previous Astronomy and Astrophysics and Heliophysics Decadal Surveys. FASR is a low-cost, low-risk, and high-reward facility that would play a unique and productive role in serving the wider solar community.

Although the case for more extensive laboratory experiments and development programs related to SAP science is made forcefully in most decadal studies, little progress has resulted. LMAP, the heliophysics laboratory program recommended in the 2014 Heliophysics Decadal Survey, has not yet been implemented by NASA. A related but very modestly funded program, the Heliophysics Technology and Instrument Development for Science, includes some laboratory plasma studies of chemical, spectroscopic, and nuclear measurements supporting observations and models. U.S. federal laboratories managed by DoD and DOE could be excellent resources for the SAP community, which lacks access to these capabilities. In return, the laboratories gain expertise in previously underexplored plasma regimes and opportunities to compare laboratory results with cosmic plasmas. For example, major laboratory facilities such as UCLA's LAPD and NRL's SPSC currently offer limited but vital opportunities for SAP-related experiments. A comprehensive program that facilitates coordinated experiments between federal laboratories and the SAP community should be developed and implemented across NASA, NSF, DOE, and DoD.

Missions

New missions offer great opportunities for discovery SAP science. Solar Orbiter, a European Space Agency mission with some U.S.-built components, was launched on 10 February 2020. Its primary science goals are to perform close-up, high-resolution studies of the Sun and its inner heliosphere, while orbiting at 0.3-0.9 AU from the Sun. The combination of Solar Orbiter and Parker Solar Probe will provide unprecedented opportunities to investigate multiscale phenomena in the corona and solar wind from separate vantage points, through complementary in-situ and remote-sensing observations. Solar Orbiter will address the following fundamental questions:

- How and where do the solar wind plasma and magnetic field originate in the corona?
- How does solar activity drive heliospheric variability?
- How do solar eruptions produce energetic particles that traverse the heliosphere?
- What drives the solar dynamo and its connections between the Sun and the heliosphere?

The Ionospheric Connection Explorer (ICON) will investigate the connections between the neutral atmosphere and ionosphere, with three instruments that measure temperature, velocity, and composition of gases far from the spacecraft and a pair of identical in-situ instruments that characterize the plasma around the spacecraft. Its local measurements will complement the global imaging obtained by GOLD. ICON will determine, for the first time, how dynamic terrestrial weather events, such as cyclones and El Niño, affect the ionosphere. ICON was launched on 9 October 2019, and is currently in its commissioning phase.

Geospace Dynamics Constellation (GDC) is an ambitious space-mission concept recommended by the 2013 Heliophysics Decadal Survey for implementation as the next NASA Heliophysics LWS mission, which is currently undergoing an implementation study in preparation for the Announcement of Opportunity. GDC will address crucial questions pertaining to the dynamic processes active in Earth's upper atmosphere; their local, regional, and global structure; and their role in driving and modifying magnetospheric activity. GDC will be the first mission to address these questions on a global scale with a constellation of spacecraft that permit simultaneous multi-point observations of a critically undersampled region of the ionosphere and thermosphere. This investigation is central to understanding the basic physics and chemistry of the upper atmosphere and its interaction with Earth's magnetosphere, and will provide insights into space weather processes throughout geospace. According to the recent Science and Technology Definition Report for GDC, the primary goals are to understand:

- how the high-latitude ionosphere-thermosphere (IT) system responds to variable solar wind/ magnetosphere forcing; and
- how internal processes in the IT system redistribute mass, momentum, and energy.

Because spatial scales are vast and energetic-particle kinetics and charge exchange are particularly important, no current models comprehensively describe the heliospheric system fully. Physical understanding is hampered by the very limited set of observations. To remedy this gap, the Interstellar Mapping and Acceleration Probe (IMAP), an integrated and coordinated suite of 10 instruments, was selected last year by NASA for launch in 2024. IMAP addresses two critical problems in SAP physics: the acceleration of energetic particles in interplanetary space and the interaction of the solar wind with the local interstellar medium. IMAP's science objectives are to:

- improve understanding of the composition and properties of the LISM;
- advance understanding of the temporal and spatial evolution of the dynamic boundary between the solar wind and the ISM;
- identify and advance understanding of processes governing the interactions between the magnetic field of the Sun and the LISM; and
- identify and advance understanding of particle injection and acceleration processes near the Sun, in the distant heliosphere, and in the heliosheath.

The HelioSwarm mission concept is a constellation of small spacecraft with a wide range of spatial separations that would simultaneously sample key physical parameters in the turbulent solar wind. By measuring properties that relate directly to the cascade of energy across scales to where energy is dissipated, and into different physical regions, a constellation mission in the solar wind will enable direct tests of current conflicting models for the spectral and spatial distributions of turbulent power, thus increasing our understanding of turbulent SAPs.

An Interstellar Probe was one of the top-10 priorities recommended as new imperatives for NASA by the 2013 Heliophysics Decadal Survey. A NASA-funded study for a "Pragmatic Interstellar Probe" showed that speeds at least three times that of Voyager 1 were possible using available/near-term technology, enabling the Probe to reach the pristine LISM within 50 years. An augmented Interstellar Probe would address not only plasma physics of the heliosphere but also fundamental planetary science and astrophysics, as outlined by the following science goals:

- Understand our heliosphere as a habitable astrosphere.
- Investigate the plasma physical processes and global nature of the outer heliosphere, the boundary regions, the VLISM and beyond to the pristine LISM.
- Understand the evolutionary history of the solar system. Explore dwarf planets and Kuiper Belt Objects through flybys observing atmospheric and surface properties. Determine the large-scale distribution of the circumsolar debris disk.
- Open the observational window to early galaxy and stellar formation. Measure the integrated diffuse extragalactic background light from redshifted stars and galaxies dating back to ~200 million years after the Big Bang.

The primary missions of the recently launched Spectrum-Roentgen-Gamma (Spekrt-RG) spacecraft are to find and map all massive galaxy clusters in the observable universe at X-ray wavelengths, and to search for other cosmic X-ray sources, including active galactic nuclei, star formation regions, and stellar activity. Several astrophysical satellites that probe hot cosmic plasmas with high-energy emissions are planned: for example, the Athena X-ray observatory, the Hard X-ray Modulation Telescope, the Imaging X-ray Polarimetry Explorer, and the X-ray Imaging and Spectroscopy Mission. In parallel, radio and millimeter-wavelength observatories that probe nonthermal emission from relativistic magnetized cosmic plasmas have been recently updated, are developing new capabilities (e.g., interferometric observations by the Event Horizon Telescope of the plasma orbiting the M87 supermassive BH; Figure 7.2), or are in the final design stages (e.g., the upcoming multinational SKA radiotelescope scheduled for completion in 2025). These technological advances will ensure a flow of new discoveries and new physical insights from a wide range of astrophysical plasma environments.

INTERNATIONAL

Comparison of International PSE Community to United States

Active non-U.S. SAP research programs exist throughout the world, with the largest groups found in China, India, Russia, several European countries, the UK, and Japan. Scientists everywhere have benefitted from NASA's open data policy, utilizing observations from heliophysics and astrophysics missions. The Japan Aerospace Exploration Agency (JAXA) and European Space Agency (ESA) missions are less generous with their data, in general, although joint missions with NASA typically adopt NASA's policies. Data from ground-based facilities such as the Nobeyama Radio Observatory (Japan), the Nançay Radio Observatory (France), and the Low Frequency Array (LOFAR; Netherlands and other European countries) can be obtained by submitting observing proposals or contacting observatory staff. Some major plasma physics programs that emphasize SAP simulations and/or data analysis are located at Katholieke Universiteit (KU) Leuven (Belgium), Max Planck Institute (Germany), Nanjing University (China), Kyoto University (Japan), Indian Institute for Astrophysics and the Physical Research Laboratory (India), University of St. Andrews and the Imperial College London (UK), the University of Paris/Meudon Observatory (France), and the Space Research Institute (Russia). Anecdotal evidence suggests that SAP programs at non-U.S. academic institutions are attracting more students than U.S. institutions, and that faculty positions at these international institutions are more plentiful than in the United States. China in particular has sent many graduate students and postdoctoral associates to study at international universities and laboratories, and has expanded the number of SAP faculty positions substantially in the past decade.

Since 2010 the number of countries launching/developing SAP space missions and building or planning new ground-based facilities has grown. India is preparing to launch Aditya-L1 in 2020, a mission that will observe the Sun's photosphere (soft and hard X-ray), chromosphere (UV) and corona (visible and near-infrared light); study the solar particle flux, reach the L1 orbit, and measure magnetic field strength variation around L1. SMILE, a Chinese/ESA collaborative mission under development, will observe the global structure of Earth's magnetosphere in soft X-rays. Solar C is planned as a successor to Hinode by JAXA in collaboration with ESA and NASA. This mission will focus on high-resolution VUV spectroscopy and multichannel EUV solar imaging from the chromosphere to the corona. As noted above, the Russian Space Agency, in collaboration with the Max Planck Institute for Extraterrestrial Physics in Germany, launched the Spektr-RG high-energy astrophysics space observatory to galaxy clusters and active galactic nuclei.

As a result of these international activities, the United States is beginning to lose its leadership in SAP studies, missions, and facilities. Other nations, such as China and India, are prioritizing science to a degree far above that in the United States. The reasons are multifaceted. The United States is building and launching spacecraft with SAP payloads too infrequently, training too few U.S. students, especially in instrumentation and computation; and placing increasing barriers to retaining foreign nationals at U.S. institutions (particularly government facilities). Current policies make it difficult for the United States to attract and retain excellent scientists from other countries. In addition, the increasing cost of large missions needed for breakthrough science are not easily affordable for a single national space agency without affecting adversely other essential programs. Resolving the dilemma of maintaining leadership while expanding international collaborations is a difficult but crucial task facing the PSE community and its sponsors. The findings and recommendations summarized in Chapter 7 point to some solutions.

Importance of United States to Current Collaborations

SAP research relies heavily on international collaborations, particularly in the era of open data policies for space missions. The United States has led the way in opening access to NASA mission data. Most space agencies in other nations have not yet fully adopted the same approach. The growth of publicly accessible virtual observatories, software repositories, broadly accepted data standards, and other community-based resources has enabled researchers worldwide to download and analyze multi-wavelength and multi-messenger observations more easily than ever before. Ground-based networks also are essential for global coverage of geospace and solar phenomena, as well as long-baseline interferometry.

These necessary and desired international collaborations can be difficult to establish and maintain. Most successful international programs have been enabled by professional organizations such as the United Nations, the International Council of Scientific Unions, and the International Astronomical Union, often without commensurate funding. One recent example is the International Space Weather Action Teams (ISWAT) program managed by the Committee on Space Research, a grassroots effort that has brought together self-funded working groups to tackle key problems in all facets of space weather science. Among other international programs, NSF provides opportunities for researchers with active NSF awards to apply for supplemental funding for research visits to collaborate with PIs funded through the European Research Council. In addition, establishing an internationally accessible environment for collaborative model development would accelerate building essential tools for SAP research. Greater participation and financial support by U.S. agencies, and collaborations with their foreign counterparts, would enable more rapid advances in understanding all aspects of space and astrophysical plasmas, and lead to crucial societal benefits.

Space technology exchanges are often restricted by U.S. International Traffic in Arms Regulation (ITAR) based on technology transfer with potential defense-related applications. Given the international advances that have already been independently made, ITAR restrictions on exchange of SAP data may need to be revisited to ensure that these are limiting exchange of non-sensitive data.

FINDINGS AND RECOMMENDATIONS

NASA funding for plasma-related research comes largely from its ability to support missions. Basic code and simulation development, theory, and novel data-analysis techniques vital to science missions are infrequently supported by NASA. New initiatives (e.g., DRIVE Science Centers) typically fund a few large research programs, while the smaller grants are too small and short-term to enable these computational developments.

> **Finding:** A lack of support for basic code and simulation development, theory, and novel data-analysis techniques has long been a barrier to advancing our understanding of SAPs and predictive capabilities.

In addition, the growing trend toward open-source requirements would impose an unfunded mandate on developers to make their codes publicly available and user friendly, and does not provide for user support. Coordinated multi-agency and multidisciplinary funding for development of theory, plasma codes with open source versions, numerical algorithms, and new data-analysis tools (e.g., machine learning) would maximize scientific return from current and future heliophysics and astrophysics observations and simulations.

> **Finding:** Unfortunately, the level of funding for the highly successful NSF/DOE *Partnership in Basic Plasma Science and Engineering* has lagged that recommended by the 2000 Plasma Decadal Review, despite its very central role in discovery plasma science and its capacity to create effective multidisciplinary bridges within plasma science.

The recent NSF/NASA *Next Generation Software for Data-driven Models of Space Weather with Quantified Uncertainties* is an example of a focused SAP-oriented collaboration.

> **Recommendation: NASA should join the NSF/DOE Partnership in Basic Plasma Science and Engineering to expand interdisciplinary basic plasma research that would benefit SAP. This expanded partnership would leverage strategic contributions from each agency to enable breakthrough progress that benefits a wide range of PSE activities (see Table 1, #3-#5).**

The contributions of NSF and DOE to the partnership are approximately $4 million to $5 million per year per agency. NASA joining the partnership with an equivalent contribution by NASA's Science Mission Directorate *without impacting other programs* would significantly increase its scientific impact.

> **Finding:** Solar, heliospheric, magnetospheric, and ionospheric physics, and astrophysics have untapped synergies with laboratory plasma experiments, with the common goal of understanding ambient plasma conditions and chemistry.

SAP examples include ionospheric studies with incoherent scattering radar, chemistry in giant molecular clouds in the interstellar medium, chromospheric and coronal plasmas, and the very local interstellar medium. Such laboratory SAP experiments are typically not supported by NASA whereas those agencies that have the capability to perform such experiments do not necessarily address the most critical SAP topics.

> **Finding:** Strategic funding from NASA and agencies supporting experimental facilities would enable more ambitious, innovative joint projects than a single source could support.

A successful model to emulate is NASA's Living with a Star Focused Science Team program, which investigates major heliophysics questions by assembling teams of small groups that each address selected aspects of the science.

> **Recommendation: NASA and NSF should lead an effort with DoD (especially ONR and AFOSR), DOE, and other stake-holders (see Table 1, #6 and #24) should develop a collaborative program that enables SAP scientists to collaborate with laboratory plasma experimentalists and advance both fields by leveraging their different needs and knowledge bases.**

As noted by the 2016 National Academies report *Achieving Science with CubeSats*, CubeSats and smallsats offer novel and transformational opportunities to explore geospace and the heliosphere with unprecedented spatial and temporal coverage, as needed to resolve fundamental plasma physics problems requiring multipoint observations—for example, solar wind turbulence and magnetosphere-ionosphere coupling.

Finding: Clusters of CubeSats and smallsats carrying in-situ and remote-sensing instruments are the best observing platforms for tackling many basic unsolved questions of multiscale SAPs (e.g., reconnection, turbulence, and shocks), and provide essential research and training opportunities for university faculty and students.

Finding: Existing procedures for developing, building, and operating missions are traditionally geared toward large missions, and can pose unnecessary obstacles for single spacecraft and multi-platform missions employing smallsats and CubeSats.

NSF initiated the CubeSat program, which has become an important gateway for students into experimental heliophysics and astrophysics. NASA currently provides CubeSat launches for NSF and will launch 10 NSF CubeSats in the future. The committee lauds this level of collaboration in a program that effectively combines workforce development and exciting plasma research.

Recommendation: With NASA and NSF as lead agencies, NASA, NSF, and DoD, as the primary sources of space missions, should explore avenues, including rideshares, international partners, and partnering with commercial launch providers, for reducing costs, lowering barriers, enabling higher-risk missions, and boosting launch opportunities for these pioneering investigations using Cubesats, smallsats and cluster of these satellites. (see Table 1, #7).

Finding: NSF, despite having a limited investment level in their Cubesat program, has broad access to universities and undergraduate and graduate students. This access may be important in providing basic training in PSE relevant to CubeSats. The recent solicitation for a cross-cutting NSF Ideas Lab Program focused on CubeSat innovations to push the envelope of space-based research capabilities is an example of one approach.

Recommendation: In view of their limited level of investment, NSF should identify a clearer role and "identity" in their CubeSat program that distinguishes it from its NASA counterpart. To ensure cost and resource efficiencies, NSF and NASA should coordinate further on funding opportunities.

Finding: Increased support is needed to meet the challenge of designing and constructing compact plasma and remote-sensing instrumentation suitable for Cubesats and smallsats.

Recommendation: Current NASA programs such as H-FORT, H-TIDES, and the IDP (Instrument Development Program) should be augmented to meet the growing demand for compact plasma and remote-sensing instrumentation suitable for Cubesats and smallsats.

SAP research, as in other STEM fields, is an international endeavor that often requires efforts and funding greater than any one country can support. Open data policies maximize scientific progress by expanding international community access to SAP plasma data, which is especially important for multi-wavelength/multi-messenger data sets.

Finding: The SAP community needs to agree on data standards, formatting, and processing levels for publicly available data.

Recommendation: Federal agencies that support ground-based and international space facilities (NSF, NASA, DoD, NOAA) should adopt similar open data policies and minimize barriers to international collaboration except where national security is of concern.

Recommendation: NSF should convene a workshop co-sponsored by NASA and DoD to make recommendations for how to establish and maintain open data policies.

Recommendation: Once established, maintaining and updating the open data standards should be the responsibility of governing federal organization such as one of the major contributors (NASA, DoD, NOAA) or a more specialized agency for standards such as NIST.

Hiring plasma-knowledgeable scientists within universities, national laboratories, and other institutions is critical to the long-term health of SAP and the development of the future STEM workforce. Traditionally, university physics and astronomy departments have rarely hired faculty in plasma heliophysics and plasma astrophysics, despite the highly interdisciplinary and fundamental nature of the discipline. The existing NSF program that supports the hiring of space and solar physicists, in partnership with university departments, has been quite successful, sponsoring one hire every few years.

Finding: A faculty partnership program introduced by NASA, NSF, and DOE—similar to that presented in the Finding and Recommendation section of Chapter 1 (see Table 1.1)—is needed to strengthen SAP hiring in universities and federal research facilities.

Appendixes

A

Statement of Task

As part of the Physics 2020 decadal assessment and outlook for physics, the National Academies of Sciences, Engineering, and Medicine will conduct a study of the past progress and future promise of plasma science and technology and provide recommendations to balance the objectives of the field in a sustainable and healthy manner over the long term. Specifically, the study committee will:

1. Engage stakeholders in government, the plasma sciences communities, and industry to collect perspectives on the major achievements and challenges of the past decade and the most exciting and promising areas of plasma research anticipated for the next 10 years, as well as how plasma research impacts and is impacted by adjacent areas of science and technology.
2. Assess the progress and achievements of plasma science over the past decade.
3. Identify and articulate the major scientific questions and new opportunities that define plasma science as a discipline, noting connections to and the influence on other disciplines.
4. Discuss the nature and importance of the U.S. role in multi-national plasma research activities.
5. Assess the scope of international research across the breadth of plasma science and discuss the relative standing of U.S. activities.
6. Discuss how plasma science has contributed and will likely contribute to U.S. national needs both in and beyond plasma science, including workforce development, economic prosperity, national defense, and other applications.
7. Assess whether the present plasma science workforce and training opportunities are commensurate with future workforce needs.
8. Assess and comment on the present role of, and future opportunities for, universities within large national programs organized around major research instruments or community assets (i.e., user facilities, satellites, telescopes, etc.).
9. Assess whether the structure, program balance, and level of the current U.S. research effort in plasma science across the federal and private efforts are best positioned to realize the science opportunities.

The study committee's recommendations should not alter recommendations from the Decadal Strategy for Solar and Space Physics, the mid-decadal assessment of that report, or the ongoing study on Strategic Plan for U.S. Burning Plasma Research. The committee may make recommendations or offer comments on organizational structure, program balance, and funding, as appropriate, with discussion of the evidentiary bases.

B

Findings and Recommendations

The committee offers the following findings and recommendations on the scientific front of plasma physics and on government support for plasma science. The committee supports each recommendation with a set of findings that the committee has made during the course of this study. These recommendations can be taken to strengthen our responses to specific grand challenges and to broadly advance the entire scientific frontier of plasma science.

CHAPTER 1 RECOMMENDATIONS

Stewardship and Advancement of Interdisciplinary Research

Finding: Plasma science and engineering (PSE) is inherently an interdisciplinary field of research. While the underlying science has common intellectual threads, the community is organized into sometimes isolated sub-disciplines.

Finding: What may be narrowly perceived as duplication is actually critically necessary collaboration in order needed to address the complex science challenges in PSE while rapidly translating results to society-benefiting outcomes.

Finding: Institutional barriers between sub-disciplines of PSE make mutually advantageous interactions difficult, yet interactions between sub-disciplines have led to important advances that would have been difficult to produce otherwise and should be encouraged.

Finding: A more unified voice for the field would create opportunities for interdisciplinary and translational research, and initiate activities that exploit synergies among different subdisciplines of PSE.

Recommendation: Federal agencies directly supporting plasma science and engineering (PSE) and those federal agencies benefiting (or potentially benefiting) from PSE should better coordinate their activities. This coordination, which extending into offices and directorates within larger federal agencies, would provide a more unified voice for the field, and create opportunities for interdisciplinary and translational research, and initiate activities that exploit synergies among different subdisciplines of PSE.

Finding: Fundamental research in PSE can and does rapidly translate to the development of societally relevant technologies, the benefits of which cut across the missions of many federal agencies.

Finding: The interdisciplinary and multidisciplinary strengths of PSE are not being fully utilized. This situation is to the detriment of the fundamental plasma research and to the detriment of the intended applications.

Finding: Interagency (and inter-program) initiatives would fully exploit the interdisciplinary and multidisciplinary potential of plasma science and engineering (PSE) in both fundamental and translational research if properly stewarded.

Recommendation: Federal agencies and programs within federal agencies that are separately focused on fundamental plasma research, and those that are focused on science and technologies

that utilize plasmas, should jointly coordinate and support initiatives with new funding opportunities.

Finding: The potential is enormous for PSE to contribute to one of society's greatest challenges—sustainability. The contributions that PSE could make extend from fusion-based, carbon-free electrical power generation to electrification of the chemical industry.

Finding: The translational nature of fundamental research in plasma science and engineering (PSE) needs to be formally recognized at NSF.

Recommendation: The Engineering Directorate (EngD) of the National Science Foundation (NSF) should, as a minimum, consistently list PSE in descriptions of its relevant programs and consistently participate in the NSF/Department of Energy (DOE) Plasma partnership.

Recommendation: More strategically, NSF should establish a plasma-focused program in the Engineering Directorate. that would advance engineering priorities across the board, including advance agricultural systems, energy and environment, chemical transformation, advanced manufacturing, electronics and quantum systems.

Finding: Public-private partnerships (PPP) have long been a benefit to PSE, largely in the form of SBIR (Small Business Innovative Research) and STTR (Small Business Technology Transfer) programs.

Finding: With there being few U.S. governmental programs designed to translate industrially relevant fundamental science to practice, U.S. industries are at a competitive disadvantage internationally.

Recommendation: Federal agencies focused on plasma research, and DOE in particular, should develop new models that support the translation of fundamental research to industry. Programs that support vital industries depending on plasma science and engineering (PSE) should be developed through relevant interagency collaborations.

The Plasma Science and Engineering Community

Finding: The multidisciplinary approach has been at the heart of the success of the field, while simultaneously working against the long-term viability of the field in academia.

Finding: Lack of a critical mass of faculty in PSE inevitably will lead to an erosion of U.S. capability in PSE. At the same time, the university leadership in PSE is rapidly aging and will need renewal in the coming decade.

Recommendation: Federal agencies—for example, Department of Energy (DOE), National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), and Department of Defense (DoD)—should structure funding programs to provide leadership opportunities to university researchers in plasma science and engineering (PSE) areas and to directly stimulate the hiring of university faculty.

Finding: Plasma-specific educational and research programs that also provide opportunities to diverse and less advantaged populations are needed to ensure a critically populated PSE workforce.

Finding: Plasma-specific intern programs and summer schools are needed for undergraduate and graduate students, as are programs supporting students with incomplete preparation to progress in plasma physics, such as the American Physical Society *Bridge Program*.

Finding: Requiring students to know early in their undergraduate years that plasma physics is a career goal has limited the number of students continuing in plasma physics in graduate school and has excluded less advantaged populations.

Finding: Support for junior faculty, for course development, and for curricula enhancement (e.g., inclusion of plasma physics in other courses) are necessary to enable students from a wide range of institutions to enter the field.

Finding: The committee regards multi-agency investment in education, whether through directly supporting undergraduate and graduate students or programs, or through faculty, and resource development, as being critical. The more "duplication" of effort in these areas can only further strengthen PSE.

Recommendation: Funding agencies (e.g., NSF, DOE, NASA, DoD) should structure funding to support undergraduate and graduate educational, training, and research opportunities—including faculty—and encourage and enable access to plasmas physics for diverse populations.

The Research Enterprise in Plasma Science and Engineering

Finding: Given these strong international investments, incremental progress in facilities in the United States is insufficient to maintain leadership.

Finding: A spectrum of facility scales is required by the sub-fields of PSE to address their science challenges and translational research.

Finding: Mid-scale facilities (e.g., in the $1 million to $40 million range, depending on agency) offer particularly good opportunities for broadening participation within academia.

Recommendation: Federal agencies (e.g., NSF, DOE, NASA DoD) should support a spectrum of facility scales that reflect the requirements for addressing a wide range of problems at the frontiers of PSE.

Finding: Investment in facilities without the concurrent support of research and operations is not optimum

Recommendation: Federal agencies whose core missions include plasma science and engineering (PSE)—for example, Department of Energy (DOE), National Science Foundation (NSF), National Aeronautics and Space Administration (NASA), and Department of Defense (DoD)—should provide recurring and increased support for the continued development, upgrading, and operations of experimental facilities, and for fundamental and translational research in plasma science. A spectrum of facility scales should be supported, reflecting the requirements for addressing different problems at the frontiers of PSE.

Finding: Computational Plasma Science and Engineering (CPSE) has become essential across PSE for experiment and mission design and diagnosis, idea exploration, probing of fundamental plasma physics processes, and prediction.

Recommendation: Federal agencies should support research into the development of computational algorithms for plasma science and applications for the heterogeneous device computing platforms of today and upcoming platforms (e.g., quantum computers), while also encouraging mechanisms to make advanced computational methods, physics-based algorithms, machine learning, and artificial intelligence broadly available.

Better Serving the Community

Finding: Although the majority of the FES budget is still devoted to supporting fusion science, the present office title does not now accurately reflect its broader mission. The present title may, in fact, impede the ability of FES to collaborate with other offices within DOE and with other federal agencies, including impeding its ability to garner support for non-fusion plasma research.

Finding: The national interest as a whole would be better served by renaming the office to better reflect the broader mission of FES, maximize its ability to collaborate with other agencies and to garner non-fusion plasma support.

Recommendation: Consistent with our recommendations to broaden the impact of plasma science, the Department of Energy (DOE) Office of Fusion Energy Science (FES) should be renamed to more accurately reflect its broader mission, and so maximize its ability to collaborate with other agencies and to garner nonfusion plasma support. A possible title is *Office of Fusion Energy and Plasma Sciences*.

CHAPTER FOCUSED FINDINGS AND RECOMMENDATIONS

The committee offers the following findings and recommendations on the scientific front of plasma physics and on government support for plasma science. The committee supports each recommendation with a set of findings that the committee has made during the course of this study. These recommendations can be taken to strengthen our responses to specific grand challenges and to broadly advance the entire scientific frontier of plasma science.

Chapter 2: The Foundation of Plasma Science

Finding: The theoretical PSE workforce is not large enough to meet our current needs and will become even less able to do so in the future without deliberate measures.

Recommendation: In developing their research agenda, federal agencies supporting plasma science (e.g., NSF, DOE, DoD, NASA) should make deliberate efforts to support theory.

Finding: Investigations of fundamental plasma science provide the understanding of these complex processes that underpin the behavior of plasmas across the entire realm of plasma science and engineering (PSE). Studies of fundamental processes tie together seemingly disparate phenomena across the PSE discipline and provide a unifying perspective to the vast array of PSE applications.

Finding: A widening gap between fundamental studies and application-inspired research impedes progress in both fundamental studies and application-inspired research and slows the rate of translational research that leads to societal benefiting technologies.

Recommendation: Federal agencies that fund PSE should forge partnerships with other plasma-focused agencies as well as agencies focused on applications benefiting from plasmas (or programs within agencies) to close the widening gap between fundamental plasmas science research and translational research leading to applications.

Finding: There has been a general loss of broad collaborative activities within the PSE community over the last decade.

Finding: In both experimental and theoretical/computational areas, the creation of teams with the critical mass to address important and complex issues in basic plasma science are needed.

Finding: Center-type activities can provide opportunities that strengthen the overall health of the PSE community while providing important incubators for the development of the PSE workforce.

Recommendation: The DOE should broaden its support of Plasma Science Centers through recurring solicitations at critical funding levels to provide both new opportunities to advance important areas of plasma science as well as to improve the impact of the plasma science community.

Finding: While many of the basic plasma science facilities are aging, the last decade has seen important investments in several new or expanded facilities in the range of $1 million to $4 million.

Finding: Many U.S. plasma science facilities were built during the last decade with funding provided by the NSF Major Research Instrumentation program, and many of these facilities provide opportunities for external researchers to conduct collaborative experiments with the host institutions. However, the experimental facility needs of different communities that are pursuing basic plasma science can vary widely.

Finding: Today, facilities at a spectrum of scales and reflecting the requirements for addressing different problems at the frontiers of plasma science (in the range $1 million to $20 million) are needed.

Recommendation: NSF, DOE, NASA, and other federal agencies with an interest and programs in plasma physics should provide regular opportunities for the continued development, upgrading and operations of experimental facilities for basic plasma science at a spectrum of scales.

Finding: Many potential users of these experimental facilities would benefit from small levels of support to gain experience with and obtain initial data for *proof-of-concept demonstrations* that are usually expected in a full proposal to PBPSE. A mechanism to provide one time-short term funding to perform these experiments would address this critical need.

Finding: In addition, to a shared funding resource for user support, a network of basic plasma science facilities might also coordinate on proposal selection, users groups, and outreach activities, thereby addressing the STEM pipeline into plasma science.

Finding: A network of basic plasma user facilities that would provide opportunities for access to new and upgraded plasma science facilities needs more coordination and support than currently exists.

Recommendation: Federal agencies, particularly DOE-FES and NSF-MPS, should implement a program for one-time, short-term funding for users of basic plasma science facilities.

Recommendation: A community wide workshop led by a partnership of DOE-FES and NSF-MPS should define the parameters and participation of such a program and network of user facilities.

Finding: Plasma simulation is not optimally accessible to the wide range of potential users, including experimentalists and industrial users.

Finding: Funding agencies have not traditionally supported code usability to the extent needed to make research codes user-friendly, support users of codes, or to transition existing codes to new computing architectures.

Recommendation: Funding agencies, and in particular DOE and NSF, should support mechanisms for making computational plasma software more widely accessible to non-computing experts, and to transition current codes to new computing architectures.

Finding: At the time of this writing, opportunities for machine learning (ML) and artificial intelligence (AI) that impact computations (and experiments) are only beginning to be realized. This is an extremely rapidly developing field. Leveraging these advances may require new approaches to computation.

Recommendation: To assure that PSE computations take advantage of advances in ML and AI, a periodic workshop should be held to share best practices, jointly sponsored by NSF, DOE and NASA.

Finding: There is a lack of modern educational and review material in computational PSE that addresses the methods of computation and how to make effective use of computations.

Finding: With the rapid growth of interdisciplinary research in plasma physics, it is time to consider the establishment of an annual journal that reviews major developments in all areas of plasma physics, much like the Annual Reviews of Astronomy, for example.

Recommendation: Computational PSE, supported by NSF, should include projects for writing textbooks and developing courses to train the current and next generation of computational plasma scientists, and to enable non-computer experts to make optimal use of computations.

Chapter 3: Laser-Plasma Interactions

Finding: Compact plasma accelerators, X-ray sources, and optics were invented in the United States. However, as reported in the *NAS Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light*, the United States has lost dominance in high-intensity laser research and related research that is essential to plasma science, accelerators, and their applications.

Finding: There are strategic opportunities in the next 10 years to build scientific facilities that can leap-frog international competition and enable the United States to maintain a leadership position in laser-plasma interactions.

Recommendation: To restore U.S. leadership, DOE and other agencies should formulate a national strategy to develop and build new classes of high-intensity lasers that enable now inaccessible parameter regimes.

Facilities constructed through the strategy above would produce the technologically highest intensities to open up new regimes in high field physics and ion acceleration, having repetition rates at and beyond 1 kHz, with shaped pulses enabling precision control, and with active feedback and machine learning for acceleration and plasma optics.

Finding: Plasma acceleration and controlled laser-plasma optics are rapidly advancing, driven by newly available capabilities in short pulse/broad bandwidth lasers.

Finding: Applications require robust, compact drivers. A long-term plan and resources for developing technologies that can leverage science advances into society benefiting applications are needed.

Recommendation: DOE and NSF should lead a collaborative effort with other agencies to develop an extended stewardship program for long-term, application-oriented research to enable the development of revolutionary laser sources that translate to applications.

Finding: Collaboration between agencies focused on source development (DOE, NSF) and potential user agencies (e.g., NIH, DoD) is needed to ensure that advanced laser capabilities are developed.

Finding: There is need for multiple programs and approaches in experiment, theory and computation, ranging in scale from single investigator experiments to user facilities and dedicated mission focused facilities or centers.

Recommendation: Agencies focused on the fundamentals of LPI (NSF-MPS, DOE-FES, DOE-NNSA) should collaboratively augment and create programs in plasma acceleration and optics that support a range of scales and multiple efforts and that coordinate research, user access, and educational support.

Finding: A blend of science innovation (e.g., development of new physics regimes in high field science) and long-term engineering efforts to develop new facilities has been essential to progress in laser-plasma interactions.

Finding: Together with support from other agencies and DOE support concentrated at the National Laboratories, NSF support devoted to LPI at universities is essential to the field.

Recommendation: NSF-MPS, DOE-SC, and DOE-NNSA should strongly support research in the fundamental physics of plasma optics, high field acceleration and laser sources in collaboration with other agencies. This includes research, centers, and mid-scale infrastructure.

Finding: Computation and theory has been essential to the development of the field of Laser-Plasma Interaction (LPI), providing insights and crucial input into experiment design. U.S. computation, once dominant, has lost that advantage.

Finding: A range of needed computational tools, both fluid-based and DSMC-PIC, is also needed for modeling plasma sources.

Finding: The innovation that comes from healthy competition would help restore U.S. leadership in computations for LPI.

Recommendation: NSF-MPS, NSF-CISE, and DOE-SC should support a diversity of computational and theoretical efforts to help restore U.S. leadership in computations for LPI.

Chapter 4: Extreme States of Plasmas

Finding: Innovative diagnostics and diagnostic techniques have enabled developing a detailed picture of ICF plasmas and imploded target cores with unprecedented precision, and enabled the investigation of HED matter at previously unattainable conditions.

Finding: Diagnostic innovation is an ongoing need.

Recommendation: The DOE-NNSA, DOE-FES, and NSF-MPS should increase resources for development of new diagnostics and analysis methodologies to address needs for ongoing innovation in HED physics.

Recommendation: The current NNSA ICF *National Diagnostics Working Group* charter and workshops should be expanded to explicitly include HED diagnostics, interaction with mid-scale facilities, and data analysis and data mining techniques.

Finding: While significant progress in HED science has been made in the last decade, more advances are needed to improve predictive capability.

Finding: Improving our understanding of LPI is essential for continued progress toward validated predictive capabilities, which are necessary for ignition and gain.

Recommendation: To achieve the goal of ignition and improve the quality of HED science, DOE-NNSA, DOE-FES, and NSF-MPS should expand and strengthen numerical simulation capability, focusing in particular on improved atomic and kinetic modeling (including equation of state), improved radiation transfer (including opacity), improved LPI (laser-plasma-instability) understanding, uncertainty quantification and machine learning.

Recommendation: Where possible the National Laboratories should contribute their unclassified state-of-the-art simulations codes to collaborations with academic and commercial efforts, and support training of qualified users.

Finding: Federal support of HED sciences at universities is essential to the health of HED science.

Finding: The current paucity of mid-scale pulsed power facilities is a potential danger for the field.

Recommendation: Federal support of HED at universities and mid-scale laser facilities should continue to expand, not only to benefit HED physics but also to maintain the critically needed HED workforce.

Recommendation: Mid-scale pulsed-power facilities accessible to universities should be established, with leadership of these new facilities drawn from university researchers and the national laboratories.

Finding: The basic science programs at NIF, Omega, and Z-machine have resulted in significant scientific results despite having a small fraction of the available facility time.

Finding: The high visibility of these basic science HED experiments increases the ability to recruit new talent while improving the understanding of the universe and the science underpinnings of other HED/ICF research.

Finding: Guidance is required for how best to leverage and expand the basic science programs. This guidance could come from a new HEDP Basic Research Needs report.

Recommendation: DOE-NNSA, DOE-FES, and NSF-MPS should continue and increase support for basic HED science programs at large facilities in collaboration with universities.

Recommendation: The science program direction and the appropriate level of funding and facility support should be guided by the DOE-NNSA, DOE-FES and NSF-MPS collaboratively commissioning a new HEDP Basic Research Needs report for the HEDP community.

Chapter 5: Low-Temperature Plasmas

Finding: The success of the DOE Low Temperature Plasma Science Center program underlines that there is a need to sustain LTP research directions for a sufficient period of time (5 to 10 years) and size with support on the level of ~$2 million per year to enable scientific impact and translation of research into society benefiting applications.

Finding: The increasing scope of the LTP field into new materials and biotechnology requires full participation of researchers that are traditionally funded by different agencies not focused on plasma science. This is particularly the case for electrification of the chemical industry.

Finding: U.S. funding agencies are often ill prepared to support initiatives that overlap multiple agencies and should actively pursue synergistic opportunities between agencies to maintain U.S. leadership in LTP in line with the recommendation in Chapter 1.

Recommendation: DOE-FES should establish and coordinate a multi-agency Low Temperature Plasma Science Center Program to support multidisciplinary research teams and to establish the scientific basis of emerging application areas of low temperature plasma science.

Finding: Based on the funding level for the LTP science center program, a possible minimum level of support of $20 million over 5 to 10 years for each topical initiative would be appropriate.

Finding: Advances in plasma-materials processing are challenged by the need to choose operating and plasma device designs from the enormous set of possible operating and design conditions.

Finding: There is a serious need for a more detailed understanding of the fundamental processes underpinning plasma-surface interactions that will enable us to develop predictive capabilities.

Finding: Advances in our understanding of LTP interactions with materials will enable the control of plasma-surface interactions at the atomic level which in turn will enable the next generation of materials for quantum computing, new communication and sensor technologies, and energy storage and harvesting.

Recommendation: DOE-FES and DOE-BES should develop a synergistic collaborative program to focus on the intersection of plasma and materials.

In addition to FES and BES, initiatives could be coordinated and funded between plasma-focused and materials-focused programs in federal agencies that would lead to advances in the science and technology of both fields.

Industry support could also be leveraged to stimulate fundamental research through public - private partnerships e.g. with the semiconductor industry. This public-private partnership could take the form of the federal government supporting more fundamental interdisciplinary research and industry co-funding more translational research.

Finding: The fundamental research performed in LTP is intrinsically interdisciplinary with societal benefits occurring most rapidly when that fundamental research is guided by applications.

Finding: Although the NSF/DOE Partnership in Basic Plasma Science and Engineering is a strong supporter of LTP research, the translational and convergent nature of LTP research often transcends the scope of the NSF/DOE partnership.

Finding: Support for translational and convergent research in LTP by the NSF Engineering directorate has not been consistent, has not been long term and has not kept pace with the opportunities described in this report. Deliberate actions are needed to empower these interdisciplinary opportunities.

Recommendation: NSF-MPS and NSF-ENG and funded at a level of $6 million per year, should establish interdisciplinary and inter-directorate support for emerging LTP science topics that lead to translational research.

Finding: Continuing initiatives like the DOE Low Temperature Plasma Science Center program will help sustain an internationally competitive LTP community in the United States.

Finding: LTP research at U.S. universities remains highly dispersed and it is not uncommon to find only one faculty member involved in LTP research in an entire university. This situation underlines the need for research networks and student training opportunities.

Finding: There are no multi-institutional, networking programs in the United States focused on LTPs. Training of a new generation of scientists in fundamental LTP science, including diagnostics and modeling, is a critical need for the coming 10 years, and would benefit from such programs.

Finding: Many U.S. PhD students working in the LTP field are trained with an exclusively application perspective. To sustain the field, more fundamental LTP science training opportunities for early career researchers are needed.

Recommendation: NSF should support LTP research networks in the United States by providing funding for graduate students and postdoctoral researchers to participate in exchanges between U.S. universities, and for international research experiences for junior scientists.

Finding: Fundamental research in LTP has declined in the United States over the last decade.

Finding: The demographics in the LTP field show that the leadership class will retire within the next decade with an insufficient number of early career faculty available to assume leadership positions.

Finding: There are currently too few early career LTP-oriented faculty in the United States. The hiring of faculty within universities in the 21st century needs to be viewed from an interdisciplinary perspective that recognizes the intellectual diversity of a field that spans multiple colleges and departments and would benefit from investment by federal agencies.

Recommendation: To strengthen LTP research at universities, NSF and DOE should establish specific programs that fund the creation of faculty positions similar to the NSF Faculty

Development in Space Sciences program to address the urgency of losing key expertise and leadership in low-temperature plasma science over the next decade.

Finding: The vast majority of laboratories for the study of low temperature plasmas consist of tabletop scale devices—often surrounded by a suite of diagnostic tools.

Finding: Based on its established track record, it is clear that the LTP community does not generally require nor is there demand for large, single purpose centralized user facilities having a single plasma source to make societal impact.

Finding: Leveraging the flexibility and interdisciplinarity of individual laboratories should be considered a valuable asset of LTP community, rather than comparing that style of research to large facilities in other areas of plasma science, and declaring that mode of operation a weakness.

Finding: There is a need to support the flexibility and interdisciplinarity of individual LTP laboratories perhaps through a mix of user facilities concentrating on diagnostics and improving diagnostic and source capabilities in individual laboratories that could form a distributed user facility.

Recommendation: NSF and DOE should expand opportunities to develop and acquire diagnostics, plasma sources, numerical models and reaction mechanisms in support of low temperature plasmas science, perhaps through the NSF/DOE Partnership in Basic Plasma Science.

Chapter 6: Magnetic Confinement Fusion Energy

Finding: While the United States is still a major contributor to international MFE efforts and benefits from these collaborations, the U.S. program has lost ground and is at risk of losing leadership in several areas of MFE research.

Finding: The absence of a consensus strategic plan for fusion research in the United States is an important factor in our falling behind on international developments, a situation compounded by the lack of vetted designs for new experimental facilities.

Finding: A roadmap is needed that is enabled by new experimental MFE facilities in the United States with opportunities across a range of scales when appropriate,

Finding: To enable proper planning and to enable creation of a roadmap, ongoing feasibility and facility design activities are essential.

Recommendation: DOE FES should undertake regular strategic planning, led by the U.S. MFE community, as recommended in the NAS *Burning Plasma Report*.

Recommendation: Aligning with the *NAS Burning Plasma Report*, DOE FES should develop a roadmap for the development of commercial fusion power in the United States.

Finding: Declining participation by universities in the MFE program reduces the level of innovation in the program and is a direct threat to the health of the field. It is essential that the MFE program respond to this crisis.

Finding: Renewing and growing new efforts at universities could be enabled by providing university researchers opportunities to participate in and, more importantly, lead the most important research programs in the field.

Finding: There is a need to grow efforts in fusion engineering and an opportunity exists to stimulate university programs in this area using both the indirect and direct mechanisms discussed above.

Recommendation: DOE FES should structure funding opportunities in MFE to provide leadership opportunities to university researchers and to directly stimulate the hiring of university faculty.

Finding: A recent Office of Management and Budget decision targeted at limiting duplication in education and outreach programs in funding agencies caused the loss of discipline specific graduate fellowships and outreach programs in DOE Office of Science (SC).

Finding: These programs are important but lack the effectiveness of the former graduate fellowship and NUF program in attracting new talent into the MFE field.

Finding: The NUF program and the graduate fellowship could be used as a tool to enhance diversity within the MFE research community.

Recommendation: The DOE Office of Science should restore discipline-specific graduate fellowships and undergraduate research programs that support MFE research at U.S. universities as a vehicle for attracting new and diverse talent into mission-specific areas such as MFE, and for maintaining a presence in university science and engineering programs.

Finding: There has been significant growth in non-traditional support of MFE research, i.e., support other than that provided by DOE FES, including privately funded fusion companies, philanthropic organizations, and DOE-ARPA-E.

Finding: There is a danger that the knowledge base, including that generated by former DOE FES supported research, could become increasingly fragmented. Some challenges, for example the development of key technologies and materials, are similar even if the fusion configurations are distinct. Solving these challenges through separate efforts increases overall cost and timescales.

Recommendation: Federal agencies funding the development of MFE science and technology (DOE-FES and DOE-ARPA-E) should leverage privately and philanthropically supported fusion research and vice versa.

Chapter 7: The Cosmic Plasma Frontier

Finding: A lack of support for basic code and simulation development, theory, and novel data-analysis techniques has long been a barrier to advancing our understanding of SAPs and predictive capabilities.

Finding: Unfortunately, the level of funding for the highly successful NSF/DOE *Partnership in Basic Plasma Science and Engineering* has lagged that recommended by the 2000 Plasma Decadal Review, despite its very central role in discovery plasma science and its capacity to create effective multidisciplinary bridges within plasma science.

Recommendation: NASA should join the NSF/DOE Partnership in Basic Plasma Science and Engineering to expand interdisciplinary basic plasma research that would benefit SAP. This expanded partnership would leverage strategic contributions from each agency to enable breakthrough progress that benefits a wide range of PSE activities (see Table 1, #3-#5).

Finding: Solar, heliospheric, magnetospheric, and ionospheric physics, and astrophysics have untapped synergies with laboratory plasma experiments, with the common goal of understanding ambient plasma conditions and chemistry.

Finding: Strategic funding from NASA and agencies supporting experimental facilities would enable more ambitious, innovative joint projects than a single source could support.

Recommendation: NASA and NSF should lead an effort with DoD (especially ONR and AFOSR), DOE, and other stake-holders (see Table 1, #6 and #24) should develop a collaborative program that enables SAP scientists to collaborate with laboratory plasma experimentalists and advance both fields by leveraging their different needs and knowledge bases.

Finding: Clusters of cubesats and smallsats carrying in-situ and remote-sensing instruments are the best observing platforms for tackling many basic unsolved questions of multiscale SAPs (e.g., reconnection, turbulence, and shocks), and provide essential research and training opportunities for university faculty and students.

Finding: Existing procedures for developing, building, and operating missions are traditionally geared toward large missions, and can pose unnecessary obstacles for single spacecraft and multi-platform missions employing smallsats and CubeSats.

Recommendation: With NASA and NSF as lead agencies, NASA, NSF, and DoD, as the primary sources of space missions, should explore avenues, including rideshares, international partners, and partnering with commercial launch providers, for reducing costs, lowering barriers, enabling higher-risk missions, and boosting launch opportunities for these pioneering investigations using Cubesats, smallsats and cluster of these satellites. (see Table 1, #7).

Finding: NSF, despite having a limited investment level in their Cubesat program, has broad access to universities and undergraduate and graduate students. This access may be important in providing basic training in PSE relevant to CubeSats. The recent solicitation for a cross-cutting NSF Ideas Lab Program focused on CubeSat innovations to push the envelope of space-based research capabilities is an example of one approach.

Recommendation: In view of their limited level of investment, NSF should identify a clearer role and "identity" in their CubeSat program that distinguishes it from its NASA counterpart. To ensure cost and resource efficiencies, NSF and NASA should coordinate further on funding opportunities.

Finding: Increased support is needed to meet the challenge of designing and constructing compact plasma and remote-sensing instrumentation suitable for Cubesats and smallsats.

Recommendation: Current NASA programs such as H-FORT, H-TIDES, and the IDP (Instrument Development Program) should be augmented to meet the growing demand for compact plasma and remote-sensing instrumentation suitable for Cubesats and smallsats.

Finding: The SAP community needs to agree on data standards, formatting, and processing levels for publicly available data.

Recommendation: Federal agencies that support ground-based and international space facilities (NSF, NASA, DoD, NOAA) should adopt similar open data policies and minimize barriers to international collaboration except where national security is of concern.

Recommendation: NSF should convene a workshop co-sponsored by NASA and DoD to make recommendations for how to establish and maintain open data policies.

Recommendation: Once established, maintaining and updating the open data standards should be the responsibility of governing federal organization such as one of the major contributors (NASA, DoD, NOAA) or a more specialized agency for standards such as NIST.

Finding: A faculty partnership program introduced by NASA, NSF, and DOE—similar to that presented in the Finding and Recommendation section of Chapter 1 (see Table 1.1)—is needed to strengthen SAP hiring in universities and federal research facilities.

C

Survey Data Gathering Events

November 6, 2018
60th Annual Meeting of the APS Division of Plasma Physics, Oregon

January 23, 2019
NASA Goddard/University of Maryland, Maryland

January 2019
Dusty Plasma Workshop, Germany

April 15, 2019
University of Colorado-Boulder, Colorado

April 18, 2019
Princeton Plasma Physics Laboratory, New Jersey

May 16, 2019
Laboratory for Laser Physics/University of Rochester New York

May 28, 2019
Southeastern (Huntsville, AL)

May, 2019
Southern California

June, 2019
Lawrence Livermore National Laboratory, California
Lawrence Berkeley National Laboratory, California

June 24, 2019
47th IEEE International Conference on Plasma Sciences, Florida

D

COMMITTEE MEMBER BIOGRAPHICAL INFORMATION

MARK J. KUSHNER, *Co-Chair*, is the Haddad Collegiate Professor in the Electrical Engineering & Computer Science Department at the University of Michigan, and holds appointments in the Nuclear Engineering and Radiological Science Department, Chemical Engineering Department, and Applied Physics Program. He is director of the *Michigan Institute for Plasma Science and Engineering* and the *Department of Energy Center on Plasma Interactions with Complex Interfaces*. Dr. Kushner received his Ph.D in Applied Physics from the California Institute of Technology in 1979. He served on the staffs at Sandia National Laboratory and Lawrence Livermore National Laboratory (1980-1983), and as Director of Electron, Atomic and Molecular Physics at Spectra Technology (1983-1986), before joining the University of Illinois at Urbana-Champaign (1986-2004). At UIUC, he was the Founder Professor of Engineering and held several administrative roles. Prof. Kushner was Dean of Engineering and Melsa Professor of Engineering at Iowa State University (2005-2008), before joining the University of Michigan. Dr. Kushner's research interests are in low temperature plasmas, addressing the generation and transport of charged and chemically reactive species, their interactions with surfaces for materials modification, and the development of plasma-based devices. Dr. Kushner has served in several national and international leadership roles, including editor in chief of *Plasma Sources Science and Technology*, and served on several National Academies' studies, including the last plasma science decadal survey. Dr. Kushner has received numerous awards, including the APS Allis Prize, AVS Medard Welch Award, IEEE C. K. Birdsall Award, IEEE Plasma Science and Applications Award, Semiconductor Industry Association University Research Award, and election to the National Academy of Engineering.

GARY ZANK, *Co-Chair*, is the director of the Center for Space Plasma and Aeronomic Research (CSPAR), University of Alabama Board of Trustees Trustee Professor and Aerojet/Rocketdyne Chair in Space Science, an Eminent Scholar and Distinguished Professor, and Chair of the Department of Space Science (SPA) at the University of Alabama in Huntsville. Dr. Zank's research interests extend across space physics, plasma astrophysics, and plasma physics. Although his research is related primarily to theory, modeling, and simulations, Dr. Zank is involved in numerous experimental and observational programs. Some areas of research include the interaction of the solar wind with the partially ionized interstellar medium. Dr. Zank received his Ph.D in applied mathematics from the University of Natal in South Africa in 1987. He has been recognized in his field through the receipt of numerous honors and awards throughout his career. In 2017, he was named the first University of Alabama Board of Trustees Trustee Professor, was elected in 2016 as a member of the National Academies of Sciences, Engineering, and Medicine, was recognized internationally in 2015 with the AOGS Axford Medal, the highest honor given by the Asia Oceania Geosciences Society (AOGS). Other awards include his being a fellow of the American Geophysical Union, the American Physical Society, and the American Association for the Advancement of Science. In 2017, he was also elected an AOGS Honorary Member and was chosen by the International Space Science Institute (ISSI) to be the 2017 Johannes Geiss Fellow. Dr. Zank has served on a number of National Academies' ad hoc and standing committees.

AMITAVA BHATTACHARJEE is Professor of Astrophysical Sciences and Head of the Theory Department of the Princeton Plasma Physics Laboratory. He also serves as co-director of the Princeton Center for Heliophysics. He received his Ph.D. at Princeton University (1981) in theoretical plasma physics from the Department of Astrophysical Sciences. He has taught previously at Columbia University (1984-93) in the Department of Applied Physics, at the University of Iowa (1993-2003) in the Department of Physics and Astronomy, and the University of New Hampshire (2003-12), where he served as Paul Professor of Space Science. At the University of Iowa, he received the James Van Allen Natural Sciences Fellowship (1996), the Faculty Scholar Award (1997-2000), and the Michael J. Brody Award (2003). He has served as senior editor of the Journal of Geophysical Research-Space Physics, as chair of the Division of Plasma Physics of the American Physical Society, and as founding chair of the Topical Group in Plasma Astrophysics of the American Physical Society, and on various prize and fellowship committees. He is a fellow of the American Physical Society, the American Association of the Advancement of Science, and the American Geophysical Union. His research interests include magnetic reconnection, turbulence and singularity formation, kinetic theory, free-electron lasers, and complex (or dusty) plasmas.

PETER J. BRUGGEMAN is a Professor and Associate Department Head of Mechanical Engineering at the University of Minnesota. He is also the director of the High Temperature and Plasma Laboratory and associate director of the Department of Energy Center for Low Temperature Plasma Interactions with Complex Interfaces. His primary research interests are in low temperature plasmas including plasma diagnostics, plasma-liquid and materials interactions and non-equilibrium plasma kinetics and chemistry applied to plasma processes for environmental, biomedical and renewable energy technologies. Previously, Dr. Bruggeman was on the faculty of Eindhoven University of Technology (the Netherlands) in the Department of Applied Physics. He is a recipient of several awards including the 2012 Hershkowitz Early Career Award, the 2013 International Union of Pure and Applied Physics Young Scientist Medal and Prize in Plasma Physics, the 2016 U.S. Department of Energy Early Career Award and the 2018 Peter Mark Memorial Award of the American Vacuum Society. He earned his PhD in Applied Physics from Ghent University (Belgium). He serves as section editor for low temperature plasmas of the Journal of Physics D: Applied Physics (Institute of Physics Publishing) and as elected member of the board of directors of the International Plasma Chemistry Society.

TROY CARTER is a Professor of Physics at the University of California, Los Angeles. He received B.S. degrees in physics and nuclear engineering from North Carolina State University in 1995 and a Ph.D. in astrophysical sciences from Princeton University in 2001. Prof. Carter is the director of the Basic Plasma Science Facility (BaPSF), a national user facility for plasma science supported by DOE and NSF. He is also the director of the Plasma Science and Technology Institute (PSTI), an organized research unit at UCLA. His research focuses on experimental studies of fundamental processes in magnetized plasmas and is motivated by current issues in magnetic confinement fusion energy research and in space and astrophysical plasmas including magnetic reconnection, turbulence and transport in magnetized plasmas, and the nonlinear physics of Alfvén waves. He was a co-recipient of the 2002 APS Division of Plasma Physics Excellence in Plasma Physics Research Award and is a fellow of the American Physical Society. Prof. Carter has served on a number of advisory committees, including the DOE Fusion Energy Sciences Advisory Committee, the Fachbeirat for the Max-Planck Institute for Plasma Physics, and program advisory committees for the DIII-D tokamak, the Alcator C-Mod tokamak, and the NSF Physics Frontier Center CMSO.

JOHN CARY is a professor of physics at the University of Colorado, Boulder and CEO of Tech-X Corporation. Dr. Cary's research focuses on the discovery of new methods for accelerating charged particles, heating and transport of magnetically confined plasma, dense plasma focus, and advanced computation on new computer architectures. His research interests are concentrated in beam/accelerator physics, plasma physics, nonlinear dynamics, and computational physics. Dr. Cary's accelerator/beam physics interests are currently in advanced accelerator concepts: the generation and use of large (10-100 GV/m) fields through laser-plasma interaction. His plasma physics interests are currently in the simulation of the nonlinear interactions of radio frequency electromagnetic fields with plasma as occurring in plasma heating. In recent years, he has devoted extensive effort to computational methods, including algorithm development. He is the originator of the arbitrary-dimensional, parallel, hybrid, plasma simulation code, VORPAL. Dr. Cary received a Ph.D. and M.S. in physics at University of California Berkeley in 1979 and 1975 respectively, and bachelor's degrees in physics and mathematics at the University of California, Irvine in 1973. He is a senior member of IEEE and a fellow of the APS Division of Plasma Physics, which he chaired 2017-2018. He is a recipient of many awards, such as the IEEE NPSS Particle Accelerator Science and Technology Award. His other service includes being Associate Editor of the Reviews of Modern Physics and other journals and being on the organizing and program committees for the Annual Meeting of the Division of Plasma Physics, the Particle Accelerator Conferences, and other national and international conferences in plasma and beam science.

CHRISTINE A. COVERDALE is a plasma physicist at Sandia National Laboratories. Dr. Coverdale joined Sandia in 1997 and in 2011 was named a distinguished member of the technical staff. She has been involved in a broad range of experiments at the Saturn and Z pulsed power facilities centered around nuclear weapons certification and other national security projects. She also works on radiation detection systems and diagnostics to assess warm and hard X-rays from Z-pinch plasmas. Dr. Coverdale has a doctorate in plasma physics from the University of California, Davis, and has authored or co-authored more than 120 papers, and regularly presents at conferences. She served three terms on the executive committee of the IEEE Plasma Science and Applications Committee and has served as the technical program chair or co-chair for the IEEE International Conference on Plasma Science in 2009, 2010, 2012, 2015, and 2021. She also served a four-year term on the IEEE Nuclear Plasma Sciences Society Administrative Committee. Dr. Coverdale was on the Executive Committee of the American Physical Society (APS) Division of Plasma Physics and severed for several years as the senior editor for High Energy Density Physics for IEEE Transactions on Plasma Science. She has served on multiple awards committees for IEEE NPSS and APS-DPP, including fellowship committees and is a fellow of both the IEEE and APS.

ARATI DASGUPTA is a senior research physicist at the Naval Research Laboratory. Dr. Dasgupta received her BS in physics with Honors, MS, and PhD from the University of Maryland before joining the Naval Research Laboratory in 1986. She is a Section Head leading basic and applied research programs in atomic processes in laboratory and astrophysical plasmas that span pulsed power radiation sources, inertial confinement fusion (ICF), laser-matter interaction, plasma spectroscopy, low temperature plasma processing, and ultra-short wavelength lasers. Presently her research focus is on non-local thermodynamic equilibrium kinetics modeling and simulation of HEDP experiments of multi-keV plasma radiation sources on Sandia's Z machine and National Ignition Facility (NIF) at LLNL, ICF using symmetry capsule (Symcap) implosion on NIF, magnetized plasma on Jupiter Laser Facility at LLNL, and radiation physics for high Z_A elements on the NRL NIKE laser in support of ICF. She is a Fellow of the APS and the Washington Academy of Sciences. She is a member of several science panels, and served on DOE's Fusion Energy Sciences Advisory Committee (FESAC) and was part of a committee in writing OFES/DOE's Strategic Planning report in 2014 and DOE's ReNeW report on HEDLP in 2009. Currently she is a member of the APS Committee of Status of Women in Physics and chair of its awards sub-committee. She is also a member of the advisory committee (AdCom) of IEEE's Nuclear and Plasma Sciences Society. She has served on several APS committees including fellowship committees of DAMOP and DPP, and chaired Women in Plasma Physics Committee of the DPP. She is the author (on invitation) of a chapter in a book titled "Blazing the Trail; Essays by Leading Women in Science" and presented a public lecture at the University of Wisconsin, La Crosse, in their yearly Public Lecture Series featuring prominent women in physics, astronomy, and engineering.

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EDWARD THOMAS JR. is the Charles W. Barkley Endowed Professor of Physics and the Associate Dean for Research and Graduate Studies in the College of Sciences and Mathematics at Auburn University. He earned his Bachelor’s degree from the Florida Institute of Technology, a Master’s Degree from MIT, and a PhD from Auburn University. Prof. Thomas began his research career studying edge particle transport in fusion plasmas. Over the years, his work has become centered in basic plasma physics where his group conducts experimental plasma physics research on dusty (complex) plasmas, magnetized plasmas and plasma diagnostic development—with an emphasis on the particle, wave, and energy transport in low temperature plasmas. Most recently, he has led the development of the Magnetized Dusty Plasma Experiment (MDPX) device. Previously, Prof. Thomas was a faculty member at Fisk University in the Department of Physics. He is an elected member of the International Union of Radio Science (URSI), Commission H, and is a fellow of the American Physical Society and the National Society of Black Physicists. He has served as a member of numerous advisory committees for the American Physical Society, National Science Foundation, Department of Energy, National Research Council, European Space Agency, and several research centers in the United States, Europe and India—including the National Academies Plasma Science Committee and the Department of Energy’s Fusion Energy Sciences Advisory Committee.

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Acronyms

AFOSR	Air Force Office of Scientific Research
AFRL	Air Force Research Laboratory
ARO	Army Research Office
ARPA-E	Advanced Research Projects Agency–Energy
ASCR	Advanced Scientific Computing Research
BES	Basic Energy Sciences
DARPA	Defense Advanced Research Projects Administration
DHS	Department of Homeland Security
DoD	Department of Defense
DOE	Department of Energy
DOE-HEP	Department of Energy Office of High Energy Physics
DOE-SC	Department of Energy Office of Science
DTRA	Defense Threat Reduction Agency
EERE	Energy Efficiency and Renewable Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Agency
FES	Fusion Energy Sciences
HEP	High Energy Physics
NASA	National Aeronautics and Space Administration
NASA-HEOMD	NASA Human Exploration and Operations Mission Directorate

NASA-SMD	NASA Science Mission Directorate
NCI	Cancer Institute
NIAID	Allergy and Infectious Diseases
NIAMS	Arthritis and Musculoskeletal and Skin Diseases
NIBIB	Biomedical Imaging and Bioengineering
NIDCR	Dental and Craniofacial Research
NIGMS	General Medical Sciences
NIH	National Institutes of Health
NINDS	Neurological Disorders and Stroke
NNSA	National Nuclear Security Administration
NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
NSF	National Science Foundation
NSF-BIO	NSF Directorate for Biological Sciences
NSF-CISE	NSF Directorate for Computer and Information Science
NSF-DMR	NSF Directorate for Materials Research
NSF-GEO	NSF Directorate for Geosciences
NSF-ENG	NSF Directorate for Engineering
NSF-MPS	NSF Directorate for Mathematical and Physical Sciences
ONR	Office of Naval Research
USDA-NIFA	U.S. Department of Agriculture National Institute of Food and Agriculture