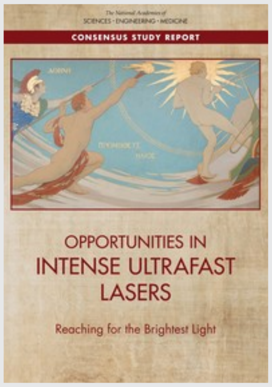


# Opportunities in Intense Ultrafast Lasers Reaching for the Brightest Light

## DETAILS

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PREPUBLICATION COPY—SUBJECT TO FURTHER EDITORIAL CORRECTION

# Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light

Committee on Opportunities in the Science, Applications, and Technology of Intense Ultrafast Lasers

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

A Consensus Study Report of

*The National Academies of*

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## BOARD ON PHYSICS AND ASTRONOMY



[1] NAS, National Academy of Sciences.

# Preface

The Committee on Opportunities in the Science, Applications, and Technology of Intense Ultrafast Lasers was formed to assess the merit and extent of the scientific and technical advances that such technology would afford the United States were such research pursued in this country. Specifically, the committee was given the charge reproduced below by the National Academies of Sciences, Engineering, and Medicine.

1. Survey high intensity science and related technology, including the following:
   - Identify science opportunities opened up by ultrafast, high peak power lasers at the frontiers of peak power and average power ("high intensity science").
   - Assess the potential impact of applications associated with high intensity science.
   - Assess the status of laser engineering and technology in the United States associated with high intensity science.

2. Review the framework in which high intensity science and the development of related technology is conducted in the United States. Such review should take place in an international context, with efforts in Europe to serve as a benchmark. In doing so, the committee is to address the following questions:
   - Is there an explicit or implicit national strategy for stewarding high intensity science in the United States? If not, can one be formulated and if so what would be an appropriate structure for such a strategy?
   - Is there a case for a large-scale initiative to coordinate, accelerate, and steward high intensity science at peak and average power well beyond the current state of the art?
   - Is there a compelling science case for the construction of a forefront U.S. facility or a staged sequence of facilities in high intensity science at peak powers of 1 petawatt to 1 exawatt? If so, what should the parameters be and what capabilities should be included in such a facility or sequence of facilities?
   - Is high peak power laser technology development in the United States being well stewarded? If not, what roadmap should the United States follow for coherently supporting the development of this technology and what new technologies, if any, should be pursued?

The concept for this study was developed by the Committee on Atomic, Molecular, and Optical Sciences (CAMOS), a standing activity of the National Academies that operates under the auspices of the Board on Physics and Astronomy. An important part of CAMOS's responsibilities is to monitor developments in the atomic, molecular, and optical (AMO) sciences and to develop white papers for potential National Academies' studies that would address issues arising in that research community. CAMOS began developing this project in 2011 and its principal focus was to help the United States develop its advanced, high-intensity laser science and technology capacities. Those efforts were motivated by three factors: (1) recent breakthroughs in ultrafast high-power lasers and the underlying technology; (2) nearly a decade of community network building in Europe with programs like Laserlab-

Europe,[1] Photonics21,[2] and Horizon 2020,[3] taking the advice recommended to U.S. agencies in the 2002 SAUUL report;[4] and (3) initiation of the first stage of the Extreme Light Infrastructure (ELI) project to build several petawatt facilities at a few key sites in Europe.[5]

Following consultation with the Academies, four agencies agreed to support the study: the Office of Naval Research (ONR), the Air Force Office of Scientific Research (AFOSR), and two divisions of the Department of Energy Office of Science. The Academies worked with these sponsors to develop a statement of task. A study committee of 15 experts in the field was formed to conduct a study responsive to the charge. The committee included experts from universities, national laboratories, small research laser companies, and large companies in the laser industry.

In response to this charge, the scope of the current report is broader than SAUUL, covering not only the highest-powered lasers but also high-intensity lasers at or just below the petawatt class that can nonetheless create high-intensity environments, often with infrastructure that can be supported by a university or regional center.

Petawatt laser facility in Shanghai, China. Several lasers with peak power above 3 PW are currently planned or under construction in Europe and Asia, but not in the United States. The science and applications opportunities of such facilities are the prime topics for this study. Source: C. Danson, D. Hillier, N. Hopps, and D. Neely, "Petawatt class lasers worldwide," High Power Laser Science and Engineering 3, (2015), DOI: 10.1017/hpl.2014.52.

To address this task our committee met five times in-person, visited 5 separate laboratories, and conducted over thirty teleconferences. The first meeting, held in Washington, D.C., allowed the committee to speak directly with representatives of interested government agencies and the Administration.  The second meeting was held in Palo Alto, California and featured visits to the SLAC National Accelerator Laboratory, Lawrence Berkeley National Laboratory (LBNL), and Lawrence Livermore National Laboratory (LLNL).  The third meeting was conducted by a subset of the committee

[1] "LASERLAB-EUROPE," accessed December 9, 2016, http://www.laserlab-europe.net/.
[2] "Photonics21," accessed December 9, 2016, http://www.photonics21.org/.
[3] "Horizon 2020 - European Commission," *Horizon 2020*, 202, accessed December 9, 2016, https://ec.europa.eu/programmes/horizon2020/.
[4] P. Bucksbaum, et al., 2002, *The Science and Applications of Ultrafast Ultra-intense Lasers.*
[5] "ELI Delivery Consortium | Home," accessed December 9, 2016, https://eli-laser.eu/.

and was held at the ELI-Beamlines site in Dolní Břežany and featured discussions with laboratory personnel, ELI leadership, and European laser science and technology leaders. The fourth meeting, held in Rochester, New York, included a visit to the Laboratory for Laser Energetics (LLE). The fifth and final in-person meeting of the committee was held in Irvine, California, at which the committee focused on coming to consensus on its report. The committee used not only its in-person meetings to gather input, but also organized many teleconferences featuring discussions experts from universities, laboratories, and industry, domestic and foreign. Many of these included presentations from scientists, engineers, and laboratory directors engaged in research development of high-intensity lasers and applications in the United States and throughout the world (for example in Figure P-1). The committee also investigated research areas in high-intensity lasers and wrote research summaries. The committee requested input from the community and maintained a website and email for this purpose.

All of these meetings, interactions, discussions, and information-gathering activities, in addition to the knowledge and perspectives of the members themselves, afforded the committee with a broad and comprehensive picture of the state and possible directions of high-intensity, ultrafast laser science and technology in the United States and abroad. With this knowledge we wrote our report and constructed our consensus findings and recommendations. It is the committee's belief that the agencies and offices identified in this report's recommendations are best positioned to decide how to effectuate them.

We believe our report provides U.S. policymakers, the community, and industry with the basis from which to build the future development of this strategically important technical area. We anticipate that the historical snapshot of the state of play will also be valuable for future policymakers and program planners.

The committee thanks the many experts with which it conversed and who attended the committee's meetings, in-person or remotely. The committee is particularly grateful to its gracious hosts at SLAC, LBNL, LLNL, LLE, and ELI-Beamlines. We also thank our sponsors at the Air Force Office of Scientific Research, Department of Energy, and Office of Naval Research for their support of and engagement with this activity.

Philip Bucksbaum, *Chair*
Committee on Opportunities in the Science,
Applications, and Technology of Intense Ultrafast
Lasers

# 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:

Gerald Blazey, Northern Illinois University,
Robert Byer, Stanford University,
Michael Ettenberg, Dolce Technologies,
Erich P. Ippen, Massachusetts Institute of Technology,
Wayne Knox, University of Rochester, and
George Sutton, SPARTA (retired).

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 Thomas Romesser, Northrop Grumman Aerospace Systems (Retired). He was 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

The laser has revolutionized many areas of science and society, providing bright and versatile light sources that transform the ways we investigate science and enables trillions of dollars of commerce. Now a second laser revolution is underway with pulsed petawatt-class lasers (1 petawatt: 1 million billion watts) that deliver nearly 100 times the total world's power concentrated into a pulse that lasts less than one-trillionth of a second. Such light sources create unique, extreme laboratory conditions that can accelerate and collide intense beams of elementary particles, drive nuclear reactions, heat matter to conditions found in stars, or even create matter out of the empty vacuum.[1]

These powerful lasers came largely from U.S. engineering, and the science and technology opportunities they enable were discussed in several previous National Academies' reports.[2] Based on these advances, the principal research funding agencies in Europe and Asia began in the last decade to invest heavily in new facilities that will employ these high-intensity lasers for fundamental and applied science.[3] No similar programs exist in the United States. This report was commissioned by four U.S. agencies—the Office of Naval Research (ONR), the Air Force Office of Scientific Research (AFOSR), and the Department of Energy's Office of Science (DOE-SC) and the National Nuclear Security Administration (NNSA)—to assess the opportunities and to recommend a path forward for possible U.S. investments in this area of science.

In response to the Statement of Task for this study (stated in the Preface),[4] the committee surveyed high-intensity science and related technology to identify science opportunities, to assess the impact of applications, and to assess U.S. technical capabilities. The committee also reviewed the current landscape in the United States for high-intensity science and the development of related technology, and compared it to the recent efforts in Europe.

The committee was asked to focus on particular questions: Is there an explicit or implicit national strategy for stewarding high-intensity science in the United States? If not, can one be formulated, and what is an appropriate structure? Is there a case for a large-scale initiative in this area? Should the United States build facilities for high-intensity science at peak powers of 1 petawatt to 1 exawatt? If so, what should be the parameters and capabilities? Is high-peak-power laser technology development in the United States being well stewarded? What roadmap should the United States follow in this area?

The National Academies assembled a 15-member panel including NAS and NAE members and others with expertise in the relevant science and technology. Following a year spent gathering thousands of pages of information, attending seminars from experts, visiting major laser laboratories in the United States and Europe, and conducting regular telephone meetings, the committee arrived at conclusions and recommendations that constitute a roadmap for action, summarized here in seven summary conclusions, and five roadmap recommendations:[5]

**Conclusion 1: The science is important.** High-intensity lasers enable a large and important body of science. (See chapter 5)

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[1] See Section 5.6.
[2] See Section 1.1.2 and references therein.
[3] See Section 1.1.3 and references therein.
[4] The Preface contains the Statement of Task.
[5] Section 7.1

**Conclusion 2: Applications exist in several areas.** Intense ultrafast lasers have broad applicability beyond science to nuclear weapons stockpile stewardship as well as to industry and medicine. Science is a main application of high-intensity lasers, and all applications of high-intensity lasers rely on the fundamental science of high-intensity laser-matter interactions. (See chapter 6)

**Conclusion 3: The community is large but fragmented.** There is a large and talented technical community already, but it is fragmented across different disciplines. Coordination between industry and government is limited and often inadequate. The scientists and engineers trained in intense ultrafast lasers contribute to the workforce for applications in photonics and optics, including high-energy lasers for defense and stockpile stewardship.

This conclusion is supported by information throughout the document, but especially in Chapter 2. Conclusions 1-3 motivate the committee's first recommendation:

**Recommendation 1: The Department of Energy should create a broad national network, including universities, industry, and government laboratories, in coordination with the Office of Science and Technology Policy, the research arms of the Department of Defense, National Science Foundation, and other federal research organizations, as the cornerstone of a national strategy to support science, applications, and technology of intense and ultrafast lasers.**

**Conclusion 4: No cross-agency stewardship exists.** No single agency currently acts as the steward for high-intensity laser-based research in the United States. Programs are carried out under sponsorship of several different federal agencies, including DOE-SC, NNSA, AFOSR, ONR, the Defense Advanced Research Projects Agency (DARPA), and the National Science Foundation (NSF), according to their various missions and without the overall coordination that exists in Europe.

Conclusion 4 is supported in Chapter 2, and leads to the committee's second recommendation:

**Recommendation 2: To increase integration and coordination in this field, the research agencies (Department of Defense, Department of Energy, National Science Foundation, and others) should engage the scientific stakeholders within the network to define what facilities and laser parameters will best serve research needs, emphasizing parameters beyond the current state of the art in areas critical to frontier science, such as peak power, repetition rate, pulse duration, wavelength, and focusable intensity.**

**Conclusion 5: The US has lost its previous dominance.** The United States was the leading innovator and dominant user of high-intensity laser technology when it was developed in the 1990s, but Europe and Asia have now grown to dominate this sector through coordinated national and regional research and infrastructure programs. In Europe, this has stimulated the emergence of the Extreme Light Infrastructure (ELI) program. At present, 80 to 90 percent of the high-intensity laser systems are overseas, and all of the highest power (multi-petawatt) research lasers currently in construction or already built are overseas.

Details supporting this conclusion are in Chapters 3 and 4. This conclusion leads to the committee's third recommendation:

**Recommendation 3: The Department of Energy should lead the development of a comprehensive interagency national strategy for high intensity lasers that includes a program for both developing and operating large-scale laboratory projects; midscale projects such as those hosted at universities; and a technology development program with technology transfer among universities, U.S. industry, and national laboratories.**

**Conclusion 6: Co-location with existing infrastructure is essential.** Co-location of high-intensity lasers with existing infrastructure such as particle accelerators has been recognized as a key advantage of the U.S. laboratories over the ELI concept in Europe.

Information describing this is in Chapters 4 and 5, and throughout the report. This conclusion leads directly to the committee's fourth recommendation:

**Recommendation 4: The Department of Energy should plan for at least one large-scale open-access high-intensity laser facility that leverages other major science infrastructure in the Department of Energy complex.**

**Conclusion 7: University/Laboratory/Industry cooperation is necessary to retain and renew the talent base.** Cooperation among all sectors—private industry, research universities, and government laboratories— in the past has proved essential and the current situation could be improved to develop a robust national talent pool and a strong technology base for this fast growing area.[6]

Based on these conclusions, the committee arrived at its final recommendation:[7]

**Recommendation 5: Agencies should create programs for U.S. scientists and engineers that include mid-scale infrastructure, project operations in high-intensity laser science in the United States, development of key underpinning technologies; and engagement in research at international facilities such as Extreme Light Infrastructure.**

Taken together, these five recommendations constitute a national strategy for high intensity laser science and technology, and lay out a roadmap for implementing this strategy.

[6] This conclusion is most directly supported by material in Chapters 2 and 4 of the report.
[7] Section 7.2.

# 1

# Introduction and Technical Summary

This chapter is a brief summary of the report. Details and background are in the subsequent chapters and appendices.

## 1.1 INTRODUCTION

In 1898, 3 years after the discovery of x-rays, 17 years before Einstein derived the notion of stimulated light amplification, and 62 years before the first laser was demonstrated, H.G. Wells created the enduring popular image of a tool that projects enormous energy as intense and invisible beams of light:

> It is still a matter of wonder how the Martians are able . . . to generate an intense heat . . . in a parallel beam against any object they choose, by means of a polished parabolic mirror . . . much as the parabolic mirror of a lighthouse projects a beam of light . . . Heat, and invisible, instead of visible, light. Whatever is combustible flashes into flame at its touch, lead runs like water, it softens iron, cracks and melts glass, and when it falls upon water, incontinently that explodes into steam. [1]

Thus the case for high-intensity laser science was first made more than a half-century before the first laser ever fired.

Presently, high-intensity laser science and engineering employing petawatt-class lasers[2] is a component of a broad range of science, technology, and industries that use lasers to make, image, and analyze materials and processes for physics, chemistry, medicine, manufacturing, and national security. The recent National Academies' report *Optics and Photonics: Emerging Technologies for the Nation*[3] describes the multi-billion dollar laser industry and the trillion-dollar economy that depends on it.

During the first half of laser history, the 1960s to the 1980s, there were several areas of application for the H.G. Wells version of lasers as tools for delivering energy at a distance in cutting, in welding, or for weapons technology. These mostly involved lasers that could deliver a lot of total energy but *not* necessarily deliver the energy rapidly. High-intensity laser science evolved following further advances in laser technology and engineering in the 1990s that made it possible to concentrate the energy of a laser into a short pulse and focus it to a small area. These led to new applications in fundamental and applied research and in commerce, which continue to expand in the current decade. These applications are evolving still more rapidly due to recent large investments in new science facilities in Europe and Asia [Fig. 1.1], as well as some important technology breakthroughs.

The committee's topic is high-peak-power short-pulse lasers for high-intensity applications, where large amounts of energy are concentrated into short pulses and small areas to reach the highest peak

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[1] H.G. H.G. Wells, *War of the Worlds; Series: Dover Thrift Editions Paperback: 160 Pages Publisher: Dover Publications (January 10, 1997) Language: English ISBN-10: 0486295060 ISBN-13: 978-0486295060*, n.d.Reprint, Dover, New York, 1997.

[2] Abbreviated PW; 1 PW = $10^{15} W/cm^2$. List of all acronyms is in Appendix A

[3] National Research Council (NRC), 2013, *Optics and Photonics: Essential Technologies for Our Nation*, The National Academies Press, Washington, D.C.

power and intensity. Therefore, this report will not discuss the early history of long-pulse or continuous lasers. Nor will it discuss some applications for long-pulse laser radiation such as melting materials or laser weapons. There is no strict lower limit for intensity-enabled science, however, because the effects of intensity also depend on other factors such as wavelength, and this study will report on science involving high-intensity lasers from the infrared to X-ray wavelengths. **Therefore, the committee's threshold criterion is that the peak intensity of the laser pulse is driving the process of interest.**

### 1.1.1 Target Readers of This Report

This report is intended primarily for its sponsors, but their purpose is only well-served if its findings, conclusions, and recommendations are useful for a broader and less technically specialized audience, including policy makers and the general public. The Executive Summary and this introductory chapter should be accessible to all. Chapter 2, on Stewardship, discusses US leadership and policies that have shaped the nation's role in this science and technology. This should also be of interest to program planners as well as the science funding community. Following this are separate chapters that delve into the details of the science and technology and contain more technical descriptions and analyses: Chapter 3 describes the laser technology and its current limitations. Chapter 4 discusses the international landscape and development of large-scale multi-national laser research institutes. Chapter 5 looks at the major science opportunities opened up by high intensity lasers, and Chapter 6 discusses applications. Chapter 7 summarizes the conclusions and recommendations of the study. Finally, there are several appendices to provide further details, including a glossary, and references to help readers who want to delve into greater detail on any of these subjects.

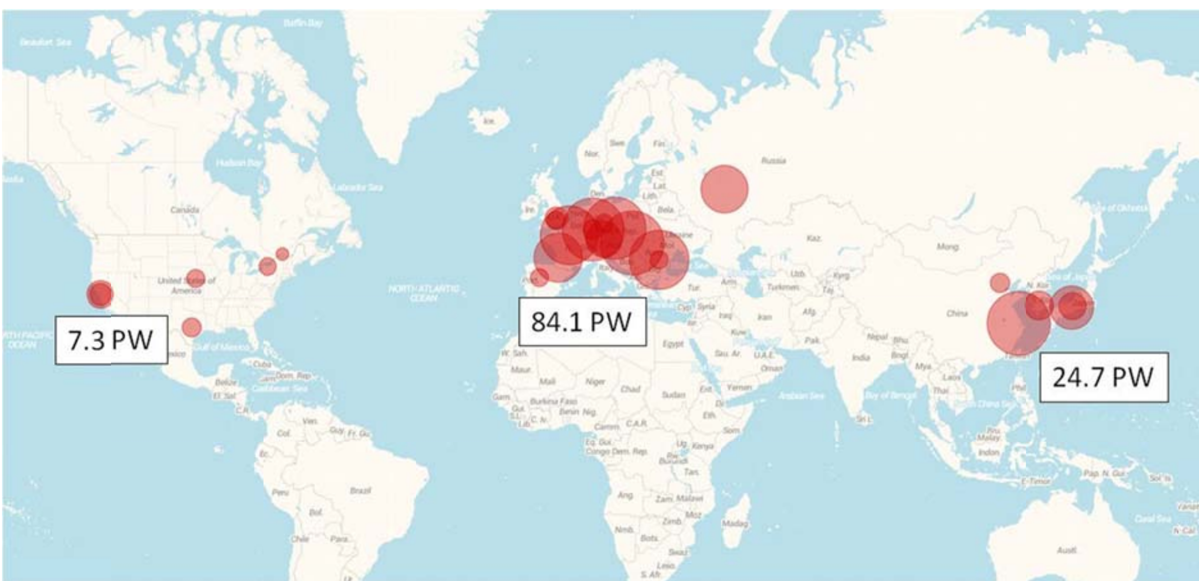


**FIGURE 1.1** Current petawatt-class lasers worldwide, showing the concentration of petawatt capacity in Europe and East Asia compared to the United States. SOURCE: Courtesy of J.L. Collier, Committee Member.

### 1.1.2 Historical Background for This Study

The historical background leading to this report is discussed in detail in Chapter 2 and in the Preface to this study. High-intensity laser science was underway at the terawatt level in the 1980s, but a real advance was the first petawatt laser built at Lawrence Livermore National Laboratory in 1996, in order to assist with the Nova program on laser fusion. In 2002, a group of U.S. scientists from universities and national laboratories assembled a report entitled *Science and Applications of Ultrafast, Ultraintense Lasers: Opportunities in Science and Technology Using the Brightest Light Known to Man*, also known as the "SAUUL" report.[4] The report was a consequence of a grassroots effort by the U.S. scientists to examine the science opportunities and technological needs and propose new models for stewardship that would leverage interagency investments. The report also proposed that a new paradigm for funding high-intensity laser science based on multi-institutional networks and mid-scale facilities was imperative for exploiting scientific opportunities. The notion of networks to organize the community was also a recommendation of the National Academies' *Harnessing Light* report carried out the previous decade.[5]

The recommendations of the SAUUL report began to receive attention, particularly in Europe, which has a thriving high-intensity laser community, and has been engaged in developing means to connect researchers in different European Union (EU) Countries. Europe developed programs through its economic and cultural "Framework" funding that included several networks devoted to short pulse and strong field research. The response in the United States was more modest but included plans for science user programs at the large lasers at Department of Energy (DOE) weapons laboratories, as well as smaller university projects funded by DOE or the National Science Foundation (NSF) to build petawatt-class lasers at the University of Michigan, University of Texas at Austin, and University of Nebraska. User networks were not created in the United States.

In the intervening years, additional National Academies' studies in related areas have continued to emphasize the science opportunities enabled by high-intensity lasers, the benefits of network organizing within the community, and the larger benefits to society from leadership in laser science and engineering. These reports include *AMO 2010: Controlling the Quantum World*,[6] *Frontiers in High Energy Density Physics*,[7] and the recent report entitled *Optics and Photonics: Essential Technologies for our Nation*.[8]

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[4] P. Bucksbaum, T. Ditmire, L. Di Mauro, J. Eberly, R. Freeman, M. Key, W. Leemans, D. Meyerhofer, G. Mourou, and M. Richardson, 2002, *The Science and Applications of Ultrafast Lasers: Opportunities in Science and Technology Using the Brightest Light Known to Man*, presented at the SAUUL Workshop, Washington, D.C., June 17-19.
"SAUUL_report.Pdf," accessed October 16, 2016, http://science.energy.gov/~/media/bes/csgb/pdf/docs/Reports%20and%20Activities/Sauul_report_final.pdf.

[5] *Harnessing Light: Optical Science and Engineering for the 21st Century* (Washington, D.C.: National Academies Press, 1998), http://www.nap.edu/catalog/5954.

[6] NRC, 2006, *Controlling the Quantum World: The Science of Atoms, Molecules, and Photons,* The National Academies Press, Washington, D.C.

[7] NRC, 2002, *Frontiers in High Energy Density Physics: The X-Games of Contemporary Science*, The National Academies Press, Washington, D.C.

[8] NRC, 2013, *Optics and Photonics.*


**FIGURE 1.2** The ELI project consists of three major sites, or pillars, with a fourth pillar yet to be named. SOURCE: R. Dabu, 2014, "High-power Laser System (HPLS) at ELI-NP," paper presented at ELI Beamlines Summer School, Prague, Czech Republic, Aug. 24-29. http://www.eli-beams.eu/wp-content/uploads/2013/11/Dabu_high_power_laser_system_at_eli-np.pdf.

### 1.1.3 Extreme Light Infrastructure (ELI)

The European research community has created the ELI project [Fig. 1.2] in the last decade to propel them towards the development goal of an exawatt class laser, 1,000 times more powerful than current petawatt lasers, achieved by concentrating kilojoules of energy into 10 fs.[9] If this power is focused to a micrometer diameter spot it will spur research relevant to nuclear physics, high energy physics, and related fields accessible at intensities up to $10^{25}$W/cm$^2$. The current ELI project is building nearly a dozen petawatt-class lasers in three new laser facilities in Eastern Europe. The EU has determined that ELI will have broad benefits for society in areas such as improved clinical cancer therapy, biomedical imaging, and nuclear materials and waste processing. Furthermore, ELI will aid the European photonics industry and will provide educational and training opportunities for new scientists and engineers in photonics and laser-enabled areas of research.

## 1.2 STATUS AND STEWARDSHIP OF HIGH-INTENSITY SCIENCE AND ASSOCIATED TECHNOLOGY IN THE UNITED STATES

Although the United States led innovations in high-intensity lasers throughout the 20th century, leadership is rapidly moving to Europe, and in some cases, to Asia as well. This is seen in the area of laser manufacturing as well as applications. The situation is described more fully in Chapter 2 of this report.

[9] G.A. Mourou, G. Korn, W. Sandner, and J.L. Collier, 2011, *Extreme Light Infrastructure Whitebook: Science and Technology with Ultra-Intense Lasers*, Thoss Media, Berlin, http://www.eli-beams.eu/wp-content/uploads/2011/08/ELI-Book_neues_Logo-edited-web.pdf.

In addition, there is broad interest in high-intensity laser science and technology across multiple U.S. science agencies, but the efforts are not well coordinated. Historical trends in federal funding for laser science and its effect on high-intensity laser research is also described in Chapter 2. Several contributions to the loss of U.S. leadership are summarized below:

First, the committee found that important scientific and economic studies of the benefits of laser science, such as the 1998 National Academies' report *Harnessing Light* report, had far greater impact on policies in Europe than in the U.S. Significant rapid coordinated strategic investments were subsequently made in Europe, Japan, and later in China and elsewhere, but not here.

Second, the U.S. research reliance on mission-based large-scale national efforts and small "single-investigator" funding across different agencies with no motivation or established protocol to coordinate them led to lack of stewardship strategy for this field. Thus the U.S. lost out on creation of research collaborative networks, mid-scale instrument development, and also has few means to manage awards for commercial development of advanced laser hardware. This has also led to a decrease in academic and commercial participation.

Third, the decline of corporate investment in long-term research in the US has hit this field especially hard, since many of its 20$^{th}$ century innovations came from Bell Laboratories, IBM Labs, Ford Labs, GE Labs, and others. Europe has responded with incentives for industrial participation in research through vehicles such as the Frauenhofer Institutes. The US has no comparable programs.

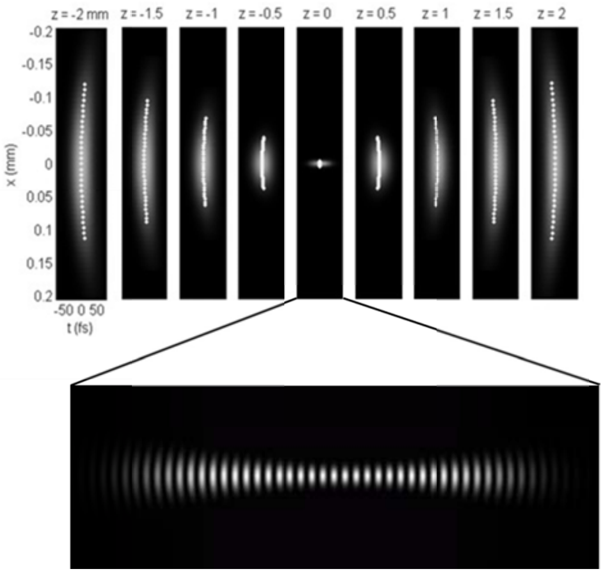
Fourth, a decade of flat federal funding has eliminated the budget flexibility needed to seed new discoveries, while economic expansion overseas has been accompanied by significant growth in foreign research infrastructure and program funds.

The recommendations laid out in the Executive Summary and Chapter 7 of this report all address these points by urging the creation of a cross-agency multiscale broad participant program to re-establish leadership-level research in high intensity laser science in the United States,

## 1.3 HIGH-INTENSITY LASER PROPERTIES

Appendix A summarizes the most important technical terms for the context of the study and defines mathematical connections between them when needed. The properties of the light are summarized in the Box 1.1, where the committee stresses the physical qualities and magnitudes and avoid equations.

**BOX 1.1  Petawatt Laser Pulses**




**What is a petawatt laser pulse?**

A petawatt is most easily understood by examining the below practical comparisons. (An example of a petawatt laser pulse studied in this report is 100 Joules of energy delivered in 100 femtoseconds, at a wavelength of 800 nm, focused to a spot 10 microns across. If we could see the pulse itself then it would appear as a tissue-paper-thin pancake of energy in the form of an electric field traveling through space at the speed of light. The figure at left shows such a laser pulse converging to a focus, where it becomes a filament about one-tenth the thickness of a human hair with about 30 optical cycles of energy.[10])

The total energy carried by this pulse of light, 100 Joules, is approximately the kinetic energy of a pitched baseball.[11]

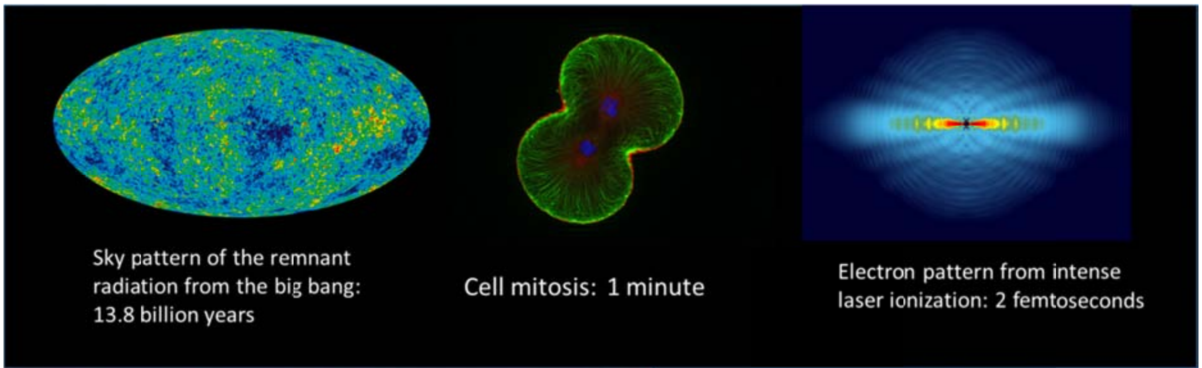
[10] R. Trebino, P. Gabolde, P. Bowlan, and S. Akturk, N.d., "Measuring Everything You've Always Wanted to Know about an Ultrashort Laser Pulse (but were afraid to ask)," presented at the Georgia Tech School of Physics, Atlanta, http://slideplayer.com/slide/3733608/.

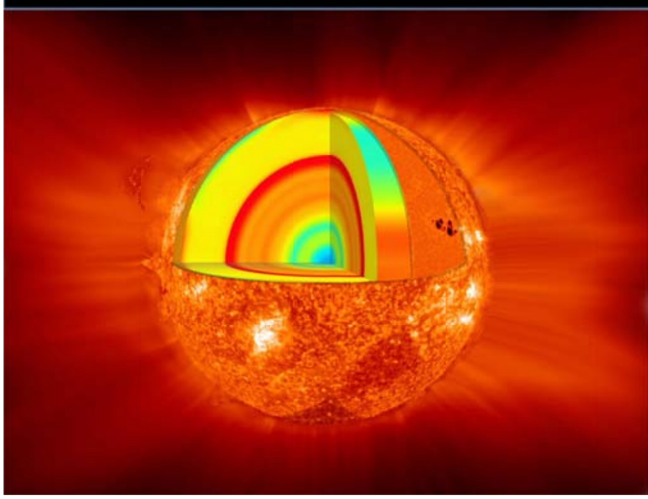
[11] AP photo of Don Larsen delivering a pitch during his World Series perfect game October 8, 1956, from http://www.nydailynews.com/sports/baseball/yankees/larsen-plays-perfect-game-world-series-1956-article-1.2382988.

Its peak power, the energy per unit time, is one petawatt, which is about one hundred times the world's total rate of energy consumption.[12] A petawatt is also the combined total solar power striking the states of California, Arizona, and Nevada on a sunny day at noon.

[12] C. Hunt, "World Bank Kicks Coal, but Will the Rest of the World Follow?" *The Conversation*, July 28, 2013, http://theconversation.com/world-bank-kicks-coal-but-will-the-rest-of-the-world-follow-16392.

Of course this enormous power is only possible because the pulse is short. 100 femtoseconds is in fact as short compared to one minute as one minute is short compared to the age of the universe.



A mirror or lens can focus this petawatt pulse to a small spot, 10 microns in this example. This corresponds to a focused electric field of more than 100 trillion V/m. When that much light is concentrated in such a small spot, the power per unit area, called the intensity, is ten-trillion-trillion $W/m^2$. The brightest point at the interior of the sun is much less intense.[13] In fact, this is about a million times the intensity equivalent of a thermonuclear explosion at ground zero.[14]

[13] NASA, "https://upload.wikimedia.org/wikipedia/commons/0/06/469368main_sun_layers_unlabeled_full.jpg

[14] "File:Operation Castle - Romeo 001.Jpg," *Wikipedia*, accessed July 13, 2017, https://en.wikipedia.org/wiki/File:Operation_Castle_-_Romeo_001.jpg.

## 1.4 HIGH-INTENSITY LASER TECHNOLOGIES

Petawatt lasers and the associated fields of high-intensity science are enabled by the technology of optical power compression that can concentrate joules of optical energy into a single packet only tens of microns in each dimension. The history of laser technical advances that led to this is described in Chapter 3 and in the associated Appendices A and B. These advances use the special properties of electromagnetic radiation.

A laser uses a mirrored cavity to circulate light through an optical amplifier medium to convert the excitation in the amplifier into additional light. High-intensity laser light uses several key additional elements. The **“Q-switch”** is a device inside the laser cavity that turns the light circulation on and off so that the amplifier medium can become highly energized before lasing depletes its excitation. A **“mode locker”** is another device inside the laser cavity that compresses the circulating optical power into pulses that are much shorter than the cavity. The third key element is **“chirped-pulse amplification”** (CPA), which is *outside* the laser cavity. This disperses the short pulse like the colors of a rainbow, enabling much higher amplification. Together these innovations have led to the laser light described in the previous section. These components are described more fully in Chapter 3, together with many figures to help the reader. There is also a glossary of technical acronyms in the Appendices of this report.

Some additional technologies bear mentioning because of their promise to extend to higher intensities. **“Optical parametric chirped-pulse amplification”** (OPCPA) is a parametric amplifier, not a laser. It converts energy from the excitation source directly into the output laser in a single step. The host medium is just a converter; it does not need to store the energy, and this has advantages for scaling to higher powers. **“Free-electron lasers”** (FELs) are wholly different kinds of lasers that can produce comparable high intensities to petawatt lasers, but at X-ray wavelengths. They utilize high-energy electron accelerators located at national laboratories in the United States, Europe, and Asia. Several are currently operating, and more are scheduled for the next decade.

## 1.5 LIMITS TO SCALING TO STILL HIGHER INTENSITY

The “Moore’s Law” analog in high-intensity lasers is shown in the following figure:

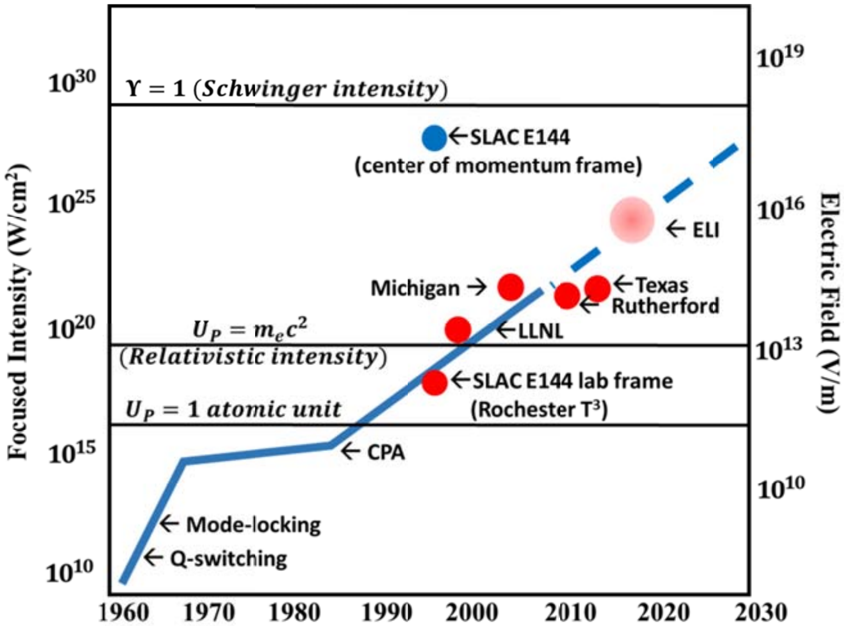



**FIGURE 1.3** Highest focused intensities over time. CPA and solid-state laser technology have pushed the present peak intensity to the range of $10^{22}$ W/cm$^2$. The European ELI project will scale this up more than one order of magnitude in the near future. Also shown is a blue dot for the SLAC E144 experiment that achieved high intensity by boosting the laser-matter interaction into a relativistic frame. The three horizontal lines show the intensity for the ponderomotive (quiver) energy $U_P$ of an electron in the focus of an 800 nm (Ti:Sapphire) laser to be equal to one atomic unit; or for $U_P$ to be equal to the electron rest mass; or for the Schwinger intensity $\Upsilon = 1$ where the vacuum becomes unstable and light is directly converted to matter. SOURCE: Philip Bucksbaum, Stanford University.

Since the invention of CPA, the power has increased about an order of magnitude every 4 to 5 years. The current limits are due to the optical elements with the lowest damage thresholds, which are the special dispersion optics required for pulse compression in CPA or OPCPA systems. More details can be found in Chapter 3 and in Appendix A4.

## 1.6 SCIENCE AND TECHNOLOGY COMMUNITY

The worldwide high-intensity laser science community includes laser engineers, scientists who need the high-intensity environments for their science, and manufacturers. A number of websites and international conferences support and track their activities. These are described in Chapter 2 of this study. The committee concludes that there is a large, active, diverse, international collection of scientists and engineers interested in high-intensity lasers as tools for working on science and technology problems in fundamental physics, imaging science, accelerator science, plasma physics, planetary and astrophysics, ultrafast chemical and cluster dynamics, and others. However, in the United States there are few opportunities for these different areas to coalesce into a single community. The situation is quite different in Europe.

A remarkable and key example of the organization of the ultrafast and high-intensity laser community is Laserlab-Europe, a confederation of 33 organizations in 16 countries that describes itself as an "Integrated Initiative of European Laser Research Infrastructures."[15] The committee heard time and again about the importance of Laserlab-Europe to organize the community, which had a great influence on science policy and created the conditions necessary to bring about the ELI program.

The largest community-driven project in high-intensity laser science today is the ELI program, located at three sites in the EU—Czech Republic, Hungary, and Romania. The European Union and member states have committed $1 billion over the next ten years to this project, which will provide the science community with multiple laser facilities tailored to the broad needs of the different science areas.

## 1.7 SCIENCE AND APPLICATIONS WITH HIGH-INTENSITY LASER LIGHT

The science and applications chapters 5 and 6 summarize the extensive case for the continued development and deployment of high-intensity lasers for research and applications. H.G. Wells' imagined futuristic application of intense lasers falls far short of a reality that includes research in particle physics, cosmology, nuclear physics, planetary astrophysics and geophysics, chemistry, atomic physics, materials science engineering, manufacturing science, and medical science. This summary chapter includes only a few highlights. The unifying theme is that high-intensity lasers provide an extreme environment that cannot be replicated more easily or at all with other laboratory techniques; therefore, these facilities are required for further progress in several areas.

### 1.7.1 High-Density Laser-Plasma Interactions

The fundamental science underpinning laser fusion is but one of the intellectual drivers for research into the interactions of intense laser radiation with high-density matter. Planetary astrophysics, geophysics, and materials science all have a need for experiments in these environments. The electric field in the laser focus in laser-matter interactions can oscillate electrons to wiggle energies over 100 MeV. The ponderomotive pressure exceeds one billion atmospheres. At these extreme conditions even the fundamentals of the laser absorption mechanism is not understood, so this is truly a new regime of plasma physics.

### 1.7.2 Connections to Astrophysics

Relativistic electron–positron (e+e−) pair plasmas are present in the early universe and also exist in exotic astrophysical objects such as blazars, pulsar winds, and gamma-ray bursts, which are of great interest in studies of the evolution of the violent events that affect the structure of the universe.[16] Intense laser-plasma interactions are the one place where these can be explored in the laboratory. Dense production of positrons ($10^{15}$ cm$^{-3}$) in high-intensity experiments have been reported recently in the focus of petawatt lasers exceeding $10^{21}$ W/cm$^2$.[17] The magnetic fields produced in these plasmas exceed $10^9$ G, far larger than fields created using other means.

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[15] "LASERLAB-EUROPE."

[16] E. Liang, 2010, Intense laser pair creation and applications, *High Energy Density Physics* 6(2): 219-22.

[17] E. Liang, T. Clarke, A. Henderson, W. Fu, W. Lo, D. Taylor, P. Chaguine, et al., 2015, High

### 1.7.3 Unique Secondary Sources

Several sections of both the science and applications chapters of this report are devoted to the use of high-intensity laser pulses to make secondary sources of particle beams or radiation. X-rays, gamma rays, protons, electrons, positrons, and neutrons have all been created using high-intensity lasers interacting with material targets. One of the ELI nuclear physics beamlines will be devoted to a brilliant beam of gamma rays produced by scattering of a petawatt laser from an electron beam. Particle beams created by intense lasers can be more effective sources for clinical medical therapies, and so this is also an important focus.

### 1.7.4 Particle Acceleration

High-intensity lasers are a well-developed route to advanced particle accelerators. They accomplish high-gradient acceleration through the low-density plasma process of plasma wakefield generation. Major projects to advance this technology have been funded in the United States by the Department of Energy Division of High Energy Physics, and currently the only approved petawatt laser for the DOE Office of Science is intended to demonstrate length-scaling of GeV-class electron accelerators using cascaded sections of plasma wakefield acceleration [Fig. 3.1]. The DOE has recently curtailed most of its research into superconducting radiofrequency (SRF) for the next linear collider. It funds some SRF research at a level that has been described on its own program solicitation page as "inadequate given the need for basic understanding of the physics…",[18] Laser-based acceleration schemes may therefore provide one of the most viable possible re-entry points for U.S. leadership in advanced technology for future linear colliders.

### 1.7.5 Quantum Vacuum Interactions and Non-perturbative Quantum Electrodynamics

The vacuum is not empty at the quantum level, but rather it is filled with matter-antimatter pairs of particles that are created and annihilated in extremely short time, on the order of Planck's constant $\hbar$ divided by the rest energy $2mc^2$, where $c$ is the speed of light and $2m$ is the mass of the particle pair. This time is about 2.5 zeptoseconds ($2.5\text{x}10^{-21}$ s) for e+e- pairs. Many years ago Schwinger, Heisenberg, Euler, and others proposed that light of sufficient intensity could heat the quantum vacuum such that matter-antimatter pairs could boil out of the it. The minimum intensity required is called the Schwinger intensity, equal to $2\text{x}10^{29}$ W/cm$^2$. A possible way to study this regime is to collide intense lasers with relativistic electron beams. This is one of the most startling and exciting new frontiers using high-intensity lasers, described extensively in Chapter 5.

### 1.7.6 Attosecond Science

High-intensity lasers are gateways to the attosecond (as, $10^{-18}$ s) timescale. Times below one femtosecond (fs, $10^{-15}$s) are important because that is the natural timescale for electron motion within a molecule following a sudden event like a fast particle collision or radioactive decay. The strong fields in high-intensity lasers can create attosecond radiation by means of high harmonic generation (HHG) in bound atoms and molecules, the non-relativistic analog of the Schwinger process described in the

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e+/e−ratio dense pair creation with 1021W.cm−2 laser irradiating solid targets, *Scientific Reports* 5. doi:10.1038/srep13968.

[18] Bruce Strauss, "Fundamental Research In Superconducting Rf Cavity Design | U.S. DOE Office of Science (SC)," accessed July 1, 2017, https://science.energy.gov/hep/funding-opportunities/fundamental-research-in-superconducting-rf-cavity-design/.

previous paragraph. X-ray free-electron lasers have also demonstrated attosecond pulses. There are also proposals for plasma-based HHG that could conceivably get to zeptosecond (zs) pulses.

### 1.7.7 Commercial Applications for High-Intensity Lasers

The first commercial application of lasers employing CPA was in approximately 2002 for use for tissue cutting in LASIK vision correction (see Chapter 6); since then the market for industrial/medical high-intensity lasers has reached several hundred million dollars per year, primarily for precision micromachining. For example, ultraprecision machining of hard materials such as for cell phone faceplates is in many cases done with high-intensity femtosecond lasers. An emerging area with a potential enabling impact in the >$100B range is in the use of high-intensity lasers to implement "tabletop X-ray lasers" through coherent upconversion.[19] More information about this and other applications in medicine and manufacturing are in Chapter 6.

[19] A laser is upconverted by a nonlinear element inserted into its beam, which generates an output laser frequency that is greater than the input laser frequency. A common example is a frequency doubler, which, as its name implies, doubles the output photon frequency.

# 2

# Stewardship in High-Intensity Laser Science and Technology

## 2.1 U.S. LEADERSHIP IN THE 20TH CENTURY

### 2.1.1 U.S. Dominated High-Intensity Laser Innovation in the 20th Century

The United States enjoyed a protracted period of technological and engineering dominance in the area of high-peak-power lasers during the 20th century. The laser fusion effort spearheaded by the Department of Energy (DOE) had many important technology spin-offs, including the development of rare-earth doped solid-state lasers,[1] development of scalable solid-state laser materials,[2] methods for cost-effective laser diodes for pump sources,[3,4] invention of chirped-pulse amplification (CPA),[5] large aperture nonlinear optics,[6] diffractive optics,[7] and others. DOE laboratories were not the ones that developed all solid-state laser (SSL) materials or cost-effective diodes for high-average-power lasers, but they are dominant in materials for high-intensity lasers.

This dominance was one aspect of the wider extraordinary impact of lasers on the U.S. economy, which has been documented in several independent reports. While some benefits were anticipated, many applications were discovery-driven. The 1998 National Academies' report *Harnessing Light: Optical Science and Engineering for the 21st Century*[8] highlighted technological accomplishments resulting from optics, making the point that optics technology has an outsize impact on society compared with its total dollar-volume in the economy; in other words, although the consumer impact is relatively invisible, the

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[1] Ralph R. Jacobs, William F. Krupke, and Marvin J. Weber, "Measurement of Excited state absorption Loss for Ce3+ in Y3Al5O12 and Implications for Tunable 5d→4f Rare- earth Lasers," *Applied Physics Letters* 33, no. 5 (September 1, 1978): 410–12, doi:10.1063/1.90395.

[2] S.E Stokowski, W.E Martin, and S.M Yarema, "Optical and Lasing Properties of Fluorophosphate Glass," *Journal of Non-Crystalline Solids* 40, no. 1–3 (July 1980): 481–87, doi:10.1016/0022-3093(80)90123-4.

[3] W. F. Krupke, "High-Average-Power, Diode-Pumped Solid State Lasers for Energy and Industrial Applications," in *Presented at the 6th International Symposium on Advanced Nuclear Energy Research, Mito, Japan, 23-25 Mar. 1994*, 1994.

[4] Andy J. Bayramian, "High Energy, High Average Power, DPSSL System For Next Generation Petawatt Laser Systems," in *Conference on Lasers and Electro-Optics* (Optical Society of America, 2016), STu3M.2, doi:10.1364/CLEO_SI.2016.STu3M.2.

[5] Donna Strickland and Gerard Mourou, "Compression of Amplified Chirped Optical Pulses," *Optics Communications* 56, no. 3 (December 1, 1985): 219–21, doi:10.1016/0030-4018(85)90120-8.

[6] Natalia P. Zaitseva et al., "Rapid Growth of Large-Scale (40-55 Cm) KDP Crystals," vol. 3047, 1997, 404–14, doi:10.1117/12.294327.

[7] J. A. Britten et al., "Large Aperture, High-Efficiency Multilayer Dielectric Reflection Gratings," in *Conference on Lasers and Electro-Optics (2002), Paper CPDB7* (Conference on Lasers and Electro-Optics, Optical Society of America, 2002), CPDB7, http://www.osapublishing.org/abstract.cfm?uri=CLEO-2002-CPDB7.

[8] National Research Council (NRC), 1998, *Harnessing Light: Optical Science and Engineering for the 21st Century*, The National Academies Press, Washington, D.C.

enabling impact—for example, in making fiber optic communication and the internet feasible—has been transformational.

### 2.1.2 U.S. Commercial Dominance in the 20th Century

U.S. commercial laser manufacturers led the market in the 20th century as well, including large companies such as Coherent Radiation, Spectra-Physics, General Dynamics, TRW, Avco, and others. Large defense contractors, such as Lockheed Martin, Boeing, Northrop Grumman, and others scaled high-average-power lasers for defense purposes. The commercial ecosystem that arose includes component companies providing optics and crystals, such as INRAD and CVI, and smaller companies, such as KMLabs or IMRA America, that specialized in the research market. The largest trade shows were also in the United States.

## 2.2 THE NEW MILLENNIUM: TRANSFER OF LEADERSHIP TO EUROPE

### 2.2.1 Science and Technology Investment in Lasers Declines in the United States as It Builds Overseas

At the end of the last century, the national and international landscape for high-intensity laser science started to change. Several reasons contributed to the changing tide.

### 2.2.2 Changes in the Relative Level of Investment in Laser Science

First, the excitement generated by discovery, scientific opportunity, and the economic benefits inspired by the 1998 National Academies' report captured the attention of the entire world. The *Harnessing Light* report of 1998 was perceived as having little impact for U.S. science and technology funding but was taken up enthusiastically elsewhere, as discussed in Chapter 4. The United States was no longer the epicenter; instead, significant strategic investment was made in Europe and Japan followed by China, Japan, Korea, and Russia. The growth outside of the United States was stunning, coordinated, and rapid.

#### 2.2.2.1 Compartmentalization of U.S. Science by Agency

Second, the binary nature of the U.S. research model, with large-scale national efforts juxtaposed to "single-investigator" funding, revealed its weakness: the relative lack of effective funding mechanisms that could explicitly help steward a research field with a wide variety of scales and contexts, including individual investigator work, mid-scale centers, large facilities, and university-laboratory collaborations. DOE has been an effective steward for large-scale laser facilities for specific research programs, such as Livermore's National Ignition Facility (NIF), which mostly serves the DOE weapons program; but no U.S. agency has an effective strategy for stewarding the advanced laser technology needed to exploit broader frontiers of science or capitalize on emerging new applications. As the increased cost for state-of-the-art high-intensity laser laboratories and infrastructure moved beyond the capabilities of most U.S.

university-based "single principle investigators (PIs)," the result was simply a significant decrease in academic participation.

#### 2.2.2.2 Decline of Corporate Research Laboratories

Third, the end of the 20th century witnessed a steady decline of corporate investment in long-term research, especially private sector basic research laboratories such as IBM Laboratories, Bell Laboratories, and GE Laboratories. The most notable was the breakup of the AT&T telephone monopoly. Its Bell laboratories was one of the great success stories of the post-WWII era, instrumental in establishing the foundations of many of the technologies that define the century, such as the transistor and the laser. It also carried out significant early work in high-intensity laser-matter interactions and short-wavelength lasers. In the 1980s, it was a dominant force in the development of femtosecond laser technology. Although Bell's interest was primarily in telecommunications applications, the "energy" derived from rapid progress in the femtosecond laser area drove the field forward and prompted others to explore the intensity frontier in ultrashort pulse lasers.

#### 2.2.2.3 Inflexibility in Federal Programs

Fourth, flat federal funding and short-term budgets resulted in U.S. science losing its flexibility and nimbleness—elements that feed new discovery. Worldwide economic expansion in the new millennium witnessed the emergence of international competition from both individual countries and consortia such as European Union. These provided new funding for research beyond existing infrastructure burdens—often explicitly looking for dynamic research areas with a proven impact. These efforts were simply in a better position to capitalize on the foundational work done by the United States. Several early reports issued in the United States predicted the impeding decline of U.S. leadership, the rise of international participation, and the cost to the United States of missed opportunities (see Section 2.8).

Despite these warnings, no federal agencies took comprehensive stewardship responsibility for high-intensity laser science and technology in the United States, although fragments of many relevant programs exist. In the past, the Department of Defense (DoD) was a strong funder of laser research; however, the decline in basic defense research support following the end of the Cold War hit the laser area particularly hard. DOE had taken the lead in large-scale high-intensity lasers as part of its laser fusion and stockpile stewardship efforts; however, the cost and difficulty of completing large projects, specifically NIF, significantly squeezed DOE funding in high-intensity laser development. Smaller, more creative and exploratory efforts in laser science became victim of the expanding needs of large-scale laser projects, leaving very little "free energy" for creative ideas in advanced high energy laser science. An example of this was the National Nuclear Security Administration (NNSA) Stockpile Stewardship Academic Alliances (SSAA) program, whose objective was in part this type of stewardship. The effort built up over a decade and exhibited vitality for a few years before being broken apart by its National Science Foundation (NSF), NNSA, and DOE fusion energy sciences (FES) patrons. FES has seen declining budgets and increasing needs, such as U.S. participation in the International Thermonuclear Experimental Reactor in France, and saw little funding available for relevant high-intensity lasers. The FES support in this area is now largely for the Linac Coherent Light Source (LCLS) end-station on matter in extreme conditions (MEC). Only the NSF-DOE plasma sciences program remains, which supports a small number of modest projects using high-intensity lasers, as one component of its program.

The consequence of these events led to the perfect storm. The decline of academic participation meant a significant loss in the training and education of the next generation of young scientists and engineers needed for driving the large-scale projects of national interest. Furthermore, the shift of U.S. efforts into a small number of in-house national laboratory projects led to the reduced participation and cooperation with private companies. Consequently, the production of state of the art in optical components and know-how were becoming increasingly absent from private companies.

### 2.2.3 Transfer of Commercial Leadership to Europe

The commercial sector changed as well. In the 21st century, the largest laser trade show became Lasers Munich. The largest laser manufacturer is now TRUMPF in Germany.[9] And European companies and laboratories are dominating many engineering innovations such as thin-disc lasers and fiber lasers. The field has undergone consolidation so that now the largest companies are multinational, including companies that began in the United States, such as Coherent[10] and Newport Corporation,[11] and companies that began overseas but are now in the United States, such as IPG Photonics.[12] The largest part of the laser business for both TRUMPF and IPG is manufacturing applications that use high energy lasers, not high-peak-power lasers, but these companies are nonetheless critical to high-intensity laser infrastructure because all CPA lasers employ just these types of high energy sources as essential components for the manufacture of peak-power petawatt (PW)-class laser systems.

### 2.2.4 Start-ups and Mergers in Europe

In recent years, EU support has resulted in a steady stream of start-up laser companies in the area of high-intensity laser technology. This is driven by a number of mechanisms: significant research funding in intense laser areas at universities and at research institutes, as well as equipment purchase funding at national laboratories, both for standard commercial off-the-shelf (COTS) lasers and for higher-risk development projects. And joint university-industry research centers such as the Fraunhofer Institutes provide substantial government support for industry-directed projects. This contrasts with the situation in the United States, where the government supports virtually no stand-alone laser development work in high-intensity lasers, but rather all such work is justified as a small part of a larger scientific project. The situation in Europe has resulted in a proliferation of companies in Europe in various areas of advanced laser technologies: One-Five,[13] Class 5 Photonics,[14] Thales Lasers,[15] Amplitude Systemes,[16] Amplitude Technologies,[17] Laser Quantum/Venteon, Ekspla, Light Conversion, FASTLITE,[18] Menlo Systems,[19] and TRUMPF Scientific Lasers.[20] Ironically, several European companies (Femtolasers,[21] Time-Bandwidth

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[9] TRUMPF Group, “Facts and Figures - TRUMPF Group,” accessed December 11, 2016, http://www.trumpf.com/en/company/facts-and-figures.html.

[10] Coherent, “Coherent Corporate Website,” accessed December 11, 2016, https://www.coherent.com.

[11] “Newport Corporation,” accessed December 11, 2016, https://www.newport.com/.

[12] “IPG Photonics Corporation,” accessed December 11, 2016, http://www.ipgphotonics.com/.

[13] “Onefive GmbH - Femtosecond and Picosecond Lasers,” accessed December 11, 2016, http://www.onefive.com/.

[14] “Class 5 Photonics,” accessed December 11, 2016, http://www.class5photonics.com/.

[15] “Lasers | Thales Group,” accessed December 11, 2016, https://www.thalesgroup.com/en/worldwide/lasers.

[16] “Amplitude Systèmes,” accessed December 11, 2016, http://www.amplitude-systemes.com/.

[17] “AMPLITUDE TECHNOLOGIES,” accessed December 11, 2016, http://www.amplitude-technologies.com/.

[18] “FASTLITE - Ultrafast - Shaping - Measurement - Control,” accessed December 11, 2016, http://www.fastlite.com/en/. accessed December 11, 2016.

[19] Menlo Systems, “Optical Frequency Combs, Terahertz Systems, Femtosecond Fiber Lasers | Menlo Systems,” accessed December 11, 2016, http://www.menlosystems.com/.

[20] “Facts and Figures - TRUMPF Group.”

[21] Spectra-Physics, “Spectra-Physics Completes Acquisition of FEMTOLASERS,” accessed December 11, 2016, http://www.spectra-physics.com/company/news/spectra-physics-completes-acquisition-of-femtolasers.

Products,[22] Lumera Laser[23]) have been purchased by U.S. companies (Newport, JDSU, and Coherent, respectively); however, the result has been a shift of the center of gravity of these companies away from the United States—for example, Coherent's workforce was already comparable or larger in Germany compared with the United States *before* announcing its intent to acquire Germany-based Rofin[24]—a company comparable in size to Coherent.

## 2.3 RECENT STUDIES SHOW A CONTINUING NEED FOR LASER TECHNOLOGY IN THE 21ST CENTURY

Prompted by the 50th anniversary of the laser's discovery and the growing worldwide optics economy, a 2010 White House Office of Science and Technology Policy (OSTP) study reassessed the impact in three economic sectors: transportation (total market estimated at $1 trillion in output in 2009-2010); the biomedical sector ($2.5 trillion); and telecom, e-commerce, and IT ($4 trillion).[25] The results are encapsulated in Figure 2.1. In response to the OSTP findings, the National Academies issued a more comprehensive report in 2013 entitled *Optics and Photonics: Essential Technologies for Our Nation* that not only evaluated the impact of lasers on the U.S. economy, but also on defense and national security, advanced manufacturing, and energy.[26] In addition, the study identified that continued leadership in all these sectors required a trained workforce supported by a foundation of strong academic research and education. This report was adopted by the White House, resulting in the $200 million Integrated Photonics Institute.[27]

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[22] Laser Focus World, "JDSU Acquires Ultrafast Laser Maker Time-Bandwidth Products," "JDSU Acquires Ultrafast Laser Maker Time-Bandwidth Products," accessed December 11, 2016, http://www.laserfocusworld.com/articles/2014/01/jdsu-acquires-ultrafast-laser-maker-time-bandwidth-products.html.

[23] Optics.org, "Coherent Extends Ultrafast Expansion with $52M Lumera Laser Buy-Out," accessed December 11, 2016, http://optics.org/news/3/12/35.

[24] Coherent-Rofin, https://www.rofin.com/, "ROFIN.COM - Lasers for Industry - Fiber Lasers, Ultrashort Pulse Lasers, Solid-State Lasers, CO2-Lasers Etc.," accessed December 11, 2016, https://www.rofin.com/.

[25] T. Baer and F. Schlachter, 2010, "Lasers in Science and Industry: A Report to OSTP on the Contribution of Lasers to American Jobs and the American Economy," presented at LaserFest 2010, http://www.laserfest.org/lasers/baer-schlachter.pdf.

[26] NRC, 2013, *Optics and Photonics: Essential Technologies for Our Nation* (Washington, D.C.: National Academies Press, 2013), http://www.nap.edu/catalog/13491.

[27] The White House, "President Obama Announces New Manufacturing Innovation Institute Competition," last update October 3, 2014, https://www.whitehouse.gov/the-press-office/2014/10/03/fact-sheet-president-obama-announces-new-manufacturing-innovation-instit.

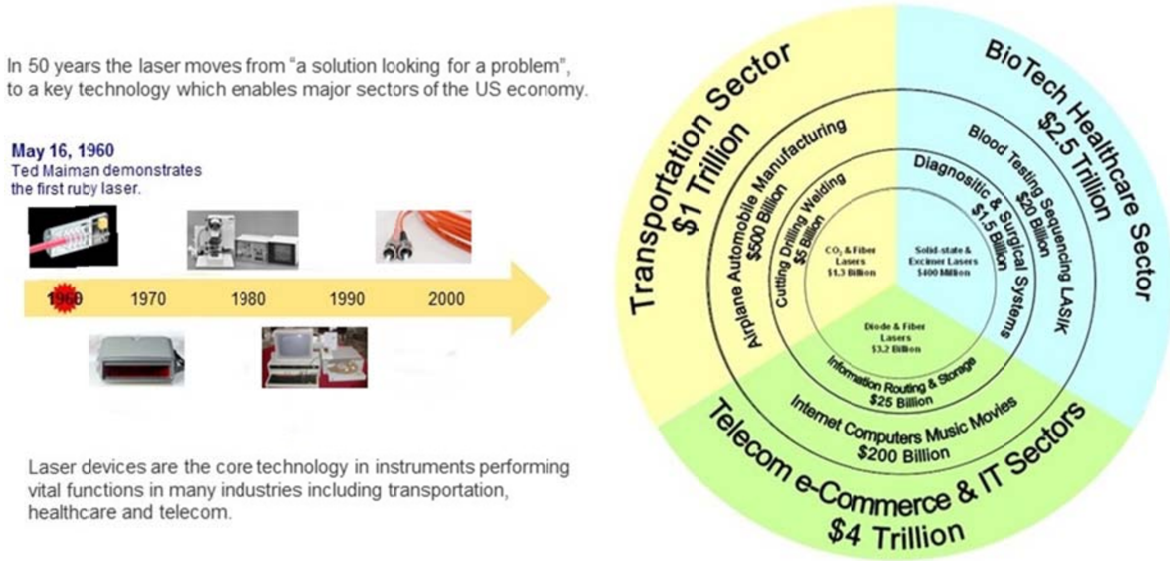


**FIGURE 2.1** Lasers play a key role in driving the U.S. economy to produce direct societal benefits. SOURCE: T. Baer and F. Schlachter, 2010, "Lasers in Science and Industry: A Report to OSTP on the Contribution of Lasers to American Jobs and the American Economy," presented at LaserFest 2010, http://www.laserfest.org/lasers/baer-schlachter.pdf.

In addition to its more tangible benefits, the laser plays a central role in basic and applied research in virtually every area of science. The topic of this report—high-intensity and very short-pulse duration—represents the leading edge of a research area that has proven its broad relevance. The laser was first demonstrated in 1960 at the Hughes Research Laboratory, and much of the early innovation emerged from small laboratories located at universities and companies throughout the United States, funded by federal agencies and private sources. National needs in defense and energy drew immediate and substantial benefits, and laser work has been recognized by a string of Nobel Prizes (40 since 1964 have relied on lasers).[28] The importance of this work initiated substantial investment in national programs at DOE and DoD laboratories. Thus, the United States developed a funding paradigm based on the nimbleness of university laboratories and the infrastructure needs for large-scale federal laboratories. Approaching the new millennium, the United States was at the pinnacle of laser research in the world.

Through this balanced effort, a new frontier emerged in laser research enabled by the development of high-intensity, ultrafast lasers. Again, U.S. scientists forged this path launched by the notable development of CPA in 1985 at the Laboratory for Laser Energetics (LLE) at the University of Rochester. This seminal technological development resulted in several important science breakthroughs, all at U.S. institutions:

- the first demonstration of a PW ($10^{15}$ W/cm$^2$) laser and its use in experiments at ultra-relativistic intensity at Lawrence Livermore National Laboratory (LLNL);[29]

[28] Nobel Prize, "Laser Facts," accessed January 8, 2017, https://www.nobelprize.org/educational/physics/laser/facts/history.html.

[29] M. D. Perry et al., "Petawatt Laser Pulses," *Optics Letters* 24, no. 3 (February 1, 1999): 160, doi:10.1364/OL.24.000160; Michael D. Perry and Gerard Mourou, "Terawatt to Petawatt Subpicosecond Lasers," *Science* 264, no. 5161 (May 13, 1994): 917–24, doi:10.1126/science.264.5161.917.

- the first anti-matter (positron) production with a laser at SLAC (1997);[30]
- the first demonstration of femtosecond X-ray generation through inverse Compton scattering at Lawrence Berkeley National Laboratory (LBNL) (1996);[31]
- the first demonstration of multiphoton Compton scattering at SLAC (1999);[32]
- the first self-amplified spontaneous emission free-electron lasing at Brookhaven National Laboratory, Los Alamos National Laboratory (LANL), and University of California, Los Angeles;[33]
- the first laser wake field GeV electron acceleration at LBNL (2006);[34] and
- the first hard X-ray free-electron laser at SLAC (2009).[35]

These pioneering achievements required large-scale facilities that were available at the various national laboratories. The campaigns were all stewarded by the DOE either through the NNSA or the Office of Science. Many seminal science discoveries were occurring concurrently in academic laboratories funded by "single-investigator" programs supported by DOE, DoD, and NSF. The United States was positioned as a world leader in both the technology and science of high-intensity lasers while supporting the development of a complementary high-tech industry.

### 2.3.1 Continuing Need for High-Intensity Lasers in the United States

U.S. government contracts still support a vibrant community of small manufacturers of high-power lasers, ultrafast CPA lasers, and components. For the present, there is sufficient expertise in the United States to support the development of facilities for high-peak-power lasers. Specific evidence for this claim is the fact that Extreme Light Infrastructure (ELI) has contracts with a U.S. company (National Energetics) and with a U.S. DOE laboratory (LLNL) for the delivery of PW-class lasers (see Chapter 3). The previous concentration of laser expertise and utilization within the NNSA laboratories, particularly

[30] M.W. Browne, "Scientists Use Light to Create Particles," accessed January 8, 2017, https://www.slac.stanford.edu/exp/e144/nytimes.html.

[31] R. W. Schoenlein et al., "Femtosecond X-Ray Pulses at 0.4 Å Generated by 90° Thomson Scattering: A Tool for Probing the Structural Dynamics of Materials," *Science* 274, no. 5285 (October 11, 1996): 236–38, doi:10.1126/science.274.5285.236.

[32] C. Bamber, S.J. Boege, T. Koffas, T. Kotseroglou, A.C. Melissinos, D.D. Meyerhofer, D.A. Reis, et al., 1999, Studies of nonlinear QED in collisions of 46.6 GeV electrons with intense laser pulses, *Physical Review D* 60(9): 092004; C. Bula, K.T. McDonald, E.J. Prebys, C. Bamber, S. Boege, T. Kotseroglou, A.C. Melissinos, et al., 1996, Observation of nonlinear effects in Compton Scattering, *Phys. Rev. Lett.* 76(17): 3116–3119.

[33] M. Babzien et al., "Observation of Self-Amplified Spontaneous Emission in the near-Infrared and Visible Wavelengths," *Physical Review E* 57, no. 5 (May 1, 1998): 6093–6100, doi:10.1103/PhysRevE.57.6093.

[34] W. P. Leemans et al., "GeV Electron Beams from a Centimetre-Scale Accelerator," *Nature Physics* 2, no. 10 (October 2006): 696–99, doi:10.1038/nphys418.

[35] P. Emma et al., "First Lasing and Operation of an Angstrom-Wavelength Free-Electron Laser," *Nature Photonics* 4, no. 9 (2010): 641–647.

LLNL, LLE, and LANL, is now broadening with plans for utilization of PW lasers at LBNL[36] and SLAC.[37]

### 2.3.2 Start-ups in the United States

Laser companies in the United States are active in development of new high-intensity laser technologies. A representative survey shows the range of activities. Small start-up company National Energetics[38] is focused on facility-scale PW lasers. The small specialty research laser company KMLabs[39] is focused on terawatt-scale, kHz Ti:sapphire lasers and commercialization of coherent EUV from high-harmonic generation secondary sources, as well as compact lasers for industrial applications. Two larger laser companies, Newport-Spectra Physics and Coherent, which have far more diverse product lines, have focused on engineering improvements to existing Ti:sapphire products as well as compact industrial lasers. Other smaller U.S.-based firms that have catered to the research market include Clark MXR[40] and IMRA America[41] (Japanese owned).

## 2.4 LANDSCAPE OF PAST AND PRESENT U.S. AGENCY STEWARDSHIP

This section describes historical trends in agency support for high-intensity science, in particular from the Department of Energy, National Science Foundation, and Department of Defense.

### 2.4.1 Historical Trends in Agency Support for High-Intensity Science

At present there is no comprehensive stewardship of high-intensity lasers for science in the United States, although pieces of many programs and activities exist in this area. In the past, DOD (Air Force Office of Scientific Research and Office of Naval Research) was a strong sponsor of laser research within its own laboratories and with other companies and universities in the United States; this declined substantially in the 1990s.[42] Laser technology is difficult to separate from other projects, but the general trend in Defense science and technology funding can be seen in Figure 2.2.

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[36] W. P. Leemans et al., "Multi-GeV Electron Beams from Capillary-Discharge-Guided Subpetawatt Laser Pulses in the Self-Trapping Regime," *Physical Review Letters* 113, no. 24 (December 8, 2014): 245002, doi:10.1103/PhysRevLett.113.245002.

[37] SLAC National Accelerator Laboratory, 2015, *New Science Opportunities Enabled by LCLS-II X-ray Lasers*, Menlo Park, Calif., June 1. https://portal.slac.stanford.edu/sites/lcls_public/Documents/LCLS-IIScienceOpportunities_final.pdf?Mobile=1.

[38] "National Energetics – High-Energy and Ultra-Intense Lasers and Laser Systems.," accessed December 11, 2016, http://nationalenergetics.com/.

[39] "KMLabs," accessed December 11, 2016, http://www.kmlabs.com/.

[40] "Clark-MXR Innovative Ultrafast Laser Solutions," accessed December 11, 2016, http://www.cmxr.com/.

[41] "IMRA - Femtosecond Fiber Lasers," accessed December 11, 2016, http://www.imra.com/.

[42] American Association for the Advancement of Science (AAAS), "Historical Trends in Federal R&D," *AAAS - The World's Largest General Scientific Society*, June 11, 2013, https://www.aaas.org/page/historical-trends-federal-rd.

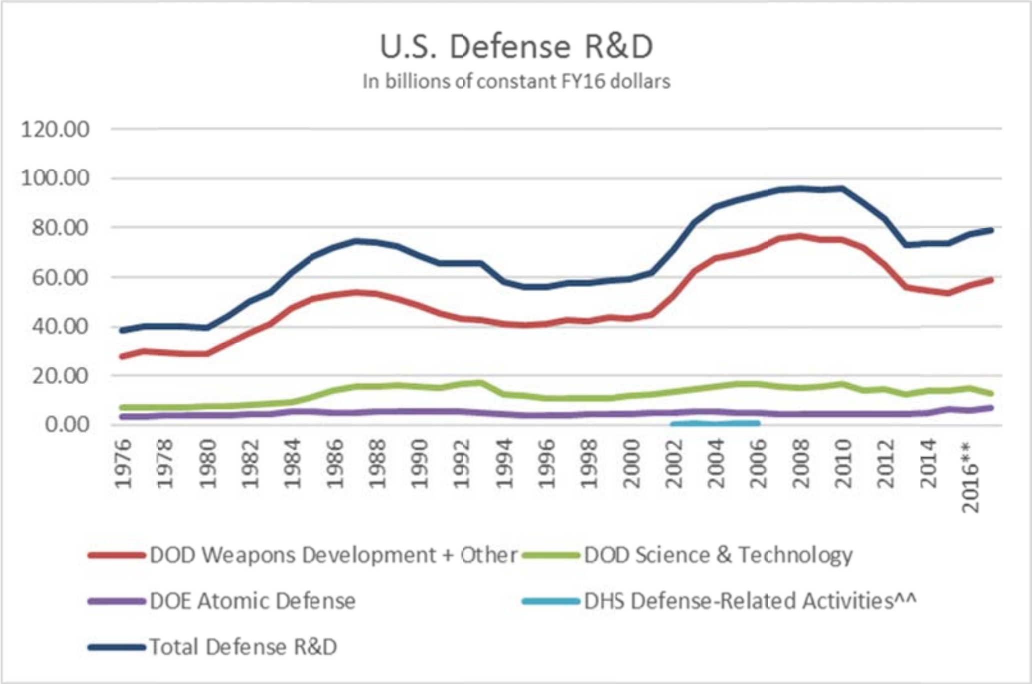


**FIGURE 2.2** U.S. research and development spending from 1976 to 2016. Science and technology spending from year to year is affected somewhat by changing definitions but shows a decrease from nearly $16 billion to under $11 billion from 1989 to 1996. SOURCE: American Association for the Advancement of Science, "Historical Trends in Federal R&D," last update February 1, 2017, https://www.aaas.org/page/historical-trends-federal-rd.

DOE led research in high-intensity lasers as part of its laser fusion efforts; however, the cost and difficulty of completing the NIF project[43] may have significantly squeezed DoE funding in high-intensity laser development. The NNSA SSAA program[44] had the objective of stewardship of this area. The effort built up over a decade and exhibited vitality for a few years but has suffered lack of coordination among its NSF, NNSA, and DOE FES contributors in recent years. FES has seen declining budgets and increasing needs to divert its core funding to satisfy the U.S. binding commitment to the European ITER tokomak fusion project[45] and seen little fusion production relevance to funding high-intensity lasers.[46] The NNSA portion of SSAA has focused attention on the MEC beamline of the LCLS. Only the NSF/DOE

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[43] Lawrence Livermore National Laboratory (LLNL), "FAQs," accessed December 11, 2016, https://lasers.llnl.gov/about/faqs#nif_cost.

[44] National Nuclear Security Administration (NNSA), "Stewardship Science Academic Alliances," *National Nuclear Security Administration*, December 21, 2011, https://nnsa.energy.gov/aboutus/ourprograms/defenseprograms/stockpilestewardship/upaa/ssaa.

[45] "US ITER," accessed December 11, 2016, https://www.usiter.org/.

[46] U.S. Department of Energy (DOE) Office of Science, "FES Budget | U.S. DOE Office of Science (SC)," accessed December 11, 2016, http://science.energy.gov/budget/budget-by-program/fes-budget/.

plasma sciences partnership program[47] remains mostly available for broader participation by the high-intensity laser community.

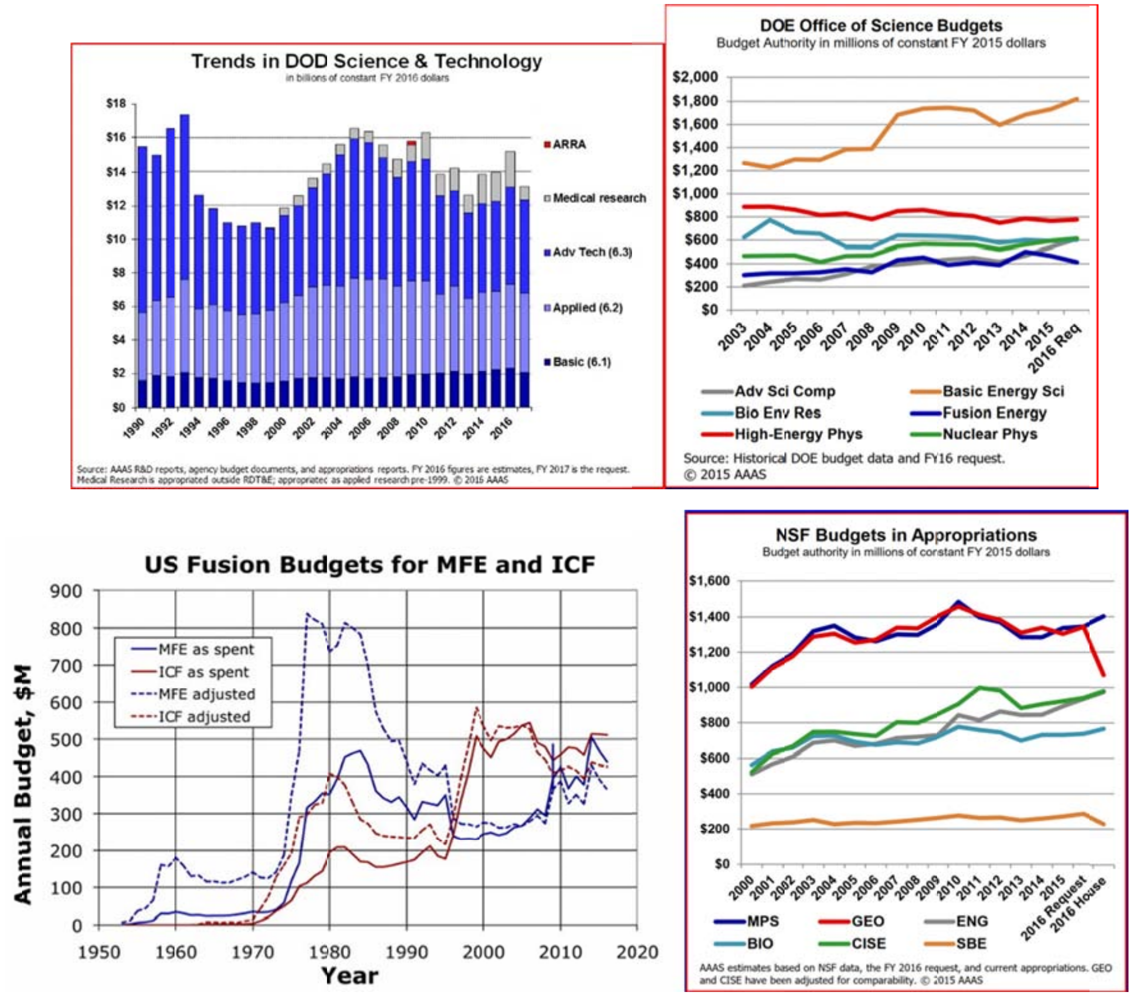


**FIGURE 2.3** Federal funding for research in areas that can use or develop high-intensity laser science.

Federal funding comes from four main sources: DOD 6.1 funding,[48] DOE FES program in the SC,[49] NSF Directorates for Mathematical and Physical Sciences and Engineering,[50] and the DOE ICF program (administered by DOD-NNSA).[51] Most funding levels have been flat or declining during the period of rapid growth in high-intensity laser technology over the past 15 years, and no single agency has taken the lead in advancing this area. (See Figure 2.3)

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[47] National Science Foundation (NSF), "NSF/DOE Partnership in Basic Plasma Science and Engineering (Nsf16564) | NSF - National Science Foundation," accessed December 11, 2016, https://www.nsf.gov/pubs/2016/nsf16564/nsf16564.htm.

[48] AAAS, "Historical Trends in Federal R&D."

[49] J. Brown, J. Hayes, S. Rhodes, and C. Webb, 2015, "Federal Funding Sources," n.d., https://www.ccas.net/files/2015%20Annual%20Meeting%20Washington%20DC/Presentations/Federal%20Funding%20Sources.pdf.

[50] Ibid."

[51] Fusion Power, "Fusion Power Associates," accessed December 11, 2016, http://fusionpower.org/.

NSF, which has supported national centers of excellence, such as the Center for Ultrafast Optical Science at the University of Michigan (1991-2002),[52] appears to no longer be directly involved in the development of high-powered or high-intensity lasers, except for some spin-off applications such as the new NSF STROBE Science and Technology Center at University of Colorado.[53] NSF also has some mid-scale instrumentation programs for modest laser development.[54]

DOD has launched several MURIs (5-year multi-site university-based research programs) in this area that have been important in supporting high intensity laser science[55] but by their nature these programs have no sustaining laboratory presence. [56]

The DOE SC has designated the Division of High Energy Physics to steward high-intensity lasers for advanced accelerator concepts. They have supported high-intensity laser programs specifically for advanced accelerators,[57] but the stewardship program does not currently emphasize other laser research. However, there is a need for high-intensity lasers in the divisions of Basic Energy Science, nuclear physics, fusion science, and other areas. The Division of Fusion Energy Science in DOE also supports high-intensity work in the area of plasma physics but not in other areas.[58] The DOE-NNSA program, which has a nuclear security mission, supports NIF and associated programs in high-intensity lasers but does not act as a steward to high-intensity lasers outside of its own missions.[59]

In summary, it appears that there is broad interest in high-intensity laser science and technology across multiple U.S. science agencies, but the efforts are not well coordinated, and there is no overall agency steward that can oversee the complementary interests and build a multi-agency high intensity facilities program.

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[52] University of Michigan, "Center for Ultrafast Optical Science," accessed December 11, 2016, http://cuos.engin.umich.edu/.

[53] NSF, "NSF Award Search: Award#1548924 - Science and Technology Center on Real-Time Functional Imaging (STROBE)," accessed December 11, 2016, https://www.nsf.gov/awardsearch/showAward?AWD_ID=1548924.

[54] NSF, "NSF PHY Midscale Dear Colleague Letter," accessed December 11, 2016, https://www.nsf.gov/pubs/2014/nsf14116/nsf14116.jsp.

[55] APAN, "MURI 15 Kickoff - Strong Field Laser Matter Interactions at Mid-Infrared Wavelengths - Research Areas - AFOSR - APAN Community," accessed December 11, 2016, https://community.apan.org/wg/afosr/w/researchareas/15602.muri-15-kickoff-strong-field-laser-matter-interactions-at-mid-infrared-wavelengths/; "2016 FY16 Radiation Balanced Lasers MURI Kick-OFF - Research Areas - AFOSR - APAN Community," accessed December 11, 2016, https://community.apan.org/wg/afosr/w/researchareas/18662.2016-fy16-radiation-balanced-lasers-muri-kick-off/; "Femto-Solid Lab Part of a $12.5 Million AFOSR MURI Program | High Energy Density Physics Scarlet Laser Facility," accessed December 11, 2016, https://hedp.osu.edu/news/femto-solid-lab-part-12.5-million-afosr-muri-program; Pavel G. Polynkin, "Experimental Component of the AFOSR-Supported MURI Program on Ultrafast Laser Filamentation in Transparent Dielectric Media," vol. 8547, 2012, 85470H–85470H–7, doi:10.1117/12.977179.

[56] All Partners Access Network (APAN), "MURI 15 Kickoff - Strong Field Laser Matter Interactions at Mid-Infrared Wavelengths - Research Areas - AFOSR - APAN Community"; "2016 FY16 Radiation Balanced Lasers MURI Kick-OFF - Research Areas - AFOSR - APAN Community"; "Femto-Solid Lab Part of a $12.5 Million AFOSR MURI Program | High Energy Density Physics Scarlet Laser Facility"; Polynkin, "Experimental Component of the AFOSR-Supported MURI Program on Ultrafast Laser Filamentation in Transparent Dielectric Media."

[57] DOE, 2013, "Lasers for Accelerators," n.d., http://science.energy.gov/~/media/hep/pdf/accelerator-rd-stewardship/Lasers_for_Accelerators_Report_Final.pdf.

[58] R. Falcone, 2008, "FESAC HEDS," n.d., http://science.energy.gov/~/media/fes/fesac/pdf/2010/Falcone_fesac.pdf.

[59] LLNL, "About NIF & Photon Science," accessed December 11, 2016, https://lasers.llnl.gov/about.

### 2.4.2 Department of Energy

DOE has two branches with large investments in high-intensity lasers, the DOE-SC and the NNSA. In fact, the NNSA constructed the world's first short-pulse PW-class laser on the Nova facility in 1992 at LLNL but was decommissioned in 1999.[60] The NNSA mission is responsible for enhancing national security through the military application of nuclear science and maintaining and enhancing the safety, security, and effectiveness of the U.S. nuclear weapons stockpile. Most of the NNSA high-intensity laser (HIL) programs are conducted at national laboratories, which include LLNL, LANL, LLE, and Sandia (Livermore and Los Alamos). These HIL assets are used to maintain and ensure the effectiveness of the American nuclear weapons stockpile and include the NIF and Jupiter Laser Facility (Livermore), Trident (Los Alamos), OMEGA and OMEGA-EP (Rochester), and the Z-Machine (Sandia). Except for the OMEGA-EP laser, these facilities provide high energy (kilojoule) pulses on nanosecond time scales for producing extreme temperatures and pressures. NNSA also uses multiple supercomputer facilities to run simulations and validate experimental data. These laboratories operate with well-defined defense programs and are generally inaccessible to the science community at large. NNSA does maintain a small number of Centers of Excellence funded by the Academic Strategic Alliance Program (ASAP). The ASAP and the Predictive Science Academic Alliance Program (PSAAP) engage the U.S. academic community in making significant advances in predictive modeling and simulation technologies. A few experimental programs are also supported by this program; the Texas-Petawatt at University of Texas, Austin is the only academic facility with PW capabilities in this program. Other collaborating universities are integrated into program activities that are intended to challenge existing notions about what is possible in science-based stockpile stewardship modeling and simulation. These programs also help with workforce development for defense programs through the training of students at partnering universities. In general, the DOE-NNSA program has a well-defined nuclear security mission and does not act as a steward of high-intensity lasers outside of that mission.

Conversely, DOE SC is the lead agency supporting fundamental scientific research for energy and the nation's largest supporter of basic research in the physical sciences. The agency provides direct support of scientific research in universities, industry, and national laboratories, and supports the development, construction, and operation of unique, open-access scientific user facilities. The primary programs funding HIL research are Basic Energy Sciences (BES), FES, and High Energy Physics (HEP). SC operates 10 open-access national laboratories. Several of these laboratories are operating facilities relevant to this study. In addition, SC is the prime steward of HIL academic research mainly through single-PI funded programs.

The DOE SC has designated the Division of High Energy Physics to steward high-intensity lasers for advanced accelerator concepts. However, this stewardship responsibility is not funded well enough to extend more broadly at present. It supports the Berkeley Lab Laser Accelerator (BELLA) Center, which focuses on the development and application of laser-plasma accelerators (LPAs). HILs are used to produce ultrahigh accelerating fields (1-100 GV/m) that may provide a compact technology for a variety of applications that include accelerators for high energy physics and drivers for high energy photon sources. This application is discussed in Chapter 5 of this report.

The LCLS at SLAC is a user X-ray free-electron laser (X-ray FEL) facility providing unprecedented intense, ultrafast hard X-rays (0.2-12 keV) for a variety of science applications. One of the experimental hutches is dedicated to studying MEC. Several HILs are collocated at the MEC. The LCLS is funded by BES. Currently, the LCLS-II upgrade project is under construction and will provide the user community with additional average power and pulse brevity capabilities. The Sub-Picosecond Pulse Source (SPPS), also at SLAC, was the prelude project (operation 2003-2007) for developing the technology and science capabilities necessary for X-ray FEL operations.

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[60] Perry et al., "Petawatt Laser Pulses."

The experience and expertise of the Department of Energy in building and operating high intensity laser facilities is well beyond other agencies in the federal government, and this makes DOE a primary agency to lead the creation of future high intensity laser scientific facilities in the United States (see Recommendation 3, Section 7.2). Furthermore, relevance to the DOE mission helps justify future resources to accomplish this.

#### 2.4.3 National Science Foundation

NSF was one of the early stewards of academic research in HIL science through various programs including single-PI grants, Science and Technology Centers (STC), Physics Frontiers Centers (PFC), and the Major Research Instrumentation (MRI) program. Over the period from 1990 to 2001, the Center for Ultrafast Optical Science (CUOS) was established at the University Michigan (UM) under the STC program. Its mission was to perform multidisciplinary research in the basic science and technological applications of ultrashort laser pulses, to educate students from a wide variety of backgrounds in the field, and to spur the development of new technologies. CUOS researchers were at the forefront of the development of ultrahigh-peak-power light pulses and their applications. CUOS was directed by Prof. Gerard Mourou, the eventual convener of the ELI project in Europe. In 2002, CUOS became part of the newly established Frontiers in Optical Coherent and Ultrafast Science (FOCUS) Center at UM, one of the first under the NSF PFC program. The FOCUS mission was to provide national leadership in the areas of coherent control, ultrafast, and high-field physics. Most notably, the FOCUS center developed the first university-based PW-class (0.3 PW) laser.[61] This was the only U.S. PW-class laser for a time, since the Nova laser at LLNL was decommissioned in 1997.[62] For nearly 20 years, CUOS and FOCUS was a unique and well-recognized incubator for multidisciplinary research, accruing singular achievements such as the record highest focused intensity of $10^{22}$ W/cm$^2$.[63] In addition to its research, it had a major impact on workforce development producing more than 150 Ph.D. students. In addition, CUOS contributed to developing industries based on its discoveries and inventions. Five companies were spun off: Picometrix (fast detectors), Clark-MXR (scientific lasers and micromachining), Translume (waveguide optics), Arbor Photonics (high power fiber laser technology), and Intralase (precision surgery).

#### 2.4.4 Department of Defense

DoD interests have focused on the development of high-energy, continuous-wave lasers (HEL) with at least 10 kilowatts of average power. In these instances, the large share of funding has been directed towards prime contractors such as Lockheed Martin, Boeing, Northrop Grumman, General Atomics, Raytheon, and other, mostly smaller, companies. The DoD baseline performance requirements are robust, high-average-power lasers with good atmospheric transmission, now built on diode-pumped slab or fiber architectures.

A portion of that funding has also gone at times to government laboratories such as LLNL, Air Force Research Laboratory, Naval Research Laboratory, and Federal Contract Research Centers such as MIT Lincoln Laboratory. There has been an HEL Joint Technology Office (HEL-JTO) that has provided some coordination of the development by the DoD to try to minimize overlapping development by the services. Key successes for the HEL-JTO have included such programs as Joint High Power Solid-State Laser (JHPSSL), which scaled SSLs first to 25 kW and then to 100 kW, with good beam quality. These

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[61] V. Yanovsky et al., “Ultra-High Intensity- 300-TW Laser at 0.1 Hz Repetition Rate.,” *Optics Express* 16, no. 3 (February 4, 2008): 2109–14, doi:10.1364/OE.16.002109.

[62] Perry et al., “Petawatt Laser Pulses.”

[63] S.-W. Bahk et al., “Generation and Characterization of the Highest Laser Intensities ($10^{22}$ W/Cm$^2$),” *Optics Letters* 29, no. 24 (December 15, 2004): 2837–39, doi:10.1364/OL.29.002837.

programs went entirely to industry. This achievement was particularly important because the 100 kW threshold had been viewed as a proof of principle for "weapons grade" power levels. Currently the armed services are contracting with industry to develop prototype laser systems for their platforms.

The DoD interest in the development of HILs in the United States is less clear. The panel is aware of an HIL built by National Energetics (U.S.) for the Kirkland Air Force Base whose interests span extremely high peak electric fields, their nonlinear propagation, and their eventual interaction with different materials.

In recent years, DoD funding has been largely responsible for keeping U.S. academic HIL research afloat. University research has been funded through several mechanisms including Defense Advanced Research Projects Agency (DARPA) and MURI programs as well as single-PI programs administered by the Air Force Research Laboratory, Army Research Office, and Office of Naval Research. An excellent example was the 2012 DARPA Program in Ultrafast Laser Science and Engineering (PULSE), which evaluated secondary sources driven by PW-class lasers, attosecond science, and frequency comb metrology.[64] There have also been several MURI programs in ultrafast science and intense laser interactions, especially in the mid-infrared and long wave spectral regime. However, for the most part, single-PI grants have been the major source of support. These programs have been essential in maintaining a viable U.S. community that can compete on the international level. However, coordination of infrastructure and networks similar to Europe are grossly lacking, and these DoD programs are not sufficient as a U.S. strategy in HIL development and science.

## 2.5 Commercial Investment and Involvement in High-Intensity Laser Component Development at U.S. Laser Laboratories

DoE laboratories, particularly the weapons laboratories LLNL, LLE, and LANL, have done in-house development of custom laser systems for their own use and most recently also have competed for international contracts to build systems for ELI. The large contract-driven laser defense companies such as Lockheed Martin and Northrop Grumman are not players in the high-intensity laser area since the dominant funding has come from DoE, and the large DoE programs are not competitively bid. The relationship with large companies is far more well-established in the high energy weapons areas, where there are opportunities to manufacture lasers for field deployment rather than single lab facilities.

The DOE SC laboratories, particularly SLAC and LBNL, engage in a mix of in-house development and procurement. Relations with the commercial laser industry have been mixed. Their interactions with the laser industry have been nearly exclusively determined by small and mid-sized programs that either purchase laser products through Federally Funded Research and Development Center (FFRDC) procurement rules or build non-commercial lasers in-house. For example, according to FFRDC rules, laboratories may only perform work that falls within the mission or special competency of the lab and may not accept work that would place the lab in direct competition with domestic private industry.

The smaller laser science research centers such as the Texas Petawatt and the high-intensity lasers at Nebraska, Michigan, Ohio State, and elsewhere rely on commercial components and some commercial systems integration. Their funding to purchase these systems often comes from instrument programs that are closely tied to the science areas the lasers will serve. Therefore these centers cannot afford in-house research and development (R&D) at the same level as the large DOE laboratories.

Some members of the U.S. laser commercial manufacturing community have reported concerns to the committee that U.S. National Laboratories are permitted to engage in laser development efforts where

[64] A frequency comb describes the spectrum of any ultrafast laser oscillator: a spectral series of equally spaced narrow frequency spikes. If stabilized it can be used as a frequency standard or as a time standard.

they are necessary to carry out their missions, and in some cases this leads to direct competition with private industry commercial R&D. These concerns are amplified by the perception that European national laboratories are more open to partnerships with European laser manufacturers, thereby effectively subsidizing foreign competitors for the global market in custom advanced laser systems. Unsurprisingly, the U.S. company representatives who reported this to the committee find this asymmetry unfair, and they also point out that this policy is at odds with the need to develop and retain high technical capabilities in strategic interest areas in the United States.

The committee requested clarification on these points from the DOE laboratories engaged in projects that require advancing the state of the art in laser technology. They confirm that the relevant FFRDC rules that the laboratories must follow give no specific mandate to steward the development of high-intensity laser technologies in private industry. Any help they give to private industry is simply in support of their science and facilities missions. It is worth noting, however, that these laboratories do offer various direct funding mechanisms for industry through programs such as the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR).[65] The laboratories that the committee contacted all support these programs. Another important industrial partnership opportunity is the Cooperative Research and Development Agreement (CRADA).[66] This is a collaborative research agreement between the laboratory and another entity for their mutual benefit. CRADAs are not grants; they must include monetary or in-kind contributions from both sides.

Difficulties about this occur when a laboratory project requires a not-yet-commercialized instrument or technology, but one that might have commercial value once it is developed. Cost, risk, and schedule then may lead the laboratory to use agency funds to develop the needed instrument in-house. However, the same laser technologies are likely to be applicable, for example, to the markets being targeted by high-tech small U.S. laser companies. The company might then be attempting to attract strategic private capital for similar product development, and thus the laboratory will be in competition with private industry to develop the same thing.

Clearly this is a source of tension between industry and the laboratories. The laboratories appear to interpret the non-compete provision narrowly to mean that they should not develop what they could acquire more efficiently. Should the laboratories undertake R&D, or should research be contracted out, and how is this determined? Here is an area where a more coordinated view of stewardship could be useful.

A rather different situation occurs when a DOE laboratory agrees to take non-DOE funds to perform what is called “work for others.” This is called a Strategic Partnership Project (SPP). The idea is to provide access for non-DOE entities to unique expertise not available in the private sector. Here the review and approval process for any SPP agreement includes a specific determination that the work requires unique laboratory capability.

In either case, the decision to make versus buy within the project is an explicit part of the acquisition process. This topic is covered in requirements reviews, procurement reviews, and design reviews. Acquisition professionals with expertise in the industries and technologies needed for the project, in concert with knowledgeable scientists and engineers, conduct supplier-base evaluations. The evaluations assess project risks (cost, schedule, performance) based on the maturity of both the proposed design and the industrial supplier base.

[65] National Institutes of Health, “NIH Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) Programs,” accessed December 11, 2016, https://sbir.nih.gov/.

[66] SLAC National Accelerator Laboratory, “Industry,” *Research Partnerships*, March 13, 2015, https://partnerships.slac.stanford.edu/industry.

### 2.5.1 Commercial Availability and Key Components Suppliers

Table 2.1 addresses the commercial sources and viability of key components needed for construction of PW-class lasers and high-intensity free-electron lasers.

**TABLE 2.1** Commercial sources and viability of key components needed for construction of PW-class lasers and high-intensity free-electron lasers

| Component | Source | Location | Comment |
|---|---|---|---|
| **Large Nd:glass slabs** | Schott Glass | USA | Limited market, Hoya in Japan exited business |
| **Large-aperture Ti:sapphire crystals** | Crystal Systems | US | Parent company is in Chapter 11, Crytur in Czech Republic developing capability |
| **Large-aperture Yb:YAG crystals** | Several | Japan, Czech Republic | Konoshima makes ceramic material but business is limited. Capabilities developing at Crytur in Czech Republic |
| **Large-aperture LBO crystals** | Multiple | Worldwide | Capabilities now in France, Russia, developing in China |
| **Large-aperture KDP crystals** | LLNL, Cleveland Crystals, others | Worldwide | Capabilities in Russia and China |
| **Flashlamps** | Multiple | Worldwide | Still viable business, includes replacements |
| **High-power diode lasers** | Multiple | Worldwide | Commercial driver is industrial, for materials processing |
| **Large-aperture gratings** | LLNL, Plymouth Gratings, Horiba Jobin Yvon | US, EU | Embargoed to China, likely leading to development there |
| **High-damage-threshold coatings for optics** | Multiple | Worldwide | Technology is widely diversified, as it can be applied to multiple uses |

| | | | |
|---|---|---|---|
| **Free-electron laser undulators, and superconducting RF linacs** | National Laboratories in the US, Japan, and Europe | Worldwide | Each linear accelerator is a custom installation. Much cooperation among national laboratories. |
| **Linac klystrons** | Commercial and laboratory | US, Japan | Megawatt-class klystrons are often laboratory-industry partnerships |
| **X-ray optics** | Fraunhofer, Zeiss, Horiba Jobin Yvon, SESO | EU | Verifiable surface quality |

There are two general categories of components in this list. The first are items that have uses in other applications, notably large-volume businesses, where the suppliers are spread worldwide. The second are items that are only found in high-peak-power or intense sources. Here, there can be problems in establishing or maintaining a viable business, as sales tend to be highly variable and depend on the construction of systems for large facilities. Notable in this category are large-aperture components, such as Nd:glass, Ti:sapphire, and nonlinear crystals. Vendors of these have to establish a worldwide sales force to sustain a business. In some cases, special components such as large-aperture gratings might be placed on restricted export lists. In general, the effect of restrictions is to spur local development of the component in countries, such as China, that have strong technology support and capabilities.

## 2.6 WORKFORCE DEVELOPMENT

The importance of a trained technical workforce in optics and photonics has been emphasized in several reports. It was stated as a prime motivation for the Obama Administration's Integrated Photonics Initiative,[67] the National Academies' report on optics and photonics,[68] the DOE Stockpile Stewardship programs,[69] and the recent NSF report on optics and photonics.[70]

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[67] The White House, "FACT SHEET." last update December 21, 2016, https://obamawhitehouse.archives.gov/the-press-office/2016/12/21/fact-sheet-obama-administration-announces-new-manufacturing-usa.

[68] NRC, 2013, *Optics and Photonics*.

[69] "Fiscal Year 2016 Stockpile Stewardship and Management Plan," accessed January 8, 2017, https://nnsa.energy.gov/sites/default/files/FY16SSMP_FINAL%203_16_2015_reducedsize.pdf.

[70] NSF MPSAC, "Report of the Optics and Photonics Subcommittee of the MPS Advisory Committee," 2015, https://nsf.gov/mps/advisory/mpsac_other_reports/optics_and_photonics-final_from_subcommittee.pdf.

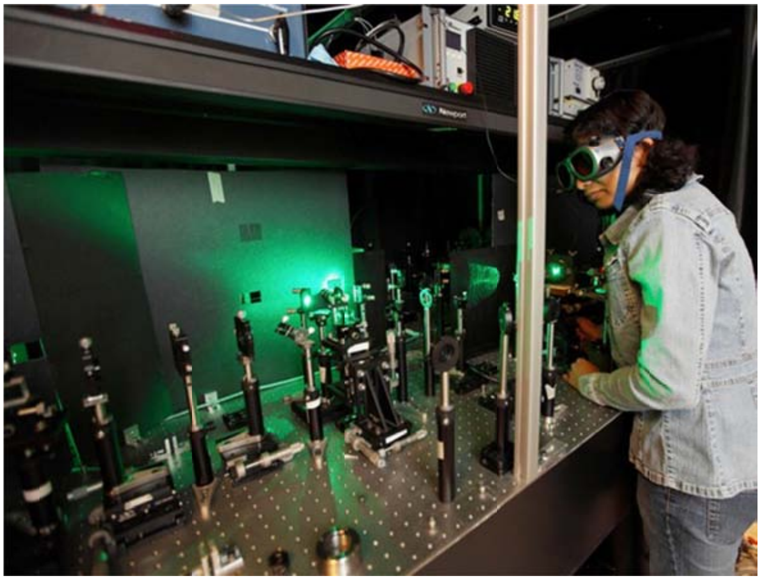

**FIGURE 2.4** A primary goal of Stockpile Stewardship is workforce development. SOURCE: National Nuclear Security Administration, "Stewardship Science Academic Alliances," last update December 21, 2011,https://nnsa.energy.gov/aboutus/ourprograms/defenseprograms/stockpilestewardship/upaa/ssaa.

## 2.7 EUROPEAN MODEL FOR LASER STEWARDSHIP

Following the formation of the EU in 1993, a series of strategic investments began among EU nations. These investments aimed at capitalizing on scientific opportunities by organizing existing strengths, building on new strengths, promoting human mobility (workforce development) among EU nations, and stimulating economic development in the world market. The area of lasers and photonics was identified as one of five key enabling technologies essential for the scientific future and the socio-economic security of EU countries. High-intensity laser science was one area of focus since several EU nations had a long tradition of strength in this area. Prior to the EU involvement, national stewardship was the appropriate funding model. As in the United States, as the cost of conducting research in this area escalated, it became increasingly difficult to sustain a viable national effort. The EU federation presented an opportunity to coordinate these efforts and leverage individual national investments. As a consequence, European laboratories pursuing high-intensity science began to organize under EU stewardship while in the U.S. large-scale and "single-PI" efforts remained status quo. Even though the 1998 National Academies' study on optics and photonics was largely ignored in the United States, it did provide an ideal roadmap for Europe.

One important element of EU stewardship was the formation of Laserlab-Europe, an integrated initiative of European research infrastructure. The objectives were to (1) maintain a competitive, interdisciplinary network of European national laboratories; (2) strengthen Europe's leading role in laser research by pushing the laser concept into new directions and opening new applications of key importance in research and innovation; (3) offer transnational access to top-quality laser research facilities in a coordinated fashion for the benefit of the European research community; and (4) broaden the base in laser research and applications by reaching out to neighboring scientific communities and by assisting in the development of laser research infrastructure on both the national and the European level. Established in 2001, the consortium currently consists of 33 leading institutions from 16 EU countries. Laserlab-Europe coordinates a peer-reviewed proposal process open to researchers from academia, national laboratories, and industry. In its current manifestation, Laserlab operates on an annual budget of €10 million. The funding supports the users and associated facility infrastructure. Laserlab-Europe has been highly successful for promoting scientific discovery and human mobility, as well as initiating new European projects.

As Laserlab-Europe developed and provided access to state-of-the-art high-intensity laser facilities, several EU funding programs were established to promote the formation of scientific groups distributed throughout EU countries. These programs' primary purposes were to push the frontiers of science, train young scientists, and mobilize human capital.

Currently, Horizon 2020 is the biggest EU Research and Innovation program ever with nearly €80 billion of funding available over 7 years (2014 to 2020), in addition to the private investment that this project will attract. It promises more breakthroughs, discoveries, and world firsts by taking great ideas from the laboratory to the market. The goal is to ensure that Europe produces world-class science, removes barriers to innovation, and makes it easier for the public and private sectors to work together in delivering innovation.

The lack of U.S. stewardship in the HIL area is particularly dire, especially in comparison with Europe, in the area of commercial activity. In recent years, EU support has resulted in a steady stream of start-up laser companies in the area of high-intensity laser technology. This is driven by a number of mechanisms: significant research funding in intense laser areas at universities and at research institutes, as well as equipment purchase funding at national laboratories, both for standard commercial off-the-shelf (COTS) lasers and for higher-risk development projects; nd joint university-industry research centers such as the Fraunhofer Institutes provide substantial government support for industry-directed projects. This contrasts with the situation in the United States, where the government supports virtually no stand-alone laser development work, but rather all such work is justified as a small part of a larger scientific project. The more favorable situation in Europe has resulted in a proliferation of companies in Europe in various areas of advanced laser technologies: One-five, Class-Five lasers, Thales Lasers, Amplitude Systemes, Amplitude Technologies, Laser Quantum/Venteon, Expla, Light Conversion, FASTLITE, Menlo Systems, and TRUMPF Scientific Lasers. Ironically, several European companies (Femtolasers, Time-bandwidth Products, Lumera Laser) have been purchased by U.S. companies (Newport, JDSU, and Coherent, respectively); however, the result has been a shift of the center of gravity of these companies away from the United States—for example, Coherent's (California headquarters) workforce was already comparable or larger in Germany compared with the United States *before* announcing its intent to acquire of Germany-based Rofin—a company comparable in size to Coherent.

### 2.7.1 Operations Model for Petawatt Lasers in Extreme Light Infrastructure

The ELI project uses infrastructure funds from the EU to construct the laboratories, but a different mechanism is required to fund the operations and carry out the research. Here the European model is called ELItrans. This is a 3-year €3.4 million project to make the transition from building to operating. Details are to be found in the European Union project document for ELItrans.[71]

## 2.8 PAST U.S. REPORTS EXAMINING THE PROSPECTS OF HIGH-INTENSITY LASER SCIENCE

Several reports were published at the turn of the new millennium that identified the scientific opportunities enabled by high-intensity lasers, the relevance to national security, and the need for stewardship and federal agency coordination. These reports represented the combined efforts of the

[71] EU Community Research and Development Information Service, "ELITRANS-Facilitating the transformation of ELI from ERDF funded, distributed infrastructures towards a unified ELI-ERIC," last update November 5, 2015, http://cordis.europa.eu/project/rcn/199115_en.html.

scientific and science policy communities. Here the committee mentions four specific reports, with a synopsis of two that address fundamental questions of matter under extreme conditions, and a more detailed summary of two that address policy issues: the 2002 Science and Applications of Ultrafast Lasers (SAUUL) report and the 2007 Interagency Task Force report.

As agencies pursue multi-year policies designed to promote their scientific missions, community-based reports such as these provide vital continuing assessments to assure agency accountability to the public and to the science community. This accountability function underscores the importance of study recommendations 1 and 2 (Section 7.2).

### 2.8.1 Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century

This report identifies the rapidly emerging field of high energy density science as a key in developing an understanding of physics of extreme astrophysical environments. Laboratory-based plasma science driven by high-intensity lasers is recognized as one of the primary tools for addressing these questions. The report strongly endorses enhanced exploration of laboratory high energy density plasmas and recommends federal interagency cooperation to fully exploit the available scientific opportunities.[72]

### 2.8.2 Frontiers in High Energy Density Physics: The X-Games of Contemporary Science

In this report key scientific questions are surveyed, and a number of disparate activities are united into an overall framework. The report also pointed out the interdisciplinary (and interagency) nature of the field and provided specific recommendations to strengthen the field.[73]

### 2.8.3 Science and Applications of Ultrafast Lasers

An early prognosticator of the impending international landscape in high-intensity lasers was the 2002 report entitled the *Science and Applications of Ultrafast, Ultraintense Lasers: Opportunities in Science and Technology Using the Brightest Light Known to Man*, also known as the SAUUL report.[74] The report came from a grassroots effort by U.S. scientists that anticipated that the extraordinary advances in high-intensity laser technology in the 1990s would enable extraordinary scientific and technological advances. Readiness to exploit these opportunities would require technological needs and most importantly, a community and federal coordination for developing strategies and stewardship that would leverage interagency investments. The report encapsulated the discussions of a workshop that was

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[72] NRC, 2003, *Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*, The National Academies Press, Washington, D.C.

[73] NRC, 2003, *Frontiers in High Energy Density Physics: The X-Games of Contemporary Science*, The National Academies Press, Washington, D.C.

[74] P. Bucksbaum, T. Ditmire, L. Di Mauro, J. Eberly, R. Freeman, M. Key, W. Leemans, D. Meyerhofer, G. Mourou, and M. Richardson, 2002, *The Science and Applications of Ultrafast Lasers: Opportunities in Science and Technology Using the Brightest Light Known to Man*, presented at the SAUUL Workshop, Washington, D.C., June 17-19.

held during June 17-19, 2002, in Washington, D.C. The workshop was attended by academic, industrial, and government laboratory scientists and supported by the DOE Offices of BES and FES, the NNSA Office of Defense Programs, and the NSF Division of Physics.

#### 2.8.3.1 Summary of the SAUUL Report

The study identified five areas where opportunities for major breakthroughs exist for high-intensity lasers: fusion energy, compact particle accelerators, ultrafast X-ray generation, high energy density physics (HEDP), and attosecond science. After assessing the state of these areas, four key findings were reached:

1. High-intensity laser science was the fastest growing subfield of basic and applied research in the United States, Europe, and Japan.
2. The application of high-intensity lasers has evolved into a broad and interdisciplinary endeavor from its early inception.
3. The state of the art of laser technology enabling these applications is more complex and expensive than in the past.
4. U.S. leadership in this field requires a new mode of community and federal organization.

#### 2.8.3.2 The SAUUL Model for Future Coordination in U.S. High-Intensity Laser Technology and Science

The report concludes that the United States has been a traditional leader in high-intensity lasers. However, moving into the future, the complexity and expense of the infrastructure is not consistent with established modes of federal funding. The maintenance and operation of these high-intensity lasers has grown beyond the means of single PIs with university-based programs. In addition, national laboratories' mission is stewardship of more complex facilities, but this precludes access to the broader user community to drive applications or transfer technology to commercial enterprises. Furthermore, the sizes of high-intensity laser facilities (mid-scale) may be below the threshold for major national laboratory projects such as accelerator-based sources. The report recognized that since high-intensity laser science spans a large number of subfields, no single federal agency has responsibility for this field as a whole, which poses a threat for U.S. leadership.

The SAUUL report envisioned a small number of U.S. centers or nodes distributed among universities and national laboratories, as illustrated in Figure 6.5. For example, university facilities can provide unrestricted access while co-location at large-scale national facilities could provide unique scientific opportunities. The centers will provide both critical mass of expertise and the resources to maintain essential facilities for the community, analogous to Laserlab Europe. Surrounding these facilities would be a network of users, i.e., a network of single-PI groups in different institutions, but with coordinated scientific thrusts. In this scenario, a particular network can compete for user time at any of the node center facilities. The main facilities and the networks could be supported by either a single agency or and agency consortium. In this model, the node/network will provide stability but also needed flexibility for rapidly emerging opportunities. The federal funding box in Figure 2.5 is a coordinated multi-agency body, which is non-existent in the United States.

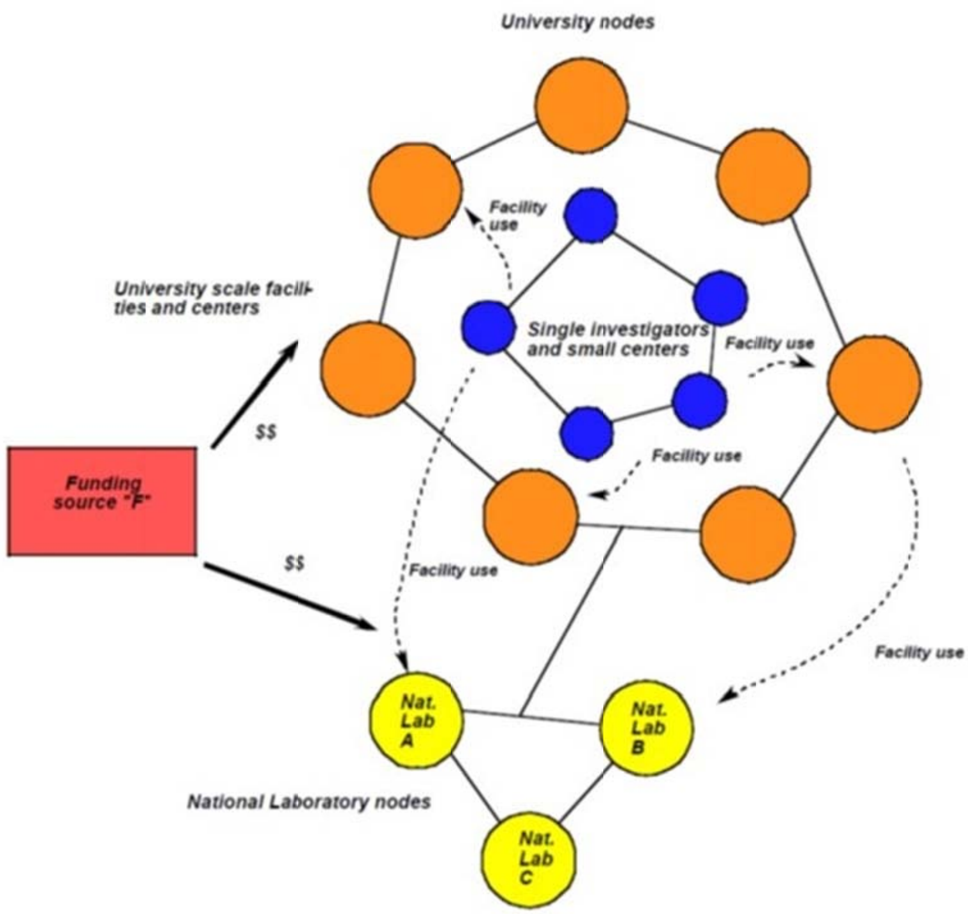


**FIGURE 2.5** The SAUUL report conceptual structure of a network in the United States devoted to advancing HIL science. In the network concept, both university and national laboratories maintain unique high-intensity facilities. Investigators from all sectors can compete for access, which is generally open. However, the lack of stewardship and coordination in the United States does not support this concept. SOURCE: P. Bucksbaum, T. Ditmire, L. Di Mauro, J. Eberly, R. Freeman, M. Key, W. Leemans, D. Meyerhofer, G. Mourou, and M. Richardson, 2002, *The Science and Applications of Ultrafast Lasers: Opportunities in Science and Technology Using the Brightest Light Known to Man*, presented at the SAUUL Workshop, Washington, D.C., June 17-19.

### 2.8.4 The Interagency Task Force Report on High Energy Density Physics

In 2007, the *Report of the Interagency Task Force on High Energy Density Physics* was prepared under the auspices of the National Science and Technology Council Committee on Science Interagency Working Group on the Physics of the Universe. The charge was specific to HEDP—the study of matter subject to extreme conditions of temperature and density. The Interagency Working Group report was a direct response to the findings of the aforementioned reports. The task force identified that a key component of HEDP research is enabled by high-intensity lasers. Furthermore, HEDP research is necessary to accomplish specific scientific and national security missions of several Federal agencies. The task force indicated that in spite of significant agency investments, the federal mechanism for stewarding fundamental research is poorly defined or nonexistent. The report emphasized the need to improve federal stewardship of HEDP, particularly the study of laboratory high-density plasmas, and strengthen the level of university activities. The report discussed HEDP relevance to federally funded missions, as well as action items to leverage federal priorities and needs.

The report enumerates several actions that would improve stewardship and advance research consistent with federal priorities and plans:

1. SC and NNSA within DOE would establish a joint HEDP program responsible for stewarding fundamental high energy density laboratory plasma science.
2. The joint program would be developed with the active participation and input from the scientific community and solicited by DOE.
3. The joint program will develop a coordinated strategic plan for a national program in consultation with NSF.
4. NNSA would develop a management process to provide access to its major facilities by users external to the NNSA complex.

These recommendations for a more coordinated national plan were echoed throughout this and other reports. Unfortunately, many of the recommendations were ignored in this country, while national and international coordination outside of the United States was intensive.

# 3

# Current and Future Intense Source Technology

This chapter is a summary of the technology of high-powered pulsed lasers for high-intensity laser science. The first section describes current laser sources operating at the petawatt (PW) level. The next looks toward the future, both at technologies under development and complete systems under various stages of construction, proposal, or development. The final section provides a comparison of the technologies, present and future, as well as issues related to achieving the next levels of high intensities needed for scientific breakthroughs. This includes non-standard technologies such as X-ray free-electron lasers (FELs) and fiber lasers, which utilize wholly different technical concepts to get to future higher intensities.

The report includes extensive tutorial material in several appendixes for readers who need to know more about the technologies discussed. Appendix B1 provides a background for solid-state lasers. Appendix B2 covers the nonlinear optics related to optical parametric amplifiers, particularly the broadband optical parametric chirped-pulse amplifiers (OPCPAs) used in some intense sources. Appendix B3 provides details of some enabling technologies. Appendix B4 describes systems under construction or in planning stages, including X-ray FELs. These appendixes include much background material that readers familiar with laser technology may bypass to reach discussions of specific PW-class systems.

Solid-state lasers are the general technology that has enabled demonstration and operation of PW-class systems and generation of intensities up to $10^{22}$ W/cm$^2$. Solid-state lasers are either the basic source or the drive source for nonlinear amplifying media, in the case of OPCPA systems. To date, PW levels of output have been achieved directly from two solid-state laser media, neodymium-doped glass (Nd:glass) and titanium-doped sapphire, (Ti:sapphire) as well as OPCPAs pumped by Nd:glass lasers. All of them are described here. The chapter concludes with a discussion of advanced technologies and X-ray FELs. The latter achieve similar high intensities to PW lasers but with much lower power and far shorter pulse durations. The committee also refers the reader to appendixes that describe various specific systems, including brief summaries of critical supporting technologies that are used to facilitate or enhance system operation.

## 3.1 CURRENT PETAWATT-CLASS SOLID-STATE LASERS AND OPTICAL PARAMETRIC CHIRPED-PULSE AMPLIFIERS

Table B1.1 in Appendix B1 lists important characteristics of many common laser materials. While there are many different combinations of demonstrated laser-active ions and host materials, only two solid-state lasers have been operated with peak power outputs at the PW level. The two materials (Nd:glass and Ti:sapphire) that, to date, have led to PW-class scaling are related in that the technology of both are often incorporated in complete systems. The OPCPA-based sources to date have relied on Nd:glass systems as pump lasers.

A common element in all PW-class lasers is a simple U.S.-based invention, chirped-pulse amplification (CPA). This first allowed existing nominally low-power systems, based on Nd:glass as the laser gain medium and traditionally operating at the sub terawatt (TW) level, to be configured for much higher power operation at minimal cost. The adaptation of this CPA technique applied to these existing Nd:glass systems formed the basis of most activity at the onset of the PW era, most notably pioneered at the Lawrence Livermore National Laboratory (LLNL) where the first PW laser pulse was produced in 1996 by converting a beamline of the exiting Nova system.[1] Nova PW was closed very shortly after this first demonstration, and the mantle of driving PW-scale science predominately fell to the Rutherford Appleton Laboratory in the UK, with the conversion of the Vulcan system[2] to the PW level, and the Japanese Gekko PW system.[3] Over that time new, original systems, based on Ti:sapphire as the gain medium, began to emerge, which owing to its far larger gain bandwidth (compared to Nd:glass) significantly reduced the physical scale and thus entry-level cost to the field. The subsequent emergence of several commercial organizations offering cost-effective products based on Ti:sapphire has really propelled the global uptake of relevant technology and consequently has taken the field forward. In recent years, advanced developments such as optical parametric chirped-pulse amplification (OPCPA) and diode-pumped solid-state lasers (DPSSL) driven CPA have further diversified the technological basis of the field and opened up new scientific and application environments.

Table 3.1 provides a summary of the characteristics of three techniques used to date for PW-class outputs. These include the energy, pulse length, and repetition rate of the system. It should be noted that this table includes only the range of parameters associated with PW-class systems and not the wide range available from these technologies in general.

**TABLE 3.1** Summary of the key parameters of the four major technologies used in petawatt-class lasers and X-ray FEL high intensity lasers.

| PW Technology | Energy | Pulse Length | Repetition rate | Comments |
|---|---|---|---|---|
| **Nd:glass** | very high (kJ+) | Long (0.15 ps to ns) | very low <0.02 Hz | Established technology; large scale facilities; low efficiency |
| **Ti:sapphire** | Medium (10 – 100 J) | Short (> 10 fs) | Low - High (0.01 Hz – 10 Hz) | Established & new technology; medium scale; scope to improve repetition rate, energy |
| **OPCPA** | medium – very high (5 J – kJ) | Short (> 10 fs) | Low - High (0.01 Hz – 10 Hz) | New technology; medium scale; scope to develop; high risk development |
| **FEL** | Low (0.5mJ-5mJ) | Ultrashort (0.3-30 fs) | Very High (100 Hz – 1MHz) | Ultrahigh intensity comes from tighter focus and shorter pulse. Not a Petawatt peak power laser. Low risk but high capital and operating cost. |

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[1] Perry et al., "Petawatt Laser Pulses."

[2] C.N. Danson, P.A. Brummitt, R.J. Clarke, J.L. Collier, B. Fell, A.J. Frackiewicz, S. Hancock, S. Hawkes, C. Hernandez-Gomez, and P. Holligan, 2004, Vulcan Petawatt—an ultra-high-intensity interaction facility, *Nuclear Fusion* 44(12): 239–246.

[3] Y. Kitagawa et al., "Prepulse-Free Petawatt Laser for a Fast Ignitor," *IEEE Journal of Quantum Electronics* 40, no. 3 (March 2004): 281–93, doi:10.1109/JQE.2003.823043.

**TABLE 3.2** A comparison of existing, planned, and proposed sources discussed in this chapter.

| Type | Pump | Status | Peak pwr. (PW) | Pulse energy (J) | Pulse-width (fs) | Pulse rate | Notes |
|---|---|---|---|---|---|---|---|
| **Nd:glass** | FL | OP | 1 | 130 | 130 | 1/hour | Texas Petawatt (U. Texas, Austin) |
| **Nd:glass** | FL | UC | 10 | 1500 | 150 | 1/min. | By National Energetics, US, for L4 at ELI-Beamlines |
| **Ti:sapphire** | FL-Nd:YAG | OP | 1.3 | 40 | 30 | 1 Hz | BELLA at LBNL, Berkeley, CA |
| **Ti:sapphire** | FL-glass | OP | 5.3 | 127 | 24 | Low | At SIOM, Shanghai, China |
| **Ti:sapphire** | DP-glass | UC | 1 | 30 | 30 | 10 Hz | HAPLS, by LLNL, for L3 at ELI-Beamlines |
| **Ti:sapphire** | FL-glass | UC | 10 | 210 | 21 | 1/min. | By Thales, France for ELI-NP (2 systems) |
| **Ti:sapphire** | FL-glass | UC | 10 | 150 | 15 | 1/min. | APOLLOn system in France |
| **OPCPA** | FL-glass | OP | 1 | 32.6 | 32 | Low | At SIOM, Shanghai, China |
| **OPCPA** | FL-glass | UC | 20 | 600 | 30 | Low | VULCAN 20 PW at CLF, Rutherford Laboratories, UK |
| **OPCPA** | FL-glass | Prop | 75 | 1500 | 20 | 1/105 min. | EP-OPAL at LLE, Rochester, NY |
| **OPCPA** | DP-Yb:YAG | Prop | 1 | 10 | 10 | 100 Hz | Part of GEKKO-EXA, ILE, Osaka, Japan |
| **Yb:CaF$_2$** | DP | UC | 1 | 150 | 150 | 1 Hz | PENELOPE, HZDR, Dresden, Germany |
| **Yb:fiber** | DP | Prop | 0.1 | > 10 | 100-200 | > 10 kHz | 100 kW ave. power, ICAN, now |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | | XCAN, possibly in France |
| **X-ray FEL with high intenstity focus** | 2-16 GeV Cu linac | OP | 6x10-4 | 0.003 | 5-50 | 120Hz | Wavelength 0.11-4.4nm LCLS at SLAC in the US. Other FELs with high intensity capabilities: SACLA (Japan). In construction: European X-ray FEL (Hamburg), PAL (S. Korea), SwissFEL (Switz.), LCLS-II (SLAC).[4] |

NOTE: FL, Flashlamps; DP, Diode lasers; FL-Nd:YAG, Flashlamp-pumped Nd:YAG; FL-Glass, Flashlamp-pumped Nd:glass; DP-Glass, Diode-pumped Nd:glass; DP-Yb:YAG, Diode-pumped Yb:YAG; OP, Operational; UC, Under construction; Prop, Proposed or notional.

### 3.1.1 Glass-based Systems

The first laser to deliver petawatt performance was the "Nova Petawatt," based at the Nova Facility at the Lawrence Livermore National Laboratory (LLNL).[5] This system used Nd:glass as its main amplification medium, which produced an amplified pulse of 660 J in a 440 fs pulse, resulting in 1.5 PW incident on the target. This result is indicative of how glass-based systems operate; they rely on very high-energy pulses (hundreds of J and above) contained in a long pulse (~picoseconds – nanoseconds). The use of glass as the main amplifier medium restricts these systems to low repetition rates (< 1 Shot/min); due to the thermal properties of glass, sufficient time must be left between shots to allow the glass to cool in order to prevent damage to the system or adversely affect the beam properties. For example, the Vulcan laser at the UK's Central Laser Facility (CLF) has a repetition rate of 1 shot every 20 minutes. Research is currently underway to increase this to 1 shot every minute through enhanced thermal management.

Nd:glass-based systems have sufficient bandwidth to generate sub-ps pulsewidths and a low enough saturation fluence for efficient extraction, typically in multi-pass designs, but not so low as to make amplified spontaneous emission (ASE) an unmanageable challenge. (In contrast, and ignoring the issue of scaling material sizes, the other common Nd-doped materials in table B1.1 have too high a gain and hence ASE issues at large stored energies, along with too narrow a linewidth for efficient sub-ps-pulse amplification.) Nd:glass can be pumped by flashlamps due to the overlap of lamp emission and the

[4] C. Pellegrini, A. Marinelli, and S. Reiche, 2016, The physics of X-ray free-electron lasers, *Reviews of Modern Physics* 88(1): 015006.

[5] Perry et al., "Petawatt Laser Pulses."

higher-lying levels of the Nd ion, and can be readily fabricated in very large sizes, [Fig. 3.1] as developed through years of work related to the quest for laser-driven inertial confinement fusion (ICF).


**FIGURE 3.1** "Continuous melt" processed Nd-doped glass used for the National Ignition Facility. SOURCE: Courtesy of the U.S. Department of Energy.

Two important examples of Nd:glass PW systems are the original PW system, which was built using an arm of the LLNL NOVA fusion research laser, and the Texas Petawatt, which has attempted to produce the shortest pulses that can be supported in Nd:glass. Both of these are described in Appendix B1. Their designs underscore three limitations to this technology: (1) The gain bandwidth limits output pulses to 0.5 ps in single-glass amplifiers in Nd:glass; therefore, large pulse energies are required and large diffractive optics must be designed to handle the energy [Fig. 3.2]. (2) Mixed-glass amplifiers can expand the bandwidth leading to shorter pulses and lower overall pulse energies, but this is ultimately limited by the properties of Nd:glass to pulse durations of about 0.15 ps. For details, consult Appendix B1. (3) A significant limitation of glass as a laser host is poor thermal conductivity compared to crystalline hosts such as sapphire or YAG. Thus, the pulse repetition rate in the largest system is about one shot per hour or lower, and experiments must be designed for this.

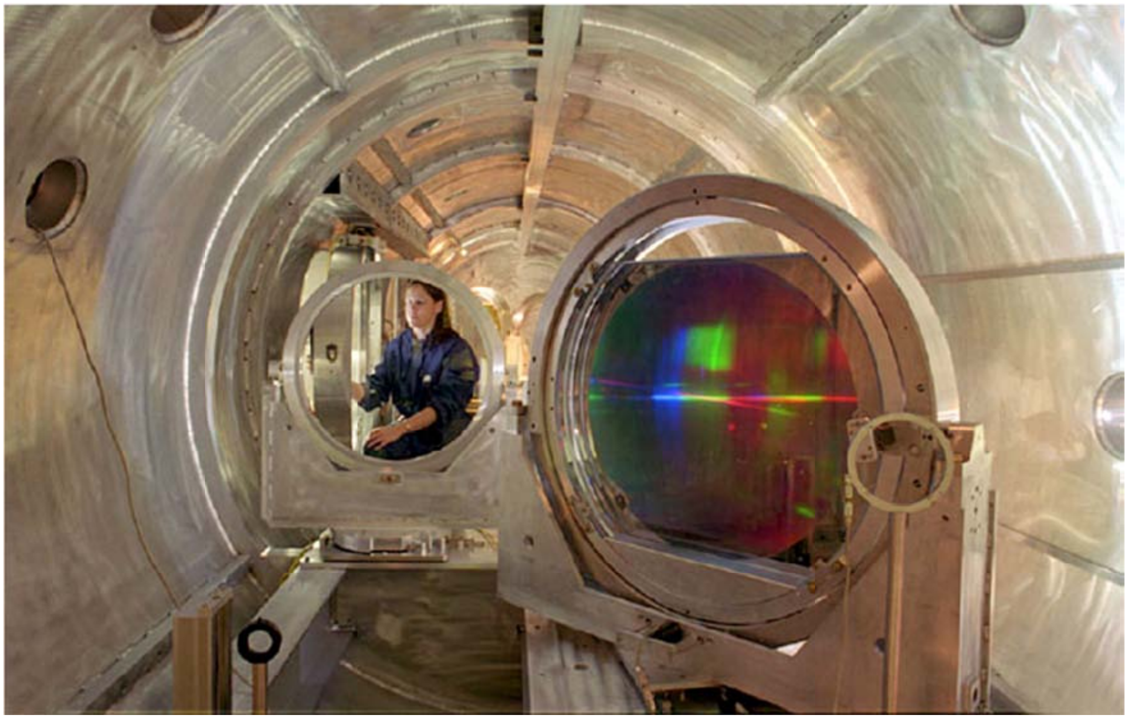

**FIGURE 3.2** Photograph inside the pulse compressor stage of the LLNL PW laser, showing large-aperture grating developed for the system. SOURCE: T. Ditmire, University of Texas at Austin, "A Path Towards an Exawatt Laser," presentation to the committee on May 10, 2016.

### 3.1.2 Titanium:Sapphire-based Systems

Ti:Sapphire has been used as the primary amplifier medium for ultrafast lasers for decades due to its inherent broad bandwidth that is necessary to amplify short pulses. The lasers operate around a central wavelength of 800 nm and are typically pumped using green (515nm – 532nm) lasers. The green pump light can be generated by frequency doubling a number of different infrared laser sources including flash-lamp-pumped Nd:glass lasers (high energy, low rep rate), diode-pumped Nd:YAG lasers (lower energy, high rep rate), or diode-pumped Yb:YAG lasers (high energy, medium rep rate). The former is the typical method adopted for PW-class lasers in this category to date, which results in a limited repetition rate.

The Ti:sapphire gain medium has the largest linewidth of all the materials in common use, allowing amplifier systems to operate with 15-30-fs-duration pulses. This reduces the pulse energy for PW operation to well under 100 J. The gain cross section is high and saturation fluence low, and the host material has excellent thermal and mechanical properties. The most evident challenge is the short storage time of 3.2 µs, reflecting the relation in Eq. B.1b in Appendix B1, which shows both a large linewidth and cross section arise at the expense of a long storage time. Fortunately, the absorption band (Figure B1.4 in Appendix B1) overlaps with the second-harmonic of Nd-doped (or Yb-doped) solid-state lasers, which can pump the upper laser level. Thus, one can employ pump sources based on conventional ns-pulsewidth, flashlamp-pumped, Nd-doped solid-state lasers with long upper-state lifetimes and thus good energy storage. As long as the energy put into the Ti:sapphire upper energy level is extracted within a short (< 1 µs) period, the stored energy from the pump laser can be efficiently extracted by a large-bandwidth, stretched pulse. An important point is that multiple pump lasers can be used, as long their beams all overlap inside the active volume of the laser material, and thus energy scaling of the Ti:sapphire laser is not limited by the energy available from a single pump source.

In terms of technology interrelationships, to date, PW-class Ti:sapphire lasers have most often employed high-energy Nd:glass lasers as pumps, while Ti:sapphire mode-locked lasers and often low-energy amplifiers are employed in PW-class Nd:glass lasers.

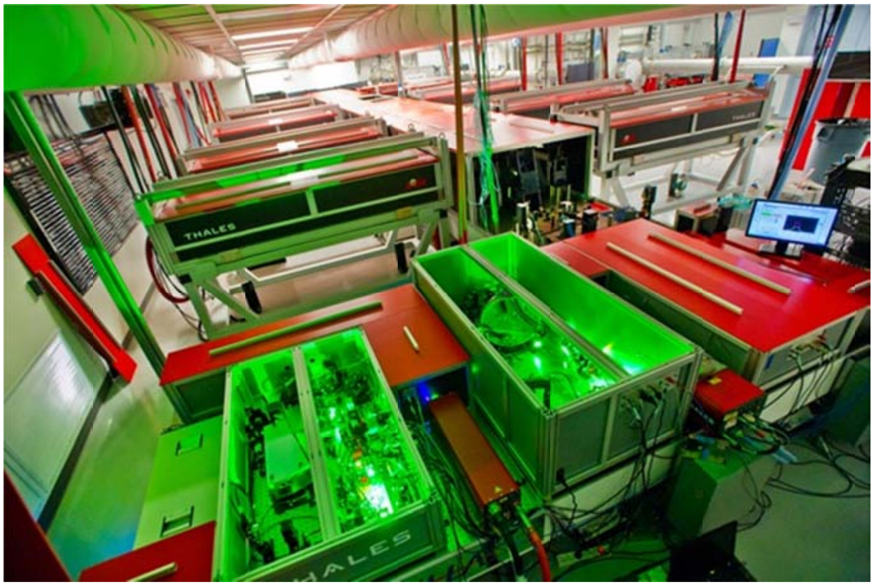


**FIGURE 3.3** Nd:YAG pump laser bay of the BELLA Ti:Sapphire petawatt laser at the Lawrence Berkeley National Lab. SOURCE: http://blogs.scientificamerican.com/observations/files/2012/08/BELLA-laser.jpg.

#### 3.1.3 Optical Parametric Chirped-Pulse Amplification-based Systems

The OPCPA concept for large-aperture systems was developed at the CLF to further increase the energy of high-power laser facilities,[6] with the first practical demonstration on the Vulcan laser at the CLF.[7] In this technique (see Figure 3.4) the frequency-doubled light from a high-energy laser facility is transferred to a chirped short pulse laser via parametric amplification in a nonlinear optical material, typically potassium dihydrogen phosphate (KDP) or lithium triborate (LBO) crystals. The parameter space available to the OPCPA technique is greater than its alternatives, as is shown in Table 3.1. The potential pulse energy for PW-class systems is 5J – kJ, made possible by the extremely broad bandwidth and large aperture crystals available to support the parametric process. The technology is well developed in the low energy, high repetition rate regime, and significant developmental work has been conducted at the high energy, low repetition rate regime.

At present, a number of advanced high-peak-power systems use lower energy OPCPAs in the initial stages of systems, where the high and relative freedom from amplified spontaneous emission (ASE) are major advantages. Their use is described in more detail is different sections of Appendixes B.

Provided one can find large-enough-aperture nonlinear crystals, sufficiently broad-bandwidth chirped signal pulses, and high-energy pump lasers, OPCPA technology can be scaled up in energy to reach the PW peak-power level. At present there are three published examples of such systems, all employing frequency-doubled Nd:glass lasers as pump sources.  Their deployment worldwide as petawatt sources is described in section 4.5.3 of the Internaional Landscape chapter of this study, and additional details are in Appendix B.

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[6] Ross et al, “The prospects for ultrashort pulse duration and ultrahigh intensity using optical parametric chirped pulse amplifiers”, Optics Communications, Volume 144, Issue 1, 1997, Pages 125-133, ISSN 0030-4018.

[7] Chekhlov et al, “35 J broadband femtosecond optical parametric chirped pulse amplification system”, Optics Letters, 31, 24, 2665-3667 (2006)

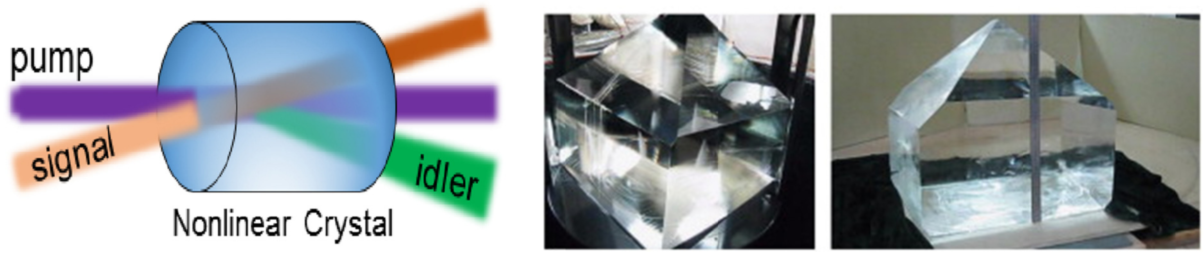


**FIGURE 3.4** Left: OPCPA concept: A nonlinear crystal converts narrow-band pump laser energy to chirped signal laser energy. Right: Large aperture nonlinear crystal growth. SOURCE: Left: 1. J. Ma, J. Wang, B. Zhou, P. Yuan, G. Xie, K. Xiong, Y. Zheng, H. Zhu, and L. Qian, "Broadband, efficient, and robust quasi-parametric chirped-pulse amplification," Opt. Express, OE 25, 25149–25164 (2017); Right: 1. X. Zhuang, L. Ye, G. Zheng, G. Su, Y. He, X. Lin, and Z. Xu, "The rapid growth of large-scale KDP single crystal in brief procedure," Journal of Crystal Growth 318, 700–702 (2011).

### 3.1.4 State of Current Intense Sources

This section briefly assesses and summarizes the state of current intense sources.

1. Current approaches to PW-class systems involve CPA technology and, to an almost exclusive degree, employ some combination of Nd:glass lasers, Ti:sapphire lasers, and OPCPAs.
2. Nd:glass laser amplifiers can be direct sources of PW-level pulses, or provide pump energy, when frequency doubled, to Ti:sapphire lasers or OPCPAs.
3. Ti:sapphire laser amplifiers provide shorter pulses than Nd:glass laser direct sources (130-440 fs *vs.* 20-30 ps), and thus require less pulse energy to reach the PW level.
4. At present, PW-class OPCPAs used as the final stage in systems provide pulsewidths in the 32-70-fs range, thus also requiring lower pulse energies than Nd:glass lasers.
5. The highest peak power system in operation is at the SIOM in Shanghai, and it uses Nd:glass-laser-pumped Ti:sapphire technology to generate a 5.3- PW, 127 J, 24-fs pulse.[8]
6. The highest pulse rate of current PW-level systems is 1 pulse per second, for the BELLA Ti:sapphire system at LBNL, which uses flashlamp-pumped Nd:YAG lasers as pumps. All the other systems, with Nd:glass-laser-based pumps, operate at several orders-of-magnitude lower rates.

## 3.2 FUTURE INTENSE SOURCE TECHNOLOGY AND SYSTEMS

All current PW systems utilize power-amplifier technologies such as flashlamp pumping that are both well-developed and, at the industrial level, close to being obsolete. Nd:glass lasers, because of their limited average power, find little use in applications other than high-energy systems for ICF research or intense sources for science. Even the lamp-pumped Nd:YAG lasers used in the higher repetition rate

[8] R. Li, L. Yu, Z. Gan, C. Wang, S. Li, Y. Liu, X. Liang, et al., 2016, "Development of a Super Intense Laser Facility at Shanghai," presentation at IZEST Conference Extreme Light Scientific and Socio-Economic Outlook, Paris, Nov. 25-29.

projects such as the Berkeley Lab Laser Accelerator (BELLA) system at LBNL [see Fig. 3.3] are being replaced for materials processing applications by other types of lasers [see Sec. 5.2].

### 3.2.1 Technical Advances

In Appendix B3, the committee describes some technologies, such as diode pumping, that are already being explored for application to intense sources and can be the basis for future systems with performance that goes beyond the limits currently set by flashlamp-pumped, Nd-doped lasers. The committee also considers technologies that will facilitate pushing the upper boundaries of peak power and lower boundaries of pulsewidth, to enable reaching focused intensities of $10^{22}$ W/cm$^2$ and higher.

### 3.2.2 Planned Future Sources

In Appendix B4, the committee reviews future intense sources at their current stages of development, some under construction, some at the early demonstration stages, and others that have been proposed. One common theme is to increase the peak power to the 10-PW level, with some systems under construction, and to go beyond that, still at the conceptual stage.

Beyond mere power scaling, another path to better exploration of high intensity applications is to increase the pulse rate beyond the very limited range of present Nd:glass lasers and even the 1 Hz rate of Nd:YAG-pumped, Ti:sapphire lasers. For scientific studies, higher rates allow an improvement in the productivity of experiments and in their statistical validity. From a technology standpoint, higher rates can allow a much improved means of reaching high intensities, through active feedback from measurements of the focused spot from the system.

Yet a third scaling parameter besides repetition rate and peak power is laser wavelength. Since the focused intensity based on the diffraction limit scales as the inverse-square of the laser wavelength, some of the most intense sources are Angstrom-class X-ray free electron lasers (see Figure 3.5 for two examples). This is also reviewed in Appendix B4. Since the gain medium in an FEL is the relativistic electron beam, there are some unique features compared to conventional gain media. The gain bandwidth is limited only by the radiation per undulator period, since the electrons slip one X-ray cycle on every undulator wiggle. The more conventional limitations of material properties of the gain medium are absent in an FEL. Current FELs are capable of 100 attosecond pulses, but there are designs for sub-attosecond pulses (zeptosecond range). In addition, relativistic electron beams produced in continuous superconducting radio frequency structures can produce X-rays with kilowatt average powers. Such applications are described more fully in Ch. 4.

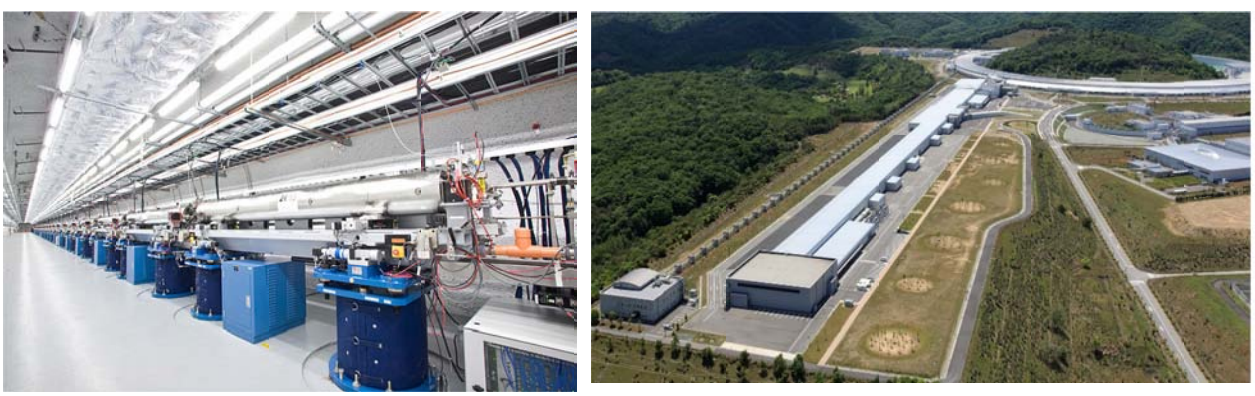

**FIGURE 3.5** Two X-ray free-electron lasers in current operation. Left: LCLS at the SLAC National Accelerator Laboratory, California USA. Right: SACLA at Spring8, Japan. SOURCE: SLAC, Spring8.

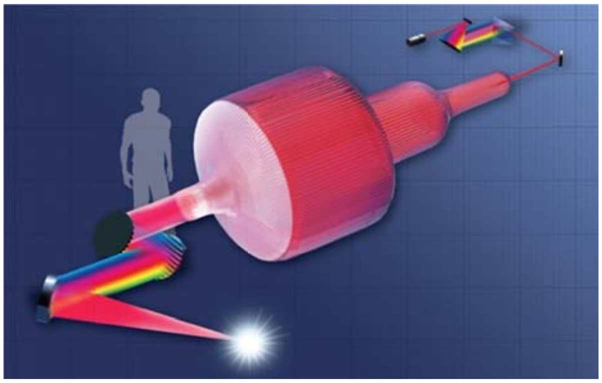

**FIGURE 3.6** Design of the ICAN laser at IZEST. Image Credit: Phil Saunders/spacechannel.org.

#### 3.2.2.1 Futuristic Technologies: ICAN

There have been proposals for systems based on coherent combination of large numbers of fiber lasers. The intention is to produce a system capable of high average powers, combined with high wall plug efficiency. These aims would be accomplished by amplifying a matrix of lasers through Yb-doped fiber. The International Coherent Amplification Network (ICAN) [see Fig. 3.6], part of the International Center on ZettaExawatt Science and Technology (IZEST), aims to do just this.[9] The laser has begun the combination of a small amount of fibers, with more planned in the future. The proposed final specification of ICAN is to provide 1 KJ energy ultra-short pulses (of under 10 fs) at a high repetition rate of 10 KHz, but present work has much more modest goals. Funding and construction of a completed facility based on this technology is considered wholly aspirational at this point; therefore, while fiber-based systems should be considered for a long-term roadmap, they are not technologies that can be considered viable in the near- to medium-term. Appendix B3 provides more details on the technology of fiber lasers, along with examples of the current state of the art.

### 3.2.3 State of Future Intense Source Technology

This section briefly assesses and summarizes where future source technology is headed.

1. The technology of diode-laser pumping, which has revolutionized the operation of lower-power solid-state lasers, is emerging for use in all the stages of PW-class lasers, including diode-pumped, high-energy Nd:glass lasers used to drive final-stage Ti:sapphire amplifiers and possibly next as drivers for the final stages in OPCPA systems.
2. Diode pumping has enabled a new class of solid-state lasers, based on Yb-doped materials, which, compared to Nd-doped materials, feature a relatively low level of material heating per W of output power and, for some materials, such as Yb doped mixed oxide ceramics, a much larger bandwidth.
3. More advanced cooling of large-aperture laser materials is being employed to increase the pulse rate of high-peak-power systems, featuring either gas or liquid flow between relatively thin disks of gain media.
4. Fiber-geometry solid-state lasers, primarily based on Yb-doped silica glass media, have revolutionized the technology of high-cw-power lasers, providing powers on the order of 10 kW in near-diffraction-limited beams. They are severely limited in generation of high peak

[9] W. S. Brocklesby et al., "ICAN as a New Laser Paradigm for High Energy, High Average Power Femtosecond Pulses," *The European Physical Journal Special Topics* 223, no. 6 (May 1, 2014): 1189–95, doi:10.1140/epjst/e2014-02172-4.

powers by a number of issues, primarily due to nonlinear effects and optical damage in the small-aperture, long-interaction-length media. The highest single-fiber peak power generated to date has been 3.8 GW (2.2 mJ in 415 fs) from a CPA-based system.[10]

5. Active efforts are underway to scale cw and peak powers of fiber-laser-based sources through beam and/or pulse-combination schemes, with the highest peak power to date of 35 GW (12 mJ in a 262-fs pulse) achieved by a system employing both spatial and temporal beam combining. Techniques are under investigation to extend the number of combined fiber lasers from the current 10s to several orders-of-magnitude higher.
6. Coherent spectral combination techniques, primarily with OPCPAs, are being developed to permit generation of pulses in the several-fs region, greatly reducing the pulse energy needed to reach the PW peak-power level.
7. Several CPA pulse-compression schemes to either replace or enhance present grating technology for PW-class systems are under investigation. They are at an early stage of development, with performance either orders-of-magnitude below desired levels, or yet-to-be-demonstrated.

### 3.2.4 State of Future Intense Source Systems

This section briefly assesses and summarizes where future intense source systems are headed.

1. All of the technologies in current systems also feature in planned 10-PW-class lasers, but, to date, higher-peak-power sources, at the planning level, propose to use OPCPAs, since the aperture of available nonlinear crystals such as KD*P exceeds that of present Ti:sapphire crystals.
2. Many of the higher-peak-power systems continue to employ flashlamp-pumped Nd:glass, with higher pulse rates (1 per minute) enabled by active cooling of large discs of glass.
3. A diode pumped Nd:glass laser, HAPLS laser, (see Chap 6), is used as a pump for a Ti:sapphire laser under construction at LLNL and will enable operation at 1-PW level with a 10-Hz pulse rate and 300 W of compressed, average power.
4. Many of the “front ends” of the systems under construction make use of broadband parametric amplifiers and pulse-contrast enhancement techniques such as crossed polarized wave (XPW) to yield high levels of pulse-contract ratio. This property becomes increasingly important as the pulse energies increase to reach 10 PW and higher powers.
5. Two systems under development feature direct generation of near PW-peak power pulses from diode-pumped Yb-doped media. They feature optical efficiencies below the 10 percent level, with pulsewidths in the 100-fs region.
6. Other work in Yb-doped materials seeks to obtain ns-duration pulses for applications as pumps for OPCPAs. With cryogenic cooling, Yb:YAG lasers have generated 100-J-level pulses with >20 percent optical efficiency. One system, in the planning stage, seeks to generate 25 kW of average power (250-J pulses) and drive a PW-level OPCPA at a 100-Hz rate.
7. The most ambitious system proposed (ICAN) in terms of average power would do coherent beam-combining of > 10,000 fiber lasers to produce > 0.1 PW-peak-power pulses, at a > 10-kHz rate, for > 100 kW of average power. Those numbers are many order-of-magnitude greater than present fiber-laser technology and issues such as phasing control of such a larger

[10] T. Eidam, J. Rothhardt, F. Stutzki, F. Jansen, S. Hädrich, H. Carstens, C. Jauregui, J. Limpert, and A. Tünnermann, 2011, Fiber chirped-pulse amplification system emitting 3.8 GW peak power, Opt. Express 19(1): 255-260.

number of fibers and obtaining a high pulse-contrast ratio remain as significant challenges that are well beyond current or near-future technology.

8. Free-electron lasers now operate at much shorter wavelengths (soft to hard X-rays) than the solid-state lasers now used to reach PW peak powers. On that basis, they can, in principle, reach the same intensity levels now possible with PW-class lasers but with much lower pulse energies. To date, they have reached intensities of $10^{20}$W/cm$^2$ but in the future may reach and could exceed the intensities of much-longer-wavelength sources.

## 3.3 COMPARISON OF HIGH-INTENSITY SOURCE TECHNOLOGIES

Table 3.2 provides a comparison of existing, planned, and proposed sources discussed in this chapter, emphasizing the highest levels of various measures of performance (e.g., power, pulse rate) attained in existing facilities and the specified or proposed measures otherwise. In the prior sections and appendixes to this chapter, the report has covered current technologies and the systems using them to reach the PW level, and described systems that are under construction, planned or conceptualized.

In building facilities for intense sources one has a variety of options for the source configuration; the choices are driven by numbers of factors including the science/engineering to be done, the system initial size and cost, the operating cost, and the reliability of the source. Concerns such as the pulse rate are important in terms of the productivity of the facility. In the facilities under construction in Europe and, to a lesser extent, in Asia, multiple sources based on different technologies are being deployed to, in principle, increase the breadth of science to be done and also increase productivity.

Below the committee discusses some other more qualitative properties of the various technologies.

**TABLE 3.3** Comparison of Technologies for High-Intensity Lasers

| Technology | Pros | Cons |
|---|---|---|
| **Nd:glass** | High energy pulses | Low pulse rate |
| | Maturity | Long pulses |
| | Relative low cost | Supply chain |
| **Ti:sapphire** | Highest peak power | Heat dissipation |
| | Good conversion of pump to output | ASE |
| | Flexibility, simplicity of pump lasers | Ultimate energy limit from crystal size |
| **OPCPA** | No ASE | Burdensome pump requirements |
| | Large-aperture media | Crystal size limits for non-KD*P systems |
| | No inherent heating | Untested at highest energies, rates |
| | Potential for fs-duration pulses | |
| **Yb-doped bulk** | Simplicity for direct lasers | Not yet at PW level as direct sources |
| | Potential for high efficiency | Long pulsewidths |
| | High average powers as pumps | Low efficiency to date as direct sources |
| **Yb-doped fibers** | Promise of high efficiency | Many orders of magnitude from PW |
| | Promise of high average power, | Technology of massive beam combination |

| | | |
|---|---|---|
| | PW<br>Now high average ultrafast source | not at hand |
| **Linac-based light sources** | Shortest wavelength (X-ray FELs), and tunable over many decades of wavelength.<br>Tightest focus (sub-micron)<br>Intensities exceed Schwinger limit for PW lasers scattering from >10 GeV beams | Linacs are extremely expensive (~$1B)<br>Science access is limited to a few places in the world.<br>Highest intensities are only reached in a relativistic reference frame, limiting the general utility. |

### 3.3.1 Nd:glass

Nd:glass systems are the oldest direct PW-class technology and remain the established pump source for high-peak-power Ti:sapphire and OPCPA systems. As a direct source, advances in technology have enabled the pulsewidth to reduce from 500 fs to about 150 fs, which is key to enabling the construction of a 10-PW source for ELI-Beamlines in the Czech Republic. Nd:glass systems are well suited for science applications where high pulse energy as well as peak power are important. Recent advances in liquid or gas cooling of glass disks will increase the pulse rate to 1/minute with flashlamp pumping and to the 10-Hz region with diode pumping. The latter also facilitates an increase in conversion of pump light from the 1-2 percent possible with flashlamps to about 20 percent with diode lasers.

The positive aspects of Nd:glass technology include its relative maturity and low cost, at least for flashlamp–pumped lasers, and this has allowed worldwide proliferation of systems. It is, for example, used for shot peeing turbine blades in commercial jet aircraft engines.[11] Flashlamp pumping is giving way to diode-pumping as the commercial cost of diodes comes down. LLNL has shown ICF power-plant designs that could be based on diode-pumped Nd:glass, in the event that ICF can eventually prove to be feasible.[12] There could be a problem with future viability of the technology, however, if key commercial suppliers of large glass slabs and flashlamps decide to exit the business.

### 3.3.2 Ti:sapphire

At this writing, Ti:sapphire technology has enabled the highest-peak-power laser system yet demonstrated (5.3 PW) and also features in systems under construction to reach the 10-PW level at ELI-NP (Romania), in France and possibly in China.

In common with OPCPAs, it requires a laser as a pump source, as direct diode pumping looks to be a very remote future possibility. Compared to OPCPAs, Ti:sapphire to date has shown higher

[11] Graham Hammersley, Lloyd A. Hackel, and Fritz Harris, "Surface Prestressing to Improve Fatigue Strength of Components by Laser Shot Peening," *Optics and Lasers in Engineering*, Laser Material Processing, 34, no. 4 (October 1, 2000): 327–37, doi:10.1016/S0143-8166(00)00083-X.

[12] C. D. Orth, S. A. Payne, and W. F. Krupke, "A Diode Pumped Solid State Laser Driver for Inertial Fusion Energy," *Nuclear Fusion* 36, no. 1 (1996): 75, doi:10.1088/0029-5515/36/1/I06; A. C. Erlandson et al., "Comparison of Nd:Phosphate Glass, Yb:YAG and Yb:S-FAP Laser Beamlines for Laser Inertial Fusion Energy (LIFE) [Invited]," *Optical Materials Express* 1, no. 7 (November 1, 2011): 1341, doi:10.1364/OME.1.001341; "Design and Performance of a Diode-Pumped Nd:Silica-Phosphate Glass Zig-Zag Slab Laser Amplifier for Inertial Fusion Energy," *Japanese Journal of Applied Physics* 40, no. 11R (November 2001): 6415, doi:10.1143/JJAP.40.6415.

efficiency in converting pump energy to output energy, about 50 percent before compression, double that of present OPCPAs. Also in contrast with OPCPAs, Ti:sapphire technology does not connect pump phase to output phase and is capable of accumulating energy from multiple, multi-mode and random-phased pumps, with only modest pump-timing requirements. This enables future high-energy and high-average power systems that can make use of multiple, relatively low-energy, diode-pumped pump lasers.

Unfavorably in comparison with OPCPAs, heat dissipation in Ti:sapphire crystals is inherent to laser operation, although cryogenic cooling can greatly reduce the effects of the heat. Also unfavorable is the need to counter the effects of transverse ASE at high stored energies, although approaches using time-separated pump pulses (extract during pumping) have so far allowed scaling beyond that possible with a single pump pulse. Ultimate energy limits may come about from the available size of crystals, which cannot equal the aperture of OPCPA crystals such as KD*P.

Ti:sapphire technology still has widespread commercial viability, but at present there is only one commercial source of the large-aperture crystals employed in the highest-energy systems, with a concern that the limited market for these could threaten future supplies.

### 3.3.3 Optical Parametric Chirped-Pulse Amplification

As with Ti:sapphire, OPCPAs are laser-pumped systems. Following on the prior discussions and details in the appendixes, in comparison to Ti:sapphire, the lack of transverse ASE and the ability to obtain very large-aperture KD*P nonlinear crystals enables scaling, on paper so far, to energies well above 10 PW. Under the proper conditions, OPCPAs can also produce shorter pulses through spectral beam combining. The lack of inherent heating in the OPCPA process promises future scaling to high average powers provided appropriate pump lasers can be developed.

On the other hand, besides the need for precise control of the pulsewidth and timing, OPCPAs do place a burden on the pump laser in terms of its beam quality. In theory, the OPCPA idler wave can carry off pump beam phase inhomogeneity, but in practice back-conversion that occurs as the pump-signal conversion increases to 25 percent and beyond does require good phase properties. Other issues include the coupling of pump intensity to signal phase, requiring relatively uniform pump intensity. These sensitivities to pump beam quality are a challenge to average-power scaling for high-energy OPCPAs. As with Ti:sapphire, alternative nonlinear crystals, such as LBO, which have more desirable thermos-mechanical properties compared to KD*P, require further development of large-aperture growth techniques.

As this chapter has described, OPCPAs in combination with Nd:glass and Ti:sapphire final amplifiers have proven to be an excellent combination to providing short output pulses with high temporal contrast. Much remains to be done in operational systems to advance OPCPAs also as final-stage amplifiers, as the great majority of present 10-PW-class systems under construction still rely on Nd:glass or Ti:sapphire final amplifiers.

### 3.3.4 Yb-doped Bulk Lasers

The appeal of direct diode-pumped, Yb-doped bulk lasers is simplicity, ultimate electrical efficiency, and the chance for average-power scaling enabled by the favorable properties of crystals as active media. To date, the major problem is the high saturation fluence of available Yb-doped crystals, which has led to long pulsewidths and low final-stage efficiencies (below 10 percent) in converting diode pump energy to output pulse energy for systems attempting to reach the PW peak-power level. This technology would benefit from further development of host media with higher gain cross sections with appropriate bandwidth.

A more promising approach to the use of Yb-doped crystals is their application as a ns-duration, high-energy, efficient pump sources for either Ti:sapphire or OPCPA final stages. With 100-W-average-power-systems now operational, and kW-average-power sources under construction or planning, the Yb-doped devices can provide some of the first tests to determine the actual average-power capabilities of OPCPA-based, high-energy, and peak-power sources.

### 3.3.5 Yb-doped Fibers

Yb-doped fiber systems are the furthest away from PW-class capability, and barring a major technical breakthrough, combined with a substantial increase in development funding, will not reach that capability for a considerable time. They do provide the highest average powers for ultrafast systems, at very limited pulse energies.

The major driving force for the technology is the promise of high efficiency combined with a high average power and pulse rate, a requirement for future applications for intense sources, such as drivers for advanced particle accelerators.

### 3.3.6 Linac-based Sources (Free-Electron Lasers, Beam-Laser Scattering)

Conventional radiofrequency (RF) and superconducting RF electron linear accelerators offer two advanced means of reaching high intensities: FELs and relativistic scattering. The machines are in the billion-dollar range and so only exist at national laboratories.

Current focused X-ray intensities from FELs are comparable to the performance of petawatt lasers and are limited by the quality of sub-micron focusing technologies, which may improve in the future.

The intensity in the center of momentum frame for a laser backscattering from a relativistic electron beam enters a new, much higher regime than anything envisioned for lasers alone. If a PW-class focused laser is directed at a >10 GeV electron beam, the resulting intensity exceeds the Schwinger limit. A summary of these comparisons is captured in Table 3.3.

### 3.3.7 Intensity Considerations

The discussions have generally emphasized source performance in terms of peak power, with the pulsewidth and pulse energy as parameters. In many of the science and engineering applications the focused intensity of the source is the key performance parameter, and for most if not all the sources the committee discusses, data on this is limited or a goal for the system. Intensity is a function not only of the peak power, but also of the output beam quality and the beam focusing optics used in the system.

Measurements of beam quality have tended to be a challenge (even definitions can vary), especially for sources with a pulsed output and even more so for sources with a limited pulse rate. The use of CPA in intense lasers leads to an additional complication, as all the wavelengths present in the beam may not have the same beam properties, and thus the focused beam may contain some form of spectral distortion that leads to a reduced peak intensity. In general, nonlinear effects in the gain media, especially in the final amplifier stages, can lead to spatial and temporal phase distortion in the output beam. There are some special concerns about OPCPA systems where pump spatial or temporal intensity fluctuations may also lead to complex phase irregularities in the beam.

For beam focusing optics, the challenge as the pulses get shorter is to accommodate the broad spectral linewidth, which rules out the use of refractive optics. Mirrors are an option, but dielectric-coated mirrors face limits on obtaining a constant-phase, high-reflectivity over a large wavelength region, and metallic mirrors have inherent absorption that can limit operation at high pulse rates. Discussions of future spectrally combined sources that produce several-fs-duration pulses require accompanying ultra-broadband focusing optics to reach high intensities. Finally, X-ray FELs can reach very high intensities only if focusing optics with sufficient spatial accuracy can be fabricated. 100-nm focal spot sizes have been demonstrated, but this is far from the diffraction limit. Diffraction-limited optics for X-ray sources require absolute accuracies about three-orders-of-magnitude better than those for the near-infrared. However, given the very short wavelengths involved, even if the focusing optics are not diffraction-limited, the focal spot area will still be many orders-of-magnitude smaller than that for solid-state laser sources.

Unfortunately, there is no simple way to obtain a good measure of intensity, and for many systems this number must be inferred from the physical results of experiments conducted with the beam. In principal, the development of adjustable, phase-correcting optics, both temporal and spatial, can allow a substantial enhancement ability of sources to focus to a high intensity. As LLNL has pointed out to the community, for low pulse-rate sources these corrections are “feed-forward” in that the corrections are applied based on a measurement of the last beam, with iterations necessarily somewhat of a “cut-and-try” nature.[13] As pulse rates increase (above about 5 Hz), one can apply active “feedback” control using goal-seeking algorithms that apply corrections without requiring physical understanding of what the corrections actually do. Technologies where this high rate is possible will almost exclusively involve diode-pumped lasers. Future development of intense sources may seek to trade high peak power at low pulse rates for lower peak powers at higher rates, if the latter sources can be operated with active feedback to generate higher intensities.

## 3.4 NATIONAL ORIGINS OF TECHNOLOGY SOURCES

The discussion in this chapter (and appendixes) has presented some mention of the national origins and commercial status of various technologies. Below is a concise summary of that information with some additional commentary, which will serve as an introduction to the next chapter of the study, the International Landscape. This also forms part of the basis for Conclusion 5 described in Chapter 7 of this report.

In general, the United States has originated key technologies employed for PW-class lasers and FELs capable of high intensities. The list includes the following:

- Nearly all of the solid state lasers that have been applied, including Nd:glass, Nd:YAG, Yb:YAG, and Ti:sapphire
- The CPA technique that was critical to the overall approach
- The lamp-pumped, high-energy Nd:glass systems that were used in the first PW system and are still being used to scale to higher powers
- Large-aperture gratings that also enabled the first PW system
- High-power diode lasers and diode-pumped solid-state lasers, including low-heat-generation Yb-doped lasers
- Nonlinear optics, notably harmonic generation and parametric devices
- Cladding-pumped fiber lasers that have allowed scaling of fiber-geometry systems to high average powers;
- The original free-electron laser concept and the extension to self-amplified spontaneous emission (SASE) that made X-ray FELs possible.

The origins of other technologies are diverse. The OPCPA concept originated in Lithuania in the 1990s and was first scaled to near-PW-class peak powers in the UK. The rapid growth of large-aperture KDP-family crystals originated in Russia but was subsequently scaled further in the United States for the ICF program, which employs large-aperture crystals to generate the ultraviolet (UV) energy now employed in experimental work. The nonlinear materials beta barium borate (BBO) and LBO, now used extensively as high-gain OPAs in the first stages of PW-class lasers and now also as the final stage (for

[13] Lawrence Livermore National Laboratory (LLNL), 2016, High-power high-intensity lasers for science and society, white paper submitted to the National Academy of Sciences Committee on the Opportunities in the Science, Applications, and Technology of Intense Ultrafast Lasers, LLNL-TR-704407.

LBO) in an OPCPA system, were first grown in China. The XPW technique for pulse-contrast enhancement was developed in France.

In terms of current trends, this chapter illustrates that the United States continues to develop advanced PW-class lasers, with the mixed-Nd:glass, Texas Petawatt laser, which had origins in the ICF effort, leading to the ongoing development of a 10-PW system being built in the United States by National Energetics for ELI-Beamlines in the Czech Republic. The HAPLS system, under construction at LLNL, also for delivery to ELI Beamlines, represents a significant milestone in diode-pumped sources and also in high-average-power Ti:sapphire lasers. However, the construction of higher-peak-power Ti:sapphire lasers is now being done in China and by two French companies, Thales and Amplitude Technologies, for delivery to ELI-NP in Romania and ELI-ALPS in Hungary. High-power OPCPAs have been built in Russia and China, with even higher-power units under development in the UK. Recent work to develop broad-bandwidth, diode-pumped, Yb-doped crystals has been primarily in France, and construction of high-peak-power systems is in progress in Germany. Efforts on high-pulse-energy Yb:YAG lasers as pump sources for Ti:sapphire and OPCPA systems are to be found in the UK, in cooperation with the Czech Republic, and in Japan.

Although the United States has extensive ongoing efforts on beam-combined fiber lasers to generate high cw powers, beam-combined, CPA-architecture fiber-laser work is centered in Germany and to a lesser extent in France, with limited work in the United States.

The U.S. program to develop a high-energy Nd:glass laser for ICF at LLNL and also LLE has had a major role in the early development of PW-class lasers, and much of the technology for scaling the energy of Nd:glass lasers has originated from this program. Considerable expertise in mega-Joule class Nd:glass lasers and CPA technology can be found at LLNL and LLE. At LLNL there is a CPA-based advanced radiographic capability (ARC) system, which is a PW-class CPA source with a long pulsewidth of about 30 ps. ARC has a specialized application to ICF diagnostics. Beyond the LLNL-developed HAPLS laser, which will be shipped to the Czech Republic, at present, there is no new construction of PW-class lasers at either LLNL or LLE. LLE does have a proposal to build the EP-OPAL, OPCPA-based, 75 PW source but no significant funding to do so.

In terms of commercial expertise, there is one company in the United States, National Energetics, active in building PW-class, Nd:glass lasers. Another company, Continuum, now owned by Amplitude Technologies in France, does have background in high-energy Nd:glass and Nd:YAG lasers. Otherwise, companies in the United States, such as Coherent, Spectra-Physics, and KMLabs, have concentrated on lower-power ultrafast sources, primarily based on Ti:sapphire, to address the still-large scientific market for these devices. It is to be expected that the ELI program in the UK, besides providing business to the French companies Thales and Amplitude Technologies, will create EU-based spin-off companies that specialize in high-peak-power laser systems.

# 4

# International Landscape

## 4.1 INTRODUCTION

Over the last two decades there has been a significant growth across the world in the abundance of laser facilities capable of producing peak powers on the order of petawatt (PW) levels. In these systems, for a fleeting moment, a laser pulse can be produced that has an instantaneous power that dwarfs the global electricity supply, which can be focussed to power densities about 22 orders of magnitude greater than sunlight. Consequently, any matter that the laser interacts with is rapidly subject to extreme change, generally becoming transformed into its fourth state—plasma. Depending on the configuration of the interaction, a diverse range of science and applications emerge from this extreme environment.

This section contains a review of high-power petawatt-class systems globally. There are many high-power laser systems and facilities, and for clarity and the purposes of this survey a cut off is applied below 0.5 PW. A comprehensive list appears at the end of the chapter. The review is organized by laser technology class, as in general this also provides a natural demarcation between the science and applications that can be accessed. Finally, a distinction is made between systems that are currently in existence and operational, systems that are under construction (i.e., funded), systems that are not yet funded but are clearly and formally defined by the report and the national roadmap, for example, and finally other systems that are aspirational in character.

Given the scope of research made possible by PW-class lasers, there are a number of large-scale facilities internationally that host such systems. At the time of writing, there are over 50 PW-class lasers worldwide in operation, under construction, or in the planning phase. A comprehensive description of these facilities at the end of 2015 was published by Danson et al.[1] These range from smaller commercial systems that can fit into a large laboratory up to building scale systems like the National Ignition Facility (NIF) in the United States.[2] The global spread of these facilities is shown in FIGURE 4.1, which shows a record of systems identified by the International Committee for Ultra-Intense Lasers (ICUIL), an Organisation for Economic Co-operation and Development (OECD) sub-committee, and their host facilities on a world map. A detailed discussion of worldwide petawatt-class facilities is given in Appendix E.

Attaining high peak power relies on the correct combination of two properties—energy and time—specifically, a high energy laser pulse delivered over very short timescales. This is the essence of a high-peak-power laser, whether designed to generate tens to millions of Joules of energy in a pulse that is femtoseconds to nanoseconds long. The application and relevant science depends heavily on the exact nature of the parameters of the laser and the geometry of the interaction; the number and scope of applications are many and are described in Chapters 5and 6.

[1] C. Danson, D. Hillier, N. Hopps, and D. Neely, 2015, Petawatt class lasers worldwide, *High Power Laser Science and Engineering*, 3: e3.

[2] National Ignition Facility and Photon Science, "What Is NIF?", https://lasers.llnl.gov/about/what-is-nif, accessed January 30, 2017.


**FIGURE 4.1** 2016 world map by the International Committee for Ultra-Intense Lasers (ICUIL) showing the global extent of PW-class (here, greater than 0.1 PW) laser facilities. SOURCE: Dr. C. P. J. (Chris) Barty, Lawrence Livermore National Laboratory.

## 4.2 GLOBAL TRENDS AND DISTRIBUTIONS

The introduction included FIGURE 4.1, the ICUIL world map, which shows the broadly global distribution of high-power laser facilities and research centers. A more informative representation of FIGURE 4.1 shows the global, aggregated distribution of peak power that is currently either operational or under construction. It is clear that significant concentration occurs in Europe, owing principally to the self-organization of the various institutes and countries involved via European Union programs that have supported and brought a strategic aspect to the field over several decades. The United States is notably behind. The full listing of the PW-class systems and their key parameters are included at the end of this review in Appendix E

If one considers systems that are planned, in the sense that they are at an advanced stage of definition and appear in (inter)national road maps or from major (inter)national infrastructures, etc., then the general position globally does not change significantly. This is reflected in FIGURE 4.2.

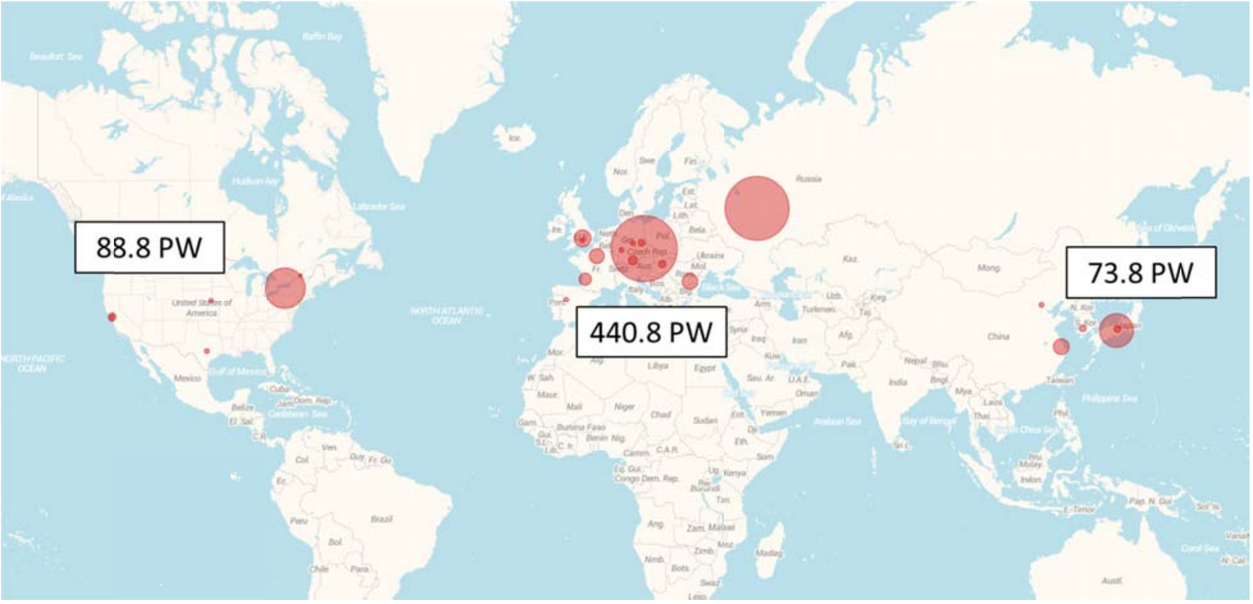


**FIGURE 4.2** Bubblechart of total peak power for operational, under construction, and proposed high power laser facilities. SOURCE: J. Collier, Rutherford Central Laser Facility.

The leading position, in terms of total peak power, currently held by the European countries has developed only recently. In fact, if one looks at the growth in the number of operational PW-class laser systems by date (see FIGURE 3), the United States has been superseded by Asia and Europe only in the past two years. This is due to a rapid increase in the number of systems under construction in these regions, while the United States has remained level since 2012. This has not stopped the global trend showing significant growth in the number of systems—the dashed line in FIGURE 4.3 shows the continuation of this growth by systems that are planned but that currently have no published completion date. Again, here there is a sharp increase in the number of systems within Europe.

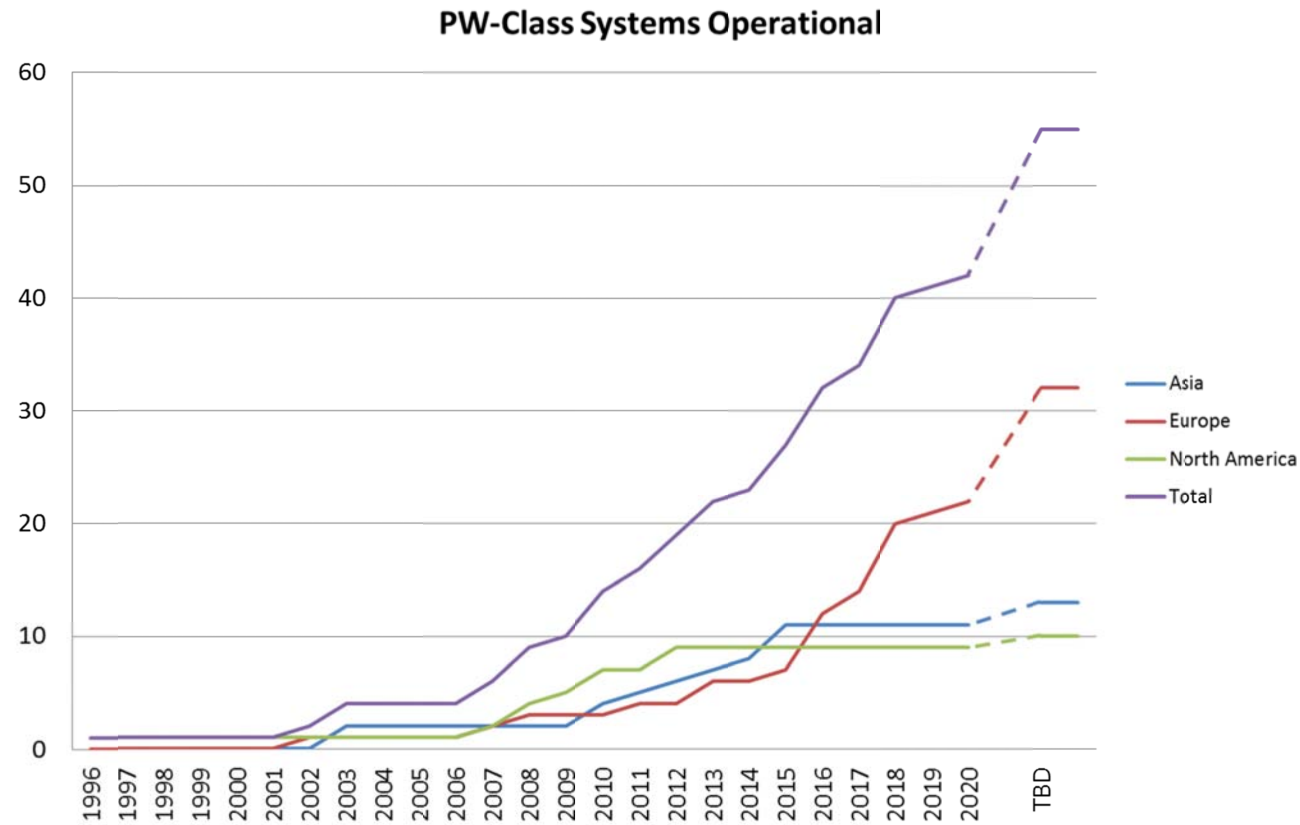


**FIGURE 4.3** Increasing worldwide count of petawatt-class laser systems, categorized by the continent in which that system is operated. SOURCE: J. Collier, Rutherford Central Laser Facility.

To more clearly see the number of systems coming online, FIGURE 4.3 shows the number of systems brought online each year by North America (green), Europe (blue), and Asia (red). Systems that are expected to be operational beyond 2020 or whose completion dates have not been published are combined in the TBD column. This graph shows that initial development of PW-class lasers was dominated by North America in the mid-2000s, but that this lead has slowly shifted towards Asia and then Europe in the present day and up to 2020. Even if one includes systems that are only proposed, North America is notably behind.

At the time of writing, North America has 9 PW-class systems either operational, under construction, or planned; Asia has 12; and Europe has 32. The significant increase in development within Europe can be broadly attributed to key European-wide projects such as the Extreme Light Infrastructure (ELI)[3]and Laserlab.[4] These projects and others like them will be discussed in more detail in Section 4.3 4.3 Extreme Light Infrastructure & Europe.

[3] Extreme Light Infrastructure (ELI), “What is ELI?”, https://eli-laser.eu/, accessed January 30, 2017.
[4] Laserlab, “Laserlab Europe,” http://www.laserlab-europe.net/, 2016, accessed January 30, 2017.

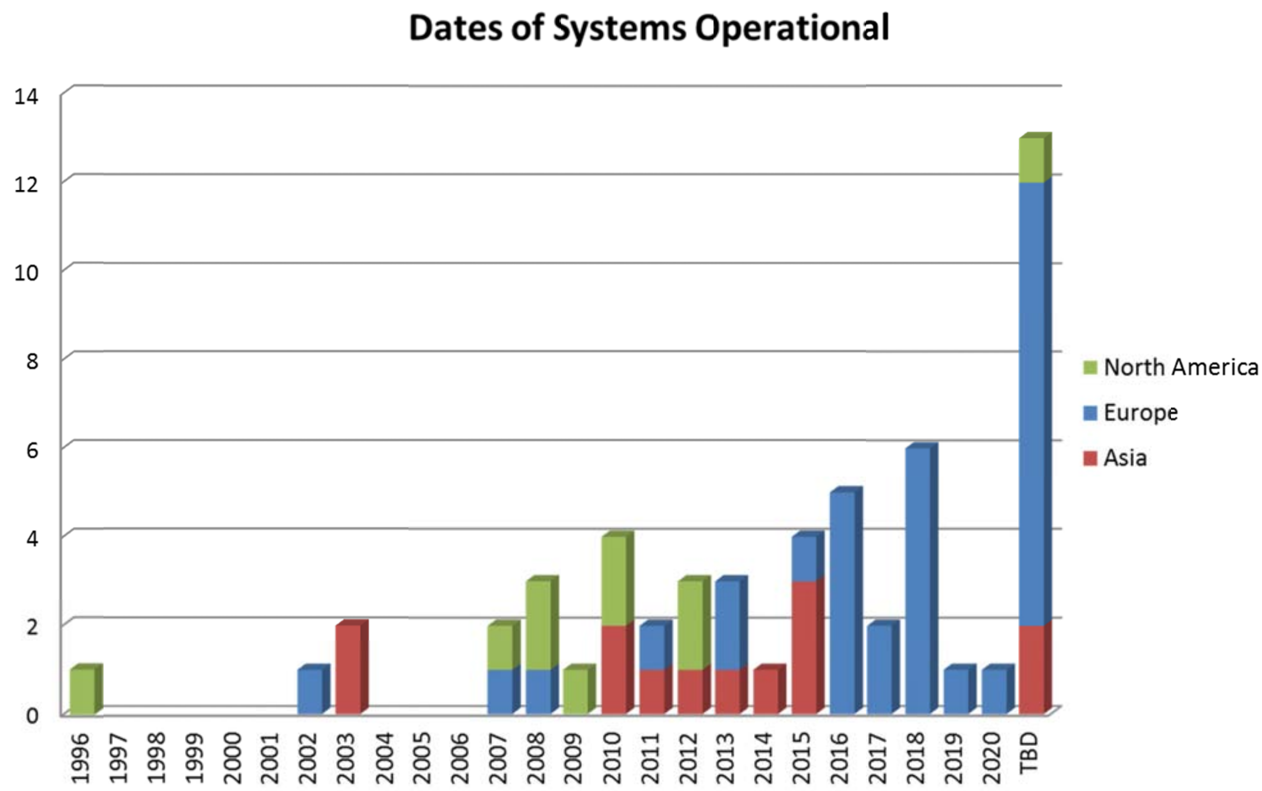


**FIGURE 4.4** Number of petawatt-class laser systems coming online each year, sorted by the continent in which those systems are based. This chart includes operational and under construction facilities. Proposed facilities are marked as "TBD." SOURCE: J. Collier, Rutherford Central Laser Facility.

Changing focus to the distribution of PW-enabling technology within each major region shows another difference between North America and Europe. FIGURE 4.5 is a compilation graph that shows the number of systems in each region and the technology used for the main amplifier (refer back to Chapter 2 for the main technology types) and their respective numbers. For example, North America is shown to have 9 PW-class systems operational, under construction, or planned. Of these 9 systems, 4 are glass-based; 3 are Ti:Sapphire-based, 1 is a megajoule system, and 1 is based on the optical parametric chirped-pulse amplification (OPCPA) technique. This shows a heavy weighting towards the older glass-based technology compared to the newer Ti:Sapphire technology, and only one planned system utilizes the latest OPCPA technology. In contrast to this, the distribution of technologies within Europe is large. The most common type is Ti:Sapphire, but there are a number of operational/under construction or planned OPCPA and diode systems. The diverse range of technologies in development highlights the fact that PW-class laser development has garnered much support within Europe and that funding exists to further develop and exploit these new technologies.

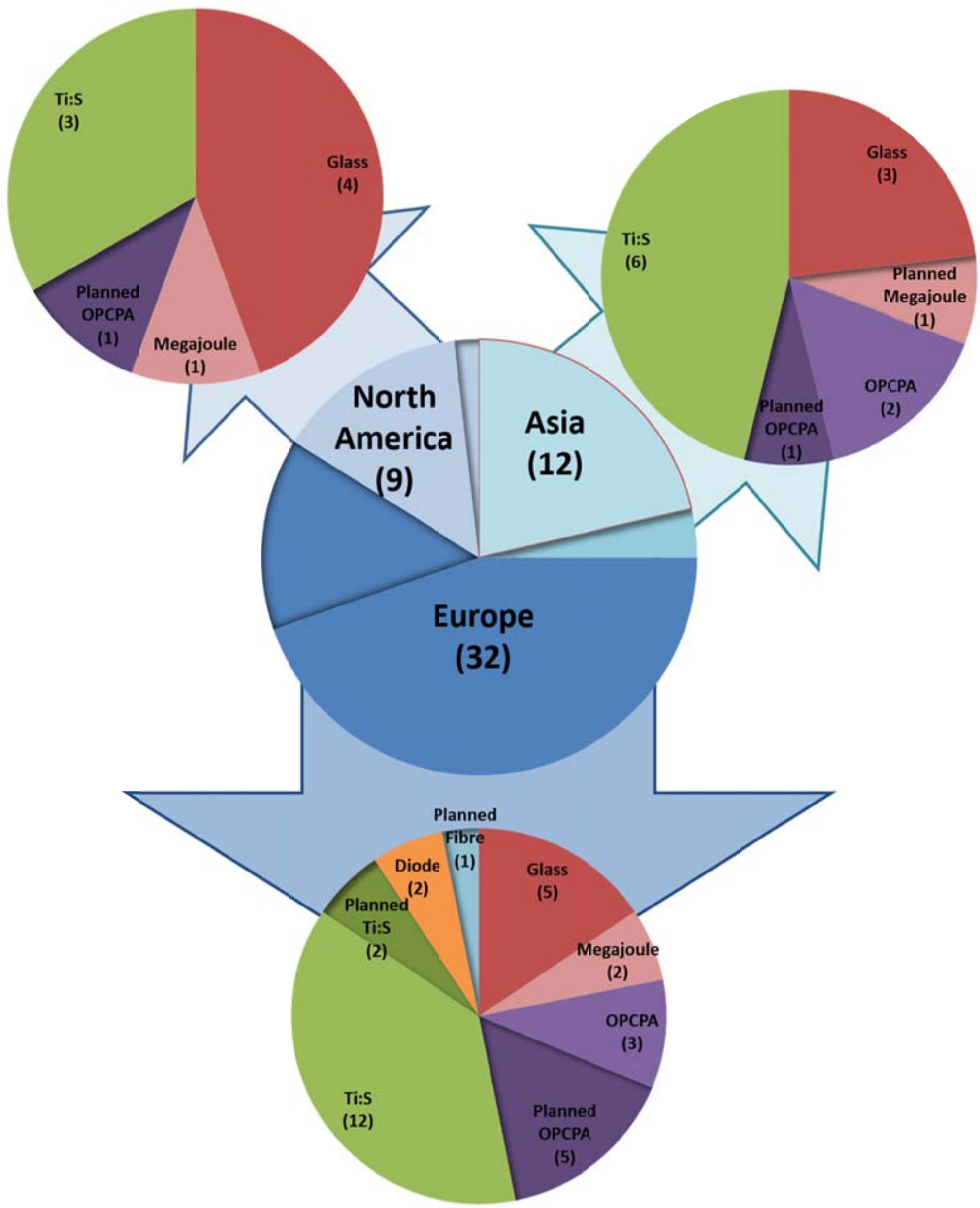


**FIGURE 4.5** Proportion of technology types by continent, including planned systems. SOURCE: J. Collier, Rutherford Central Laser Facility.

The substantial growth of PW-class OPCPA systems over the coming years compared to other technologies is highlighted in FIGURE 4.6, which shows the peak power versus operational date of all systems included within this review. Each system is represented by a symbol representing its main technology type: glass (diamond), Ti:Sapphire (triangle), OPCPA (square), diode-pumped (cross), megajoule (circle), and fiber (plus). Additionally, the status of the system is indicated by color: decommissioned (black), operational (green), under construction (orange), and planned (red). This somewhat complicated graph contains a strong message; the technology of choice for PW-class systems is changing from the original glass systems, through the established Ti:Sapphire systems, toward OPCPA systems, which enable much higher peak powers.

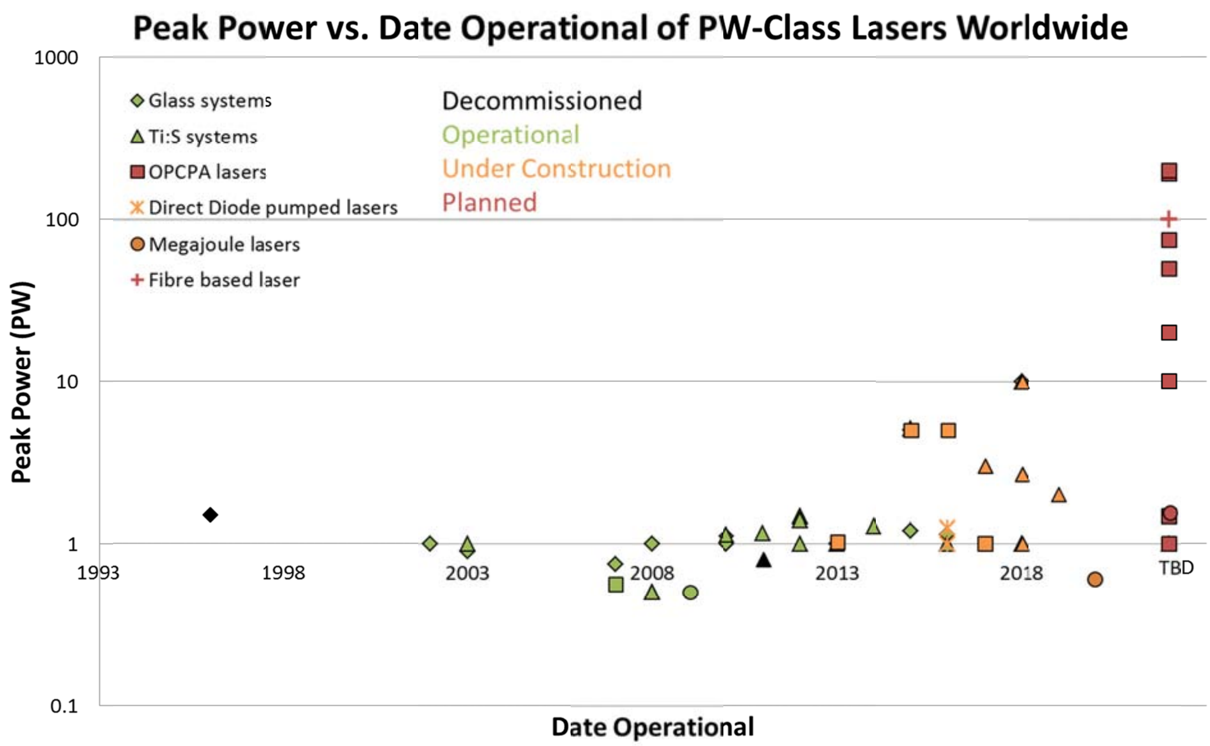


**FIGURE 4.6** Operational dates of PWt-class facilities according to their maximum peak power output. The facilities are denoted to their corresponding statuses. SOURCE: J. Collier, Rutherford Central Laser Facility.

In addition to the move toward OPCPA-based technology there has, in recent years, been a concerted effort to increase the average power and hence repetition rate of large-scale facility lasers, with the aim of developing new areas of application for the unique sources produced. This trend towards higher average powers is illustrated in FIGURE 4.7, which shows the expected operational dates for the Ti:Sapphire lasers in this review with a repetition rate of > 1 Hz. All but two use flash lamps as the primary means of optically pumping the system.

One of the most important recent technological advances in this area is the use of diode laser pumping architectures. Here, efficient diode pump lasers replace inefficient flash lamps that generate large amounts of excess thermal energy, which must be removed or managed. The highest repetition rate that has been achieved using traditional flash-lamp technology is the Advanced Laser Light Source (ALLS) in Canada. This system operates at 0.5 PW at a repetition rate of 2.5 Hz,[5] with diode-pumped technology opening an enhancement path to 10's of Hz, although commercial systems at slightly less power and higher repletion rate are available.

In terms of diode-pumped Ti:S systems, there are only two systems currently planned or under construction in the world—the ELI Beamlines L3 laser,[6] which is being constructed by Lawrence Livermore National Laboratory (LLNL) in the United States, and the 10 Hz PW system currently planned for construction by the CLF in the United Kingdom. At its current schedule, L3 is likely to be operational

[5] Advanced Laser Light Source, Canada, "Specialized Labs and Equipment," https://navigator.innovation.ca/en/navigator/advanced-laser-light-source-alls, accessed January 30, 2017.

[6] B. Rus, P. Bakule, D. Kramer, G. Korn, J.T. Gren, J. Novak, M. Fibrich, et al., 2013, ELI-Beamlines laser systems: status and design options, *Proc. SPIE* 8780: 87801T.

for users in 2018. In the United Kingdom, Rutherford Appleton Laboratory (RAL) has developed a diode-pumped solid-state laser (DPSSL) system called DiPOLE (100 J @10 Hz)[7] as a Ti:S driver and has a planned project PULSAR to establish a 10 Hz PW capability. All other Ti:S systems that operate at 1 PW or above have repetition rates limited to 1 Hz or lower.

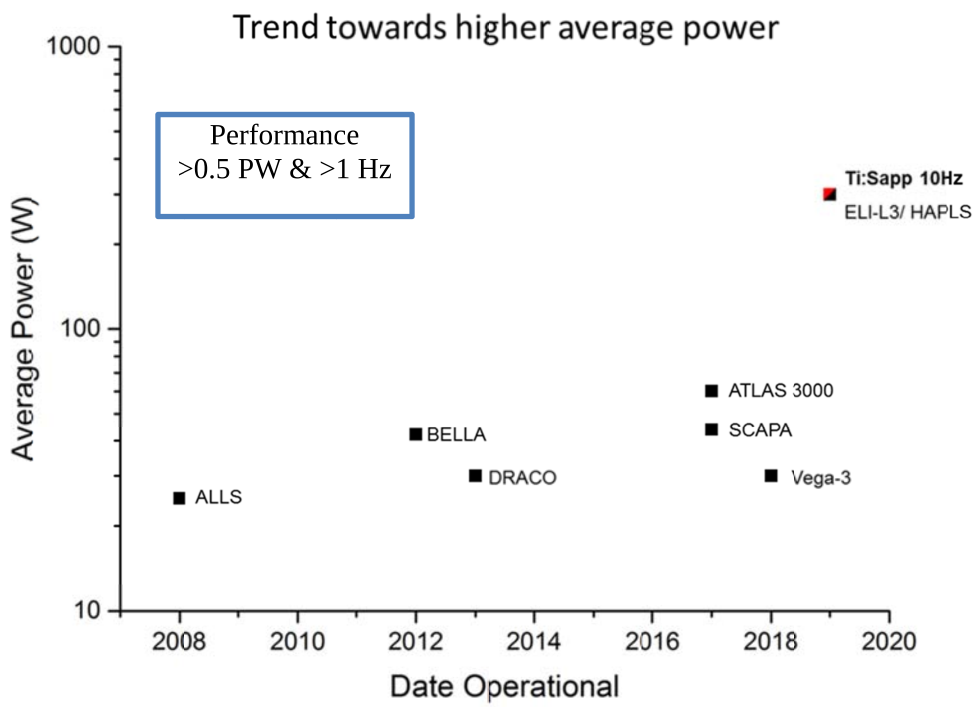


**FIGURE 4.7** Graph demonstrating the trend towards higher average power PW-class lasers. This includes all PW-class lasers within the review with a repetition rate > 1Hz. SOURCE: J. Collier, Rutherford Central Laser Facility.

## 4.3 EXTREME LIGHT INFRASTRUCTURE & EUROPE

The Extreme Light Infrastructure (ELI; Figure 4.8)) is a unique development, scientifically, technologically, strategically and politically. It is a large scale international laser infrastructure of ~$B capital cost that is being constructed in the European Union, made possible via the use of European Regional Development Funds (ERDF). It boasts a technical specification that is beyond anything that currently exists.

[7] P.D. Mason, M. Fitton, A. Lintern, S. Banerjee, K. Ertel, T. Davenne, J. Hill, et al., 2015, Scalable design for a high energy cryogenic gas cooled diode pumped laser amplifier, *Applied Optics* 54(13): 4227-4238.

Above: ELI-Nuclear Physics (Romania)
Left: ELI-Beamlines (Czech Republic)

**FIGURE 4.8** Images of facilities within the Extreme Light Infrastructure (ELI). SOURCE: ELI-laser.eu

**ERDF -** Historically, ERDF have been used to support public infrastructure development such as roads, railways, airports etc. throughout the European Union, but the application of ERDF to scientific infrastructure, while always possible, had never been used before. ELI fundamentally changed that and furthermore developed a truly unique implementation plan that has seen the physical infrastructure actually constructed in three different Eastern European countries—The Czech Republic, Hungary and Romania. These so called "pillars" of ELI despite being located in different physical locations will be operated as if they were a single entity via an EU device known as a European Research Infrastructure Consortium (ERIC). A 4$^{th}$ pillar, a 200 PW capability, was identified at the time of its proposal but its implementation has been held until a sufficiently robust technological basis for its development exits. Opportunities for US involvement in the fourth pillar depend on future investments as discussed in Section 7 of the report, particularly Conclusions 6 and 7, and Recommendations 3 and 4.

**ERIC -** The ERIC is a form of intergovernmental agreement among EU nations, enshrined in European law, that has been specifically developed to support pan-European research infrastructures, where arrangements are needed that transcend national boundaries. Traditionally this has required specific inter-governmental agreements or treaties to be individually developed, negotiated and enacted, which is a time consuming and cumbersome process. As an international organisation, ERIC has its own legal personality and enjoys a number of significant benefits. A pre-cursor organisation, known as the ELI Delivery Consortium (ELI-DC) has been created to establish the ELI-ERIC and to secure the necessary financial backing from the various EU member states interested in participating in ELI-ERIC. Currently the membership of ELI-DC stands at CZ, RO, HU, IT, DE, FR, and the UK. The legal status of an ERIC allows for the participation of non EU countries as members (that would have to accept the jurisdiction of the European Court of Justice) and the individual statues of any ERIC can allow for partnerships with non EU countries. ELI is due to come on line to users from around 2018.

ELI in many ways is the product of the many coordinating actions of the European Commission, which over a series of so called "Framework Programs", including the ESFRI Roadmap, structured the research landscape in Europe. These programs promoted cooperation, interconnection and mobility of people, which led progressively to a more strategic character in the way scientific communities formed and acted. The history of high power laser research in Europe is a prime example of this European cooperative strategy.

## 4.4 PETAWATT-CLASS LASER USER COMMUNITY

Estimating the scientific productivity of the field, and indeed the size of the scientific community involved, is a challenge as there are no centralized records that can be consulted. This study has estimated the size and productivity of the community of interest using Web of Science (WoS)[8] using various search terms in an attempt to provide some general indication. A full listing of the search terms and the method used for the search is described in Appendix C1.

The search resulted in approximately 21,000 publications spanning 45 years and contributed by 91 individual countries. The number of publications released per year was very low up to 1990, when publications in the field of PW-class lasers began to climb significantly each year. This coincides with the development and commissioning of the first PW-class facility, Nova, as shown in FIGURE 4.9. The yearly increase in publications in this field is continuing to grow, in line with the number of operational facilities.

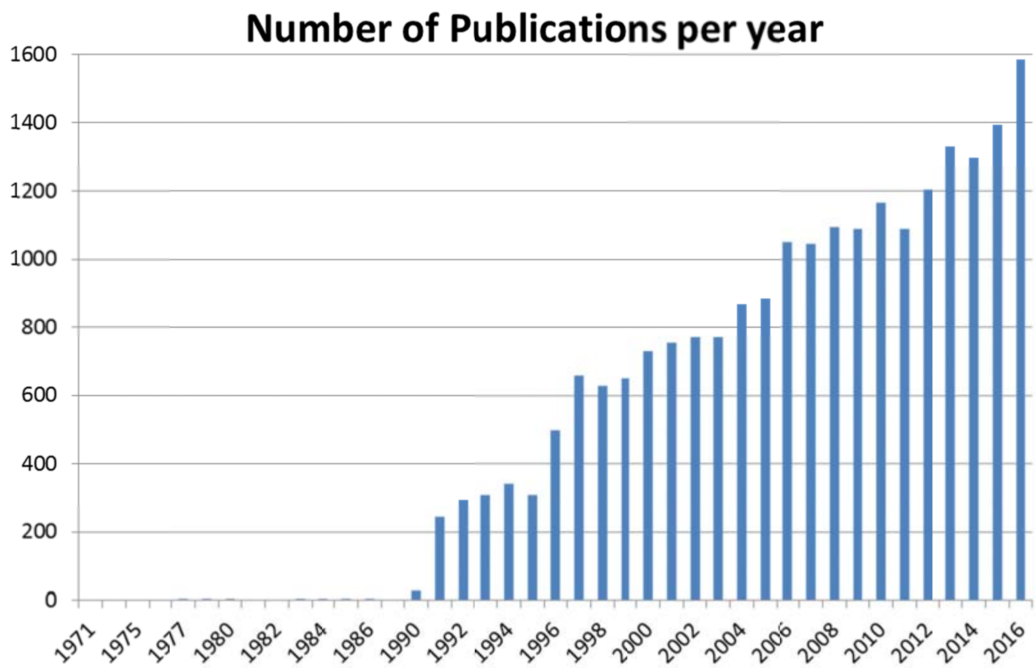


**FIGURE 4.9** Total number of publications in the field of PW-class lasers per year (based on WoS search described in Appendix C1). Note: Year 5 only shows partial results; there was no actual downturn in that year. SOURCE: John Collier, Rutherford Central Laser Facility.

There are three continents that have contributed to the vast majority of publications in the field; these are North America, Europe, and Asia. However, if one separates this search down to individual countries, as shown in FIGURE 10, then the United States is shown to be the most active single country in terms of total number of publications. The percentage shown is the fraction of publications that include

[8] Clarivate Analytics, "Web of Science," http://ipscience.thomsonreuters.com/product/web-of-science, accessed January 30, 2017.

at least one author from that country. For example, if a publication has two authors from the United States and one from the United Kingdom, both countries get a single point for this publication. The United States has authors on 28 percent of all publications within this search, more than twice that of Germany, the second highest publisher.

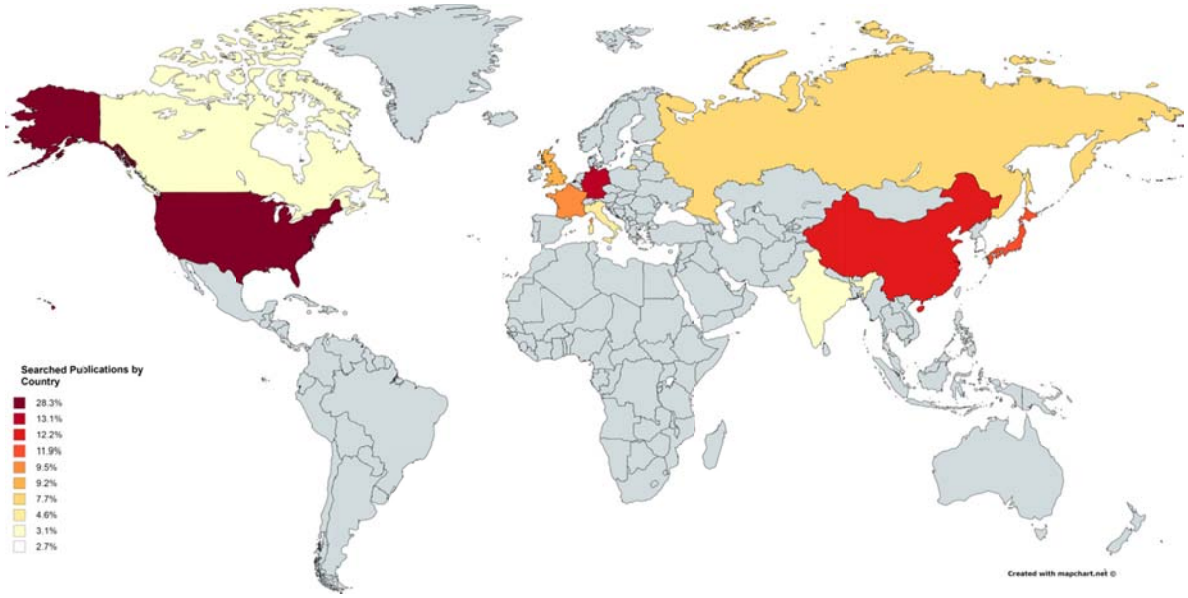


**FIGURE 4.10** World map showing the total percentage share of publications in the field of PW-class lasers for top 10 countries (based on WoS search described in Appendix C1). SOURCE: J. Collier, Rutherford Central Laser Facility.

Due to the complication of duplicates from individual countries within a continent, it is not possible to extract meaningful data on the continental distribution of publications from this particular search.

From a facility perspective, there are in over 2,000 organizations that have an author within this search. The total number may be somewhat lower due to misspelling, but this, coupled with the fact that 91 countries appear in this search, shows the global reach of the user community in this field. Of the organizations, the top 15 are shown in TABLE 4.1 for reference. As with the countries, these are facilities that have at least one author on a paper. Again, one can see that the United States and its facilities and departments appear high on this list. The "enhanced" organizations list is produced by combining results which appear to be same institute (i.e., change of name or same postcode given).

**TABLE 4.1** The Top 15 Organizations Within the Publications Search, the Number of Publications with Associated Authors, and Their Percentage of the Total Number

| Organizations (Enhanced) | Number of Records | % of Total |
|---|---|---|
| UNITED STATES DEPARTMENT OF ENERGY DOE | 1677 | 7.773 |
| CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS | 1046 | 4.848 |
| CEA | 1022 | 4.737 |
| RUSSIAN ACADEMY OF SCIENCES | 999 | 4.63 |
| LAWRENCE LIVERMORE NATIONAL LABORATORY | 945 | 4.38 |
| CHINESE ACADEMY OF SCIENCES | 824 | 3.819 |
| UNIVERSITY OF CALIFORNIA SYSTEM | 768 | 3.56 |
| UNIVERSITE PARIS SACLAY COMUE | 666 | 3.087 |
| OSAKA UNIVERSITY | 516 | 2.392 |
| ECOLE POLYTECHNIQUE | 514 | 2.382 |
| MAX PLANCK SOCIETY | 487 | 2.257 |
| STFC RUTHERFORD APPLETON LABORATORY | 391 | 1.812 |
| UNITED STATES DEPARTMENT OF DEFENSE | 355 | 1.645 |
| PIERRE MARIE CURIE UNIVERSITY PARIS 6 | 355 | 1.645 |
| CZECH ACADEMY OF SCIENCES | 334 | 1.548 |

SOURCE: WoS analytics.

What this data shows clearly is that while North America does not have the same diversity or number of PW-class facilities as Europe or Asia, the United States is producing a proportionally large number of publications in this field, highlighting how active the user community here is. If this interest from the user community were to be matched by funding and development of new facilities, one would expect this lead to be maintained in the least, and potentially increase. This analysis has contributed to Conclusion 3 of this report (see Chapter 7).

# 5

# Science Motivation

## 5.1 INTRODUCTION TO THE INTENSITY ROADMAP OF OPPORTUNITIES AND DISCOVERY

This chapter and the next summarize the case for development and use of high-intensity lasers for research and applications. The impact of high-intensity laser technology on science is unusually strong and broad, spanning from the most basic questions of the cosmos to potential applications in medical therapy.

The primary motivation for high intensity science is that it overturns the foundational assumption that the forces exerted by light are weak, and may therefore be treated as small perturbations to the forces that shape matter. The fields in a high intensity laser focus exert forces that are stronger than the physical systems they encounter – stronger than the chemical forces holding molecules and solids together; stronger than the coulomb fields that bind electrons in atoms; and ultimately stronger than the vacuum itself. This chapter introduces the scientific opportunities that are enabled by high intensity. Conclusion 1 is supported by the material here.

The high-intensity laser research opportunities described in this chapter cannot all be realized with only one type of large laser facility. Petawatt lasers configured to study particle acceleration are not optimized to excite or probe high density matter, for example. The facility location can also be important for some applications: A laser co-located with relativistic electron accelerators can enable science that would be difficult or impossible to explore with a stand-alone laser facility; large magnetic fields are needed to study some aspects in materials science. In addition, auxiliary coherent sources such as high energy pulsed lasers or X-ray free-electron lasers (FELs) may be needed to study extreme conditions such as hot dense plasmas.

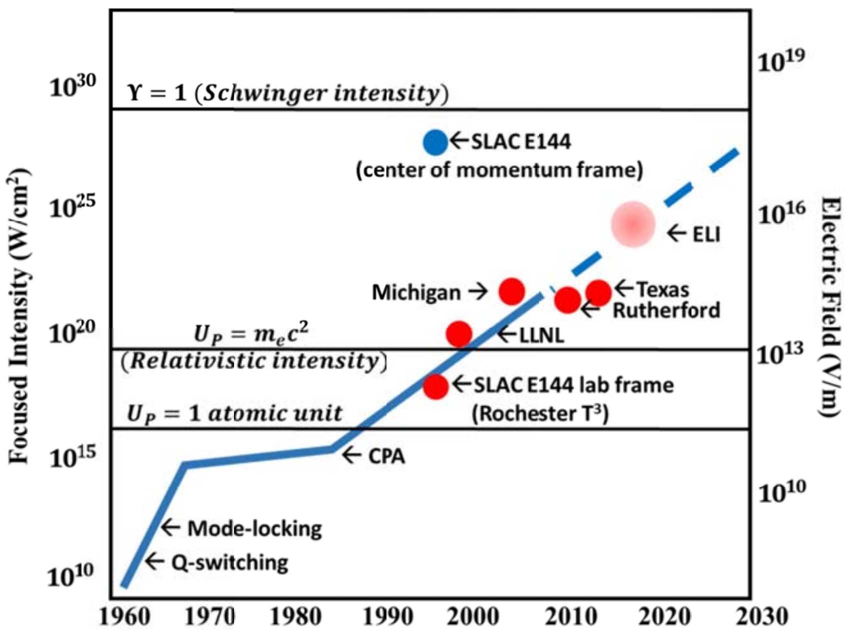

FIGURE 1.3 (reproduced from Chapter 1). High intensity phenomena that lie outside the regimes of validity for conventional perturbation theories occur when the force exerted by the laser field exceeds the binding forces. For atomic binding energies this regime is at1 TV/m. Deeply bound electrons reach this regime at higher fields. Ultimately the vacuum itself is unstable to stimulated creation of matter from light for fields of about one million TV/m.

Figure 1.3 in the introductory chapter of this report, reproduced here for convenience, describes the regimes of extreme field physics associated with the historical development of technology for high peak power lasers. The threshold laser intensity for entrée to each regime is set by parameters that characterize the laser and physical system that describe the interaction. The dimensionless Keldysh parameter $\gamma_k$, for example, was an early measure of the level of extreme of a laser field that relates the electric field in the focused laser to the electric field binding an electron in an atom. It works out to the ratio of two rates: the laser angular frequency $\omega$, and the bound electron's tunneling rate in the intense field, Γ. The tunneling regime occurs for $\gamma_K$<1, which means that ionization occurs in less than one optical cycle. For hydrogen this corresponds to peak electric fields of about 50 billion V/m , corresponding to laser intensities of ~0.3 PW/cm$^2$ at optical wavelengths. As Figure 1.3 in Chapter 1 shows, this is also the laser field corresponding to an atomic unit, where the laser field exceeds the coulomb field binding the electron to the proton, so that the standard atomic physics perturbation theory description of ionization due to absorption of multiple photons breaks down. See Appendix A for more information.

The Keldysh parameter can also be expressed as $\gamma_k = \sqrt{I.P./2U_P}$, where *I.P.* is the ionization potential of the atom, and $U_P$ is the laser "ponderomotive potential," the time averaged wiggle kinetic energy of a free electron in the oscillating field of the laser. $U_P$is proportional to $I\lambda^2$, where $I$ is the laser intensity and $\lambda$ is the laser wavelength. This is also shown in FIGURE 1.3, for laser wavelengths on the order of 0.8-1.0 microns, the most common wavelengths used for petawatt lasers.

Chirped-pulse amplification enabled a trend that continues today to advance the research frontier that can be accessed with higher peak laser fields and shorter pulses. One important consequence was the development of methods to study ionization on timescales shorter than a single optical cycle, termed "attosecond science."[1] The current well-established model of strong-field ionization is based on sub-femtosecond motion of atomic electrons. Some of the important primary references to this model will be summarized briefly in Section 5.2, because this is part of the core underlying science in this field.

Shorter intense pulses from CPA lasers also led to more exploration of tabletop laser-driven coherent soft X-ray sources such as high harmonics or attosecond continuum radiation, with applications in science and technology. This will be discussed more fully in Chapter 5. The underlying science is field ionization of higher Z ions and nonlinear interactions of laser-driven electrons in plasmas.

CPA sources focused to intensities above $\sim 10^{18} W/cm^2$ have ponderomotive potential energies that approach or exceed the rest energy of the electron. These relativistic laser field strengths enable a new regime of high-intensity physics. A dimensionless measure of the entrée to the relativistic regime is the normalized laser vector potential $a = eA_o/mc$, where $e$ and $m$ are the electron charge and mass, $A_o$ is the laser vector potential (given here in SI units), and $c$ is the speed of light.[2] The relationship between the laser intensity, the laser field, and the laser vector potential, is shown in Appendix A. For $a$~1, an electron can be accelerated by the laser field to nearly the speed of light in a distance of the order of the laser wavelength (~ 1 μm). This intensity regime opens up the field of relativistic nonlinear optics, which

[1] P.M. Paul, E.S. Toma, P. Breger, G. Mullot, F. Auge, Ph. Balcou, H.G. Muller, and P. Agostini, 2001, Observation of a train of attosecond pulses from high harmonic generation, *Science* 292(5522): 1689-1692.; M. Hentschel, R. Kienberger, Ch. Spielmann, G.A. Reider, N. Milosevic, T. Brabec, P. Corkum, U. Heinzmann, M. Drescher, and F. Krausz, 2001, Attosecond metrology, *Nature* 414: 509-513.

[2] J.D. Jackson, 2001, *Classical Electrodynamics*, 3rd ed., Wiley, New York.

includes applications in laser-driven particle acceleration[3] and short wavelength radiation sources.[4] Extreme fields can also arise as secondary sources from intense laser-matter interactions—in particular, as a consequence of bright relativistic electron and ion beams generated through laser-gas and laser-foil interactions. For example, giga-gauss scale magnetic fields have been generated by interaction of ~$10^{20}$ $W/cm^2$ laser pulses with thin foils.[5]

Finally, at the frontiers of intensity, one enters the quantum electrodynamics (QED) regime, where the vacuum itself becomes unstable and matter is created by light. The threshold laser field strength $E_0$ for entering this regime is the Schwinger field $E_S$, for which the work done on an electron-positron pair over one Compton wavelength is equal to their rest mass: $eE_S\lambda_C = 2mc^2$. This occurs for $E_S = 1.3 \times 10^{18}\ V/m$, corresponding to intensity$I_S = 2.3 \times 10^{29}\ W\ /\ cm^2$.[6] This field is of sufficient strength to accelerate the virtual electrons and positrons that fleetingly appear from vacuum QED fluctuations. At the same time, virtual electrons and positrons can mediate photon-photon interactions, which could continue to generate pairs in a cascade-like process.[7]

While this intensity level is not currently achievable, the QED regime may be accessed by colliding an ultra-relativistic electron beam from either a conventional laser accelerator or laser-driven wakefield accelerator with an extreme light infrastructure (ELI)-type laser. For interactions in a boosted frame of reference, the appropriate dimensionless parameter for entering the QED regime is $\chi = \gamma E_0/E_S$ , where $\gamma$ is the boosted frame's Lorentz factor, reducing the required laser intensities in experiments involving particle accelerators.

In the electron's frame, the laser's intensity will undergo a relativistic boost, reducing the required laboratory-frame intensity. An alternate scheme, using a laser assist beam for extreme nonlinear four-wave mixing in vacuum, is depicted in Figure 5.1. This is discussed in section 5.6.

[3] E. Esarey, C.B. Schroeder, and W.P. Leemans, 2009, Physics of laser-driven plasma-based electron accelerators, *Rev. Mod. Phys*. 81: 1229.

[4] CORDE, 2015 ; S.V. Bulanov, N.M. Naumova, and F. Pegoraro, 1994, Interaction of an ultrashort, relativistically intense laser-pulse with an overdense plasma, *Phys. Plasmas* 1: 745.

[5] A. Saemann, K. Eidmann, I.E. Golovkin, R.C. Mancini, E. Andersson, E. Förster, and K. Witte, 1999, Isochoric heating of solid aluminum by ultrashort laser pulses focused on a tamped target, *Phys. Rev. Lett.* 82: 4843.

[6] J.A. Frenje, P.E. Grabowski, C.K. Li, F.H. Séguin, A.B. Zylstra, M. Gatu Johnson, R.D. Petrasso, V. Yu Glebov, and T.C. Sangster, 2015, Measurements of ion stopping around the Bragg peak in high-energy-density plasmas, *Phys. Rev. Lett.* 115: 205001; A. Di Piazza, C. Muller, K.Z. Hatsagortsyan, and C.H. Keitel, 2012, Extremely high-intensity laser interactions with fundamental quantum systems, *Rev. Mod. Phys.* 84: 1177.

[7] W.P. Leemans, J. Daniels, A. Deshmukh, A.J. Gonsalves, A. Magana, H.S. Mao, D.S. Mittleberger, et al., 2013, BELLA lasers and operations, p. 1097 in *Proceedings of PAC2013*, Sept. 29-Oct. 4, Pasadena, Calif.

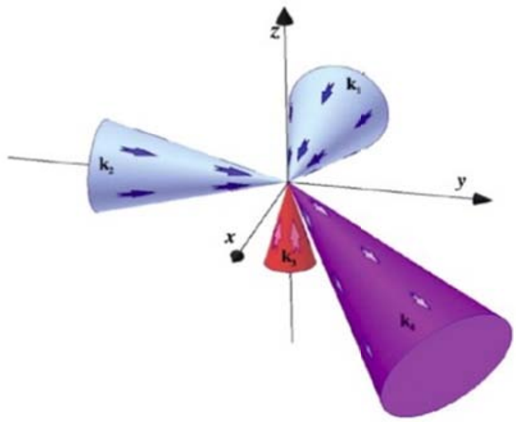


**FIGURE 5.1** Illustration of laser-assisted photon-photon scattering. Input beams shown in blue, assist beam in red, and output scattered beam in violet. SOURCE: E. Lundström, G. Brodin, J. Lundin, M. Marklund, R. Bingham, J. Collier, J.T. Mendonça, and P. Norreys, 2006, Using high-power lasers for detection of elastic photon-photon scattering, *Phys. Rev. Lett.* 96: 083602.

The following sections discuss opportunities that follow this "extreme" intensity roadmap from the non-relativistic light-matter interaction into the realm of QED physics.

## 5.2 ULTRAFAST SPECTROSCOPY AND ATTOSECOND SCIENCE: THE ATOMIC UNIT OF INTENSITY 1-1000 PW/CM$^2$

### 5.2.1 Extreme Nonlinear Optics: Interrogating the Electrons in Matter

Electron dynamics in atoms, molecules, plasmas, and condensed phase materials is a primary interest for physics, chemistry, and materials science. The principal means of study has always been spectroscopy. Sources based on extreme nonlinear optics using CPA lasers and gas targets have extended the range of spectroscopic tools to the vacuum ultraviolet spectral region.

A key nonlinear process that has enabled this extension is high harmonic generation (HHG), which occurs when a laser carrying an atomic unit of intensity interacts with a gas of atoms. Field ionization followed by field-driven recombination converts some of the laser light into a frequency comb of coherent extreme ultraviolet (EUV) or soft X-ray radiation.[8] HHG has become a powerful secondary table-top source of soft X-rays. The utility and full implications of the HHG process have continued to

[8] A. McPherson, G. Gibson, H. Jara, U. Johann, T.S. Luk, I.A. McIntyre, K. Boyer, and C.K. Rhodes, 1987, Studies of multiphoton production of vacuum-ultraviolet radiation in the rare gasses, *Journal of the Optical Society of America B* 4: 595-601; M. Ferray, A. Lhuillier, X.F. Li, L.A. Lompre, G. Mainfray, and C. Manus, 1988, Multiple-harmonic conversion of 1064-Nm radiation in rare-gases, *J. Phys. B* 21: L31-L35; K.J. Schafer, B. Yang, L.F. DiMauro, and K.C. Kulander, 1993, Above threshold ionization beyond the high harmonic cutoff, *Phys. Rev. Lett.* 70: 1599-1602; P.B. Corkum, 1993, Plasma perspective on strong-field multiphoton ionization, *Phys. Rev. Lett.* 71: 1994-1997; M. Lewenstein, P. Balcou, M.Y. Ivanov, A. L'Huillier, and P.B. Corkum, 1994, Theory of high-harmonic generation by low-frequency laser fields, *Phys. Rev. A* 49: 2117-2132.

grow at an ever-increasing rate, which now span from electron and spin dynamics in atomic, molecular, and materials systems, to imaging with temporal resolution to make molecular movies, to high-precision spectroscopy. These applications are discussed more fully in Chapter 5.8.

### 5.2.2 The Attosecond Timescale in Atoms and Molecules

In 2001, experimental observation of attosecond laser-induced phenomena was first reported.[9] In these studies, an attosecond pulse or train of pulses were synthesized from a broadband high harmonic frequency comb created through intense laser-atom interactions. As of this writing, HHG from gases remains the most versatile demonstrated signature for attosecond electron-atom collisions. Current sources of laser-driven attosecond pulses and pulse trains made from these interactions have been demonstrated over 10-150 eV XUV photon energy range with $10^8$ to $10^{10}$ photons per pulse[10] and 1-2 keV range with $10^4$ to $10^5$ photons per pulse.[11] The repetition rate of these sources is tied to the laser repetition rate and varies from ~10 Hz to 10 kHz, corresponding to ~μW average power. Current sources can drive linear absorption processes, but current pump-probe arrangements rely on a reference strong field, usually the fundamental femtosecond laser field, to initiate and drive nonlinear dynamics in matter.

Over the last decade, the worldwide activity in attosecond properties of matter has grown exponentially. However, current source parameters are limiting potential applications due to the poor conversion efficiency of laser light into attosecond soft X-ray pulses in coherently driven gases. Consequently, future opportunities will be significantly enhanced by novel sources such as X-ray FELs or sources that can scale to higher average and peak power, motivated by new optical laser drivers and paradigms for subcycle laser-matter response. In fact, the Extreme Light Infrastructure-Attosecond Light Pulse Source (ELI-ALPS) facility in Hungary is dedicated to pursuing this frontier. Figure 5.2 summarizes the history and future of ultrafast pulse generation driven by high-intensity lasers.

[9] P.M. Paul, et al., 2001, Observation of a train of attosecond pulses; M. Hentschel, et al., 2001, Attosecond metrology.

[10] Z. Chang, 2011, *Fundamental of Attosecond Optics,* CRC Press, Boca Raton.

[11] T. Popmintchev, M-C Chen, D. Popmintchev, P. Arpin, S. Brown, S. Ališauskas, G. Andriukaitis, et al., 2012, Bright coherent ultrahigh harmonics in the keV x-ray regime from mid-infrared femtosecond lasers, *Science* 336(6086): 1287-1291.

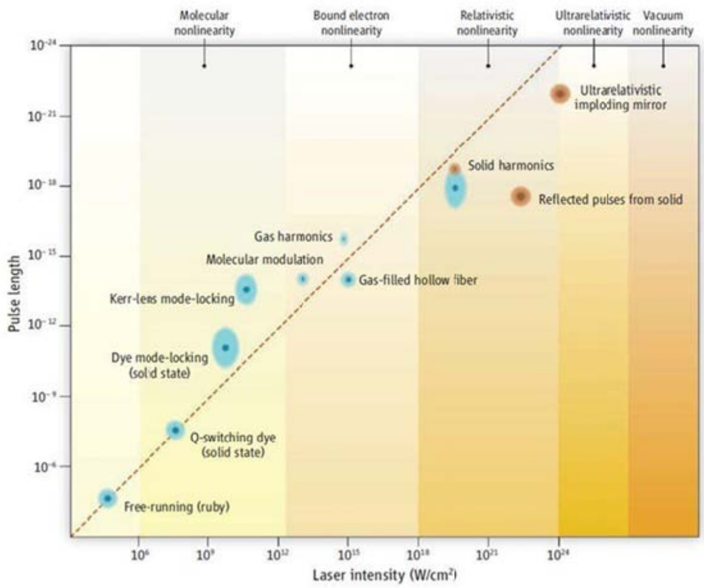


**FIGURE 5.2** A plot of the correlation between pulse duration of coherent light emission and the laser intensity. These entries encompass different underlying physical regimes that exhibit molecular, bound atomic electron, relativistic plasma, ultra-relativistic, and vacuum nonlinearities. Blue patches represent experimental data; red patches denote simulation or theory. SOURCE: G. Mourou and T. Tajima, 2011, More intense, shorter pulses, *Science* 331: 41-42.

### 5.2.2.1 Attosecond Response of Matter Driven by High-Average Power Lasers

All stable matter is held together by electrons, whose mass ($m$=9x$10^{-31}$kg) and charge ($e$=-1.6x$10^{-19}$ c), along with Planck's constant, lead to the quantum time scale of tens to hundreds of attoseconds for motion in a chemical or atomic bond. This motion cannot be directly observed using conventional experimental tools, but can be studied using a powerful method where an electron is displaced with an attosecond pulse from a laser, and then probed later to measure the change. High intensity lasers are essential to produce these attosecond pulses. There are two current paths for expanding research using current attosecond generation and detection methods and laser technology: (1) increase the number of photons per pulse by scaling the source geometry to higher laser pulse energy or (2) increase the number of pulses per second via larger average power drive lasers. The latter approach has several advantages including good data collection statistics with use of multiple simultaneous particle and photon diagnostics. Currently, 10 W average power drive lasers based on femtosecond titanium sapphire (Ti:Sapphire) amplifier architecture routinely operate at 1-10 kHz repetition rate. Maintaining a constant peak power, an increase in repetition rate to 100 kHz-1 MHz would require 1 kW drivers, thus increasing the attosecond source to nearly mW average power.

### 5.2.2.2 Attosecond Pulses from X-ray Free Electron Lasers

X-ray free-electron lasers (FELs), described in chapter 2, have great potential for generating bright attosecond pulses, but controllable isolated attosecond pulses have not yet been reported.[12] There are several advantages of an X-ray FEL: the attosecond pulses can be generated in the soft and hard X-ray regime, (0.1-10 keV), have high pulse energy (µJ), and produce high average power (1 watt). The X-ray FEL sources are national laboratory-scale facilities while current HHG sources are tabletop and more readily commercialized for broader use.

#### 5.2.2.3 Sub-Attosecond Emission from Relativistic Plasmas

Extreme intensities in the relativistic regime ($a$>1) interacting with a solid target is a promising route for generating substantially brighter, harder X-rays (> 150 eV) with sub-attosecond (zeptosecond) duration. This technology could change the scope of ultrafast applications beyond current capabilities dramatically by reaching the nuclear time scale.

High harmonics radiation can be generated during relativistic laser-plasma interaction when the density scale-length is less than the laser wavelength.[13] Under these conditions the laser's electric field can couple efficiently to the critical density surface, which acts as a relativistic oscillating mirror,[14] generating both odd and even harmonics. The coherent oscillation and the sharp density gradient of the mirror cause the entire spectrum to phase-lock. Theoretically this could produce a train of zeptosecond X-ray pulses phase-matched in a small solid angle.[15] Furthermore, the large nonlinearity allows efficient coupling into the HHG comb. Researchers using the Vulcan laser facility in the UK have measured X-ray HHG extending to 3.3 Å (3.8 keV) from a high energy (> 200 J) petawatt-class laser-solid (CH-film) interaction.[16]

## 5.3 HIGH-INTENSITY PETAWATT LASER STUDIES OF HIGH ENERGY DENSITY SCIENCE, PLANETARY PHYSICS, AND ASTROPHYSICS

Laboratory-based experiments that create and explore extreme states of matter characterized by high density, temperature, and pressure—high energy density science—are the only terrestrial means for addressing issues relevant to the physics of planetary interiors, for example. High energy density science (HEDS) can be categorized as the study of warm dense matter (WDM) or hot dense matter (HDM), described in FIGURE 5.3.

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[12] W. Helml, A.R. Maier, W. Schweinberger, I. Grguraš, P. Radcliffe, G. Doumy, C. Roedig, et al., 2014, Measuring the temporal structure of few-femtosecond free-electron laser X-ray pulses directly in the time domain, *Nat Photon* 8: 950–957; C. Feng, J. Chen, and Z. Zhao, 2012, Generating stable attosecond x-ray pulse trains with a mode-locked seeded free-electron laser, *Phys. Rev. ST Accel. Beams* 15: 080703; E. Prat and S. Reiche, 2015, Simple method to generate terawatt-attosecond x-ray free-electron-laser pulses, *Phys. Rev. Lett.* 114: 244801; J.D. Sadler, R. Nathvani, P. Oleśkiewicz, L.A. Ceurvorst, N. Ratan, M.F. Kasim, R.M.G.M. Trines, R. Bingham, and P.A. Norreys, 2015, Compression of x-ray free electron laser pulses to attosecond duration, *Scientific Reports* 5: 16755.

[13] B. Dromey, M. Zepf, A. Gopal, K. Krushelnick, K. Lancaster, M.S. Wei, R. Clarke, et al., 2006, High harmonic generation in the relativistic limit, *Nature Phys*. 2: 456-459.

[14] S.V. Bulanov, et al., 1994, Interaction of an ultrashort, relativistically intense laser-pulse.

[15] G.D. Tsakiris, K. Eidmann, J. Meyer-ter-Vehn, and F. Krausz, 2006, Route to intense single attosecond pulses, *New J. Phys.* 8: 1-20.

[16] B. Dromey, et al., 2006, High harmonic generation in the relativistic limit.

The study of these regimes is also relevant for applications in energy and national security. This is discussed in Section 6.3

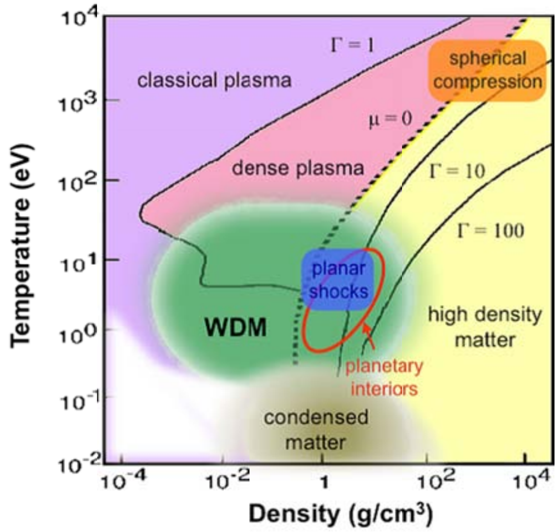


**FIGURE 5.3** States of matter plotted in temperature/density phase space. Shown are the locations for WDM and regions of strongly coupled plasmas (Γ>1). SOURCE: K. Falk, 2015, "Warm Dense Matter," presented at ELI Summer School, Sept. 21-25, Bucharest, Hungary.

*Warm dense matter* (WDM) is a regime that lies between traditional plasma physics, which applies to ionized matter at high thermal temperature and low density, and traditional condensed matter physics, which applies to thermally cold, dense matter. In the WDM regime of temperature/density space, neither condensed matter concepts of relatively cold near-degenerate Fermi gas metals apply, nor do the kinetic energy-dominated statistical physics models of plasmas. WDM occurs in the interior of planets like Jupiter and in laser-heated systems that start as a cold solid and end up as an ionized plasma, such as X-ray-driven inertial fusion. Here the average potential energy between charged particles can exceed their thermal energy.

*Hot dense matter* (HDM) occurs in stellar interiors, supernovae, and accretion discs. It also occurs in thermonuclear explosions or laser-driven inertial fusion experiments. Here, typical thermal energies can exceed inter-particle potential energies.

Researchers interested in exploring these physics regimes in the laboratory, either for astrophysics or for fusion or plasma physics, must create simultaneous conditions of high temperature and high density in a target and then view these conditions during the short time before radiation or collisional processes remove energy from the target, or the target distorts from mass flow. Transient high temperatures and densities imply the need for ultrafast, short wavelength probe beams.[17] Ultrafast pulses of intense hard X-rays with photon energies of about 10 keV or greater can penetrate the plasma to reveal the conditions of its interior. X-ray scattering from these intense regions can accurately measure the plasma temperature and density using Thomson scattering from the plasma electrons; therefore, such X-ray sources are essential tools in all laboratories pursuing HEDS.

The conditions for HEDS, in almost all laboratories where it is studied today, are produced by nanosecond pulsed lasers approaching 1 MJ per pulse, such as the Lawrence Livermore National Laboratory (LLNL) National Ignition (NIF) laser, the Rochester OMEGA laser, and the CEA Le Laser Mégajoule in France. The nanosecond-scale pulse duration for optimal heating is the set target size (~0.1-

[17] R.W. Lee, 2007, *High Energy Density Science at the Linac Coherent Light Source*, Lawrence Livermore National Laboratory, UCRL-TR-236300.

1 mm) divided by the plasma sound speed (~km/s). These are the highest energy lasers in the petawatt class, although their pulse durations are so long that generally they operate with sub-petawatt peak power. The requirement for nanosecond pulses means that these lasers do not employ CPA or aim for very broad bandwidth, two of the primary characteristics of ultrafast petawatt technology. Rather, they employ large aperture scaling with multiple arms of many stages of solid-state gain media in slabs on the order of 1 meter across and excited by very high energy flashlamps.

### 5.3.1 Planetary Physics and Astrophysics

For planetary physics, understanding the equation-of-state of extreme matter stands as a central challenge.[18] The interiors of giant planets exist in a pressure/temperature regime where accurate equation-of-state calculations are extremely difficult. Understanding chemistry under these extreme conditions is particularly challenging because molecules, atoms, and ions coexist in a fluid that is coupled by Coulomb interactions and is highly degenerate (free electrons governed by quantum and thermal effects). These strong interactions dominate in the steady-state interiors of giant planets such as Saturn and Jupiter and in brown dwarfs since their low mass never generates sustained thermonuclear fusion as in stars.

For astrophysics, laboratory experiments can provide important input data to models or help reveal the underlying mechanisms driving complex hydrodynamic processes. For instance, theoretical models of processes such as galaxy formation and stellar core collapse often rely on parameters not yet measured, such as the opacities that determine photon transport.[19] Similarly, high-field magneto-hydrodynamics is conjectured to play a role in ultra-energetic cosmic ray generation[20]—laser plasma studies can shed light on this process—while a focus on turbulence in shear flow can provide insight into momentum transport in plasmas and possibly explain how angular momentum is removed during matter accretion by black holes.[21]

Extreme states of matter can be created using PW-class lasers over a wide range of photon energies. Currently, PW-class lasers operate at near-visible wavelengths and, depending on focusing, offer the highest on-target intensities. On the other hand, X-ray FELs are capable of producing more uniform heating since the low absorption cross section at short wavelength allows X-rays to penetrate compared to visible radiation. Uniform heating is critical to experiments that aim to measure equations-of-state.

Petawatt-class lasers (femtosecond pulses with <~1 kJ energy or nanosecond pulses with ~MJ energy (e.g., NIF, or in combination) are capable of heating samples to energy densities (pressure and temperature) much larger than other laboratory approaches such as gas guns and high explosives. Consequently, lasers can produce matter under reproducible conditions that, with rigorous scaling, are equivalent to those in large astrophysical systems, such as supernova, Herbig-Haro gas jets,[22] or giant planets. They can also be used to probe these states either directly through absorption/scattering or indirectly by producing secondary probes such as X-rays, electrons, and protons or directly with X-ray FELs.

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[18] F.D. Stacey, 2005, High pressure equations of state and planetary interiors, *Rep. Prog. Phys.* 68: 341.

[19] E. Bohm-Vitense, 1989, *Introduction to Stellar Astrophysics, Vol. 1: Basic Stellar Observations and Data,* Cambridge University Press, New York.

[20] K. Asano and P. Meszaros, 2016, Ultrahigh-energy cosmic ray production by turbulence in gamma-ray burst jets and cosmogenic neutrinos, *Phys. Rev. D* 94: 023005.

[21] M. Hoshino, 2015, Angular momentum transport and particle acceleration during magnetorotational instability in a kinetic accretion disk, *Phys. Rev. Lett.* 114: 061101.

[22] Reipurth, B. and S. Heathcote, 1997, 50 years of Herbig-Haro research, pp. 3-18 in *Herbig-Haro Flows and the Birth of Stars: Proceedings of the 182nd Symposium of the International Astronomical Union* (B. Reipurth and C. Bertout, eds.), Springer, The Netherlands.

With continued advances in modeling of planetary and astrophysical phenomena, one can anticipate that data from laboratory experiments will play an increasingly important role. Below the committee discusses some scientific and/or experimental issues relevant to planetary physics and astrophysics.

#### 5.3.1.1 Giant Planets: Plasma Coupling and Degeneracy

Coupling in plasmas is typically characterized by a dimensionless parameter, $\Gamma = (Ze)^2/akT$, where $a$ is a characteristic separation distance between ions of charge state $Ze$. For $\Gamma << 1$, thermal effects dominate and the plasma is considered ideal. Strong coupling by Coulomb interactions occurs for $\Gamma \geq 1$. Figure 5.3 shows that Jupiter and the brown dwarf Gliese 1229B, which are composed of H and He, are strongly coupled and highly degenerate. For $\Gamma >> 1$, the coupling becomes so strong that ions freeze into a crystal lattice. At high density and low temperature ($kT < \varepsilon_F$, the Fermi energy), the plasma becomes degenerate, e.g., right of the $\varepsilon_F = kT$ line in Figure 5.3. Here Pauli exclusion plays a major role, through electron degeneracy, in determining the pressure. Hence the internal structure and the magnetic fields of giant planets are determined by knowledge of the equation-of-state at high pressures, $10^{11}$ - $10^{13}$ pascal. Calculations based on first-principles theories are extremely difficult and inaccurate. Thus, PW-class laser experiments in this regime are a vital component in efforts to improve our understanding of planetary physics.

#### 5.3.1.2 Dynamic Ramped Compression

PW-class lasers have demonstrated compression of a few terapascal (14-times the pressure in the earth center),[23] with dynamic ramp compression (DRC) of diamond to unprecedented densities of $12 g/cm^3$.[24] The DRC method can produce extreme pressures that are much larger than using static methods, e.g., diamond anvil cells. In addition, DRC has advantages over other methods like light-gas guns or explosives since it can produce less dissipative heating, thus producing compression at lower temperature.[25] Sufficient control of these experiments is necessary to avoid shock compression. Consequently, these experiments are more aligned with the ambient environment of a planet's interior.

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[23] R.F. Smith, J.H. Eggert, R. Jeanloz, T.S. Duffy, D.G. Braun, J.R. Patterson, R.E. Rudd, et al., 2014, Ramp compression of diamond to five terapascals, *Nature* 511: 330-333.

[24] R.F. Smith, et al., 2014, Ramp compression.

[25] R.F. Smith, et al., 2014, Ramp compression.

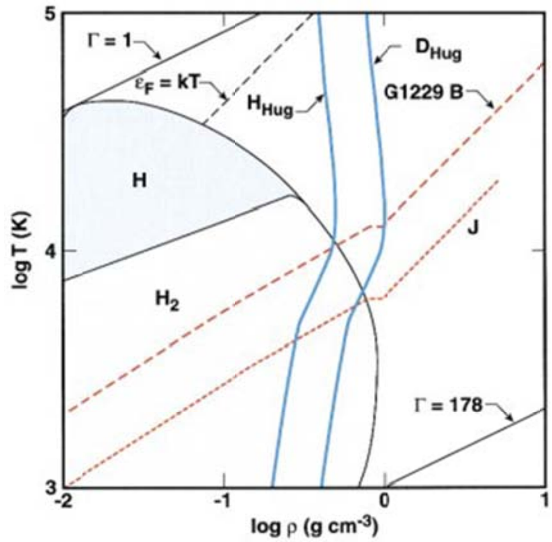


**FIGURE 5.4** Theoretical phase diagram of hydrogen relevant to Jupiter (J) and brown dwarf (G129B). $H_{Hug}$ and $D_{Hug}$ are the model hydrogen and deuterium Hugoniots. SOURCE: G.W. Collins, L.B. Da Silva, P. Celliers, and R. Cauble, 1998, Measurements of the equation of state of deuterium at the fluid insulator-metal transition, *Science* 281(5380): 1178-1181.

*Phase transitions* play an important role in planetary physics and astrophysics, and this can also be studied using high-intensity lasers. For instance, understanding the high pressure phases of carbon is important since carbon is a major element of giant planets such as Uranus and Neptune.[26] PW-driven shock wave measurements of the diamond principal Hugoniot have been made at pressures between 6 and 19 Mbar using the Laboratory of Laser Energetics (LLE) OMEGA laser. The Hugoniot curve traces the path accessed by the laser-induced shock driven in the material. The results were in good agreement with published ab initio calculations and indicated that in the solid-liquid coexistence regime between 6 and 10 Mbar, the mixed phase may be slightly more dense than would be expected from a simple interpolation between liquid and solid Hugoniots.[27]

Near Jupiter's surface ($10^{11}$ pascal and fraction of an electron volt), hydrogen exits in molecular form but it dissociates and ionizes deeper into the planet's core ($>10^{12}$ pascal and few eV). This transition from insulator to conductor in the convective zone is believed to be responsible for Jupiter's 10 to 15 gauss magnetic field. An open question is whether there is a sharp plasma phase transition. Experiments performed on the Nova laser at LLNL initially suggested that the transition was continuous,[28] and subsequent experiments unambiguously demonstrated that the transition from non-conducting molecular hydrogen to atomic metallic hydrogen at high pressure is a continuous transition. This suggests that the

[26] W.B. Hubbard, 1981, Interiors of the giant planets, *Science* 214(4517): 145-149.

[27] D.G. Hicks, T.R. Boehly, P.M. Celliers, D.K. Bradley, J.H. Eggert, R.S. McWilliams, R. Jeanloz, and G.W. Collins, 2008, High precision measurements of the diamond Hugoniot in and above the melt region, *Phys. Rev. B* 78: 174102.

[28] G.W. Collins, L.B. Da Silva, P. Celliers, and R. Cauble, 1998, Measurements of the equation of state of deuterium at the fluid insulator-metal transition, *Science* 281(5380): 1178-1181.

metallic region of Jupiter's interior extends out to 90 percent of the radius of the planet and may explain why the magnetic field of Jupiter is so much stronger than that of the other planets of our solar system.[29]

A *supernova* (SN), the explosion of a star, is a spectacular event that can outshine a star's entire host galaxy. Supernovae involve a broad range of physical processes across disparate areas of science such as nuclear physics, general relativity, and fluid mechanics. Type-II Supernovae—thought to occur as a result of gravitational collapse—pose a number of challenges to first principles models. Laboratory experiments exploring relevant hydrodynamic phenomena can improve our understanding of these complex astrophysical events.

It is believed that when an exploding star's core collapses, an outward propagating shock is launched which reaches the star's surface and leads to a burst of (optical) luminosity.[30] Theory indicates that 2D and 3D hydrodynamic effects play an important role in the rise of the luminosity burst—the observable detected by optical telescopes. The shock wave drives a stellar mixing process as an outward flow of heavy elements from the star's core mixes with the hydrogen and helium that dominate at the star's surface. While the Rayleigh-Taylor (RT) hydrodynamic instability is thought to play an important role in this hydrodynamic mixing,[31] simulations of the RT instability have failed to explain SN observations.[32] Given that unresolved hydrodynamic problems limit our understanding of supernovae, laboratory experiments that seek to observe the nonlinear hydrodynamics of this mixing process are well motivated. Experiments can test codes that simulate the nonlinear behavior to determine if any other physics, not present in the simulations, appears in the experiments.

*Opacity measurements*. The kinetic energy release in a typical supernova event is ~$10^{44}$ joules, with only a few percent of this energy emitted as visible radiation.[33] Since SN light detected by optical telescopes does not come from the exploding star's core, where the energy is released, but rather from the star's outer shell (photosphere), understanding the core-to-photosphere energy transport is very important to interpreting measured SN visible light curves. The transport of stellar matter and radiation is a complex and theoretically challenging hydrodynamic problem. Photon transport through a medium is characterized by the medium's opacity, making opacity models particularly critical to modeling supernovae and other astrophysical phenomena such as the pulsing of Cepheid variable stars.[34] PW-class experiments enhance our understanding of variable stars by providing direct opacity measurements under astrophysically relevant conditions.

*Relativistic plasmas and gamma-ray bursts.* At sufficiently high energy density, relativistic plasma physics becomes important, and PW-class studies in this regime could provide information important to a number of astrophysical processes. Relativistic plasmas, for instance, are thought to be important to the origin of cosmic rays, beams of relativistic particles such as protons and atomic nuclei. The precise acceleration mechanisms are uncertain but shock fronts are thought to provide the

[29] P.M. Celliers, G.W. Collins, L.B. Da Silva, D.M. Gold, R. Cauble, R.J. Wallace, M.E. Foord, and B.A. Hammel, 2000, Shock-induced transformation of liquid deuterium into a metallic fluid, *Phys Rev Lett.* 84: 5564-5567.

[30] T. Shigeyama and K. Nomoto, 1990, Theoretical light curve of SN 1987A and mixing of hydrogen and nickel in the ejecta, *Astrophys. J.* 360: 242–256.

[31] W.D. Arnett, 1988, On the early behavior of supernova 1987A, *Astrophys. J.* 331: 377–387; D. Arnett, B. Fryxell, and E. Muller, 1989, Instabilities and nonradial motion in SN-1987A, *Astrophys. J. Lett.* 351: L63–L66.

[32] P.G. Sutherland, 1990, Gamma-rays and x-rays from supernovae, p. 111 in *Supernovae* (A.G. Petschek, ed.), Springer-Verlag, New York.

[33] B.A. Remington, R.P. Drake, and D.D. Ryutov, 2006, Experimental astrophysics with high power lasers and Z pinches, *Rev. Mod. Phys.* 78: 755-807.

[34] E. Bohm-Vitense, 1989, *Introduction to Stellar Astrophysics, Vol. 1*.

acceleration, and it has been argued that cosmic rays could be produced along with gamma-ray bursts (GRBs).[35]

*Magnetic fields in astrophysics.* Strong magnetic fields play an important role in a number of astrophysical processes such as solar flare generation and conversion of stored stellar energy into either randomized (thermal) or directed (e.g., particle acceleration) kinetic energy.[36] PW-class studies of ultra-high magnetic field generation and interactions can address important questions such as whether magnetic fields affect cosmological structure formation and how strong magnetic fields originated in the universe.

### 5.3.2 Isochoric Heating and High Energy Density Plasmas

The study of the material properties of matter uniformly heated to extreme pressures is of interest for basic studies of strongly coupled plasmas, degenerate and non-degenerate warm dense matter, and the understanding of high density plasmas characteristic of inertial confinement fusion experiments and defense applications. Constant volume heating (isochoric heating) is desirable using intense ultrashort laser pulses,[37] as there is little material motion or expansion/compression during such pulses and uniform conditions can be subsequently probed. Such heater pulses can be from high-intensity ultrashort pulse lasers[38] or from X-ray FEL sources such as Linac Coherent Light Source (LCLS) or Flash,[39] or possibly a timed combination. The material and its electronic and structural properties can then be interrogated with auxiliary ultrashort particle and photon probe beams synchronized to the high-intensity ultrashort heater pulse. These probes can be secondary sources from the laser itself (such as laser accelerated electron bunches, laser-driven wakefield acceleration-driven betatron sources, or Compton scattering sources), or an X-ray FEL. Particle probes such as protons can image electric and magnetic fields internal to the material,[40] while high energy photon probes can generate radiographic images[41] or reveal internal structure and dynamics through their coherent and incoherent scattering spectra.[42]

Isochorically-heated material can remain at near-solid density when heated by an intense short pulse[43] or can be strongly compressed to many times solid density by separate, longer duration laser pulses after which it is strongly heated by a short pulse.[44] Isochoric heating can also be accomplished

[35] M.V. Medvedev and O.V. Zakutnyaya, 2009, Magnetic fields and cosmic rays in GRBs: a self-similar collisionless foreshock, *The Astrophysical Journal* 696: 2269–2274.

[36] M.V. Medvedev and A. Loeb, 1999, Generation of magnetic fields in the relativistic shock of gamma-ray burst sources, *ApJ*, 526: 697-706.

[37] R.R. Fäustlin, Th. Bornath, T. Döppner, S. Düsterer, E. Förster, C. Fortmann, S.H. Glenzer, et al., 2010, Observation of ultrafast nonequilibrium collective dynamics in warm dense hydrogen, *Phys. Rev. Lett.* 104: 125002.

[38] A. Saemann, et al., 1999, Isochoric heating of solid aluminum.

[39] R.R. Faustlin, et al., 2010, Observation of ultrafast nonequilibrium collective dynamics.

[40] C.K. Li, F.H. Séguin, J.A. Frenje, J.R. Rygg, R.D. Petrasso, R.P.J. Town, P.A. Amendt, et al., 2006, Measuring E and B fields in laser-produced plasmas with monoenergetic proton radiography, *Phys. Rev. Lett.* 97: 135003.

[41] F.J. Marshall, P.W. McKenty, J.A. Delettrez, R. Epstein, J.P. Knauer, V.A. Smalyuk, J.A. Frenje, et al., 2009, Plasma-density determination from x-ray radiography of laser-driven spherical implosions, *Physics Review Letters* 102(18): 185004.

[42] S.H. Glenzer and R. Redmer, 2009, X-ray Thomson scattering in high energy density plasmas, *Rev. Mod. Phys.* 81: 1625.

[43] Y. Ping, D. Hanson, I. Koslow, T. Ogitsu, D. Prendergast, E. Schwegler, G. Collins, and A. Ng, 2006, Broadband dielectric function of nonequilibrium warm dense gold, *Phys. Rev. Lett.* 96: 255003.

[44] S.H. Glenzer and A.J. Mackinnon, 2015, *New Science Opportunities enabled by Petawatt-class Lasers at LCLS-II*, SLAC National Accelerator Laboratory, Menlo Park, Calif.

using ultrashort charged particle beams driven by a primary ultrashort intense laser pulses. Figure 5.3 shows the states of matter plotted versus density and temperatureOne area of application of well-characterized isochorically heated matter is studying their interaction with high energy ions, including α-particles (helium nuclei).[45] A useful measurable parameter describing the interaction is the α-particle stopping power. This has application to heating of laboratory and solar/astrophysical fusion plasmas and will inform use of high energy ions as probes and as therapeutic interaction beams.[46] The short pulse α-particle beam will be produced from laser solid interaction, and the dense target can be generated with a portion of the same beam.

Another area is fundamental—the material properties of dense hydrogen and deuterium plasmas, the most basic of materials. Aside from its relevance to theoretical models of condensed matter physics in extreme conditions, the study of dense hydrogen is directly relevant to an understanding of planetary interiors and stars (as discussed in Sec 5.3.3) and fusion plasmas.[47] Intense heating using a combination of laser pulses can generate hydrogenic plasmas at variable density and temperature, allowing exploration of various phases and their electronic and structural properties, potentially including the long sought after metallic hydrogen state.[48] Such targets can be probed, for example, using short LCLS X-ray pulses to measure density, temperature, conductivity, ion-ion correlations, structure factors, and transport coefficients using both collective scattering (coherent Thomson scattering) from density structures and scattering from individual electrons (incoherent Thomson scattering, transitioning to Compton scattering for high energy probe photons),[49] as well as supplemented by older shock-based diagnostics such as interferometry of and pyrometry of induced shock fronts.[50] The shortness of the available probes driven by the laser itself and from X-ray FELs can enable time resolution in such measurements, making possible the tracking of electron-ion equilibration, the evolution of electron degeneracy, and the assessment of the applicability of equation-of-state models.

Laser plasma backlighters have most often been used as probes in these experiments. Their primary limitations, even those driven by petawatt lasers, are that they have insufficient brightness and time resolution. Since they are incoherent point sources, their total useful flux depends on the solid angle of the X-ray shadow from the backlighter source that is cast by the target on an area detector illuminated by the X-rays. On the other hand, X-ray FELs are far brighter, have transverse coherence, and are directional. In addition, with pulse durations well under 100 fs, they are an effective probe with sufficient time resolution to view the HED transient state. For this reason, the co-location of ultrashort high-intensity lasers and X-ray FELs is particularly advantageous for such experiments.

### 5.3.3 Science That Combines X-ray Free-Electron Lasers, High Energy Electron Accelerators, and Petawatt-Class Lasers

X-ray FELs are high-intensity light sources of a special nature that can be used for unique science tasks related to their short wavelength (see Chapters 1 and 2, Section 5.2, and Section 5.7). In addition to

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[45] J.A. Frenje, et al., 2015, Measurements of ion stopping around the Bragg peak.

[46] C.K. Li, et al., 2006, Measuring E and B fields in laser-produced plasmas; J.A. Frenje, et al., 2015, Measurements of ion stopping around the Bragg peak; S.V. Bulanov and V.S. Khoroshkov, 2002, Feasibility of using laser ion accelerators in proton therapy, *Plasma Physics Reports* 28(5): 453-456.

[47] K. Falk, 2015, “Warm Dense Matter,” presented at ELI Summer School, Sept. 21-25, Bucharest, Hungary.

[48] E. Conover, 2016, The pressure is on to make metallic hydrogen, *Science News* 190(4): 18.

[49] S.H. Glenzer and R. Redmer, 2009, X-ray Thomson scattering.

[50] K. Falk, E.J. Gamboa, G. Kagan, D.S. Montgomery, B. Srinivasan, P. Tzeferacos, and J. F. Benage, 2014, Equation of state measurements of warm dense carbon using laser-driven shock and release technique, *Phys. Rev. Lett.* 112(15): 155003.

this, conventional petawatt lasers can carry out many research applications when combined with X-ray FELs. This topic has always been one of the main science drivers for X-ray FELs. Early conceptions of this new regime of high-intensity physics are described in *LCLS:The First Experiments*.[51] Further workshops over the past 15 years have continued to develop this theme. Petawatt lasers now exist at SACLA, and they are already in the advanced planning stage at LCLS and European X-ray FEL.[52]

Here the committee summarizes one compelling science case for the study of High Energy Density Science. The high-energy nanosecond Nd:glass lasers used in most HEDS research are large billion-dollar-class stand-alone facilities. None is located in the vicinity of the half-dozen or so hard X-ray FELs, which are also of billion-dollar class. Instead, HEDS lasers such as NIF and OMEGA employ auxiliary high-intensity short laser pulse-driven plasmas which act as sources of X-rays to back-light the HED plasmas of interest. The backlighter drive lasers are optimized to produce very high temperature plasmas that generate hard X-rays. This can be a femtosecond PW-class laser source, and X-ray backlighters of this type have been discussed in Chapter 3.

X-rays from FELs are employed in these experiments either to view the conditions created by conventional high-intensity lasers or to create the extreme conditions themselves.[53] These are "single-shot" experiments, and therefore require the high X-ray flux delivered only by X-ray FEL, which are about one thousand times shorter (less than 100 fs) and one million times more energetic (millijoules of energy) than the largest synchrotron sources.

## 5.4 PETAWATT LASER-DRIVEN PARTICLE ACCELERATORS

### 5.4.1 Particle Acceleration and Particle Physics

Particle accelerators driven by intense, short pulse lasers are in development for the purpose of a new technology of ultra-high gradient devices that occupy a much smaller footprint than conventional machines. A primary limitation of conventional charged particle accelerators for particle physics and higher intensity sources is their size and the associated costs of large conventional machines. Smaller and lower cost laser-driven acceleration solutions are therefore valuable.[54] High particle energy, high beam intensity and brightness, and high efficiency are important goals of this research. Laser-driven accelerators will enable applications for discovery science in particle physics and other basic sciences, as well as applications in medical physics and compact light source development. To set the scale, electron accelerators at >10 GeV and proton accelerators at >100 MeV will demand lasers of PW-peak power, high repetition rate, high average power, and high efficiency. The research and development of laser-driven accelerators is intimately tied to the technological development of ultrafast PW-class lasers.

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[51] Stanford Linear Accelerator Center (SLAC), 2003, *LCLS: The First Experiments*, http://slac.stanford.edu/pubs/slacreports/reports03/slac-r-611.pdf.

[52] S.H. Glenzer and A.J. Mackinnon, 2015, *New Science Opportunities*; M. Nakatsutsumi and Th. Tschentscher, 2013, Conceptual Design Report: Scientific Instrument HED, European X-Ray Free-Electron Laser Facility GmbH, Hamburg, Germany.

[53] S. H. Glenzer et al., "Matter under Extreme Conditions Experiments at the Linac Coherent Light Source," *Journal of Physics B: Atomic, Molecular and Optical Physics* 49, no. 9 (2016): 092001, doi:10.1088/0953-4075/49/9/092001.

[54] England, "Dielectric Laser Accelerators," Rev Mod Phys. 86, 1337 (2014); and The Economist, "Small Really is Beautiful," Oct. 19, 2014.

Particle accelerators of higher energy and higher luminosity[55] are required to advance the frontiers of particle physics. The highest center-of-mass energy (CME) for searching for new particles and probing for new fundamental interactions are provided by intersecting particle storage rings, which collide two intense beams of particles. Currently, the Large Hadron Collider (LHC) (i.e., proton-proton beams) at CERN is the state of the art in this field. The aim of the LHC is to allow physicists to test the predictions of different theories of particle physics, including measuring the properties of the Higgs boson (awarded the 2013 Nobel Prize in Physics)[56] and searching for the large family of new particles predicted by supersymmetric theories,[57] as well as other unsolved questions about fundamental particles. Increasing the CME in the next generation collider using current accelerator structures is a challenge due to the unfavorable technical scaling with size (the LHC tunnel is already 17 miles in circumference) and economics (the LHC cost $4.75 billion to construct and costs $1 billion per year to operate).[58] At dawn of the new millennium, Figure 5.5 shows that these challenges have greatly reduced the projections in achieving higher CME for colliders.[59]

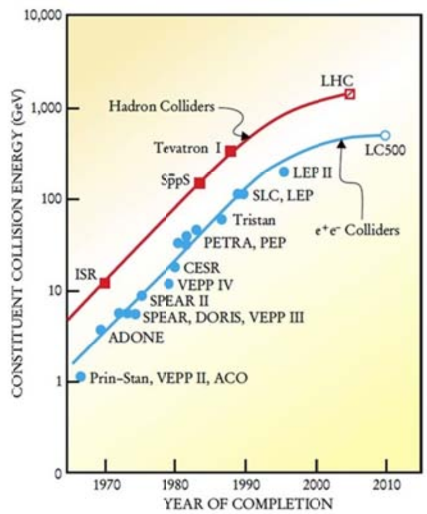


**FIGURE 5.5** Effective constituent collisions energy of hadron colliders (top curve) and electron-positron colliders (bottom curve). The Livingston plot shows that the CME increased by a factor of 100 every 25 years but this has dramatically decreased entering the new millennia. This saturation has many contributions including technical and economics. SOURCE: M. Tigner, 2001, Does accelerator-based particle physics have a future? *Phys. Today* 54(1): 36.

To go beyond the current state of the art, the high energy physics Particle Physics Project Prioritization Panel (P5) report recommended a greatly expanded accelerator research and development program that would emphasize the ability to build very high-energy accelerators (larger acceleration

[55] In particle physics, luminosity measures the ability of a particle accelerator to produce the required number of interactions and is the proportionality factor between the number of events per second and the collision cross section, and has units of $cm^{-2}\ s^{-1}$.

[56] CERN, "The Higgs Boson," https://home.cern/topics/higgs-boson, accessed February 9, 2017.

[57] CERN, "United Forces," http://home.cern/about/physics/unified-forces, accessed February 9, 2017.

[58] A. Knapp, 2012, "How Much Does It Cost To Find A Higgs Boson?" *Forbes Magazine*, July 5.

[59] M. Tigner, 2001, Does accelerator-based particle physics have a future? *Phys. Today* 54(1): 36.

gradients) beyond the High-Luminosity LHC and International Linear Collider at dramatically lower cost.[60] PW laser-driven acceleration is one concept under consideration.

The technical requirements for colliders are extreme, and development of a future high energy collider is the most challenging and long-term application of laser-driven particle accelerators. Conventional charged particle accelerators have already enabled the development of coherent and incoherent high energy photon sources having application to basic science, engineering, and medicine. Laser-driven high-energy accelerators make possible a new generation of such light sources on a much more compact scale (meter scale), including FELs and Thomson scattering sources producing high-energy X-rays. Early experiments have already demonstrated some of these sources.[61] The compact scale of these laser-driven sources will facilitate their wide application. The high energy charged particles from laser-driven accelerators can also be employed for medical imaging, radionuclide production, and cancer therapy. Of particular use for cancer therapy are high energy proton beams, which have a well-defined stopping distance (Bragg peak) in human tissue, thus reducing collateral tissue damage. Currently, proton cancer therapy is performed at large and expensive cyclotron facilities, making laser-driven sources especially desirable.

Several techniques for laser-driven electron acceleration are under investigation. The most successful method, demonstrating the highest energy and beam quality, uses laser-driven plasmas as the acceleration medium. This scheme is called “laser-driven wakefield acceleration” (LWFA) and uses the large longitudinal electrostatic field of a laser-driven plasma wave to effect the acceleration. Two other schemes using short pulse lasers, well behind LWFA in development, will not be discussed in detail here. One uses quasi-phase matching in corrugated plasma guiding structures of the propagating optical laser field to the electrons, directly accelerating them,[62] and is called direct laser acceleration (DLA). The other scheme is non-plasma based and uses micron-scale dielectric structures driven by optical lasers.[63] As this method is also reliant on direct acceleration by the laser, it is also referred to as DLA, where the first letter can signify “dielectric” or “direct.”

### 5.4.2 Laser-Driven Plasma Wakefield Acceleration

LWFA is realized by using an intense, ultrafast laser pulse to produce a ponderomotive force to drive a plasma wave. The plasma wave is created as the laser pulse propagates in subcritical density plasma generated in a gas jet or in a plasma discharge, using high-intensity optical guiding using pre-formed plasmas[64] or self-guiding.[65] The enormous axial electrostatic field of the plasma wave, which propagates with the group velocity of the laser pulse, can accelerate electrons externally injected or self-

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[60] Particle Physics Project Prioritization Panel, 2014, *Building for Discovery: Strategic Plan for US Particle Physics in the Global Context*, https://science.energy.gov/~/media/hep/hepap/pdf/May-2014/FINAL_P5_Report_Interactive_060214.pdf.

[61] V. Malka, J. Faure, Y.A. Gauduel, E. Lefebvre, A. Rousse, and K.T. Phuoc, 2008, Principles and applications of compact laser–plasma accelerators, *Nat. Phys.* 4: 447-453.; E. Esarey, et al., 2009, Physics of laser-driven plasma-based electron accelerators.

[62] [York 2008]

[63] R.J. England, R.J. Noble, K. Bane, D.H. Dowell, C-K Ng, J.E. Spencer, S. Tantawi, et al., 2014, Dielectric laser accelerators, *Rev. Mod. Phys.* 86(4): 1337.

[64] C.G. Durfee and H.M. Milchberg, 1993, Light pipe for high intensity laser pulses, *Phys. Rev. Lett.* 71: 2409; [Spence2000] Erlich, 1996

[65] E. Esarey, et al., 2009, Physics of laser-driven plasma-based electron accelerators.

injected from the plasma background by wave-breaking or ionization injection.[66] Relativistic electrons injected with the proper phase can be accelerated and focused by the wakefield. Figure 5.6 illustrates a LWFA.

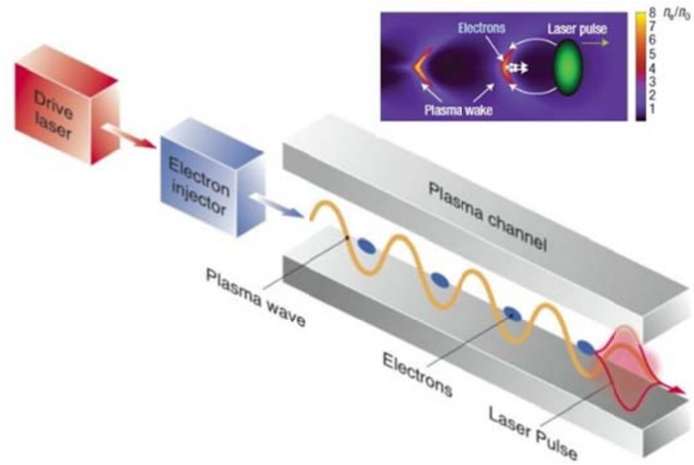


**FIGURE 5.6** Schematic illustration of a seeded laser-driven plasma wakefield accelerator. SOURCE: W.P. Leemans, 2010, White Paper of the ICFA-ICUIL Joint Task Force—High Power Laser Technology for Accelerators, http://icfa-bd.kek.jp/WhitePaper_final.pdf. The inset illustrated the plasma electron density behind the laser pulse for a self-injection mechanism in the so-called bubble regime. SOURCE: V. Malka, J. Faure, Y.A. Gauduel, E. Lefebvre, A. Rousse, and K.T. Phuoc, 2008, Principles and applications of compact laser–plasma accelerators, *Nat. Phys.* 4: 447-453.

The energy gain of the accelerated particles is limited by depletion of the energy of the laser pulse and dephasing as the accelerated electrons advance from an accelerating to a decelerating bucket in the plasma wave. Both of these limitations point to the need for high energy/intensity lasers: high energy pulses counterbalance depletion and drive large amplitude plasma waves over long propagation distances especially at low plasma densities where dephasing is minimized. Using a PW-class laser, the Berkeley Lab Laser Accelerator facility at Lawrence Berkeley National Laboratory has reported a record 4.2 GeV electron beam in single 10 cm plasma channel, with 10 GeV in 1-meter appearing feasible.[67]

Achieving even higher beam energies requires a "staging" of many laser-plasma acceleration modules in order to mitigate depletion and dephasing. Acceleration to beam energies above 1 TeV would require more than 100 acceleration stages. Staging places stringent requirements on the quality of the accelerated beam, as well as demanding a mechanism for introducing new laser pulses between stages. Despite the challenges, staging has been recently demonstrated at the ~100 MeV level in a proof-of-principle experiment .[68]

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[66] V. Malka, et al., 2008, Principles and applications of compact laser–plasma accelerators; E. Esarey, et al., 2009, Physics of laser-driven plasma-based electron accelerators.

[67] W.P. Leemans, A.J. Gonsalves, H-S. Mao, K. Nakamura, C. Benedetti, C.B. Schroeder, Cs. Tóth, et al., 2014, Multi-GeV electron beams from capillary-discharge-guided subpetawatt laser pulses in the self-trapping regime, *PRL* 113(24): 245002.

[68] S. Steinke, J. van Tilborg, C. Benedetti, C.G.R. Geddes, C.B. Schroeder, J. Daniels, K.K. Swanson, et al., 2016, Multistage coupling of independent laser-plasma accelerators, *Nature* 530: 190.

The concept of an *electron-positron collider* based on the LWFA technique is schematically illustrated in Figure 5.7. Electrons are injected into the first stage of the electron acceleration arm where they are accelerated to 10 GeV by the wakefield driven by a laser pulse. From the first stage, the accelerated electrons will enter the next acceleration stage. A new laser pulse is introduced between stages. In this example, the electron arm consists of 100 10-GeV stages, bringing the electron beam to an energy at collision of 1 TeV. A single LWFA stage is used to produce positrons to be injected into the positron acceleration arm. The positron arm also consists of 100 acceleration stages.

In order to achieve the necessary luminosity demanded by the high energy physics community, an electron-positron collider would require a repetition rate of 15 kHz. Energy efficiency from wall plug to beam of 10 percent would lead to a total power of 100 stages of 100 MW (one arm). Additional key accelerator and laser parameters can be found in Leemans (2010).[69] Nonetheless, the laser requirements are very challenging and beyond current state of the art, thus necessitating advances in PW-class laser technology. The primary mission of the Extreme Light Infrastrucutre-Nuclear Physics (ELI-NP) project in Prague is to push this frontier.

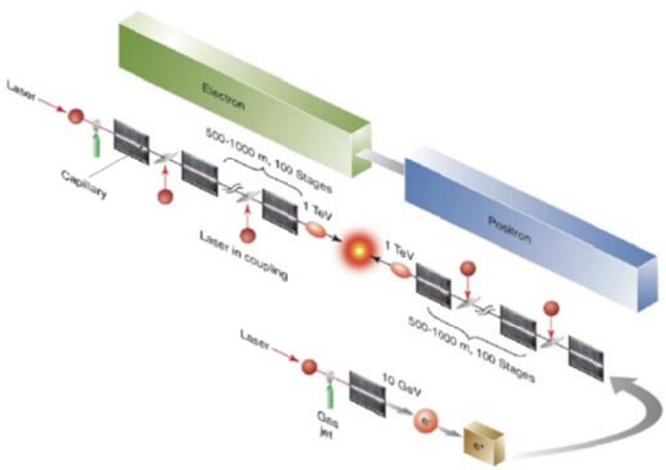


**FIGURE 5.7** Concept for an LPA-based electron-positron collider. Both the electron and positron arms start with a plasma-based injection-acceleration module. Electrons are accelerated to 1 TeV using 100 laser-plasma modules, each consisting of a 1-m long preformed plasma channel driven by PW-class lasers. SOURCE: W.P. Leemans, 2010, White Paper of the ICFA-ICUIL Joint Task Force—High Power Laser Technology for Accelerators, http://icfa-bd.kek.jp/WhitePaper_final.pdf.

The laser requirements for *LWFA-driven X-ray FEL* are not as stringent as for colliders.[70] A single acceleration stage of 10 GeV, or less, could provide a compact source to power an FEL producing femtosecond X-rays for basic science applications. Multiple 10-GeV stages would provide X-rays at higher energies than current FELs. Low repetition rates could provide high-peak brightness light for user experiments; however, large-scale user facilities requiring high-average brightness would require high repetition rate, e.g., PW peak power pulses at 1 kHz beyond the current state of the art. Since the X-ray FEL requirements are less demanding than collider requirements, a LWFA-driven FEL could be a

[69] W.P. Leemans, 2010, White Paper of the ICFA-ICUIL Joint Task Force—High Power Laser Technology for Accelerators, http://icfa-bd.kek.jp/WhitePaper_final.pdf.
[70] V. Malka, et al., 2008, Principles and applications of compact laser–plasma accelerators.

stepping stone in the development of an LWFA-based collider or as an ultimate goal of development of the LWFA technique.

## 5.5 INTENSE LASER DRIVEN PARTICLE SOURCES OF ENERGETIC PHOTONS, NEUTRONS, AND POSITRONS

The generation of short, high flux pulses of energetic photons, neutrons, and positrons by intense laser interaction with matter offers new and unique opportunities in scientific, engineering, and medical imaging. Applications in materials processing and in radiography both call for intense and bright sources of X-rays, positrons, protons, and neutrons that can be supplied by intense lasers. Laser-driven sources can replace much larger facilities such as cyclotrons, synchrotrons, and nuclear reactors if more compact or portable sources of energetic photons or particles are needed. Laser-driven sources can also provide higher source brightness and shorter pulse duration than conventional particle facilities.

The LWFA schemes described in Section 5.4.2 provide a route using electrons to drive secondary processes, e.g., X-ray FEL. However, other intense short pulse laser-driven processes enable generation of high energy protons, neutrons, positrons, and photons. For cases where compact or portable sources of energetic photons or particles are needed irrespective of pulse duration, laser-driven sources may replace much larger facilities such as cyclotrons, synchrotrons, and nuclear reactors. When high source brightness and short pulse duration are also needed, PW-driven sources are unique, and there is no other conventional facility to match them, except for X-ray FEL sources of coherent ultrafast X-rays.

### 5.5.1 Photon Sources

There are currently four main intense laser-based approaches for X-ray and γ-ray generation.

*Relativistic Thomson backscattering of intense laser pulses from relativistic e-beams.* An intense laser pulse counter-propagating with respect to a relativistic ($\gamma >> 1$) electron bunch can backscatter. The backscattered radiation, in the direction of the electron beam, has a maximum X-ray energy of $\hbar\omega_X = 4\gamma^2\hbar\omega_L$. Thus, the laser frequency is $\gamma^2$-boosted into the X-ray regime. The electron beam can originate either from a conventional accelerator, such as a linear accelerator, or in an all-optical configuration from a laser-driven accelerator, such as a LWFA. Photon energies can range from keV to MeV.[71] Assuming an all-optical system, a range of laser energies will be appropriate, depending on the desired backscattered photon energy. For >1 MeV photons, $\gamma > \sim 200$ (or ~100 MeV e-beams) are needed. For this purpose, a 10 TW laser system is sufficient. Higher energy lasers could increase the number of backscattered photons while maintaining constant intensity.

*Betatron radiation from laser-accelerated electrons.* As LWFA electrons propagate through the plasma, they transversely oscillate about the plasma ion column and emit forward-directed X-rays with a high degree of transverse coherence.[72] Photons are typically generated in the tens of keV range.

*Directing laser-plasma accelerated electron bunches into a high-Z dense material* to produce short pulses of bright, forward directed γ-rays via bremsstrahlung radiation.[73] Photon energies are typically > 1MeV, depending on the energy of the laser accelerated electrons.

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[71] K. Khrennikov, J. Wenz, A. Buck, J. Xu, M. Heigoldt, L. Veisz, and S. Karsch, 2015, Tunable all-optical quasimonochromatic Thomson x-ray source in the nonlinear regime, *PRL* 114(19): 195003.

[72] S. Corde, K. Ta Phuoc, G. Lambert, R. Fitour, V. Malka, A. Rousse, A. Beck, and E. Lefebvre, 2013, Femtosecond x rays from laser-plasma accelerators, *Rev. Mod. Phys*. 85(1).

Both betatron and plasma sources can operate in a limited way with laser powers as low as 10 TW but higher powers lead to increased photon numbers.

*Short-wavelength high harmonics from laser-driven relativistic mirrors.* When a laser pulse with normalized vector potential *a*>1 interacts with a sharp solid density interface, its ponderomotive pressure drives an oscillating relativistic mirror in the induced plasma.[74] This leads to generation of a spatially and temporally coherent beam of odd and even high harmonics into the specular reflection direction of the driving pulse, with as much as ~$10^{-6}$ efficiency per harmonic. Succsessful operation relies on pulses with extremely high contrast ratios as defined in Appendix A1. The need to maintain a sharp initial interface puts severe limits (< $10^{-11}$) on the prepulse level, demanding pre-pulse mitigation using complex and intrinsically low repetition rate plasma mirrors.

### 5.5.2 Neutron Sources

Three intense laser-based generation schemes for neutrons are currently under investigation.

The first method is *laser-accelerated proton collisions with nuclei and generation of neutrons* via the (p,n) reaction in low-Z foil targets, such as Be.[75] Such neutron beams can be used as passive or active material probes, including hidden contraband materials.

A second method under study is generation of bremsstrahlung γ-rays from stopping of laser-accelerated electron beams in high-Z targets followed by *neutron-emitting (γ n) decay of photo-activated nuclei*.[76]

A third method creates *neutrons from nuclear DD-fusion of* $D_2$ *clusters* irradiated by intense laser pulses.[77] Here, fusion is induced by collisions of keV energy deuterium nuclei from cluster plasma explosions in a laser-heated gas of $D_2$ clusters.

None of these techniques generates femtosecond neutron pulses—the duration is limited by the non-relativistic neutron velocities to their target, as well as transit time of the initiating γ-rays or protons traversing the converter target. How to generate ultrashort neutron pulses is still an open question with important potential applications such as time-resolved neutron diffraction.

The typical laser systems used in neutron generation experiments are large; for example, one study used the Los Alamos Trident laser with ~100 J in a sub-picosecond pulse.[78] This is motivated by the low conversion efficiency of laser energy to accelerated protons or to gamma rays.

### 5.5.3 Positron Sources

Intense laser plasma interactions can generate positrons via two leading processes:

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[73] Y. Glinec, J. Faure, L. Le Dain, S. Darbon, T. Hosokai, J.J. Santos, E. Lefebvre, et al., 2005, High-resolution x-ray radiography produced by a laser-plasma driven electron source, *PRL* 94(2): 025003.

[74] B. Dromey, et al., 2006, High harmonic generation in the relativistic limit.

[75] M. Roth, D. Jung, K. Falk, N. Guler, O. Deppert, M. Devlin, A. Favalli, et al., 2013, Bright laser-driven neutron source based on the relativistic transparency of solids, *PRL* 110(4): 044802.

[76] I. Pomerantz, E. McCary, A.R. Meadows, A. Arefiev, A.C. Bernstein, C. Chester, J. Cortez, et al., 2014, Ultrashort pulsed neutron source, *PRL* 113(18): 184801.

[77] T. Ditmire, J. Zweiback, V.P. Yanovsky, T.E. Cowan, G. Hays, and K.B. Wharton, 1999, Nuclear fusion from explosions of femtosecond laser-heated deuterium clusters, *Nature* 398: 489-492.

[78] M. Roth, Bright laser-driven neutron source based on the relativistic transparency of solids, *op.cit*.

1. *Bethe-Heitler process.* Laser accelerated electrons produce γ-rays from bremsstrahlung in a high-Z converter foil, and a γ-ray of energy greater than 1.022 MeV undergoes pair production in the foil to generate an electron and a positron.[79] This process dominates in thick, high-Z targets (such as Pb).
2. *The trident process.* Laser accelerated electrons collide directly with the target Au foil nuclei, yielding $e^{-}$–$e^{+}$ pair production from electron–nucleus collisions.[80] This process dominates in thinner foils.

Positron generation can occur with lasers of a few TW, but generation of large numbers or high densities of positrons can require hundreds of TW.[81]

Particle beams have scientific applications that will be discussed in the remainder of this chapter. They are also useful in some medical and security applications, which are discussed in Chapter 6.

## 5.6 HIGH-INTENSITY, ULTRAFAST LASERS FOR NUCLEAR PHYSICS

### 5.6.1 Introduction

High power PW-class lasers can enable the production of high energy charged particles, γ-rays, and neutrons, with peak flux orders of magnitude higher than possible with conventional accelerators. These high flux beams interacting with a PW-laser can probe a new regime of nuclear physics, which can lead to practical applications in nuclear and material science.[82] The thrust of the ELI-NP facility, under construction in Bucharest, Romania, is based on investigations of laser-induced nuclear reactions. The aim is to achieve a better understanding of nuclear properties, nuclear reaction rates in laser plasmas, and the development of novel characterization methods based on nuclear techniques. In addition to their discovery science role, these facilities will produce nuclear reactions for many non-science applications, including energy and security. The ELI-NP infrastructure will support two synchronized 10 PW lasers for conducting ultrafast particle-light interaction studies at intensities of $10^{24}$ W/cm$^2$. See the ELI-NP website for more details.[83]

### 5.6.2 High Power Laser Systems for Nuclear Physics

High power laser systems enable numerous scientific opportunities. For instance, fission-fusion experiments using ion beams generated by high-intensity lasers illuminating thin metal production targets

[79] C. Gahn, G.D. Tsakiris, G. Pretzler, K.J. Witte, C. Delfin, C.G. Wahlström, and D. Habs, 2000, Generating positrons with femtosecond laser pulses, *App. Phys. Lett.* 77(17): 2662-2664.

[80] H.C. Scott, C. Wilks, J.D. Bonlie, E.P. Liang, J. Myatt, D.F. Price, D.D. Meyerhofer, and P. Beiersdorfer, 2009, Relativistic positron creation using ultraintense short pulse lasers, *PRL* 102(10): 105001.

[81] Hui Chen et al., "Relativistic Positron Creation Using Ultraintense Short Pulse Lasers," *Physical Review Letters* 102, no. 10 (March 11, 2009): 105001, doi:10.1103/PhysRevLett.102.105001.

[82] F. Negoita, M. Roth, P.G. Thirolf, S. Tudisco, F. Hannachi, S. Moustaizis, I. Pomerantz, et al., 2016, Laser driven nuclear physics at ELI-NP, *Romanian Reports in Physics* 68: S37–S144.

[83] Extreme Light Infrastructure-Nuclear-Physics, http://www.eli-np.ro/, accessed February 9, 2017.

enable nuclear physics experiments aimed at understanding how the elements are made in the cosmos. They will also enable studies of strong-field quantum chromodynamics and of laser-gamma interactions.

### 5.6.3 γ-ray Beam Systems for Nuclear Physics

γ-ray beam systems enable a number of types of experimental studies of nuclear physics, particularly of nuclear structure and nucleosynthesis. γ-ray beams are made by scattering a laser beam off an electron beam; through the incoherent Compton scattering process, energy from the scattered electron is transferred to the scattered photon. The energy of the scattered photon depends upon the energy of the electron beam, the scattering angle, and the wavelength of the laser beam. Typically, γ-ray energies in the MeV range are used for nuclear structure studies or to induce nuclear reactions for other applications. For example, an ultra-short burst of γ-rays, together with high energy protons, can be used, through either [γ,n] and [p,n] reactions, to create short-lived radioisotopes for ultrafast photonuclear studies. This could offer an alternate approach to conventional accelerators for isotope production for clinical medical and materials applications.

### 5.6.4 Applications Beyond Nuclear Physics

The laser-based facilities and techniques developed for the study of nuclear physics could also be used in many other future applications, some of which are outlined here. In most of these applications, high γ-ray beam intensity shortens the time to scan the object.

*Energy applications:* High power laser systems enable testing of new materials for use in the extreme environments of fusion and fission energy applications. Nuclear resonance fluorescence (NRF) with gamma beams can be used to identify isotopes in radioactive waste.

*Medical applications:* High energy particle- and photo-induced nuclear transitions can be used to produce radioisotopes for medical applications with gamma beam systems. The cost effectiveness of high-intensity laser isotope production methods for medical applications is uncertain.

*Security applications:* NRF with γ-ray beams can be used to search containers for nuclear material and explosives.

*Materials applications:* High power laser systems enable testing of materials for use in extreme environments. They enable study of new materials for use in components of accelerators, such as high power targets and beam collimators. They also enable testing materials for space science, simulating the radiation environment of space missions, and they make possible studies of effects of radiation on biological systems.

*Computed tomography (CT):* CT can be performed with γ-ray beams—for instance, for non-destructive inspection of objects.

## 5.7 EXTREME INTENSITY: TOWARD AND BEYOND THE SCHWINGER LIMIT OF $10^{14}$ PW/cm$^2$

### 5.7.1 Introduction

Elementary particle interactions can be studied in new ways using the extreme fields of focused petawatt-class lasers, where the strength of the laser field can exceed the dielectric breakdown strength of the vacuum, known as the Schwinger limit, thereby providing an exotic form of particle production that cannot be studied without petawatt-class lasers. These laser beams can distort the properties of the vacuum, probing its properties such as vacuum birefringence. Laser fields can also be controlled to minimize (or eliminate) particle collisions, allowing nonlinear processes to be studied with precision.

QED studies with petawatt lasers must be pursued at facilities that have co-located relativistic particle accelerators in order to achieve the highest effective fields, because the laser intensity in the center of momentum frame scales as $\gamma^2$, where $\gamma$ is the Lorentz factor of Special Relativity. Conventional RF accelerators such as those at the Stanford Linear Accelerator Center (SLAC) routinely operate at $\gamma^2 \sim 10^9$ and have achieved values of $\gamma^2$ approaching $10^{10}$, a 10-billion-fold enhancement in the laser intensity as viewed in the particle rest frame. For large γ, even a moderately intense laser field can, in the rest frame of the relativistic particle, become an ultra-intense laser field.

The general science case for fundamental particle physics with intense lasers can be traced back to the remarkable success of QED in regimes where perturbation theory is valid, that is, for particle scattering experiments, high resolution Lamb shift or Rydberg measurements, and trap- or ring-based measurements of the anomalous magnetic moments of fermions. Calculations using covariant perturbation expansions have been used to compare experimental results to fundamental interaction theories. Intense lasers have the potential to create field strengths significantly exceeding the range of applicability of perturbation theory, giving rise to new effects, including many-body relativistic vacuum physics and possibly a hint of physics beyond the Standard Model.

The physics case for QED experiments using intense lasers has two general justifications. First, many basic QED processes have not yet been observed or have not been observed in sufficiently clean experiments to allow for detailed comparison with QED predictions. Second, many extensions of the standard model predict as yet unobserved particles/fields. If such particles exist, they typically modify the vacuum polarizability and can therefore have observable consequences on QED processes. Therefore, measurement of fundamental QED processes can, when carefully compared to theory, constitute a search for physics beyond the standard model.

### 5.7.2 The Schwinger Limit

The Schwinger limit is the laser intensity where the vacuum becomes unstable to the production of electron-positron pairs. It can be calculated within QED but can be estimated accurately using simple ideas based on the uncertainty principle.[84-88]

The quantum vacuum contains virtual relativistic matter-antimatter pairs that exist for times consistent with quantum uncertainty: $\Delta t \leq \hbar/2mc^2$. Even for the lightest particles, electrons and positrons, this is an exceedingly short time, equal to $0.5\alpha^2$ atomic units of time, or about 0.7

[84] Sebastian Meuren, Christoph H. Keitel, and Antonino Di Piazza, "Semiclassical Picture for Electron-Positron Photoproduction in Strong Laser Fields," *Physical Review D* 93, no. 8 (April 21, 2016): 085028, doi:10.1103/PhysRevD.93.085028.

[85] A. Hartin, "The Stimulated Breit-Wheeler Process as a Source of Background E+e− Pairs at the International Linear Collider," *Pramana* 69, no. 6 (December 1, 2007): 1159–64, doi:10.1007/s12043-007-0247-6.

[86] Bamber et al., "Studies of Nonlinear QED in Collisions of 46.6 GeV Electrons with Intense Laser Pulses."

[87] G. Breit, "Collision of Two Light Quanta," *Physical Review* 46, no. 12 (1934): 1087–91, doi:10.1103/PhysRev.46.1087.

[88] Sebastian Meuren et al., "High-Energy Recollision Processes of Laser-Generated Electron-Positron Pairs," *Physical Review Letters* 114, no. 14 (April 9, 2015): 143201, doi:10.1103/PhysRevLett.114.143201.

zeptoseconds ($0.7\times10^{-21}$ s). During their brief existence, these charged particles can interact with an applied laser field $E$. The maximum work the field can impart to an electron-positron pair is therefore on the order of $2Ec\Delta t \approx E\lambda_C$, where $\lambda_C = h/mc$ is the Compton wavelength. The vacuum becomes unstable at the Schwinger field $E_s$ when this work exceeds the rest mass of the particle pair, $E_s\lambda_C > \sim 2mc^2$ . Above this threshold field (intensity), laser energy is efficiently converted to matter-antimatter pairs. This corresponds to $E_s > 1.3\text{x}10^{16}$ V/cm, or $I_s > 2.3\text{x}10^{29}$ W/cm$^2$, the Schwinger intensity.

### 5.7.3 Vacuum Polarization: Matter from Light

There are many closely related processes for producing matter from light. A listing of these is given below.

#### 5.7.3.1 Schwinger Critical Field Exceeded in Laser Collisions with Relativistic Electrons

$$2Ec\Delta t \approx E\lambda_C = 2mc^2$$

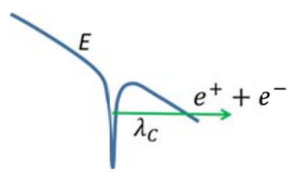


**FIGURE 5.8** The laser field distorts the vacuum, here depicted schematically as a bound state potenntial with well depth 2mc$^2$. At sufficient levels of distortion, pairs can tunnel out of the vacuum.

In its current configuration, the SLAC linear accelerator in Menlo Park, California, operates as three 1-km linear accelerators, two of which are capable of producing ~ 15GeV electrons ($\gamma = 30{,}000$). If one of these relativistic electron beams collides with a focused laser with peak intensity in the range of $10^{21} W/cm^2$, this is sufficient to exceed the Schwinger limit by more than an order of magnitude and produce copious amounts of matter in the laser focus (Figure 5.8). The committee stresses that this field will not be achieved at ELI, since none of the ELI sites is collocated with a GeV-scale linear accelerator, and without it the laser must supply 1 billion times more intensity, e.g., 1 Exawatt focused to a 20 nm focal spot.

#### 5.7.3.2 Cascade Processes

The presence of a single fermion, or even a single high energy photon to initiate pair formation, is expected to make a significant difference and can lead to a cascade in very general circumstances. For intensities above ~$3\text{x}10^{23}$ W/cm$^2$, the number of pairs produced by photon-induced pair production rises steeply. These pairs are accelerated and generate additional photons and pairs. At ~ $10^{24}$ W/cm$^2$, the laser power is predicted to be divided roughly equally between photons and electron-positron pairs, each with energy ~80 MeV, independent of the number of electrons initially in the interaction region. Complete conversion of laser energy to photons and pairs implies the production of $4x10^{10}$ pairs per Joule of laser energy. There are many calculations covering variations of geometry and polarization.[89]

### 5.7.3.3 Linear Breit-Wheeler Process (Basic and Stimulated)

The Breit-Wheeler (BW) process is represented by a perturbative Feynman graph describing two photons colliding to produce an e-e+ pair (Figure 5.9).

$$\gamma + \gamma' \rightarrow e^{+} + e^{-}$$

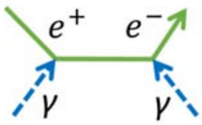


**FIGURE 5.9** Feynman diagram depiction of the Breit-Wheeler process for pair production from the vacuum.

Since the energy of the e-e+ pair is ~1 MeV, the photons are nominally gamma rays, but in principle these could be made using nonlinear laser-matter interactions with a petawatt-class laser. These gammas must collide at a nonzero crossing angle to satisfy momentum conservation. Breit and Wheeler calculated that the cross section for this process was of order $r_e^2$, where $r_e = e^2/mc^2$ is the classical electron radius. This simple process has never been directly observed by colliding two real gamma ray beams. Subsequent calculations identified resonances in the BW cross section that increase the cross section by several orders of magnitude and are associated with the so-called stimulated BW process.[90]

### 5.7.3.4 Multiphoton Breit-Wheeler Process

The multiphoton Breit-Wheeler process refers to a BW process whereby one of the gammas is replaced by several lower energy photons (Figure 5.10).

$$\gamma + n\hbar\omega \rightarrow e^{+} + e^{-}$$

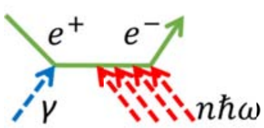


**FIGURE 5.10** The multiphoton extension of the Breit-Wheeler process.

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[89] C.P. Ridgers, C.S. Brady, R. Duclous, J.G. Kirk, K. Bennett, T.D. Arber, A.P.L. Robinson, and A.R. Bell, 2012, Dense electron-positron plasmas and ultraintense γ rays from laser-irradiated solids, *Phys Rev Letters* 108(16): 165006; A.R. Bell and J.G. Kirk, 2008, Possibility of prolific pair production with high-power lasers, *Phys Rev Letters* 101(20): 200403.

[90] Op. cit. 95.

The multiphoton BW process was observed in the E144 experiment at SLAC which studied the collision of a 46.6 GeV electron beam with terawatt 527nm laser pulses.[91] The effective intensity in the rest frame of the electron beam was below the Schwinger intensity but in the regime to see nonlinear QED effects. Roughly 100 positrons were detected and attributed to the cooperative interaction of laser photons with a back-scattered Compton gamma ray.

#### 5.7.3.5 Spin Polarization

Pair production by a high-energy photon and a strong laser field show differences between boson and fermion pair production in an oscillating electric field and also show that the existence of a fermionic (bosonic) particle in the initial state leads to suppression (enhancement) of the pair-production probability due to the different quantum statistics. This has been discussed extensively.[92]

#### 5.7.3.6 Breit-Wheeler with Short Pulses

The BW process can be modified by finite pulse duration and is also predicted to be sensitive to the carrier-envelope relative phase. Again, none of these subtle effects has been observed.[93]

#### 5.7.3.7 Hohlraum Breit-Wheeler

Large numbers of BW pairs per laser shot are predicted using a laser-accelerated particle beam to produce gammas, which then interact with thermal radiation made by a laser-heated hohlraum.[94]

#### 5.7.3.8 Delbrück Scattering

Delbrück scattering (DS) is the deflection (coherent elastic scattering) of high-energy photons in the Coulomb field of nuclei and is a consequence of vacuum polarization.[95,96] The electrons/positrons of

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[91] D.L. Burke, R.C. Field, G. Horton-Smith, J.E. Spencer, D. Walz, S.C. Berridge, W.M. Bugg, et al., 1997, Positron production in multiphoton light-by-light scattering, *Phys. Rev. Lett.* 79(9): 1626.

[92] (Tsai (1993); D.Y. Ivanov, G.L. Kotkin, and V.G. Serbo, 2005, Complete description of polarization effects in *e* + *e*- pair productionby a photon in the field of a strong laser wave, *Eur. Phys. J. C* 40: 27; Popov (1972); Krekora, Su, and Grobe, 2004; Cheng et al., 2009; Wagner et al., 2010a,b)

[93] A.I. Titov, B. Kampfer, H. Takabe, and A. Hosaka, 2013, Breit-Wheeler process in very short electromagnetic pulses, *Physical Review A* 87(4): 042106.

[94] O. J. Pike, F. Mackenroth, E.G. Hill, S.J. Rose, 2014, A photon–photon collider in a vacuum hohlraum, *Nature Photonics* 8: 434–436.

[95] Cheng, Hung, Er-Cheng Tsai, and Xiquan Zhu. “Delbrück Scattering.” Physical Review D 26, no. 4 (August 15, 1982): 908–21. doi:10.1103/PhysRevD.26.908.

the vacuum are capable of producing coherent-elastic photon scattering because the recoil momentum during absorption and emission of the photon is transferred to the total atom while the electrons remain in their state of negative energy. Delbrück scattering is therefore analogous to atomic Rayleigh scattering except that in the latter case, the electrons are bound in the electron cloud of the atom.

#### 5.7.3.9 Trident Process

The trident process refers to e-e+ pair production via a collision between one or more real photons and a virtual photon that is provided by a strong field, typically that of a heavy nucleus. This process is inefficient, producing ~$10^{-4}$ positrons for each fast electron.[97]

#### 5.7.3.10 Muon and Pion Pairs

Muons and pions are heavier than electrons (207 and 273 times, respectively) so that their production via a Schwinger tunneling mechanism is unachievable with foreseeable lasers and electron accelerators. (The Schwinger critical field for muon/anti-muon production is~ $5.6 \times 10^{24}$ V/cm). However, muons are easy to detect and to differentiate from electrons, so novel mechanisms for muon pair production that are related to the collective copious production of e+e- pairs may be studied with great sensitivity, and there are several different types of proposals for muons from laser-generated e+e- plasmas.[98,99] Muon and pion pairs have also been predicted to arise from a collision between an X-ray laser beam and a relativistic nuclear beam.**[100]**

### 5.7.4 Nonlinear Thomson and Compton Scattering

An electron driven by an electromagnetic field emits radiation in a scattering process termed Thomson scattering when quantum effects such as photon recoil are negligible and Compton scattering when they are not. Multiphoton versions of these processes correspond to events where more than one photon is scattered.

Thomson and Compton scattering have been theoretically considered many times in the literature. One recent description of multiphoton Compton scattering accounted for the electron and photon

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[96] Koga, James K., and Takehito Hayakawa. “Possible Precise Measurement of Delbr\"uck Scattering Using Polarized Photon Beams.” Physical Review Letters 118, no. 20 (May 17, 2017): 204801. doi:10.1103/PhysRevLett.118.204801.

[97] Hu, Huayu. “Complete QED Theory of Multiphoton Trident Pair Production in Strong Laser Fields.” Physical Review Letters 105, no. 8 (2010). doi:10.1103/PhysRevLett.105.080401.

[98] M. Yu. Kuchiev, “Production of High-Energy Particles in Laser and Coulomb Fields and the <span Class,” *Physical Review Letters* 99, no. 13 (2007), doi:10.1103/PhysRevLett.99.130404.

[99] Carsten Müller, Karen Z. Hatsagortsyan, and Christoph H. Keitel, “Particle Physics with a Laser-Driven Positronium Atom,” *Physics Letters B* 659, no. 1 (January 17, 2008): 209–13, doi:10.1016/j.physletb.2007.11.002.

[100] I. Kuznetsova, D. Habs, and J. Rafelski, 2008, Pion and muon production in e-, e+, γ plasma, *Physical Review D - Particles, Fields, Gravitation and Cosmology* 78(1): 014027; Thoma, (2009a, 2009b); A.I. Titov, B. Kämpfer, and H. Takabe, 2009, Dimuon production by laser-wakefield accelerated electrons,

*Phys. Rev. ST Accel. Beams* 12(11): 111301;Bychenkov et al. (2001); C. Müller, C. Deneke, and C.H. Keitel, 2008, Muon-pair creation by two x-ray laser photons in the field of an atomic nucleus,

*Phys. Rev. Lett.* 101(6): 060402; Muller, Deneke et al., 2009; Dadi and Muller (2011) polarizations,[101] while others have evaluated the effects of finite, even ultrashort, pulse duration on multiphoton Thomson and Compton scattering.[102] For this latter consideration, the main differences with respect to the monochromatic case are a broadening of the lines, corresponding to the emitted frequencies, and the appearance of sub-peaks, due to interference between emission from the front and back ends of the laser pulse. Similarly, Thomson and Compton scattering have been shown to exhibit observable effects of the relative carrier envelope phase.[103]

From an experimental perspective, Bula et al. (1996) reported observation of multiphoton Compton scatter for the first time in an experiment involving a collision between a relativistic (46.6 GeV) electron beam and visible (527 nm) laser photons focused to an intensity, in the electron rest frame, of ~$10^{18}$ W/cm$^2$.[104] Four-photon Compton scattering was observed indirectly via a nonlinear energy shift in the spectrum of the outgoing electrons. More recently, multiphoton Thomson scattering of laser radiation in the X-ray domain was reported[105] as was anomalous X-ray Compton scattering.[106] In this latter paper, 9 keV X-rays interacting with a Be target produced a single higher-energy photon redshifted from the second harmonic. The anomalous redshift was attributed to scattering from X-ray excited states produced via the interaction of the intense X-ray beam (4x$10^{20}$ W/cm$^2$) with the solid Be target.

Since high-energy photons can be emitted via Thomson and Compton scattering, these processes have been of interest for producing short wavelength radiation. The main advantages of these sources compared, for instance, to synchrotron sources, are their compactness, wide tunability, short pulse durations (femtosecond or shorter), and the potential for high brightness. Applications based on these advantages are considered in Chapter 6.

### 5.7.5 Radiation Reaction

Radiation reaction (RR) refers to the damping/friction experienced by a charged particle arising from the electromagnetic field the particle itself has radiated. RR becomes important when the momentum change due to the electron radiation competes with the Lorentz force of the laser. In the regime $a$>>1 but $\chi=\gamma E_0/E_s$ <<1, the electron trajectory can be significantly affected by cumulative emission of photons, each of which causes a recoil negligible compared to the Lorentz force and the electron energy. As the laser field $E_0$ increases to $\chi$~1 into the quantum-dominated regime, the recoil can be a sizeable fraction of the electron energy.[107]

While high intensity (>$10^{24}$ W/cm$^2$) is typically required before RR effects become important, observable effects have been predicted at lower intensity (>$10^{22}$ W/cm$^2$). Simulations, for instance, show that the predicted angular width of radiation emitted in laser/electron collisions changes significantly if RR effects are included: a 10 degree angular change is predicted for an optical intensity of 5x$10^{22}$ W/cm$^2$

[101] Ivanov, Kotkin, and Serbo (2004)

[102] M. Boca and V. Florescu, 2009, Nonlinear Compton scattering with a laser pulse, *Phys. Rev. A* 80(5): 053403.

[103] Krajewska and Kamin´ski (2012b)

[104] C. Bula, K.T. McDonald, E.J. Prebys, C. Bamber, S. Boege, T. Kotseroglou, A.C. Melissinos, et al., 1996, Observation of nonlinear effects in Compton scattering, *Phys. Rev. Lett.* 76(17): 3116.

[105] M. Babzien, I.B. Zvi, K. Kusche, I.V. Pavlishin, I.V. Pogorelsky, D.P. Siddons, V. Yakimenko, et al., 2006, Observation of the second harmonic in Thomson scattering from relativistic electrons, *Phys. Rev. Lett.* 96(5): 054802.

[106] Reis (2015)

[107] Extremely high-intensity laser interactions with fundamental quantum systems, A. Di Piazza, C. Muller, K. Z. Hatsagortsyan, and C. H. Keitel, Rev. Mod. Phys., 84, 1177-1228 (2012).

and an initial electron energy of 40 MeV.[108] Similarly, another investigation found that self-field effects induce peculiar electron spin dynamics.[109] More generally, quantum mechanical calculations indicate that RR effects primarily modify the spectrum of radiation emitted by a charged particle as follows: the photon yield is increased at low photon energies and decreased at high photon energies so that there is an overall shift of photon spectrum to low energy.[110]

From an applications perspective, when a relativistic electron beam collides with a sufficiently intense laser pulse, RR effects can strongly alter the beam dynamics. Classical calculations indicate that RR has a beneficial effect on an electron beam, predicting that the laser interaction tends to reduce the beam's energy spread. However, when quantum effects become important, RR induces the opposite effect and the electron beam energy spread increases upon interacting with a laser pulse. The intrinsic stochasticity of photon emission, which becomes important in the quantum regime, is identified as the underlying mechanism for the increased energy spread.[111] Beam cooling is important, for instance, for accelerator and FEL applications.

In a related paper, Capdessus et al. find that stochastic electron motion in combined laser and plasma (electrostatic) fields strongly affects the spectrum of radiation generated by accelerated electrons during high-intensity laser plasma interaction. This is explained as a collective effect occurring for laser intensities above $10^{22}$ W/cm$^2$ and plasma densities more than 10 times the critical density. The authors suggest that their findings may be important for laboratory modeling of radiation-dominated relativistic astrophysical events and that they can be tested in experiments with solid hydrogen and deuterium targets.[112]

With regard to applications in e-e+ production, a theoretical investigation concluded that RR effects inhibit the development of an e-e+ cascade, a process theorized to produce a high density e-e+ plasma.[113]

### 5.7.6 Vacuum Polarization: Elastic Light Scattering

Classically, photons (transverse EM fields) do not interact with one another; a fact reflected in the linearity of the Maxwell equations. However, the underlying quantum nature of the vacuum implies a nonzero vacuum polarizability that enables photon-photon interactions. Photons can, for instance, fluctuate into e-e+ pairs, which can in turn directly interact with one another.

#### 5.7.6.1 Vacuum Birefringence

One way to observe vacuum polarization effects is to detect their influence on the polarization properties of a probe electromagnetic beam. Within the framework of QED, the vacuum can be a birefringent medium due to the presence of a "background" electromagnetic field. This field will in general polarize the vacuum and in doing so introduce a preferred vacuum direction. This nonisotropic

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[108] A. Di Piazza, K.Z. Hatsagortsyan, and C.H. Keitel, 2009, Strong signatures of radiation reaction below the radiation-dominated regime, *Phys. Rev. Lett.* 102(25): 254802.

[109] S. Meuren and A. Di Piazza, 2011, Quantum electron self-interaction in a strong laser field, *Phys. Rev. Lett.* 107(26): 260401.

[110] Op. cit. 90, Di Piazza

[111] N. Neitz, "Stochasticity Effects in Quantum Radiation Reaction," *Physical Review Letters* 111, no. 5 (2013), doi:10.1103/PhysRevLett.111.054802.

[112] R. Capdessus, E. d'Humières, and V.T. Tikhonchuk, 2013, Investigation of collective electron effects in radiation production, *Phys. Rev. Letters* 110(21): 215003.

[113] I.V. Sokolov, N.M. Naumova, J.A. Nees, and G.A. Mourou, 2010, Pair creation in QED-strong pulsed laser fields interacting with electron beams, *Phys. Rev. Lett.* 105(19): 195005.

vacuum polarization amounts to vacuum birefringence and can lead to observable effects on a probe laser beam, rotating its polarization axis and/or inducing ellipticity. Calculations indicate that a linearly polarized X-ray beam co-propagating with an intense laser will emerge elliptically polarized.[114]

#### 5.7.6.2 Light-Light Scattering in the X-ray Regime

Recently, a search for light-light scattering in the X-ray regime was performed using the SACLA X-ray FEL. A signal, photons scattered elastically along the boost axis of the two-photon system, was not observed. Owing to high background counts, the inferred upper limit on the cross section for light-light scattering was well above the predicted QED value. Improvements to the X-ray FEL beams are expected to increase the experimental sensitivity close to the QED predicted signal level.[115]

### 5.7.7 Beyond the Standard Model

#### 5.7.7.1 Light Scattering Through A Wall Experiments

Light scattering through a wall (LSW) experiments search for hidden sector particles, such as Axions, Axion-like particles (ALPs), and paraphotons, by searching for transmission of (real) photons through barriers that are effectively impenetrable within the Standard Model. The particles of interest are weakly interacting; in particular, they are typically assumed to have zero electric charge. Transmission may occur as real photons transform into hidden sector particles that propagate through the barrier and then oscillate back into real photons to be detected on the other side of the barrier.

Magnetic fields are used to drive Axion/ALP oscillation, while magnetic fields are typically not used in paraphoton searches. LSW experiments have been performed in optical and X-ray regimes since these different spectral regions are optimized for particles of different mass and/or photon coupling strength.

Since the oscillation probability for Axions/ALPs scales with magnetic field strength, the highest practical field strength is desirable. While searches to date have used static fields in the few Tesla range, high-intensity lasers have been considered for LSW experiments owing to their very high peak magnetic fields (~ $6.5 \times 10^5$ T at $10^{22}$ W/cm$^2$). The small space-time footprint of an intense laser pulse, compared to a CW-laser/static-magnetic-field configuration, works against high-intensity experiments, reducing the advantage associated with high peak fields. Still, initial analysis of high power (~ 1 PW) LSW experiments suggests that they should be competitive with CW-laser/static-field experiments.[116]

#### 5.7.7.2 Minicharged Particle Experiments

In addition to electrically neutral BSM particles such as axions, yet unobserved particles with nonzero charge may also exist. These particles could either be very heavy and therefore appropriate for

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[114] T. Heinzl, B. Liesfeld, K.-U. Amthor, H. Schwoerer, R. Sauerbrey, and A. Wipf, 2006, On the observation of vacuum birefringence, *Opt.Commun.* 267(2): 318-321.

[115] T. Inadaa, T. Yamajia, S. Adachia, T. Nambab, S. Asaia, T. Kobayashib, K. Tamasaku, et al., 2014, Search for photon–photon elastic scattering in the X-ray region, *Physics Letters B* 732: 356-359.

[116] J.T. Mendoca, 2007, Axion excitation by intense laser fields, *Europhysics Letters* 79(2).

large-scale accelerator experiments, or they could be light and weakly charged, so-called minicharged particles, well suited for laser-based searches.[117]

Vacuum nonlinearities associated with minicharged particles may be observable in a strong external laser field, modifying the vacuum birefringence effects expected within the Standard Model (i.e., deviations from QED predictions would be observed).[118] Analysis indicates that strong field vacuum birefringence experiments could significantly improve existing experimental constraints on minicharged particles in the mass range below 0.1 eV.[119]

### 5.7.7.3 Quantum Electrodynamics Experiments

Beyond the specific minicharged particle predictions mentioned above, there is a rather broad array of weakly interacting particles predicted by various extensions of the Standard Model.[120] Generally speaking, the existence of additional particles modifies the vacuum polarizability, leading in principle to observable consequences in a range of QED processes. While only a modest number of specific experimental predictions exists at present, theoretical guidance for observing signatures of BSM physics in QED experiments can be expected to grow as experimental approaches both diversify and mature.

### 5.7.7.4 Unruh Radiation

Intense lasers can rapidly accelerate electrons and it has been suggested that high-intensity lasers could achieve accelerations comparable to those experienced in the vicinity of a black hole.[121] Such rapidly accelerated electrons are expected to emit Unruh radiation. This may be useful in exploring as yet unresolved issues associated with the Hawking radiation predicted to arise near a black hole event horizon.

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[117] (Gies, 2009)

[118] Gies, H., J. Jaeckel, and A. Ringwald, Phys. Rev. Lett. 97, 140402 (2006)

[119] Ibid.

[120] Asimina Arvanitaki, Savas Dimopoulos, Sergei Dubovsky, Nemanja Kaloper, and John March-Russell, Phys. Rev. D 81, 123530 (2010)

[121] Pisin Chen, “Accelerating Plasma Mirrors to Investigate the Black Hole Information Loss Paradox,” *Physical Review Letters* 118, no. 4 (2017), doi:10.1103/PhysRevLett.118.045001.

# 6

# Applications

## 6.1 INTRODUCTION

Applications of high-intensity lasers stem from direct laser beam interactions with matter and from interactions with matter of the secondary particle and photon sources they drive. The most common applications are motivated by scientific, commercial, medical, and security needs. The division between this chapter and Chapter 5 is somewhat artificial: Science is clearly a main application of high-intensity lasers, and all applications of high-intensity lasers rely on the fundamental science of high-intensity laser-matter interactions.

The use of lasers in applications has economic and practical motivations. In manufacturing, for example, robotic lasers have been programmable in a way that mechanical cutting tools had not been, with the same factory floor laser station capable of cutting, drilling, measuring, and in some cases welding and peening. High-intensity short pulse lasers, in particular, have unique capabilities for precision, mainly due to minimal thermal energy deposition in materials, resulting in negligible collateral damage beyond the desired interaction volume. This can yield high aspect ratio holes and precisely imprinted patterns unrealizable with long pulse or continuous wave (CW) lasers. For medical uses, lasers have reduced the need for sterilization or anesthetics, and intense laser pulses can be delivered to internal tissues via optical fibers. In security, lasers can accelerate charged particles to relativistic energies, and beams of these particles can be used as probes of concealed materials in ways that complement the penetrating power and contrast available with x rays. And in science, the high intensity and short duration laser pulses make possible new techniques for ultrafast imaging of a wide range of transiently evolving matter.

The direct photonics economy, which includes manufacturing and deploying all kinds of lasers and components, is estimated in the annual range of $300 billion globally.[1] This feeds a multi-trillion dollar economy that depends on laser products and services in myriad ways.[2] The contribution of high-intensity short-pulse lasers to this economic activity is increasing rapidly. Even in areas that do not directly use high-intensity lasers, such as communications, developments motivated by high-intensity laser design, such as dispersion and pulse shape control, will increasingly play a major role.

Lasers occupy a major economic footprint in our national defense and security. The United States invests a significantly larger share of its tax revenues in defense than any other nation. It is expected that lasers will become an increasingly important element of this effort, owing to applications in communications, remote sensing, directed energy, and the production and diagnosis of materials in

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[1] Photonics21, "2020 Photonics Roadmap," accessed January 8, 2017, http://www.photonics21.org/download/Brochures/Photonics_Roadmap_final_lowres.pdf.

[2] T. Baer, 2010, *Lasers in Science and Industry: A Report to OSTP on the Contribution of Lasers to American Jobs and the American Economy*, http://www.laserfest.org/lasers/baer-schlachter.pdf; National Research Council, 2012, *Optics and Photonics: Essential Technologies for Our Nation*, The National Academies Press, Washington, D.C.; The White House, "President Obama Announces New Manufacturing Innovation Institute Competition," last update October 3, 2014, https://www.whitehouse.gov/the-press-office/2014/10/03/fact-sheet-president-obama-announces-new-manufacturing-innovation-instit.

extreme environments. The utility of high-intensity short-pulse lasers spans a significant portion of this security space.

## 6.2 LASER TECHNOLOGY USED IN MANUFACTURING

Laser material processing is now a major component of the manufacturing process. Lasers accomplish tasks ranging from heating for hardening, melting for welding and cladding, and the removal of material for drilling and cutting. Typical intensities required for such tasks include heat treating at $10^3 – 10^4$ W/cm$^2$, welding and cladding at $10^5 – 10^6$ W/cm$^2$, and material removal $10^7 – 10^9$ W/cm$^2$ for drilling, cutting, and milling. Figure 6.1 depicts laser processing activities as a function of the laser pulse width.[3]

**Laser Process Map**

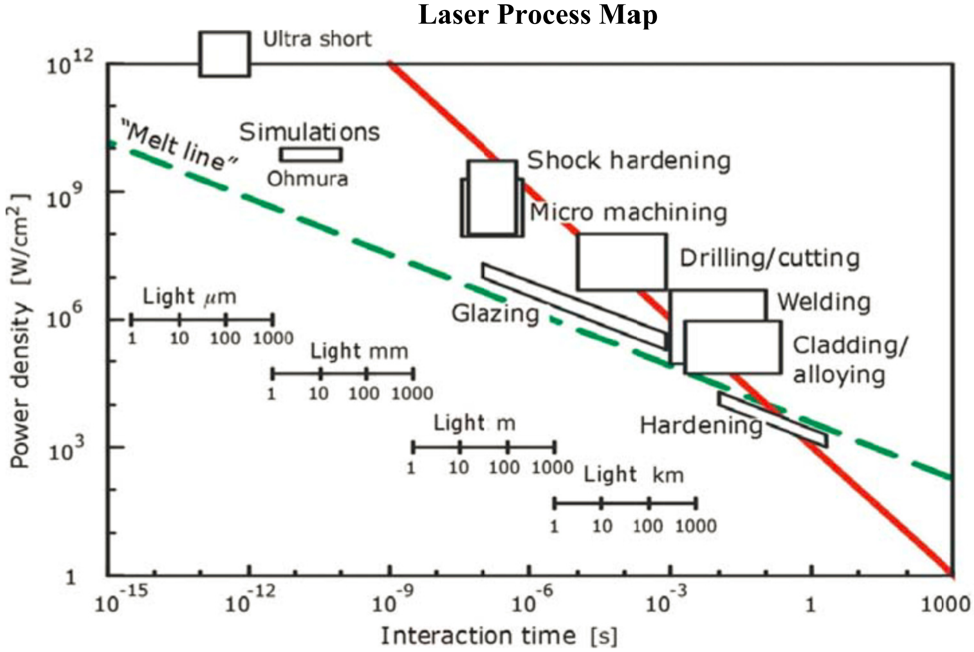


**FIGURE 6.1** This shows how intensity (i.e., power density) maps onto laser processing applications. A continuous wave laser beam is represented by the number $10^0$ while $10^{-3}$, $10^{-6}$, $10^{-9}$, and $10^{-12}$ seconds represents millisecond, microsecond, nanosecond, and picosecond time scales, respectively. SOURCE: J. Meijer, K. Du, A. Gillner, D. Hoffmann, V. S. Kovalenko, T. Masuzawa, A. Ostendorf, R. Poprawe, and W. Schulz, CIRP Annals - Manufacturing Technology 51, 531 (2002).

Femtosecond laser processing for materials manufacturing is expanding as robust commercial lasers become available. Typical operating parameters for commercial lasers used for manufacturing include pulse widths of 100-200 fs, peak energies of 50-150 µJ, average powers of 100-150 W, and pulse repetition rates up to 1 MHz.[4] Table 6.1 shows a list of 20 global industrial laser companies whose short-pulse lasers range in pulse width from <6 fs to ~1 ns.

[3] William M. Steen and Jyotirmoy Mazumder, *Laser Material Processing* (London: Springer London, 2010), http://link.springer.com/10.1007/978-1-84996-062-5.

[4] F. Korte, S. Nolte, B.N. Chichkov, T. Bauer, G. Kamlage, T. Wagner, C. Fallnich, and H. Welling, 1999, Far-field and near-field material processing with femtosecond laser pulses, *Applied Physics A* 69(1): S7–S11.

**TABLE 6.1** A Selection of Industrial Ultrafast Laser Companies with Typical Parameters

| Laser Name | Power | Duration |
|---|---|---|
| **AMPHOS GmbH** | 400 W | 100 fs |
| **Amplitude Systemes** | > 100 W | < 500 fs |
| **Calmar** | < 4 W | < 100 fs |
| **Clark MXR** | 20 W | <150 fs |
| **Coherent** | < 100 W | < 15 ps |
| **EKSPLA** | ~ 1 W | ~ 100 fs |
| **ESI** | 25 W | ~ 1 ns |
| **FemtoLasers** | ~ 0.5 W | < 6f s |
| **Fianium** | > 5 W | < 200 fs |
| **IMRA America** | > 20 W | < 400 fs |
| **JENOPTIK Laser GmbH** | ~ 5 W | ~ 500 fs |
| **KM Labs** | 1.4 W | < 12 fs |
| **Laser Quantum** | > 1.8 W | < 15 fs |
| **Light Conversion Ltd.** | ~ 20 W | < 290 fs |
| **PolarOnyx** | > 1 W | 100 fs |
| **Rofin Sinar Laser GmbH** | 10 W | 700 fs |
| **Spectra Physics** | > 16 W | < 400 fs |
| **TOPTICA Photonics AG** | ~ 0.5 W | < 150 fs |
| **TRUMPF Scientific Lasers GmbH+Co.KG** | Up to hundreds of W | Sub-ps to ns |
| **R.P.M.C. Lasers** | 50 W | < 1 ps |

SOURCE: Compiled by the Committee.

High-intensity femtosecond laser processing is considered a "cold" process since the substrate does not heat during the interaction.[5] The physical mechanism used in material removal is plasma formation leading to ablation rather than melting. High-value commercial applications include surface processing, where the laser may be used to clean surfaces,[6] or may be used in texturing of surfaces to decrease reflectivity,[7] provide hydrophobic surfaces,[8] or create chemically reactive surfaces.[9] Another

[5] X. Liu, D. Du, and G. Mourou, "Laser Ablation and Micromachining with Ultrashort Laser Pulses," *IEEE Journal of Quantum Electronics* 33, no. 10 (October 1997): 1706–16, doi:10.1109/3.631270.

[6] P. Pouli et al., "Femtosecond Laser Cleaning of Painted Artefacts; Is This the Way Forward?," in *Lasers in the Conservation of Artworks* (Springer, Berlin, Heidelberg, 2007), 287–93, doi:10.1007/978-3-540-72310-7_33.

[7] A. Y. Vorobyev and Chunlei Guo, "Enhanced Absorptance of Gold Following Multipulse Femtosecond Laser Ablation," *Physical Review B* 72, no. 19 (November 21, 2005): 195422, doi:10.1103/PhysRevB.72.195422.

[8] Max Groenendijk, "Fabrication of Super Hydrophobic Surfaces by Fs Laser Pulses," *Laser Technik Journal* 5, no. 3 (May 1, 2008): 44–47, doi:10.1002/latj.200890025.

extremely useful property of the cold plasma ablation of high-intensity lasers is the ability to drill clean, small, deep holes in materials without damaging the surrounding material.[10]

The technology is now commonly used in the medical industry for fabricating high quality surgical stents.[11] The medical industry has need for micron size feature such as 1µ diameter holes with a large length to diameter ratio. Single-mode fs laser technology is proving the best tool for these needs.

Femtosecond laser ablation depths from a single laser pulse can be more precise than material removal with conventional laser melting, as shown in Figure 6.2.[12] Cracks due to thermal damage are present at picosecond to femtosecond pulses but nearly disappear when the pulse duration is reduced to 5 fs.[13] Since thermal damage and stress-induced cracking depends on the average power of the femtosecond laser source, absorbed laser power leads to melting or thermal shock even with picosecond or femtosecond pulse duration.

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[9] E. Stratakis, "Ultrafast Laser Micro/Nano Processing for Microfluidic and Tissue Engineering Apllications," in *2011 Conference on Lasers and Electro-Optics Europe and 12th European Quantum Electronics Conference (CLEO EUROPE/EQEC)*, 2011, 1–1, doi:10.1109/CLEOE.2011.5943318.IEEE Photonics Society, European Physical Society, and the Optical Society, Munich, Germany.

[10] Sergei M. Klimentov et al., "The Role of Plasma in Ablation of Materials by Ultrashort Laser Pulses," *Quantum Electronics* 31, no. 5 (2001): 378, doi:10.1070/QE2001v031n05ABEH001958; Lan Jiang et al., "Femtosecond Laser High-Efficiency Drilling of High-Aspect-Ratio Microholes Based on Free-Electron-Density Adjustments," *Applied Optics* 53, no. 31 (November 1, 2014): 7290–95, doi:10.1364/AO.53.007290; G. Kamlage et al., "Deep Drilling of Metals by Femtosecond Laser Pulses," *Applied Physics A* 77, no. 2 (July 1, 2003): 307–10, doi:10.1007/s00339-003-2120-x; V. N. Tokarev et al., "Optimization of Plasma Effect in Laser Drilling of High Aspect Ratio Microvias," *Laser Physics* 25, no. 5 (2015): 056003, doi:10.1088/1054-660X/25/5/056003.

[11] Amplitude Systems, "Ultrafast Lasers for Manufacturing Surgical Stents," *News | Amplitude Systèmes*, accessed January 8, 2017, http://www.amplitude-systemes.com/headlines-ultrafast-lasers-for-stent-manufacturing.html.

[12] Beat Neuenschwander et al., "Optimization of the Volume Ablation Rate for Metals at Different Laser Pulse-Durations from Ps to Fs," vol. 8243, 2012, 824307-824307–13, doi:10.1117/12.908583; O. Utéza, "Surface Ablation of Dielectrics with Sub-10 Fs to 300 Fs Laser Pulses: Crater Depth and Diameter, and Efficiency as a Function of Laser Intensity," *Journal of Laser Micro/Nanoengineering* 5, no. 3 (December 2010): 238–41, doi:10.2961/jlmn.2010.03.0011; Gerard A. Mourou et al., Method for controlling configuration of laser induced breakdown and ablation, US5656186 A, filed April 8, 1994, and issued August 12, 1997, http://www.google.com/patents/US5656186.

[13] M Lenzner et al., "Photoablation with Sub-10 Fs Laser Pulses," *Applied Surface Science* 154–155 (February 2000): 11–16, doi:10.1016/S0169-4332(99)00432-8.

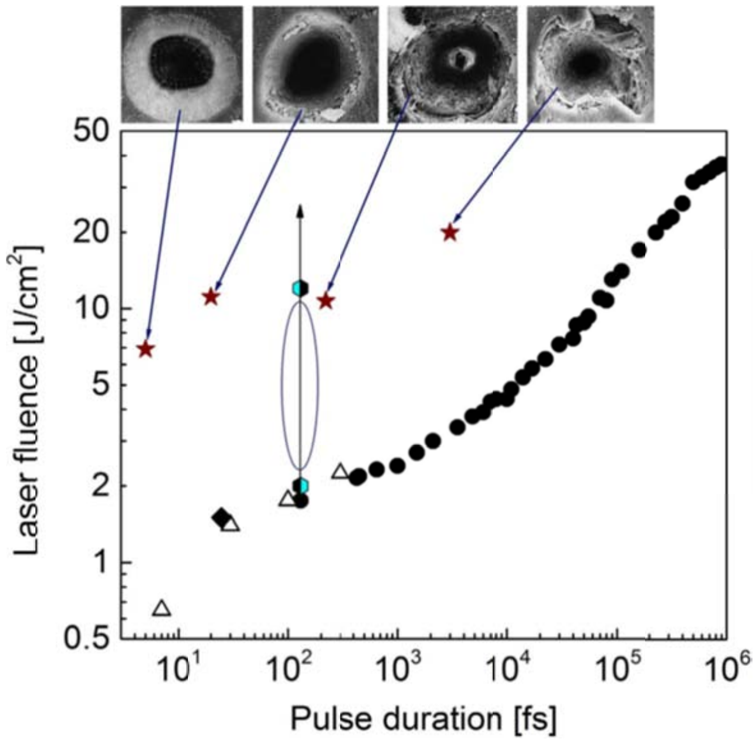


**FIGURE 6.2** The connection between the breakdown threshold and ablation quality at femtosecond to picosecond pulse duration for fused silica glass. Black points are the breakdown threshold. Red stars are specific points of ablation studies. Typical electron micrographs of the ablation spots are indicated.[14]

Other ultrashort pulse laser applications that have been studied and reported for industrial processes include higher peak power femtosecond pulses to help to improve the resolution of the laser-induced breakdown spectroscopy (LIBS) process,[15] and ultrafast laser-generated X-rays to assess rotary equipment.[16] Laser peening for generating compressive surface stresses to mitigate crack initiation and growth is an important use of nanosecond pulsed laser-generated shocks. It has been investigated using femtosecond pulses as well, where the hardening effect is dominated by ablation of the surface layer rather than shock formation.[17]

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[14] Ibid.

[15] W. Wessel et al., “Use of Femtosecond Laser-Induced Breakdown Spectroscopy (Fs-LIBS) for Micro-Crack Analysis on the Surface,” *Engineering Fracture Mechanics*, International Conference on Crack Paths 2009, 77, no. 11 (July 2010): 1874–83, doi:10.1016/j.engfracmech.2010.03.020; Timur A. Labutin et al., “Femtosecond Laser-Induced Breakdown Spectroscopy” 31, no. 1 (December 23, 2015): 90–118, doi:10.1039/C5JA00301F.

[16] V. Raspa et al., “Plasma Focus as a Powerful Hard X-Ray Source for Ultrafast Imaging of Moving Metallic Objects,” *Brazilian Journal of Physics* 34, no. 4B (December 2004): 1696–99, doi:10.1590/S0103-97332004000800034.

[17] Dongkyun Lee and Elijah Kannatey-Asibu, “Experimental Investigation of Laser Shock Peening Using Femtosecond Laser Pulses,” *Journal of Laser Applications* 23, no. 2 (March 31, 2011): 022004, doi:10.2351/1.3573370.

## 6.3 APPLICATIONS OF HIGH POWER (PETAWATT) LASERS TO THE STOCKPILE STEWARDSHIP PROGRAM

The mission of the Stockpile Stewardship Program (SSP) of the U.S. Department of Energy[18] is to maintain a safe and reliable stockpile of nuclear weapons and to support the non-proliferation missions of the agency. To support this effort, leading-edge technologies must be developed in coordination with a robust high energy density science program. The main application of high-intensity lasers to SSP science is to produce bright penetrating high-energy X-rays for radiography of high-energy-density matter. Short-pulse high-energy (kilojoule range) petawatt lasers can deposit a large amount of energy on a picosecond time scale, and this makes them a unique tool to probe inertial confinement fusion (ICF) implosions and high-energy-density physics occurring on a much longer (nanosecond) time scale. Examples of research that utilizes such X-ray sources include measurements of the equation of state for hot dense matter, which uses X-ray diffraction to observe structure when materials are compressed to high pressures. X-ray sources for radiography of ICF implosions and dense high-Z materials need picosecond-duration and require energetic X-rays in the range of 10 to 100 keV. X-ray backlighters driven by kilojoule class petawatt lasers can achieve a brightness exceeding $10^{10}$ photon/um$^2$ at x-ray energies of 50-100keV, well above the capability of conventional long-pulse (nanosecond) high-energy lasers whose brightness falls below $10^9$ photons/um$^2$ for energies above 10 keV. Scattered radiation from the drive process and the matter itself are sources of background, so several kilojoules of high-intensity laser light at ~ $10^{18}$-$10^{19}$ W/cm$^2$ are required for creating broadband backlighter sources brighter than the emission from the matter being probed (Fig. 6.3).

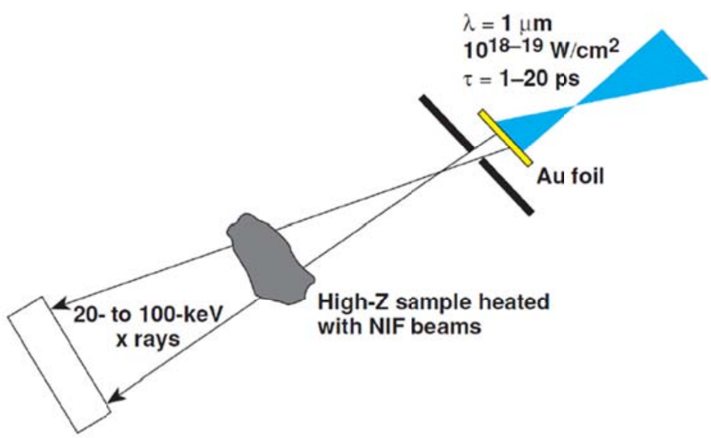


**FIGURE 6.3** X-ray backlighting of high-Z materials for SSP applications. A short-pulse intense laser irradiates an Au foil to produce intense high-energy X-rays to radiograph a high-Z sample heated by long-pulse laser beams. SOURCE: DiMauro et al, “SAUUL Presentation,” 2002, http://www.lle.rochester.edu/pub/viewgraph/PDF/PR/PRMHFRSAUUL.pdf.

Multibeam petawatt lasers are preferable since the beamlets can be staggered in time onto backlighter targets and produce a temporal sequence of radiographic images (including diffraction). For example, temporally resolved radiography could be used to diagnose the evolution of the fuel

[18] National Nuclear Security Administration, “Maintaining the Stockpile,” *Maintaining the Stockpile*, 2017, https://nnsa.energy.gov/ourmission/maintainingthestockpile.

compression of an inertial fusion implosion, strong shock propagation in materials, evolution of hydrodynamic instabilities in accelerated targets, and other high energy density physics experiments. The first facility to use multibeam backlighters driven by high-intensity laser pulses is the Advanced Radiographic Capability (ARC)[19] at Lawrence Livermore National Laboratory (LLNL). ARC provides short (1-50 picoseconds) high-power (> 1 Petawatt) laser pulses. ARC's short, wide bandwidth, 1-µm light laser pulses propagate down the existing National Ignition Facility (NIF) beamlines. The ARC pulses are amplified before being redirected through large aperture gratings performing chirped pulse compression. Each of the eight ARC beams is pointed at up to one of eight backlighter foils. Each backlighter produces a short X-ray flash—staggered in time—to provide an eight-frame backlit movie of the target imploded by NIF (Fig. 6.4). The Omega-EP laser at the University of Rochester[20] is also used to develop experimental and diagnostic techniques for such applications. In addition to peak power and pulse duration, features such as contrast ratio (described in Appendix A1) are important for such applications.

In addition to radiographic images, high-intensity lasers can create near mono-energetic K-shell emission over a wide range of frequencies (depending on the target material) to be used for diffraction experiments where the internal spatial structure of the compressed material can be determined and related to macroscopic thermodynamic properties such as equation of state and heat capacity.

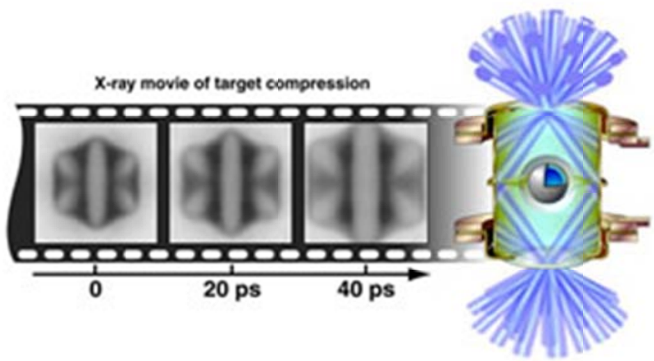


**FIGURE 6.4** Simulated temporal sequence of X-ray radiographs of an NIF implosion using the multi-beam ARC laser at Lawrence Livermore National Laboratory. SOURCE: Lawrence Livermore National Laboratory, "Short-Pulse Lasers," https://lasers.llnl.gov/science/photon-science/arc, accessed March 2, 2017.

In addition, high-intensity short-pulse lasers can be used to create radiation (both photon and particle) that can be used to interrogate systems and identify the presence of nuclear or chemical materials of concern for proliferation or homeland security[21]. Such lasers could have some advantages over

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[19] D.D. MDiMauro et al, "SAUUL Presentation," 2002, http://www.lle.rochester.edu/pub/viewgraph/PDF/PR/PRMHFRSAUUL.pdf.

[20] Laboratory for Laser Energetics, "About OMEGA EP," http://www.lle.rochester.edu/omega_facility/omega_ep/, accessed March 2, 2017.

[21] Sudeep Banerjee et al., "Compact Source of Narrowband and Tunable X-Rays for Radiography," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 350 (May 1, 2015): 106–11, doi:10.1016/j.nimb.2015.01.015.

alternative technologies, but must be capable of both high intensity and average power.[22-24] Programs and sponsorship of the laser science and technology to achieve the necessary performance (nominally kHz rep rates, 1-10 joule energy per pulse and sub 100 femtosecond pulses are required) are yet to be identified.

## 6.4 APPLICATIONS OF HIGH-INTENSITY LASERS TO MEDICINE

Many kinds of laser surgery are now available that utilize ultrafast high-intensity laser processing of tissue. Particularly well known is Laser-Assisted In-Situ Keratomileusis (LASIK), which uses ultrafast laser scalpels to make incisions in the eyeball as part of a laser sculpting protocol to improve eyesight.[25] These laser methods use some of the materials-processing benefits of high-intensity laser-matter interactions, such as reduction of collateral damage due to heating; but the lasers themselves are small-scale instruments because peak power is limited by the microscopic nature of this kind of surgery. This section will have a primary focus on medical applications that require the use of high peak power lasers that are capable of ultrahigh intensities. Those applications result from the promised ability of ultra-high-intensity laser pulses to create different kinds of high energy particles and radiation through interaction with a variety of sources.

The science and some materials applications of high power laser generation of auxiliary sources of particles and photons are reviewed in Section 6.4.3 and Section 6.3. Among the envisioned applications of these auxiliary laser-driven sources are X-ray and γ-ray imaging, therapies using high energy X-rays and γ-rays, therapies using laser-accelerated electron beams, therapies using laser-accelerated ion beams (mostly protons), and transmutation to create radioactive sources of positrons for positron emission tomography (PET).

The medical applications reviewed in this section are based on both imaging and cancer therapies based on particles generated from these ultra-high-intensity lasers. The challenge for many clinical medical applications is far greater than simply demonstrating the technology, since translating it into a clinical setting requires a sequence of research from in vitro to in vivo experiments, and then on to clinical trials.[26]

### 6.4.1 Ultrafast X-ray Radiography in Medicine

Ultra-high-intensity lasers can provide hard X-rays that emanate from an almost-point source, which provides spatially coherent X-rays. These can be transmitted through biological media and diffract,

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[22] "UNL | Novel X-Ray Method Could Detect Nuclear Materials | Office of Research & Economic Development," accessed June 30, 2017, http://research.unl.edu/blog/novel-x-ray-method-could-detect-nuclear-materials/.

[23] Andrew J. Gilbert et al., "Non-Invasive Material Discrimination Using Spectral x-Ray Radiography," *Journal of Applied Physics* 115, no. 15 (April 15, 2014): 154901, doi:10.1063/1.4870043.

[24] John Medalia, "Detection of Nuclear Weapons and Materials: Science, Technologies, and Observations," 2010, www.crs.gov.

[25] Tohru Sakimoto, Mark I Rosenblatt, and Dimitri T Azar, "Laser Eye Surgery for Refractive Errors," *The Lancet* 367, no. 9520 (May 5, 2006): 1432–47, doi:10.1016/S0140-6736(06)68275-5.

[26] U. Linz and J. Alonso, 2007, What will it take for laser driven proton accelerators to be applied to tumor therapy? *Physical Review Accelerators and Beams* 10(9): 094801.

creating phase-contrast X-ray images at high resolution and contrast.[27] Computer -based tomography can turn these into high quality 3D images.[28] These hard X-rays have been able to produce high-resolution 3D views of human bone,[29] and the phase contrast imaging provides enough contrast so tumors can be separated from healthy tissue.[30] The laser-generated coherent hard X-rays offer imaging features that cannot be achieved with ordinary X-rays emitted from tubes. In a fully integrated high-intensity laser system, these advanced imaging technologies will be used just before and after radiotherapy with laser-accelerated particles, discussed next.

### 6.4.2 Electron Beams for Cancer Therapy

Radiotherapy seeks to selectively kill cancer cells by breaking off the caps at the end of their deoxyribonucleic acid (DNA) chains without doing too much damage to healthy cells. High energy electrons have been shown to be more effective than hard X-rays because they can be more easily focused to tumor locations. High energy electrons created in bunches by ultra-high-intensity lasers using laser wakefield acceleration in plasmas are expected to replace cyclotrons and linacs for this application. After early demonstrations of effectiveness,[31] laser-accelerated femtosecond bunches of electrons were shown to have the same biological effectiveness as those from cyclotrons.[32] They have presented the first evidence that such electrons are more effective than X-rays in radiotherapy. Laser-driven electron beams have been evaluated to establish a path toward cost-effective delivery of therapeutic doses, thereby replacing conventional particle accelerators such as linacs, which can be large and costly (see footnote 38).

### 6.4.3 Ion Beams for Cancer Therapy

High energy ion beams are an important cancer therapy because of their well-defined stopping distance in human tissue, the so-called Bragg peak, where most of the ion-induced tissue damage is concentrated. Ion beams thereby minimize tissue damage along the path to a deeply located tumor and concentrate the damage at the tumor. At the present time, therapy with high energy ions (protons, etc.) requires synchrotrons or cyclotrons. Creating ion beams with ultra-intense lasers will reduce the size, cost, and undesirable radiation generation (such as that accompanying cyclotron operation). Early laser-

[27] R. Toth, J.C. Kieffer, S. Fourmaux, T. Ozaki, and A. Krol, 2005, In-line phase-contrast imaging with a laser-based hard x-ray source, *Rev. Sci. Instrum*. 76(8): 083701.

[28] J. Wenz, S. Schleede, K. Khrennikov, M. Bech, P. Thibault, M. Heigoldt, F. Pfeiffer, and S. Karsch, 2015, Quantitative X-ray phase-contrast microtomography from a compact laser-driven betatron source, *Nature Communications* 6: 7568.

[29] J.M. Cole, J.C. Wood, N.C. Lopes, K. Pode, R.L. Abe, S. Alatabi, J.S.J. Bryant, et al., 2015, Laser-wakefield accelerators as hard x-ray sources for 3D medical imaging of human bone, *Scientific Reports* 5: 13244.

[30] S. Fourmaux, S. Corde, K. Ta Phuoc, S. Buffechoux, S. Gnedyuk, A. Rousse, A. Krol, and J.C. Kieffer, 2011, Initial steps towards imaging tumors during their irradiation by protons with the 200TW laser at the Advanced Laser Light Source facility (ALLS), *Proc. of SPIE* 8079: 80791.

[31] E. Beyreuther, W. Enghardt, M. Kaluza, L. Karsch, L. Laschinsky, E. Lessmann, M. Nicolai, et al., 2010, Establishment of technical prerequisites for cell irradiation experiments with laser-accelerated electrons, *Med. Phys*. 37(4): 1392-1400.

[32] M. Oppelt, M. Baumann, R. Bergmann, E. Beyreuther, K. Brüchner, J. Hartmann, L. Karsch, et al., 2015, Comparison study of *in vivo* dose response to laser-driven versus conventional electron beam, *Radiat Environ Biophys* 54(2): 155–166.

proton radiotherapy research began in 1998 in a collaboration between Stanford and LLNL;[33] it was 10 years before beams containing high-current, ultra-short pulses of protons accelerated by ultra-short, ultra-intense lasers, produced biological effects.[34] Experiments showed that ultra-short bunches of high-energy protons produced by lasers were equally efficient in killing cancer cells as synchrotron-produced proton beams.[35]

### 6.4.4 Laser-Produced Isotopes for Positron Emission Tomography

The well-known medical procedure of PET currently requires the nearby presence of a synchrotron/cyclotron to create the short-lived radioactive sources that provide the positrons. Ultra-intense lasers show promise of creating the necessary radioactive sources—although none have yet been demonstrated in practical quantities. Initial studies at Strathclyde, UK,[36] with additional experiments carried out on the Titan laser at LLNL,[37] allowed modeling to predict that the 10 Hz Extreme Light Infrastructure (ELI) facilities should be able to create practical levels of useful positron-emitting sources.[38]

### 6.4.5 Future Considerations for Medical Applications

The expected hardware for each of these applications will be highly complex. Enough is known of the science behind the processes used that in many cases the feasibility of medical applications can be simulated, saving time and cost compared to preliminary experiments. Detailed modeling and design of the equipment required to carry out medical applications are being carried out at a number of institutions: In Germany, at LMU in Munich and at ONCORAY in Dresden; in France, at Institut Laue Langevin; and in Romania, at the National Institute of Physics and Nuclear Engineering, where they predict that “developing these techniques and applications is a promising task of ELI-NP with a strong societal component.”[39] Considerable modeling for biomedical applications is going on while the facility is being built.

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[33] R.A. Snavely, M. Key, S. Hatchett, T.E. Cowan, M. Roth, T.W. Phillips, M.A. Stoyer, et al., 2000, Intense high energy proton beams from Petawatt Laser irradiation of solids, *Phys. Rev. Lett*. 85(14): 2945-2948.

[34] A. Yogo, K. Sato, M. Nishikino, , M. Mori, T. Teshima, H. Numasaki, M. Murakami, et al., 2009, Application of laser-accelerated protons to the demonstration of DNA double-strand breaks in human cancer cells, *Applied Physics Letters* 94(18): 181502.

[35] A. Yogo, T. Maeda, T. Hori, H. Sakaki, K. Ogura, M. Nishiuchi, A. Sagisaka, et al., 2011, Measurement of relative biological effectiveness of protons in human cancer cells using a laser-driven quasimonoenergetic proton beamline, *Applied Physics Letters* 98(5): 053701.

[36] K.W.D. Ledingham, P. McKenna, T. McCanny, S. Shimizu, J.M. Yang, L. Robson, J. Zweit, et al., 2004, High-power laser production of short-lived isotopes for positron emission tomography, *J. Phys. D: Appl. Phys.* 37(16): 2341–2345.

[37] S. Kimura and A. Bonasera, 2011, Deuteron-induced reactions generated by intense lasers for PET isotope production, *Nuclear Instruments and Methods in Physics Research* A637: 164–170.

[38] E. Amatoa, A. Italiano, D. Margarone, B. Pagano, S. Baldari, and G. Korn, 2016, Study of the production yields of 18F, 11C, 13N and 15O positron emitters from plasma-laser proton sources at ELI-Beamlines for labeling of PET radiopharmaceuticals, *Nucl. Instr. & Methods in Phys. Res. Sect. A* 811: 1–5.

[39] D. Habs, P.G. Thirolf, C. Lang, M. Jentschel, U. Köster, F. Negoita, and V. Zamfir, 2011, Medical applications studies at ELI-NP. *Proc. SPIE* 8079: 1H .

In 2014, a group of pioneers (from the United Kingdom, Germany, Japan, and the United States) in laser-accelerated particle radiotherapy reviewed the status of the field: "Reaching medically relevant particle kinetic energies is obviously essential, yet equally important is the demonstration of repetition-rated, well-controlled beamlines at these energies with suitable bunch parameters that are highly reproducible. A systems mindset is necessary to incorporate, optimize and even exploit the multiple technologies that must be combined. … The full system components include the laser driver, the laser target, instrumentation for diagnostics and control and beam line (ion) optics."[40] Issues under consideration include the following: Reducing the energy spread and increasing the energy of the ion beam; controlling the angular divergence; beam transport and delivery; understanding the radiobiological basis of radiation therapy, including DNA damage, dose rate, oxygen and nitrogen effects. They conclude, "As the relevant laser, laser-plasma and target science and technologies mature, the committee remains optimistic that cost/size comparisons will become increasingly favorable..."

Researchers in Germany understand the complexity of the challenge that includes the development of transport and delivery (including gantry) systems, as key to achieving a compact laser-ion beam radiotherapy facility: "Enroute it is critical now to demonstrate the comprehensive need for laser-driven energetic ions; including applications that might require only the emergent ion 'spray' (or have minimal ion optics requirements). A balanced variety of targeted doable applications (medical and nonmedical especially for near term) can help to sustain the vision, the multidisciplinary collaboration, the cooperation of multiple communities and incremental success paths over the long term that are essential ingredients; first for ultimately realizing integrated laser drive ion acceleration systems and second for maturing it multi-faceted capability for laser-driven ion beam radiotherapy."[41]

## 6.5 HIGH POWER LASERS APPLICATIONS: FUSION ENERGY

Fundamental High Energy Density science (HED) and some of the successful research using high energy lasers such as NIF and OMEGA was discussed in some detail in Chapter 5. Here the committee introduces another possible application of high intensity lasers to that topic. Because of their ability to accelerate charged particles to high energies, high power lasers have played an important role in the development of advanced ignition schemes for fusion energy via inertial confinement (ICF). A fusion scheme that has been proposed that uses ultrafast techniques in high power lasers is Fast Ignition (FI).[42] In FI, the target is compressed to high density with a low implosion velocity and then ignited by a short, high-energy pulse of electrons or ions. Fast ignition has two potential advantages over conventional hot-spot ignition: higher gain, because the target does not need to be compressed as much (~300 versus ~ 600 g/cc), and relaxed symmetry requirements because ignition does not depend on uniform compression to very high densities. The fast-ignition concept for inertial confinement fusion was proposed with the emergence of ultrahigh-intensity, ultrashort pulse lasers using CPA.[43] The target compression can be done by a traditional ICF driver (direct-drive by lasers or ion beams, or indirect drive from X-rays using a hohlraum driven by nanosecond lasers, ion beams, or a *Z*-pinch). The ignition is initiated by a short high-intensity laser pulse (the so-called "ignitor pulse"), which produces a high-energy electron or ion beam

[40] K.W.D. Ledingham, P. R. Bolton, N. Shikazono, and C.-M. Ma, 2014, Towards laser driven hadron cancer radiotherapy: A review of progress, *Appl. Sci.* 4(3): 402-443.

[41] P.R. Bolton, 2016, The integrated laser-driven ion accelerator system and the laser-driven ion beam radiotherapy challenge, *Nucl. Instruments and Methods in Phys. Res. A* 809: 149–155.

[42] M. Tabak, J. Hammer, M.E. Glinsky, W.L. Kruer, S.C. Wilks, J. Woodworth, E.M. Campbell, and M.D. Perry, 1994, Ignition and high gain with ultrapowerful lasers, *Physics of Plasmas* 1:1626.

[43] D. Strickland and G. Mourou, 1985, Compression of amplified chirped optical pulses, *Opt. Commun*. 56: 219.

when it interacts with the target. The gain can be higher for fast ignition if the total energy of the compressor and ignitor drivers is less than that required for compression of a conventional target, as is suggested by numerical simulations.[44] A number of different schemes for coupling a high-energy, short-pulse laser to a compressed core have been proposed. The “hole-boring”[45] scheme assumed that there would be two short-pulse laser beams, one having an ~100-ps duration to create a channel in the coronal plasma through which the high-intensity laser pulse that generates energetic electrons would propagate. An alternative design uses a hollow Au cone inserted in the spherical shell.[46] The fuel implosion produces dense plasma at the tip of the cone, while the hollow cone makes it possible for the short-pulse-ignition laser to be transported inside the cone, without having to propagate through the coronal plasma, and enables the generation of hot electrons at its tip, very close to the dense plasma. A variant cone concept uses a thin foil to generate a proton plasma jet with multi-MeV proton energies.[47] The protons deliver the energy to the ignition hot spot—with the loss of efficiency in the conversion of hot electrons into energetic protons balanced by the ability to focus the protons to a small spot. The minimum areal density for ignition at the core ( $\rho R \sim 0.3$ g/cm$^2$ at 5 keV) is set by the 3.5-MeV $\alpha$ -particle range in D-T and the hot-spot disassembly time. This must be matched by the electron-energy deposition range. This occurs for electron energy in the ~1- to 3-MeV range. The minimum ignition energy of the particle beam $E_{ig}$ is independent of target size and scales only with the density of the target as $E_{ig} \sim \rho^{-1.85}$.[48]

The optimum compressed-fuel configuration for fast ignition is an approximately uniform-density spherical assembly of high-density DT fuel. High densities of large fuel masses can be achieved by imploding thick cryogenic-DT shells with a low-implosion velocity and low entropy. Such massive cold shells produce a large and dense DT fuel assembly, leading to high gains and large burn-up fractions. Experimental investigations of the fast-ignition concept are challenging. The fast-ignition concept involves extremely high energy density physics: ultra-intense lasers (intensities >$10^{19}$ W cm$^{-2}$) produce a >100-Mbar pressure, a magnetic field in excess of 100 MG, and electric fields >$10^{12}$ V/m. These laser fields generate massive currents (~GA in tens of microns diameter) at the critical surface. These currents can propagate through a variety of plasma conditions, from cold, nearly solid systems to hot (~keV), dense (~g/cc) plasmas. The sheer scale of the problem, e.g., the generation of a large current pulse of tens of picoseconds time duration that traverses ~100 $\mu$m requires the investigation of this concept and inherently requires high-energy and high-power laser facilities that are currently available (e.g., OMEGA EP, NIF-ARC, etc) to study the principles of fast ignition.

For an ignition scale target, the minimum fast particle energy required for ignition is about 20 kJ for a monoenergetic collimated beam with beam radius ~ 20 um and time duration ~ 10 ps. For a Maxwellian energy distribution and a reasonably low beam divergence, the minimum beam energy for ignition is about ~40 kJ.[49] Assuming conversion efficiency from laser to particle beam energy of ~20

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[44] R. Betti, A.A. Solodov, J.A. Delettrez, and C. Zhou, 2006, Gain curves for direct-drive fast ignition at densities around 300g⁄cc, *Physics of Plasmas* 13(10): 100703.

[45] A. Pukhov and J. Meyer-ter-vehn, 1997, Laser hole boring into overdense plasma and relativistic electron currents for fast ignition of ICF targets, *Phys. Rev. Lett.* 79(14): 2686-2689.

[46] R. Kodama, P.A. Norreys, K. Mima, A.E. Dangor, R.G. Evans, H. Fujita, Y. Kitagawa, et al., 2001, Fast heating of ultrahigh-density plasma as a step towards laser fusion ignition, *Nature* 412: 798-802; R. Kodama, H. Shiraga, K. Shigemori, Y. Toyama, S. Fujioka, H. Azechi, H. Fujita, et al., 2002, Nuclear fusion: Fast heating scalable to laser fusion ignition, *Nature* 418: 933-934.

[47] M. Roth, T.E. Cowan, M.H. Key, S.P. Hatchett, C. Brown, W. Fountain, J. Johnson, et al., 2001, Fast ignition by intense laser-accelerated proton beams, *Phys. Rev. Letts*. 86(3): 436.

[48] S. Atzeni, 1999, Inertial fusion fast ignitor: Igniting pulse parameter window vs the penetration depth of the heating particles and the density of the precompressed fuel, *Physics of Plasmas* 6: 3316-3326.

[49] A.A. Solodov, R. Betti, J.A. Delettrez, and C.D. Zhou, 2007, Gain Curves and hydrodynamic simulations of ignition and gain for direct-drive fast ignition targets, *Physics of Plasmas* 14: 101063.

percent, fast ignition ICF requires very large high power lasers of tens of petawatts with energies of hundreds of kilojoules.

## 6.6 DOD SECURITY APPLICATIONS

### 6.6.1 Ultrashort Pulse Applications

The following applications of ultra-short-pulse lasers have been considered by the Navy:[50]

- Long range directed energy, exploiting nonlinear focusing to overcome diffraction. This could include both direct target damage, or target "softening" for a high-energy laser attack.
- Long-range target impairment/disruption. An example is high-power RF generation at the target.
- Long range detection and composition probing of an atmospheric area of interest. Examples include detection of harmful aerosols and bio-agents from a safe distance, where one could distinguish between bio-aerosols and natural background aerosols.
- Filamentation for triggering and/or guiding of energy or electromagnetic waves.

To this list the committee notes that, primarily for Homeland-Security applications, there has been discussion of the use of laser Compton scattering of a high-peak-power laser from a high-energy electron beam to generate tunable, narrow-linewidth gamma rays.[51] These in turn can be used as a probe to detect, say, fissionable materials in transport vehicles. An example is the Department of Homeland Security's FINDER project for high-confidence detection of nuclear materials to enhance port security.

### 6.6.2 Propagation Applications

For light of intensity high enough to generate nonlinear effects such as self-focusing, any applications requiring remote delivery of energy suffer significant limitations due to the atmosphere. In particular, for current-generation near-infrared PW-class solid-state lasers at ~800-1000 nm, self-focusing and resultant generation of atmospheric filaments occurs for critical peak powers $P_{cr}$ ~ 2-10 GW range, depending on air's ultrafast nonlinear response as a function of laser pulsewidth.[52] This means that pulses of peak power P ~ 1 TW – 1 PW can break up into hundreds to many thousands of filaments, with that number approximately given by the ratio $P/P_{cr}$.[53] Such beam breakup leads to beam dissipation far short of its intended range, becoming a limitation on directed energy or remote sensing applications. However, there are possible strategies under development to mitigate filamentation breakup, or even find potential uses for it, both leveraging high-intensity short-pulse lasers. Because $P_{cr}$ scales as $\lambda^2$, high energy ultrashort pulses in the mid-infrared to long wavelength infrared range can be much more resistant to

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[50] Ryan Hoffman, "USPL Applications for Navy," n.d."

[51] LLNL, "S&TR | April/May 2011: Going Deep with MEGa-Rays," 2011, https://str.llnl.gov/AprMay11/barty.html.

[52] J.K. Wahlstrand, Y.-H. Cheng, and H.M. Milchberg, 2012, Absolute measurement of the transient optical nonlinearity in $N_2$, $O_2$, $N_2O$, and Ar, *Phys. Rev. A* 85(4): 043820.

[53] A. Couairon and A. Mysyrowicz, 2007, Femtosecond filamentation in transparent media, *Phys. Rep.* 441(2-4): 47-190.

filamentation than optical beams.[54] This is one of the factors spurring development of high-intensity infrared lasers using technologies such as OPCPA[55] and a revisiting of $CO_2$ laser technology. In another development, it was shown that rather than carrying significant beam energy itself, a multi-filamenting ultrashort pulse laser could imprint long-lasting waveguides in the atmosphere that can guide auxiliary high energy and high average power laser beams.[56]

## 6.7 EXTREME NONLINEAR OPTICS: HIGH-ORDER HARMONIC GENERATION

An area of high-intensity laser science with high potential impact is the generation of coherent short-wavelength (extreme ultraviolet [XUV] to soft X-ray) light through the process of high-order harmonic generation (HHG). In HHG, an intense femtosecond laser focused into a gas results in coherent upconversion of visible to infrared laser beams into laser-like EUV and soft X-ray beams. In gases these high harmonics are generated through a "recollision" process where an atom or molecule is ionized by the strong electric field of the laser, makes a "boomerang" excursion, and re-encounters its parent ion. During the re-encounter, the interaction of the high-energy electron with the parent ion can result in what is essentially sub-femtosecond Bremsstrahlung emission of a short wavelength photon. The HHG light is emitted as a directed, coherent, and collimated beam.[57]

### 6.7.1 The Strong-Field Electron Recollision Process and Its Implications

Coherent HHG emission is a universal response of atoms, molecules, and even solids to an intense femtosecond laser field. The deBroglie wavelength of the active electron is comparable to

[54] P. Panagiotopoulos, P. Whalen, M. Kolesik, and J.V. Moloney, 2015, Super high power mid-infrared femtosecond light bullet, *Nat. Phot.* 9: 543-548.

[55] G. Andriukaitis, T. Balčiūnas, S. Ališauskas, A. Pugžlys, A. Baltuška, T. Popmintchev, M.-C. Chen, M.M. Murnane, and H.C. Kapteyn, 2011, 90 GW peak power few-cycle mid-infrared pulses from an optical parametric amplifier, *Opt. Lett.* 36(15): 2755-2757.

[56] N. Jhajj, E.W. Rosenthal, R. Birnbaum, J.K. Wahlstrand, and H.M. Milchberg, 2014, Demonstration of Long-Lived High-Power Optical Waveguides in Air, *Phys. Rev. X* 4(1): 011027.

[57] A. McPherson, G. Gibson, H. Jara, U. Johann, T.S. Luk, I.A. McIntyre, K. Boyer, and C.K. Rhodes, 1987, Studies of multiphoton production of vacuum-ultraviolet radiation in the rare gasses, *Journal of the Optical Society of America B* 4: 595-601; M. Ferray, A. Lhuillier, X.F. Li, L.A. Lompre, G. Mainfray, and C. Manus, 1988, Multiple-harmonic conversion of 1064-Nm radiation in rare-gases, *Journal of Physics B-Atomic Molecular and Optical Physics* 21(3): L31-L35; B.W. Shore and K.C. Kulander, 1989, Generation of optical harmonics by intense pulses of laser-radiation, *Journal of Modern Optics* 36(7): 857-875; J.L. Krause, K.J. Schafer, and K.C. Kulander, 1992, High-order harmonic-generation from atoms and ions in the high-intensity regime, *Physical Review Letters* 68(24): 3535-3538; P.B. Corkum, 1993, Plasma perspective on strong field multiphoton ionization, *Physical Review Letters* 71: 1994-1997; M. Lewenstein, P. Balcou, M.Y. Ivanov, A. L'Huillier, and P.B. Corkum, 1994, Theory of high-harmonic generation by low-frequency laser fields, *Physical Review A* 49(3): 2117-2132; J. Zhou, J. Peatross, M.M. Murnane, H.C. Kapteyn, and I.P. Christov, 1996, Enhanced high harmonic generation using 25 femtosecond laser pulses, *Physical Review Letters* 76(5): 752-755; Z. Chang, A. Rundquist, H. Wang, I. Christov, H.C. Kapteyn, and M.M. Murnane, 1998, Temporal phase control of soft-x-ray harmonic emission, *Physical Review A* 58(1): R30-R33; A. Rundquist, C.G. Durfee, Z.H. Chang, C. Herne, S. Backus, M.M. Murnane, and H.C. Kapteyn, 1998, Phase-matched generation of coherent soft X-rays, *Science* 280(5368): 1412-1415.

interatomic spacing in molecules, so that HHG emission is sensitive to rotations, vibrations, and chemical dynamics.[58] HHG employs femtosecond-duration pulses so it can resolve dynamics in molecular systems on time scales from picoseconds to few-fs/attosecond time scales. More recent work has observed HHG from solid materials and has shown that this emission is sensitive to band structure in materials.[59] The full implications of HHG as a useful method for probing matter are still under active investigation.

Another area of recent investigation is the control of the electron recollision process itself.[60] Recent work has used recollision control to change the spectrum and polarization, and even create novel circularly polarized VUV light.[61] The temporal structure of high-order harmonic generation is intrinsically in the form of a sequence of sub-femtosecond bursts of radiation, separated in time by half of an optical cycle. When driven with a few-cycle light pulse, the emission can be confined to a single isolated attosecond pulse.[62] Attosecond science makes use of this to observe very fast processes. The HHG process itself is the first example where attosecond dynamics are clearly responsible.[63] Research in this new ultrashort time domain is discussed in Chapter 5.

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[58] J. Itatani, J. Levesque, D. Zeidler, H. Niikura, H. Pepin, J.C. Kieffer, P.B. Corkum, and D.M. Ville-neuve, 2004, Tomographic imaging of molecular orbitals, *Nature* 432(7019): 867-871; N.L. Wagner, A. Wuest, I.P. Christov, T. Popmintchev, X.B. Zhou, M.M. Murnane, and H.C. Kapteyn, 2006, Monitoring molecular dynamics using coherent electrons from high harmonic generation, *Proceedings of the National Academy of Sciences of the United States of America* 103(36): 13279-13285; H. Niikura, N. Dudovich, D.M. Villeneuve, and P.B. Corkum, 2010, Mapping molecular orbital symmetry on high-order harmonic generation spectrum using two-color laser fields, *Physical Review Letters* 105(5); S. Baker, J.S. Robinson, C.A. Haworth, H. Teng, R.A. Smith, C.C. Chirila, M. Lein, J.W.G Tisch, and J.P. Marangos, 2006, Probing proton dynamics in molecules on an attosecond time scale, *Science* 312(5772): 424-427.

[59] S. Ghimire, A.D. DiChiara, E. Sistrunk, P. Agostini, L.F. DiMauro, and D.A. Reis, 2011, Observation of high-order harmonic generation in a bulk crystal, *Nature Physics* 7(2): 138-141.

[60] P.B. Corkum, N.H. Burnett, and M.Y. Ivanov, 1994, Subfemtosecond pulses, *Optics Letters* 19(22): 1870; X. Feng, S. Gilbertson, H. Mashiko, H. Wang, S.D. Khan, M. Chini, Y. Wu, K. Zhao, and Z. Chang, 2009, Generation of isolated attosecond pulses with 20 to 28 femtosecond lasers, *Physical Review Letters* 103(18): 183901.

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[62] I.P. Christov, M.M. Murnane, and H.C. Kapteyn, 1997, High-harmonic generation of attosecond pulses in the "single- cycle" regime, *Physical Review Letters* 78(7): 1251-1254; I.P. Christov, M.M. Murnane, and H.C. Kapteyn, 1998, Generation and propagation of attosecond x-ray pulses in gaseous media, *Physical Review A* 57(4): R2285-R2288; A. Baltuska, T. Udem, M. Uiberacker, M. Hentschel, E. Goulielmakis, C. Gohle, R. Holzwarth, et al., 2003, Attosecond control of electronic processes by intense light fields, *Nature* 421(6923): 611-615.

[63] Z. Chang, A. Rundquist, H. Wang, I. Christov, H.C. Kapteyn, and M.M. Murnane, 1998, Temporal phase control of soft-x-ray harmonic emission, *Physical Review A* 58(1): R30-R33; R. Bartels, S. Backus, G. Vdovin, I.P. Christov, M.M. Murnane, and H.C. Kapteyn, 2000, Sub-optical-cycle coherent control in nonlinear optics, *Optics and Photonics News* 11(12): 23; R. Bartels, S. Backus, E. Zeek, L. Misoguti, G. Vdovin, I.P. Christov, M.M. Murnane, and H.C. Kapteyn, 2000, Shaped-pulse optimization of coherent emission of high-harmonic soft X-rays, *Nature* 406(6792): 164-166.

### 6.7.2 High-Order Harmonic Generation as a New Coherent Laser Source at Very Short Wavelengths

HHG radiation is a quintessential application of the interaction of high intensity laser radiation with matter. Currently it is a compact affordable laboratory-scale coherent vacuum ultraviolet light source has broad applications, particularly in areas where synchrotrons are inconvenient or impractical. In addition, this source has some superior features compared to synchrotrons. These include high spatial (diffraction limited) coherence and broad bandwidth femtosecond-scale temporal coherence. This makes HHG sources particularly useful for femtosecond dynamics studies.

Current areas of broad impact of HHG sources are mostly in materials and nanoscience. These include: photoemission using high-harmonic light sources;[64] time- and angle- resolved photoemission (TARPES);[65] [66] excited electron lifetime studies in the attosecond range;[67] transient reflectivity and absorption, including Magneto-Optic Kerr Effect (MOKE)[68] ultrafast demagnetization;[69] laser-induced spin currents;[70] [71] [72] [73] Achievements in this area include the ability to image buried layers in reflection

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[64] R. Haight and P.F. Seidler, 1994, High resolution atomic core level spectroscopy with laser harmonics, *Applied Physics Letters* 65: 517.

[65] S. Eich, A. Stange, A.V. Carr, J. Urbancic, T. Popmintchev, M. Wiesenmayer, K. Jansen, et al., 2014, Time- and angle-resolved photoemission spectroscopy with optimized high-harmonic pulses using frequency-doubled Ti:Sapphire lasers, *Journal of Electron Spectroscopy and Related Phenomena* 195: 231-236.

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and to characterize the diffusive properties of the interface.[74] These results suggest that HHG may have a role in the emerging industry of EUV light for nanoelectronics lithography.[75]

enables studies of the nanoscale thermal and acoustic properties of materials,[76] and measurements of thin film properties.[77] HHG light sources have also been used for studies of dynamics in molecular systems.[78] [79] [80]

### 6.7.3 Technology Needs for Future High-Order Harmonic Generation Research

The properties of HHG radiation vary quite dramatically with the parameters of the driving laser. Longer wavelength drive lasers produce coherent soft X-ray emission at shorter wavelengths. Using longer wavelength laser, coherent light at >1 keV- photon energy has been demonstrated.[81] Higher conversion efficiency can be generated using intense-field lasers at ultraviolet wavelengths.[82] A frequent limitation to wider applications is the limited average power of HHG sources, and so this is an area of active technology development.

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# 7

# Conclusions and Recommendations

## 7.1 STUDY CONCLUSIONS

The committee came to a number of conclusions based on the findings in the preceding chapters of this report. These involve all aspects of high-intensity laser science: science opportunities, applications, technology, stewardship, manpower, and the international landscape.

**Conclusion 1: The science is important.** High-intensity lasers enable a large and important body of science.

This study concludes that the case for high-intensity and high-powered laser-enabled science is unusually strong and broad. Chapter 5 shows that the research undertaken with the lasers in this study will have a major impact in the fields of plasma physics and planetary and stellar astrophysics, and is very likely to have a strong impact in accelerator physics, particle physics, and nuclear physics. These form a compelling science case for facilities in this area.

**Conclusion 2: Applications exist in several areas.** Intense ultrafast lasers have broad applicability beyond science to nuclear weapons stockpile stewardship as well as to industry and medicine. Science is a main application of high-intensity lasers, and all applications of high-intensity lasers rely on the fundamental science of high-intensity laser-matter interactions.

Chapter 6 outlines how further work in this area shows promise for more such industrial applications, including areas that are important to U.S. leadership in critical technology areas such as microelectronics. However, effective cooperation is often lacking between U.S. private industry and government laboratories in this area.

Chapter 4 describes European expenditures for major high intensity laser research centers that form a significant part of a broader plan in Europe to reinvest public funds in scientific infrastructure that will enable economic as well as technological advances in the coming decades. This connection between high intensity laser infrastructure and economic advance can also be made in the United States.

**Conclusion 3: The community is large but fragmented.** There is a large and talented technical community already, but it is fragmented across different disciplines. Coordination between industry and government is limited and often inadequate. The scientists and engineers trained in intense ultrafast lasers contribute to the workforce for applications in photonics and optics, including high-energy lasers for defense and stockpile stewardship.

Many different science areas are already planning to use petawatt or other advanced ultrafast high-intensity sources for astrophysics, plasma physics, high energy density science, and materials science, but they have different conferences, academic departments, and different funding agencies including the National Institutes of Health (NIH), the Department of Energy (DOE), the Department of Transportation (DOT), and the National Science Foundation (NSF).

Conclusions 1-3 motivate the first recommendation.

**Conclusion 4: No cross-agency stewardship exists.** No single agency currently acts as the steward for high-intensity laser-based research in the United States. Programs are carried out under sponsorship of several different federal agencies, including DOE-SC, NNSA, AFOSR, ONR, the Defense Advanced Research Projects Agency (DARPA), and the National Science Foundation (NSF), according to their various missions and without the overall coordination that exists in Europe.

Federal agencies and industry in laser-enabled science and technology contribute to research across multiple levels. DOD and DARPA have supported high-intensity laser source science and engineering through single-investigator programs and multi-investigator multidisciplinary university research initiatives. NSF supports some single investigators and mid-scale instruments and applications at university-scale research centers. DOE-SC and NNSA laboratories provide to users unique state-of-the-art large-scale facilities such as X-ray free-electron lasers and high energy pulsed lasers. Finally, industry works with some centers and single investigators to develop and provide advanced lasers and components, but there is no consistent program encouraging interagency program coordination or commercial industry involvement.

Conclusion 4 leads to the second recommendation.

**Conclusion 5: The US has lost its previous dominance.** The United States was the leading innovator and dominant user of high-intensity laser technology when it was developed in the 1990s, but Europe and Asia have now grown to dominate this sector through coordinated national and regional research and infrastructure programs. In Europe, this has stimulated the emergence of the Extreme Light Infrastructure (ELI) program. At present, 80 to 90 percent of the high-intensity laser systems are overseas, and all of the highest power (multi-petawatt) research lasers currently in construction or already built are overseas (See Ch. 3).

The United States does have the infrastructure capacity to potentially engage in facility-level high-intensity science and leverage the capabilities in ELI. This includes the capability to consider the fourth "pillar" (fouth site) of ELI in the United States within DOE laboratories. The United States also has scientists who use facilities worldwide and want to work with ELI as both users and instrument developers.

Conclusion 4 leads to the third recommendation.

**Conclusion 6: Co-location with existing infrastructure is essential.** Co-location of high-intensity lasers with existing infrastructure such as particle accelerators has been recognized as a key advantage of the U.S. laboratories over the ELI concept in Europe.

There are already conceptual designs that place petawatt-class lasers at X-ray FELS and at high energy laser facilities where expertise is strong. The United States also has laser system expertise, highly advanced laser component suppliers, and strong university research and education programs as well as major government facilities. Co-location also takes advantage of the expertise of the scientists, engineers, and technicians who already use the facilities.

This conclusion leads directly to the fourth recommendation

**Conclusion 7: University/Laboratory/Industry cooperation is necessary to retain and renew the talent base.** Cooperation among all sectors—private industry, research universities, and government laboratories—in the past has proved essential and the current situation could be improved to develop a robust national talent pool and a strong technology base for this fast growing area.

High-intensity laser technology development efforts should coordinate the talents of universities for basic research, national laboratories for large facilities infrastructure, and private companies that can serve both commercial and scientific markets. Key component suppliers and commercial laser manufacturers are important stakeholders.

Based on these conclusions, the committee arrived at its recommendations (see next section).

## 7.2 RECOMMENDATIONS

This committee recommends specific actions by the study sponsors and the U.S. funding agencies they represent that will enable and strengthen U.S. participation in high-intensity laser research. These include the following: (1) form a network, (2) engage the community, (3) develop a stewardship strategy, and (4) build one or more major facilities, and (5) create programs that engage the commercial and academic communities of interest. Taken together, these recommendations constitute a national strategy for high-intensity laser science and technology, and lay out a roadmap for implementing this strategy.

**Recommendation 1: The Department of Energy should create a broad national network, including universities, industry, and government laboratories, in coordination with the Office of Science and Technology Policy, the research arms of the Department of Defense, National Science Foundation, and other federal research organizations, as the cornerstone of a national strategy to support science, applications, and technology of intense and ultrafast lasers.**

**Recommendation 2: To increase integration and coordination in this field, the research agencies (Department of Defense, Department of Energy, National Science Foundation, and others) should engage the scientific stakeholders within the network to define what facilities and laser parameters will best serve research needs, emphasizing parameters beyond the current state of the art in areas critical to frontier science, such as peak power, repetition rate, pulse duration, wavelength, and focusable intensity.**

**Recommendation 3: The Department of Energy should lead the development of a comprehensive interagency national strategy for high intensity lasers that includes a program for both developing and operating large-scale laboratory projects; midscale projects such as those hosted at universities; and a technology development program with technology transfer among universities, U.S. industry, and national laboratories.**

**Recommendation 4: The Department of Energy should plan for at least one large-scale open-access high-intensity laser facility that leverages other major science infrastructure in the Department of Energy complex.**

**Recommendation 5: Agencies should create programs for U.S. scientists and engineers that include mid-scale infrastructure, project operations in high-intensity laser science in the United States,**

**development of key underpinning technologies; and engagement in research at international facilities such as Extreme Light Infrastructure.**

# Appendixes

# A

# Technical Background Summaries

## APPENDIX A1. TECHNICAL TERMS

### Lasers

Lasers are sources of coherent electromagnetic radiation projected in nearly collimated beams and produced by the process of quantum stimulated amplification. This electromagnetic radiation travels through vacuum at the speed of light *c*, about 30 billion cm/s, and consists of waves of oscillating electric and magnetic fields with wavelengths that range from fractions of a millimeter for far infrared sources, to fractions of one micron for visible lasers, to angstroms for X-ray lasers. In transparent media such as air or glass, the radiation travels more slowly than the speed of light in vacuum. The electric field of the light oscillates, but is usually characterized by its peak value. In the standard "SI" system of units used in physics, the units of field amplitude are volts per meter. The field also has a direction in space called the "**polarization**" of the light that is usually perpendicular to the direction of the light propagation. Polarization can be linear, but it can also be circular or elliptical, in which case the electric field oscillates in direction as well as amplitude.

Laser beams may be bright or dim, may exist at visible or invisible wavelengths, may contain a narrow or a broad range of wavelengths, and may be more or less divergent. This study concerns some of the brightest lasers, those with the highest peak power, which can deliver the highest intensity radiation. Power is the rate of energy flow in the laser beam, measured in watts. Average Power is power averaged over some relevant time interval.

### Peak Power

Peak power is the instantaneous power, usually at the peak of a laser pulse, also measured in watts. A typical laser discussed in this study may have an average power of only a few watts but could have a peak power as high as 10,000 trillion watts (10 petawatts, $10^{16}$ watts). The pulse energy is the integral of the power over the pulse duration, measured in joules. The cost of a laser tends to scale with the pulse energy rather than the peak power.

### Pulse Repetition Rate

Pulse repetition rate is another important criterion. Petawatt lasers do not generally pulse at high rate, but rather they store energy and then release it in a "single shot." Many other types of lasers have less per-shot energy but achieve high average power through high pulse repetition rates**.**

### Intensity

Intensity is power per unit area, usually at the waist, or narrowest part, of a focused laser beam, usually measured using the mixed unit Watts/cm$^2$. As with power, intensity may also be expressed as peak or average intensity. This study defines high intensity as intensities that will field ionize matter (i.e., ~$10^{14}$ W cm$^{-2}$) and ranges up through ultrahigh intensity. The highest currently-accessible peak laser field intensities are approximately 10-billion-trillion Watts/cm$^2$, $10^{22}$ Watts/cm$^2$. To put this in some context, the temperature that corresponds to this radiation intensity is 200 million degrees. This is about ten times the central temperature of the sun and 40,000 times the surface temperature. Thus it represents a unique laboratory for fundamental scientific studies.

### Peak Field Strength and Vector Potential

The intensity *I* is related to the amplitude of the oscillating electric field strength *E* of the electromagnetic radiation that makes up light. The connection is $I = \frac{c\varepsilon_0 n}{2}|E|^2$, where *c* is the speed of light, $\varepsilon_0$ is the vacuum permittivity, and *n* is the index of refraction of the medium.

As shown, the peak field strength of the laser beam scales as the square root of the intensity. When the intensity is $10^{22}$ Watts/cm$^2$, the peak electric field is about 3 trillion volts per centimeter, which is 600 times greater than the field strength that binds the hydrogen atom (5x$10^{11}$ V/m) and nearly an order of magnitude higher than the binding field of any atomic electron in nature.

The relationship between the field amplitude *E* and the electromagnetic vector potential amplitude *A* is given in SI units by $\vec{E} = -\partial\vec{A}/\partial t$ and in Gaussian units by $\vec{E} = -\partial\vec{A}/c\partial t$. Physically, the vector potential is proportional to the momentum that a charged particle acquires due to the force exerted by the field. In high intensity laser physics one often encounters the normalized vector potential *a*, which is the vector potential in units of *mc*, where *m* is the electron mass and *c* is the speed of light.

### Pulse Length and Duration

A third important quantity for high-powered lasers is pulse length and duration, which may be as short as a few cycles—a few microns for visible laser light, corresponding to a pulse duration of a few femtoseconds—or as long as a meter, corresponding to three nanoseconds duration. Shortening the pulse duration has always been an important goal for high-intensity laser science because for fixed pulse energy, the peak power increases when the duration of the pulse decreases. The most intense pulses referred to in the previous paragraphs have pulse durations on the order of 30 femtoseconds, or about 10 cycles for a wavelength of 1 um. The science chapters of this study will also describe efforts to produce pulses shorter than 1 femtosecond, in the attosecond range, which requires wavelengths in the ultraviolet or vacuum ultraviolet range. This is relevant since the generation of attosecond pulses is possible only through the application of high-intensity (femtosecond) pulse lasers.

### Coherence

Two additional properties of a laser are its spatial and spectral coherence, equivalently called transverse and temporal coherence. These have mathematical definitions as correlations between the light field at different points in space and time, respectively. For pulsed lasers, where the light field is a compact nearly monochromatic pulsed beam of light with an approximately Gaussian spatial and spectral profile, the best possible spatial coherence will lead to a focus with the smallest waist and therefore the highest intensity. This optimal focus is called the "diffraction limit," where the focal waist radius *w* of a focused beam with focal convergence angle $\Delta\theta$ and wavelength $\lambda$ has its minimum value $w \sim 2\lambda/\pi\Delta\theta$. There is a similar limit in the time domain. Short laser pulses cannot be purely monochromatic because of the well-known spectral uncertainty principle: The shortest and therefore most intense possible pulse $\Delta\tau$ for a spectral spread $\Delta f$ is called the "Fourier transform limit," given by the spectral time-bandwidth product of $\Delta f \Delta\tau \sim 1/2$.

## Wavelength

Finally, another relevant parameter is the *wavelength* of the light $\lambda$, which is directly related to the light frequency $\upsilon = c/\lambda$, the angular frequency $\omega = 2\pi\upsilon$, and the photon energy $h\upsilon$. Here $c$ is the vacuum speed of light and $h$ is Planck's constant. The light matter interaction often differs substantially depending on the wavelength of the light. Currently, high intensities as defined above can be generated at wavelength ranging from the deep-UV (~250 nm) to the mid-infrared (~4 µm) and beyond, with the vast majority of work starting in the near-infrared at either 800 nm (Ti:sapphire) or 1 µm wavelength (neodymium-based solid-state lasers). In recent years, as the physics at these wavelengths has become more-thoroughly explored, physics near the wavelength boundaries (far-IR and deep-UV) has seen an uptick in interest. Further, X-ray free-electron lasers, by virtue of the superior focusability and sub-femtosecond pulse duration that comes from their sub-nanometer wavelength, can reach comparable high intensities with only hundreds of gigawatts to terawatts of peak power rather than petawatts. These have a different science impact, though, because of photon energies in the kilo-electron-volt range instead of the electron-volt range of visible lasers.

## Contrast Ratio

Laser pulses cannot turn on and off instantaneously because the uncertainty principle limits the minimum time-bandwidth product to 0.5. In addition, amplified laser pulses nearly always contain a temporal pedestal much longer than the central peak due to the gain dynamics. This becomes important in high-intensity laser matter interactions, where damage to the target may be induced by the pedestal long before the central peak arrives. The figure of merit for this is the "contrast ratio," defined as the ratio of peak intensity to pedestal intensity in a laser pulse.

# APPENDIX A2. BRIEF HISTORY OF LASER TECHNOLOGY AND THE EMERGENCE OF PETAWATT LASER TECHNOLOGIES

## The Laser

The first demonstration of a laser in 1960 by Maiman in the United States attracted considerable attention as the first spectrally narrow (i.e., temporally coherent) optical frequency source. Perhaps more intriguing about the laser was its much higher spatial coherence than other sources of light, meaning that it could travel long distances as a narrow beam and could be focused by a lens or a mirror to a much smaller diameter than prior light sources, approaching the diameter equivalent to the wavelength of the light. Even modest powers from the laser could produce focused intensities well beyond what had been produced by any other light source or from powerful microwave sources developed for radar applications. Early laser demonstrations used focused power to drill through steel and gave way to more important uses in precision eye surgery and micro-machining of materials.

## Q-switching

Subsequent developments of laser technology of interest for this study involved concentrating the energy into a shorter pulse. An early breakthrough in this direction was Q-switching, a means developed in the 1960s to store energy in the gain medium over a long time and then extract it as laser energy over a short time. This led pulse durations on the order of the time for light to make a round trip in the laser cavity, generally 5 to 10 nanoseconds. With this, even modest pulse energies, on the order of 1 Joule, yielded instantaneous (peak) powers of 100 MW, and the intensity of light at the focus could approach $10^{15}$ W/cm$^2$. This is equivalent to a temperature of over 3 million degrees and therefore suggested to some that lasers could be used to investigate nuclear fusion.

The Department of Energy funded programs over several decades to study fusion with large amplified Q-switched laser pulses, culminating in 2009 with the multi-billion-dollar National Ignition Facility (NIF) at Lawrence Livermore National Laboratory, presently the world's most energetic laser, with 4 MJ total pulse energy. The NIF combines the pulses from 192 separate beam lines, each employing Nd-doped glass amplifiers of 3 ns Q-switched laser pulses. The combined peak power exceeds 1 x $10^{15}$ W (1 Petawatt), achieved through combining many lasers. The NIF amplifiers are large-scale modern implementations of a basic architecture that was developed in the 1960s: relatively inefficient Xe gas discharge lamps excite a rare-earth doped glass gain medium. The thermal characteristics of glass lead to a low repetition rate of ~ one pulse per hour.

## Mode Locking

Another important breakthough for high-power lasers is mode locking. This is a method of gain modulation just as is Q-switching, but in mode locking the modulator changes the gain in sync with the round-trip light travel time in the cavity. The laser energy takes the form of a very short pulse, which passes through the mode locker during its point of maximum transmission on every round-trip through the cavity. The shortest pulse possible is set by the frequency range over which a given laser material provides amplification (the laser gain bandwidth). This can be as short as 10 femtoseconds for some gain media such as Ti:Sapphire. For the case of Nd:glass, the shortest pulse is a fraction of a picosecond. There are many physical methods for mode locking, but a particularly useful method is Kerr-lens mode locking, which uses the nonlinear interaction of the light with the gain medium host (glass or sapphire, typically) to stabilize mode-locked short pulses in the cavity.

## Chirped-Pulse Amplification

Mode-locked amplified pulses should in principle be scalable to enormous peak power but a critical limitation is the damage resistance of the lasing medium itself. Picosecond or femtosecond pulses with sufficient intensity to efficiently extract energy from Nd:Glass or Ti:Sapphire will also destroy the glass or the sapphire through the process of dielectric breakdown—literally forming a spark that destroys the material. The breakthrough that resolved this limitation is chirped-pulse amplification (CPA), which is based on an idea from high-powered radar systems. The CPA concept for laser amplification was first implemented by Mourou and Strickland at the University of Rochester in the 1980s.

With CPA, the short mode-locked pulses pass through special-dispersive optics where the optical path length depends on optical frequency. This stretches the pulse length by as much as 1,000-30,000 times, thereby reducing the peak power by the same factor. Further amplification then uses a laser system similar to Q-switched amplifiers. At the output of the final amplifier, the energetic pulse is compressed in time by another set of optics to reverse the stretching. Typically the compression optics include a set of large-aperture gratings, up to 1 meter in size.

In 1996, the CPA technique was applied to a Nd:glass laser system to build the first single-beam, PW-peak power laser, with about a 0.5-ps pulsewidth, notable in that the peak power was of the same order as the entire NIF laser. Subsequent development of Nd:glass CPA systems, involving optimization of the laser gain bandwidth, has allowed operation with pulses as short as about 0.15 ps.

Broadly tunable lasers based on other solid-state media, most notably titanium-doped sapphire (Ti:sapphire), have properties well suited for energy and hence peak-power scaling. In mode-locked operation, the extremely large linewidth of the Ti:sapphire laser, centered around 800 nm, allows generation of pulses as short as 5 fs. The most common pumping source is another laser, and the relatively long storage time enables energetic pulse amplification when the pump source is a pulsed laser with sub-microsecond pulsewidth, most often a Q-switched solid-state laser.

Typical CPA Ti:sapphire lasers operate with 20 to 30 fs pulses, allowing for increasingly compact tabletop TW-scale lasers with diffraction limited focusability to generate even relativistic intensities on a tabletop, and PW-class lasers with about 5 to 7X lower pulse energies than Nd:glass CPA systems. Another important difference from Nd:glass systems is that the thermo-mechanical properties of the sapphire ($Al_2O_3$) crystal are much better compared to the oxide glasses used in high-energy systems, allowing Ti:sapphire to operate at pulse rates limited by the pump laser, and PW-class Ti:sapphire systems to operate at pulse rates of 1 to 10 pulses/sec, compared to the pulse/hour rate for energetic glass lasers.

## Commercial Chirped-Pulse Amplification Lasers

Many aspects of the high-intensity physics phenomena of interest in this report have been developed using commercialized, tabletop-scale weaker (i.e., terawatt) CPA lasers for research, rather than the large petawatt-class lasers that are the focal point of this study. Terawatt lasers can be scaled to repetition-rates in the kHz range. These typically cost under $1 million and are therefore affordable for university programs. Small specialty laser companies, such as KMLabs, and larger research laser companies, such as the European Thales Group and the American-based Coherent Radiation or Newport-Spectra, serve this market. Thales also markets custom PW laser systems, as does a small start-up, Austin-based Laser Energetics, but these are only affordable on a regional or national scale.

# APPENDIX A3. TECHNOLOGIES BEYOND CONVENTIONAL CHIRPED-PULSE AMPLIFICATION

## Optical Parametric Chirped-Pulse Amplification

At present, CPA PW-class lasers are primarily either Ti:sapphire- or Nd:glass-based, but a new technology has emerged that allows nanosecond pump lasers to convert their energy efficiently to chirped pulses comparable to CPA Ti:sapphire lasers. The approach, optical parametric chirped-pulse amplification (OPCPA), utilizes nonlinear parametric frequency amplification. An OPCPA is a parametric amplifier, not a laser. The difference is that a laser amplifies light in a two-step process: First, the gain medium is excited by some energy source; later, the energy is extracted from the gain medium by stimulated emission. A parametric amplifier converts energy from the excitation source directly into the output laser in a single step. The host medium is just a converter; it does not need to store the energy. In the case of an OPCPA, the host medium converts an energetic narrow bandwidth nanosecond laser into a broad bandwidth chirped laser pulse that can be compressed later to create a high peak power. To date, work in Russia has demonstrated a 0.56 PW system (25 J in 45 fs) and a longer pulse 1 PW device (100 J in 100 fs). These high-energy results employ Nd:glass lasers as pump lasers and thus have the same low pulse rates as Nd:glass-based CPA systems, but as the technology of energetic nanosecond lasers advances, OPCPA systems can be expected to advance in performance as well.

## Intense X-ray Free-Electron Lasers

Free-electron lasers (FELs) can produce comparable high intensities to petawatt lasers but with much lower (sub-terawatt) peak power and much shorter (sub-nanometer) wavelength. They utilize ultrarelativistic intense electron beams as a gain medium, produced in long traveling-wave radio frequency accelerator structures located at large national accelerator laboratories in the United States, Europe, and Japan. These facilities are quite expensive, on the order of $1 billion.

X-ray FELs do not employ optical CPA, but they do employ chirped pulse methods for the electrons in the accelerator. The electron bunch is chirped in an accelerating structure quite analogous to the fiber disperser that was used in the original implementation of CPA. The long chirped electron bunch is then accelerated and compressed to a short pulse with high peak charge density in a magnetic chicane that has the identical function of the grating compressors in CPA. The X-ray laser produced by these electrons has been focused to peak intensities of $10^{20}$W/cm$^2$, and higher intensities are only limited by the quality of the focusing optics. Since the wavelength is so much shorter than conventional lasers, the science case and applications are quite different: The applications of these sources are in producing and imaging high energy density matter, ultrafast X-ray diffractive imaging and molecular movies, and ultrafast high-intensity X-ray-matter interactions.

## Ultrarelativistic Particle Beams Boost Laser Intensities

With present PW-level lasers, focused intensities have reached the $10^{22}$ W/cm$^2$ region, but far higher intensities are available in the rarefied and limited environment of relativistic particle beams. When a laser pulse from a high-intensity laser collides head-on with a relativistic particle, the laser intensity as viewed in the particle rest frame is higher by a factor of $4\gamma^2$, where $\gamma$ is the Lorentz frame relativistic boost. For example, at SLAC the electron energies are in the range of 15 GeV (based on using one-third of the accelerating sections), so the $4\gamma^2$ intensity increase factor is more than one billion. This was demonstrated for focused terawatt lasers and 45GeV electron beams in the 1990s, where center of mass intensities greater than $10^{28}$ W/cm$^2$ were inferred. With a petawatt laser focused to only $10^{20}$ W/cm$^2$, the boosted intensity would exceed the "Schwinger limit," the intensity required to break down the vacuum, and this novel environment has been suggested as a laboratory for exotic phenomena in particle physics.

In subsequent sections of this report the committee provides more detailed discussions of the technology basis for present PW-class lasers, prospects for future technologies that will lead to higher peak powers as well as higher pulse rates, and status of PW-class laser capabilities specific to the United States.

## APPENDIX A4 . LIMITS TO SCALING TO STILL HIGHER PEAK POWERS AND INTENSITIES

The highest power lasers, capable of the highest focused intensities, are certainly large and expensive; but the technical limits to power are not simply the cost. Because of CPA, the laser construction expense is only a few percent of the NIF laser, but still measured in the range of $10 million, not counting conventional construction of the facility that houses them or performs experiments with the light.

The current highest-powered lasers that are under construction in Europe and Asia (though not in the United States at present) have peak power of 10 petawatts and have individual costs including conventional construction on the order of $100 million. Their power is limited by several key elements in the optical path: The gain medium, a transparent solid with a rare-earth dopant, must amplify the light used in CPA without distorting it, and the passive optical elements, which consist of lenses, mirrors, dispersive elements and other more specialized devices, must withstand the peak power inside the laser. Figure 1.1 shows a world map with the locations of most of the 0.1 petawatt or higher power lasers. Total expenditures on these facilities are reported to be in the range of $4 billion.[1]

The laser gain material of choice for most of the lasers under construction now is titanium-doped sapphire, which utilizes CPA and can efficiently convert the excitation by long energetic pulses of lower-powered laser light from more conventional lasers into extremely short and powerful laser pulses at a central wavelength of about 800 nm. Other choices for petawatt-class lasers under current construction or in advanced design include CPA with mixed glass lasers, a nonlinear conversion method called optical parametric CPA, or OPCPA.

X-ray free-electron lasers have different scaling limitations, since they use wholly different technology based on ultrarelativistic electron beams. Current design maxima are in the range of 10 millijoule pulse energies, up to terawatt peak power, below 100 nm focal waists, and below 10 femtosecond pulse durations. When combined, this is a 10 TW laser with a focused intensity of $10^{22}$ W/cm$^2$. Engineering advances in superconducting RF accelerator designs, tapered undulators, low emittance photocathodes, seeded laser operation, or focusing mirrors could improve these numbers.

### Limits to Scaling and the Path Toward Still More Intense Lasers, Exawatt

The current limits to scaling to higher powers for optical wavelength lasers is damage to optical elements, and elements with the lowest damage thresholds, which are the real limits to the maximum achievable power, are the special dispersion compensation optics required for CPA or OPCPA. These are typically diffraction gratings. Some future technological advances will be required to continue to scale laser powers to the 1,000 petawatt, or 1exawatt, level, and the current activity in this area is summarized in this report. It is likely that such lasers will approach or exceed the billion-dollar price tags of the high energy fusion lasers such as NIF or the particle accelerators used for X-ray FELs.

### Laser-Electron Colliders Scaling Limits

The benefits to combining high-intensity lasers with relativistic particle beams have several paths to scaling since the intensity in the rest frame of the electron scales as $\gamma^2$. In an earlier configuration designed to create weak vector boson particles, the SLAC accelerator generated 45GeV electrons, or

[1] International Committee on Ultrahigh Intensity Lasers (ICUIL), http://www.icuil.org/, accessed December 10, 2016.

$\gamma = 90{,}000$. If this could be combined with the current best reported intensity from a petawatt laser of $I = 10^{22} W/cm^2$, combined together these two sources could produce an almost unimaginable intensity of $10^{33} W/cm^2$, one thousand times the Schwinger intensity to spark the vacuum. This provides an opportunity to reach intensities far higher than any current or contemplated future technology.

## APPENDIX A5. HIGH INTENSITY LASER ACRONYM LIST

| Acronym | Definition |
|---|---|
| AFOSR | Air Force Office of Scientific Research |
| ALLS | Advanced Laser Light Source (Can.) |
| ALP | Axion-like particles |
| ALPS | Attosecond Light Pulse Source (Eur.) |
| AMO | Atomic, Molecular and Optical |
| APRI | The Advanced Photonics Research Institute (S. Korea) |
| ARC | Advanced Radiographic Capability |
| ASAP | Academic Strategic Alliance Program |
| ASE | Amplified spontaneous emission |
| AWE | Atomic Weapons Establishment (U.K.) |
| BBO | beta-barium borate |
| BELLA | Berkeley Lab Laser Accelerator |
| BES | Basic Energy Sciences (DOE) |
| BOC | Balanced optical cross correlator |
| BSM | Beyond the Standard Model |
| CAEP | Chinese Academy of Engineering Physics |
| CALA | Centre for Advanced Laser Applications (Ger.) |
| CALGO | $CaAlGdO_4$, a laser crystal host for Yb. |
| CAMOS | Committee on AMO Science (NAS) |
| CDI | Coherent diffractive imaging |
| CEA | Alternative Energies and Atomic Energy Commission (Fr) |
| CERN | Center for European Nuclear Research (Sw) |
| CESTA | Centre d'études scientifiques et techniques d'Aquitaine (Fr.) |
| CETAL | Centrul de Tehnologii Avansate cu Laser (Romania) |
| CILEX | Centre Interdisciplinaire Lumiere Extreme |
| CIRP | The International Academy for Production Engineering |
| CLF | Central Laser Facility (U.K.) |
| CLPU | Spanish Pulsed Lasers Centre |
| CLUPS | Laser Center of the University of Paris-South (Fr.) |
| CME | Center of mass energy |
| CNRS | National Center for Scientific Research (Fr.) |
| COTS | Commercial off-the-shelf |
| CPA | Chirped-pulse amplifiers[2] |
| CRADA | Cooperative Research and Development Agreement |
| CUOS | Center for Ultrafast Optical Science |
| DARPA | Defense Advanced Research Agency |
| DFM | Deformable mirror |
| DKDP | Deuterated potassium di-hydrogen phosphate, also called KD*P |
| DLA | Direct Laser Acceleration |
| DOD | Department of Defense |
| DOE | Department of Energy |
| DOT | Department of Transportation |
| DPA | Divided pulse amplification |
| DPSSL | Diode-pumped solid state laser |
| DRACO | Dresden Laser Acceleration Source (Germany) |

[2] Perry et al., "Petawatt Laser Pulses."

| **Acronym** | **Definition** |
|---|---|
| DRC | Dynamic ramp compression |
| EDP | Extraction during pumping |
| EEHG | Echo effect harmonic generation |
| ELBE | Electronic Linac for beams with high Brilliance and low Emmitance |
| ELI | European Laser Infrastructure |
| ERDF | European Regional Development Funds |
| ERIC | European Research Infrastructure Consortium |
| ESFRI | European Strategy Forum for Research Infrastructure |
| EUV | Extreme ultraviolet |
| FAIR | Facility for Antiproton and Ion Research |
| FAP | $Sr_5(PO_4)_3F$, a laser crystal host for Yb |
| FEL | Free electron laser |
| FES | Fusion Energy Science |
| FFRDC | Federally Funded Research and Development Center |
| FI | Fast ignition |
| FIREX | Fast ignition realization experiment |
| FOCUS | Frontiers in Optical Coherent and Ultrafast Science |
| FWHM | Full width at half maximum |
| GIST | Gwangju Institute of Science and Technology (S. Korea) |
| GSI | Gesellschaft für Schwerionenforschung |
| HAPLS | High-Repetition-Rate Advanced Petawatt Laser System |
| HED | High energy density |
| HEDP | High energy density physics |
| HEDS | High energy density science |
| HEL | High energy, continuous-wave lasers |
| HEP | High energy physics |
| HGHG | High-gain harmonic generation |
| HHG | High harmonic generation |
| HIL | High intensity laser |
| HPLS | High power laser system |
| HSG | Human salivary gland |
| HXR | Hard X-ray |
| HZDR | Helmholtz-Zentrum Dresden-Rossendorf Laboratory |
| IAP | Institute of Applied Physics |
| ICAN | International Coherent Amplification Network |
| ICF | Inertial confinement fusion |
| ICFA | International Committee for Future Accelerators |
| ICUIL | International Committee for Ultra-Intense Lasers |
| IEEE | Institute of Electrical and Electronic Engineers |
| ILE | Institute of Laser Engineering (Jap.) |
| INFLPR | National Institute for Laser, Plasma, and Radiation Physics |
| INRS | Institut national de la reserche scientifique (Can.) |
| ISO | Optical isolator |
| ITER | International Thermonuclear Experimental Reactor |
| IZEST | International Zetta-Exawatt Science and Technology |
| JAEA | Japan Atomic Energy Agency |
| JHPSSL | Joint High Power Solid-State Laser |
| JTO | Joint Technology Office |
| KAREN | Kansai Advanced Relativistic Engineering |

| **Acronym** | **Definition** |
|---|---|
| KDP | Potassium di-hydrogen phosphate |
| KD*P | Deuterated potassium di-hydrogen phosphate, also called DKDP |
| KGW | Potassium gadolinium tungstate ($KGd(WO_4)_2$) |
| KYW | Potassium yttrium tungstate ($KY(WO_4)_2$) |
| LANL | Los Alamos National Lab |
| LASIK | Laser-Assisted In-situ Keratomileusis |
| LBNL | Lawrence Berkeley National Lab |
| LBO | Lithium triborate |
| LCLS | Linac Coherent Light Source |
| LFEX | Laser for Fast Ignition Experiment |
| LHC | Large Hadron Collider |
| LIBRA | Laser Induced Beams of Radiation and Applications |
| LIBS | Laser-induced breakdown spectroscopy |
| LLE | Laboratory for Laser Energetics |
| LLNL | Lawrence Livermore National Laboratory |
| LMJ | Laser Mégajoule (Fr.) |
| LMU | Ludwig-Maximillian University |
| LOCSET | Locking of optical coherence by single-detector frequency tagging |
| LPA | Laser-plasma accelerators |
| LSW | Light scattering through a wall |
| LWFA | laser wakefield accelerator |
| MEC | Matter in extreme conditions |
| MOKE | Magneto-optic Kerr effect |
| MPQ | Max Planck Institute for Quantum Optics |
| MRI | Magnetic resonance imaging |
| MTW | Multi-terawatt |
| MURI | Multidisciplinary University Research Initiative |
| NIF | National Ignition Facility |
| NIH | National Institutes of Health |
| NNSA | National Nuclear Security Administration |
| NOPA | Non-collinear optical parametric amplifier |
| NRF | Nuclear resonance fluorescence |
| NSF | National Science Foundation |
| OAP | Off-axis paraboloid |
| OECD | Organization for Economic Cooperation and Development |
| ONCORAY | Center for Radiation Research in Oncology |
| ONR | Office of Naval Research |
| OPA | Optical Parametric Amplifier |
| OPAL | Optical Parametric Amplifier Line |
| OPCPA | Optical parametric chirped-pulse amplifier |
| OPG | Optical parametric generation |
| OPO | Optical parametric oscillator |
| OSA | The Optical Society |
| OSTP | Office of Science and Technology Policy |
| PAL | Pohang Accelerator Laboratory (S. Kor.) |
| PALS | Prague Asterix Laser System (Eur.) |
| PEARL | PEtawatt pARametric Laser |
| PENELOPE | Petawatt, Energy-Efficient Laser for Optical Plasma Experiments |
| PET | Positron emission tomography |
| PETAL | PETawatt Aquitane Laser |

| **Acronym** | **Definition** |
|---|---|
| PFC | Physics Frontier Center |
| PHELIX | Petawatt High Energy Laser for heavy Ion eXperiments |
| POLARIS | Petawatt Optical Laser Amplifier for Radiation Intensive experimentS |
| PSAAP | Predictive Science Academic Alliance Program |
| PULSE | Photon Ultrafast Laser Science and Engineering |
| PW | Petawatt |
| QED | Quantum Electrodynamics |
| QST | Quantum and Radiological Science and Technology |
| RAL | Rutherford Appleton Laboratory |
| RAS | Russian Academy of Science |
| ROI | Return on investment |
| SACLA | SPring-8 Angstrom Compact free electron LAser |
| SASE | Self-Amplified Stimulated Emission |
| SAUUL | Science and Applications of Ultrafast Ultra-intense Lasers |
| SBIR | Small Business Innovation Research |
| SC | Office of Science (DOE) |
| SCAPA | Scottish Centre for the Application of Plasma-based Accelerators |
| SEL | Station of Extreme Light Science |
| SIOM | Institute for Optics and Fine Mechanics (China) |
| SLAC | Stanford Linear Accelerator Center |
| SNL | Sandia National Laboratory |
| SPGD | stochastic parallel-gradient-descent |
| SPIE | The international society for optics and photonics |
| SPM | Self-phase modulation |
| SPP | Strategic Partnership Project |
| SPPS | Sub-Picosecond Pulse Source |
| SRF | Superconducting radiofrequency |
| SSAA | Stockpile Stewardship Academic Alliance |
| SSL | Solid-state laser |
| SSP | Stockpile Stewardship Program |
| STC | Science and Technology Center |
| STFC | Science and Technology Facilities Council (U.K.) |
| STROBE | Science and Technology Center on Real-Time Functional Imaging |
| STTR | Small Business Technology Transfer |
| SULF | Superintense Ultrafast Laser Facility |
| SXR | Soft X-Ray |
| TARANIS | Terawatt Apparatus for Relativistic and Nonlinear Interdisciplinary Science (U.K.) |
| TARPES | Time and angle-resolved photoemission |
| TBD | To be determined |
| TMI | Thermally induced mode instability |
| UFE | Ultra-broadband front end |
| UFL | Russian acronym for their megajoule-class laser |
| USN | United States Navy |
| VSF | Image relay (in vacuum) |
| VUV | Vacuum ultraviolet |
| WDM | Warm dense matter |
| WLC | White-light continuum |
| WWII | World War II |
| XCAN | Extreme Coherent Amplification Network (see also ICAN) |

| **Acronym** | **Definition** |
|---|---|
| XCELS | Exawatt Centre for Extreme Light Studies |
| XFEL | X-ray Free Electron Laser |
| XPW | Cross-polarized wave |
| XUV | Extreme ultraviolet |
| YAG | Yttrium Aluminum Garnet |
| YCOB | $YbCa_4O(BO_3)_3$ |
| YLF | Yttrium lithium fluoride ($YLiF_4$) |

# B

# Supplemental Information on the Underlying Laser Technology

## APPENDIX B1. BASICS OF SOLID-STATE LASERS
### Fundamentals of Solid-State Laser Media

While semiconductors and color centers in crystals are certainly solid-state materials, the term solid-state laser has evolved to cover lasers based on the energy-level transitions of paramagnetic ions (dopants) in a “host” crystal or glass. The ions have at least one unpaired electron in their electronic shell structure, leading to ion energy-level transitions that fall into the visible and infrared wavelength region. They have, almost without exception, been from the periodic table groups of 3d transition metals or 4f (lanthanide series) rare earths. Also, with a few notable exceptions, the laser transitions involved are between different arrangements of 3d- or 4f-shell electrons. The host materials, besides keeping the laser-active ions in place, also interact with levels in several important ways. In a static sense, the atoms surrounding the active ions lower the symmetry of the paramagnetic-ion environment and “activate” transitions between the energy levels in the same shell, which would otherwise be dipole-forbidden in free-space surroundings. The surrounding atoms also, to varying degrees, modify the energy levels of the ions, and remove level degeneracies that are present in a free-space environment. The “crystal field” theory of the static interaction has proven effective in predicting some of the ion properties and treats the atoms (ligands) surrounding the ions as simple point charges, creating an electric field that perturbs the ion electronic states. More sophisticated theories consider the wavefunctions of the surrounding electrons, rather than considering them as points.

In a dynamic sense, the host provides a way for non-radiative transitions to take place between different energy levels through conversion of the energy in the ion to atomic vibrations (phonons) in the host. The non-radiative process, especially for rare-earth ions, is often key to providing a way for the upper laser level to be fed by energy in higher-lying levels initially excited by the pumping process. The non-radiative process also provides a means, in four-level systems, for the lower laser level to de-populate after a laser transition takes place.

Figure B1.1 is a simplified energy-level diagram for a common solid-state laser based on the trivalent, rare-earth ion neodymium ($Nd^{3+}$, or simply Nd). Since the overwhelming majority of solid-state host media are insulators, the upper energy level for the laser process (labeled E3 in the figure) is populated, or pumped, by light, traditionally from a lamp but more recently from another laser. (We do not show the all of the high-lying levels that are also important for pumping with lamps.) The pump light is absorbed by transitions from lower-lying levels (E1) of the ion and puts energy into higher-lying levels (E4). The diagram shows the importance of non-radiative transitions in getting energy from the pumped levels into the upper laser level. In that process, the energy difference results in heat being deposited in the host media. In the case shown, the non-radiative transitions also act to remove energy from the lower energy levels of the ion (E2), key to avoiding the build-up of energy that could stop laser action but also act to generate heat. As we will discuss below, dealing with removal of heat from the laser medium is one of the key engineering challenges in solid-state lasers as well as a major limit to performance.

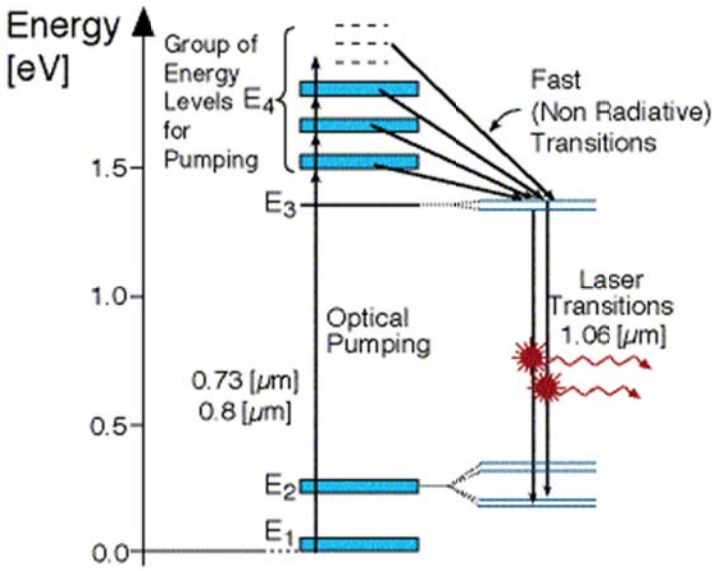


**FIGURE B1.1** Simplified energy-level diagram for a $Nd^{3+}$ ion. Each blue line represents a cluster of individual energy levels. SOURCE: Courtesy of Kansas State University, Department of Physics, http://perg.phys.ksu.edu/vqm/laserweb/ch-6/6-15.gif.

One of the important characteristics of solid-state lasers is the relatively long decay time (the upper-state lifetime, or storage time) for energy in the upper laser level compared to other lasers. In the case of classic fully allowed (dipole) transitions among energy levels, the lifetime for transitions with energies in the visible and near-infrared wavelength regions is on the order of a nanosecond (ns). As noted above, the transitions for solid-state laser ions are activated by the host medium, but not to the full amount of a classic dipole transition, and have lifetimes ranging from microseconds (μs) to 10s of milliseconds (ms). Typical Nd-doped lasers have an upper-state lifetime around 300 μs, and for, say, 1 kW of pump power, delivered in a time shorter than the upper-state lifetime, this allows storage of about 0.3 Joules (J) in the upper laser level. As noted in the Technology History section, the ability to extract this level of energy in short, ns-duration pulses led to the early use of solid-state lasers as high-intensity sources.

In the engineering of lasers, an important calculation is the power gain for amplifying the laser wavelength, $G$, in a length, $z$, of material (with only two energy levels participating) from stimulated emission. This can be given in terms of a wavelength-dependent cross section $\sigma(\lambda)$ for the laser transition by the equation:

$$G = exp\,[\sigma(\lambda)\, z\, (N_2 - N_1)]\ , \qquad \text{(B.1a)}$$

where $N_2$ and $N_1$ are the population densities (number/volume) for, respectively, ions in the excited state, or upper level, and ground state, or lower level and $\lambda$ is the wavelength, and the cross section is an area. The identification of the possibility of stimulated emission by Einstein (1917), and thus maser/laser operation, resulted from a thermodynamics argument that can be used to connect the rate of spontaneous emission from the upper to lower level to rates of stimulated emission for both upward and downward transitions between the two levels. From this relation, one can derive the cross section from the spontaneous rate (given by the inverse of the rate, the radiative upper-state lifetime, $\tau_r$ ) and for the cross section at the peak wavelength of the transition, $\sigma_p$, one can write the proportional relation:

$$\sigma_p\ \tau_r\ \propto\ \lambda^4 / n^4\, \Delta\lambda\ , \qquad \text{(B.1b)}$$

where $\Delta\lambda$ is the linewidth of the transition, given in units of wavelength, and $n$ is the refractive index of the host material. The linewidth is a measure of the wavelength extent over which gain is possible, and is typically the full width at half-maximum (FWHM) points of the cross section as a function of wavelength. We will return to the discussion of cross sections after we consider the issue of linewidth.

As discussed in the Technology History section, the development of laser mode-locking led to the generation of short pulses in the picosecond (ps) and eventually femtosecond (fs) range, and was one of the key developments that allowed laser intensities to reach their current level. The length of typical optical cavities used in laser operation, in contrast to, say microwave cavities, is a large multiple of the laser wavelength and can support a large number of (longitudinal) modes, separated in frequency by the inverse of the time it takes for the energy to traverse one trip through the cavity. The frequency separation falls in the range of MHz to GHz. In general, the frequencies have random phases with respect to each other, leading to high-frequency noise in the output of a laser running on multiple modes. A variety of techniques are available to establish a stable (or locked) phase relationship amongst the modes. If the modes have all the same phase in the frequency domain, this translates in time to a periodic series of pulses in the laser output, with the rate set by the frequency spacing of the modes. Most mode-locking techniques insert an element into the laser cavity that sets up a periodic loss in synchronization with the rate set by the cavity mode-frequency spacing, with the pulse that is formed passing through the cavity at the minimum loss point for the element.

The width of each pulse is determined by the numbers of modes that are locked, and with other factors equal, is determined by the inverse of the gain linewidth of the laser transition. The exact spectral width of a pulse is set by its temporal function. For Gaussian-shaped pulses the minimum product of the spectral width and the pulsewidth (both at FWHM) is about 0.44, while for pulses with a $sech^2$ functional shape (generated by some mode-locking schemes) the product is about 0.32. Pulses meeting these criteria are referred to as “transform-limited,” a reference to the Fourier-transform calculation that is the basis for the product relation. A simplified view of laser mode-locking, and any subsequent amplification of mode-locked pulses, requires that the laser linewidth must be equal if not greater than the spectral width. Thus, for example, a 1-ps-wide, $sech^2$ pulseshape requires a linewidth of at least 0.32 THz. At a laser wavelength of 1,000 nm this corresponds to about 1 nm.

For solid-state lasers there are several physical effects that determine the laser linewidth. We consider first the case for rare-earth-doped systems, in crystalline hosts. Here the phonons, besides providing a means to facilitate non-radiative transitions between energy levels, continually perturb the phase of wavefunctions associated with the energy levels through scattering events that do not change the level energy. This de-phasing broadens the linewidth of any transition between the levels, where the rate of dephasing events depends on the vibrational characteristics of the host material. A well-known solid-state laser, based on the Nd ion in the crystal $Y_3Al_5O_{12}$ (YAG), has a commonly used laser transition at 1,064 nm characterized by a linewidth of 0.18 THz, which could support pulses of several ps in duration. Since each ion is in the same surrounding, this type of broadening is called “homogeneous.” We noted above that the energies of the ion levels depend on the ion environment, and when this varies from one ion to another then the overall laser linewidth becomes a superposition on all of the different energies, leading to another effect on linewidth, “inhomogeneous broadening.” This effect can occur in crystals that have multiple environments for the ion, but it is most pronounced in glasses, where the lack of a well-ordered atomic structure, and thus a widely varying environment for the laser ions, leads to linewidths that are more than an order-of-magnitude larger than in single-environment crystals. The linewidths are large enough so that the structure evident in the absorption and emission spectra from Nd ions in crystals resulting from the existence of multiple, closely spaced energy levels is smoothed out to give the appearance of one continuous “band.” An example appears in Figure B1.2, showing cross section data for two commonly used Nd-doped laser glasses. With such a broad effective linewidth, Nd:glass lasers can generate and amplify sub-ps-duration pulses.

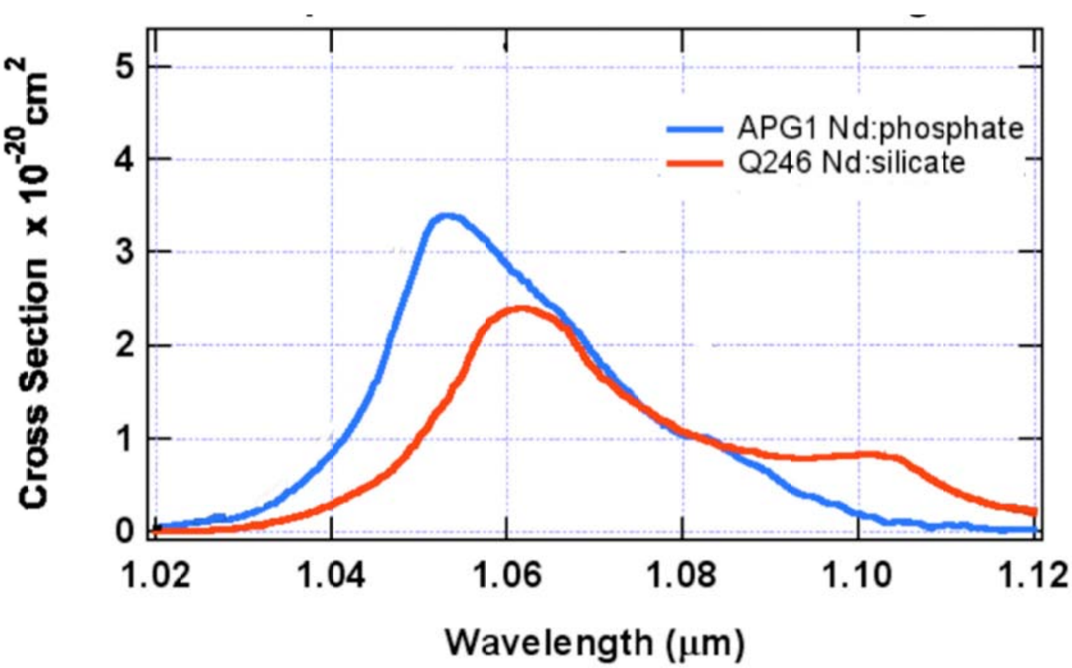


**FIGURE B1.2** Gain cross section as a function of wavelength for two commonly used Nd-doped glasses. SOURCE: T. Ditmire, University of Texas at Austin, "A Path Towards an Exawatt Laser," presentation to the committee on May 10, 2016.

For solid-state laser generation and amplification of pulses in the femtosecond range, linewidths broader than shown in the figure are required. A 10-fs $sech^2$ pulse transforms to a 32 THz linewidth, about 100 nm for a 1,000-nm laser. Such large linewidths are possible but require a stronger interaction between the laser ion and the host than is found for rare-earth ions when the transitions remain among levels in the 4f shell. For that interaction, when the ion energy-level changes the relatively tightly bound and compact 4f wavefunctions do not create a major perturbation to the surrounding environment as they change from one energy level to another, and the distances from the laser ion to the nearby ions remain unchanged. For 3d-transition-metal ions the case is generally different, as the d-electron wavefunctions have a larger spatial extent and a more profound impact on the surrounding ions when they change state. Figure B1.3 illustrates the difference in the interaction. We plot the laser-ion energy level as a function of the distance from the surrounding ions, for the simple case where all of these ions change position in the same manner, the so-called "breathing mode" of ion motion. There is some minimum energy of the overall system, an equilibrium position, such that a displacement in either direction leads to a higher energy. The surrounding ions will vibrate about this position (quantized as phonons) at a frequency determined by the particular host. In Figure B1.3(a) when the ion energy level changes the equilibrium position does not change the case, as we noted, for transitions between 4f energy levels. This is also true for the first (ruby) laser transition at 694.3 nm based on 3d $Cr^{3+}$ ions in $Al_2O_3$, where the only difference in electronic states is the spin configuration, and the spatial nature of the wavefunction does not change. The more general case for 3d laser-active ions is that an energy-level change does result in a new equilibrium position, as illustrated in Figure B1.3(b). The effect of this equilibrium shift is profound on the linewidth of the transitions, both upward (absorption) and downward (emission), associated with laser operation. The key physics in the absorption and emission processes are that the electronic transitions occur so quickly (on the order of $10^{-16}$ seconds) that the surroundings do not have time to adjust position, but do so (in about 1 ps) only after the transitions take place. In the figure, we label one absorption transition from point 1 to 2, and an emission transition taking place, after the system has reached the new equilibrium position, from points 3 to 4. It is evident that the absorption and emission have different energies. Since there is vibration about the equilibrium point, there is a distribution of energies for both absorption and emission, leading to a broadened linewidth for both.

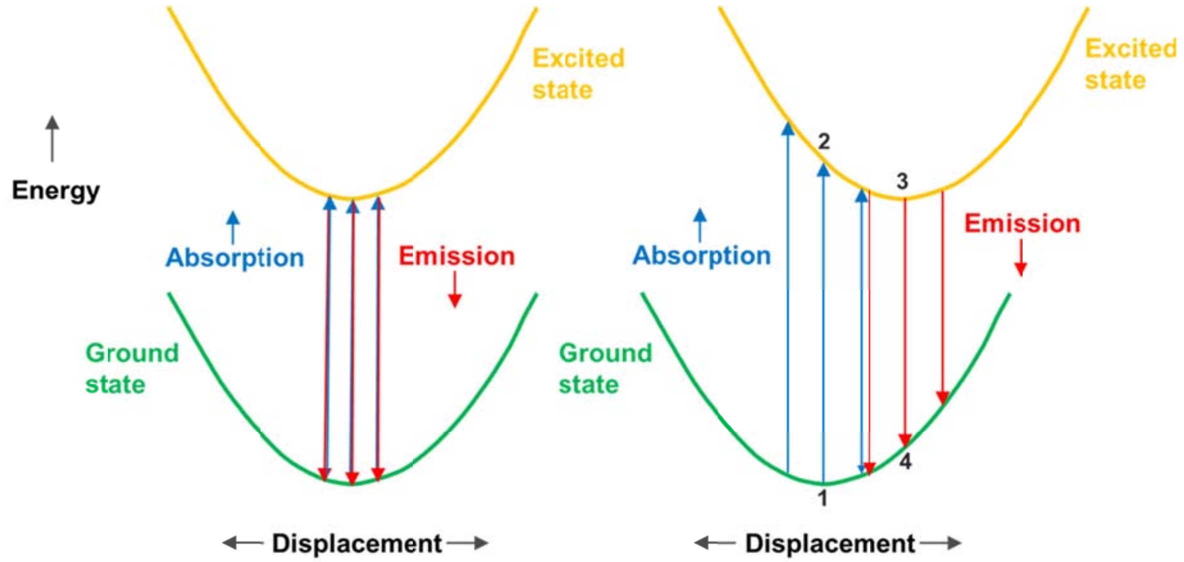


**FIGURE B1.3** (a, left.) Configuration coordinate diagram, no change in host environment. (b, right). Same but with a shift in relative positions of the surrounding ions. SOURCE: P.F. Moulton, 1985, Spectroscopic and laser characteristics of Ti:AI2O3, *J. Opt. Soc. Am. B* 3(1): 125-133.

The type of transition illustrated in Figure B1.3(b) is often referred to as "vibronic," a mix of vibrational and electronic, and also "phonon broadened," but this is less precise, as we noted above that phonons play a role in determining linewidth even for the case of no equilibrium shift.

In contrast to the ruby laser, other early solid-state lasers operated on 3d-ion vibronic transitions. L.F. Johnson and co-workers in 1963 reported "optical maser oscillation from the 3d $Ni^{2+}$ ion in $MgF_2$ involving simultaneous emission of phonons,"[1] and later operation from $Co^{2+}$ and $V^{2+}$ ions,[2] where broad wavelength tuning was achieved. The major drawback to these first vibronic lasers was that, because of thermally induced non-radiative processes between the laser energy levels, relatively low-threshold operation with lamp pumping required cooling of the laser crystals to cryogenic temperatures. Moulton reported the first laser operation from the 3d ion $Ti^{3+}$ in the same host crystal $Al_2O_3$ (sapphire, the material, not the gemstone) used for the ruby laser,[3] with more details on that provided later.[4] Figure B1.4 shows Ti:sapphire cross sections for absorption and emission from the lowest energy level of the ion to the first excited state, clearly a vibronic transition. The difference between the observed emission spectrum and the gain cross section reflects corrections needed to follow Einstein's formulation for gain from stimulated emission.[5] Of note is the very broad gain linewidth, about 100 THz. This has allowed

[1] L.F. Johnson, R.E. Dietz, and H.J. Guggenheim, 1963, Optical maser oscillation from Ni2+ in MgF2 involving simultaneous emission of phonons, *Phys. Rev. Lett.* 11(7): 318-320.

[2] L.F. Johnson, and H. J. Guggenheim, 1967, Phonon terminated coherent emission from V2+ ions in MgF2, *J. App. Phys. 38*(12): 4837-4839.

[3] P.F. Moulton, 1982, Titanium-doped sapphire: A new tunable solid-state laser, in *Physics News* (Phillip F. Schewe, ed.), American Institute of Physics.

[4] P.F. Moulton, 1985, Spectroscopic and laser characteristics of Ti:AI2O3, *J. Opt. Soc. Am. B* 3(1): 125-133.

[5] A. Einstein, 1917, Strahlungs-emission und -absorption nach der Quantentheorie, *Physika Zeitschrift* 18(121).

generation of 3.6-fs-duration pulses at 800 nm,[6] slightly more than one optical cycle, the shortest yet generated directly by a laser.

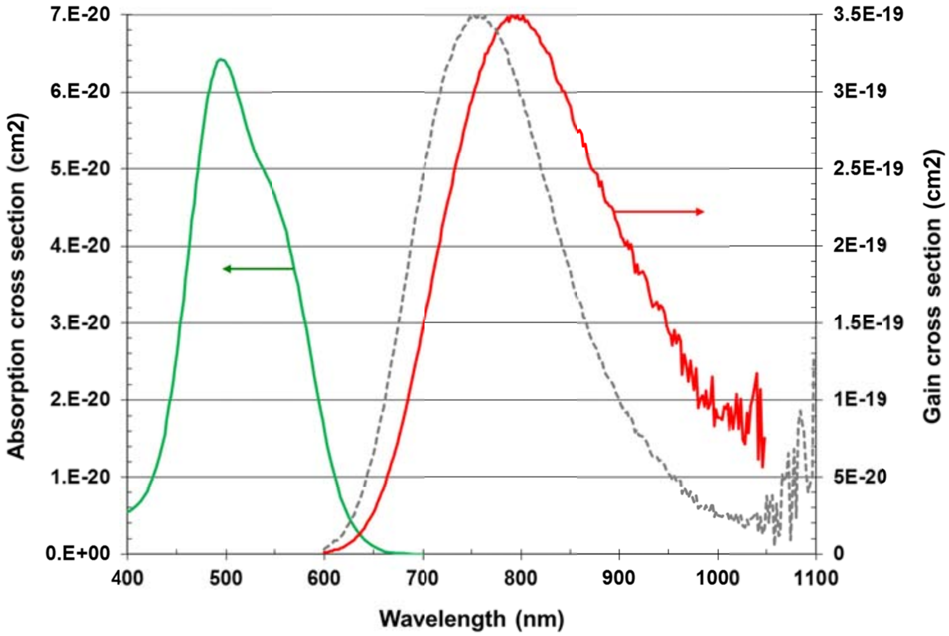


**FIGURE B1.4** Absorption and emission cross sections for Ti:sapphire and a relative plot (dashed curve) of the measured emission spectrum. The noise in the long-wavelength region is from the detection system. SOURCE: P.F. Moulton, 1985, Spectroscopic and laser characteristics of Ti:AI2O3, *J. Opt. Soc. Am. B* 3(1): 125-133. *[check on permissions]*

### Petawatt-Class Solid-State Lasers, Criteria

Table B1.1 lists important characteristics of laser materials. We include the saturation fluence, $E_{sat}$, which is given by the relation

$$E_{sat} = hc / (\lambda\sigma), \qquad \text{(A.3)}$$

with *h* Planck's constant, *c* the speed of light, $\lambda$ the laser wavelength and $\sigma$ the peak laser transition cross section. In Table B1.1, we use this simplified relation, which assumes that the absorption cross section can be ignored, appropriate for the materials we consider. (If absorption cannot be ignored, the denominator should be the sum of the two cross sections.) For a laser pulse to efficiently extract the energy stored in the upper laser level, the incident fluence, for one pass through the laser material, should be several times the saturation fluence. For systems that pass the laser pulse through the material multiple (N) times, the amount required for efficient extraction can be divided by N, provided the energy does not decay during the time required for the multi-pass process.

[6] S. Rausch, T. Binhammer, A. Harth, F. X. Kaertner, and U. Morgner, 2008, Few-cycle femtosecond field synthesizer, *Opt. Exp.* 16(22): 17410-17419.

**TABLE1 B1.1** Key Characteristics of Common Solid-State Laser Materials

| Material | **Wavelength (nm)** | **Storage time (msec)** | **Cross section ($cm^2$)** | **Gain linewidth (nm)** | **Saturation fluence ($J/cm^2$)** |
|---|---|---|---|---|---|
| ***4f rare-earth dopants*** | | | | | |
| **Nd:YAG** | 1064 | 0.24 | $2.8 \times 10^{-19}$ | 0.6 | 0.66 |
| **Nd:$YVO_4$** | 1064 | 0.09 | $1.1 \times 10^{-18}$ | 1.0 | 0.17 |
| **Nd:YLF** | 1047 | 0.485 | $1.8 \times 10^{-19}$ | 1.0 | 1.0 |
| **Nd:glass** | 1050-1060 | 0.3-0.4 | $3\text{-}4 \times 10^{-20}$ | 20-30 | 4.7-6.3 |
| **Yb:YAG** | 1030 | 0.95 | $2.1 \times 10^{-20}$ | 9 | 9.2 |
| **Yb:YAG (77K)** | 1030 | 0.85 | $1.1 \times 10^{-19}$ | 1.5 | 1.8 |
| **Yb:$CaF_2$** | 1030 | 2.4 | $3.0 \times 10^{-21}$ | 50 | 64 |
| **Yb:CALGO** | 1040 | 0.4 | $7.5 \times 10^{-21}$ | 70 | 25 |
| **Yb:S-FAP** | 1047 | 1.1 | $6.1 \times 10^{-20}$ | 4 | 3 |
| **Er:YAG** | 1645 | 7.6 | $5.0 \times 10^{-21}$ | 5 | 24 |
| **Er:glass** | 1550 | 7.9 | $8.0 \times 10^{-21}$ | 55 | 16 |
| **Ho:YAG** | 2090 | 8.5 | $1.3 \times 10^{-20}$ | 25 | 7.3 |
| **Ho:YLF** | 2050 | 15 | $1.8 \times 10^{-20}$ | 25 | 5.3 |
| ***3d transition-metal dopants (vibronic transitions)*** | | | | | |
| **Co:$MgF_2$ (77K)** | 1900 | 1.4 | $1.5 \times 10^{-21}$ | 600 (50 THz) | 68 |
| **Cr:$BeAl_2O_4$** | 755 | 0.26 | $7 \times 10^{-21}$ | 55 (29 THz) | 37 |
| **Cr:LiSAF** | 850 | 0.067 | $5.0 \times 10^{-21}$ | 190 (85 THz) | 4.7 |
| **Ti:sapphire** | 800 | 0.0032 | $2.5 \times 10^{-19}$ | 225 (100 THz) | 1.0 |
| **Cr:ZnSe** | 2450 | 0.006 | $1.3 \times 10^{-18}$ | 1000 (50 THz) | 0.06 |

NOTE: All data for materials at 300 K unless noted.

We noted in the Technology History section a major challenge in the direct amplification of ps- and shorter-duration pulses would be damage to the laser material and associated optics. If we assume a saturation fluence of 5 $J/cm^2$, the peak power incident of the laser material for efficient single-pass extraction with a 1-ps pulse would be 5 $TW/cm^2$, much greater than the ps-pulsewidth optical damage limit for common materials and optical coatings. The invention of chirped-pulse amplification [Mourou, Strickland] provided a solution to this problem through stretching of pulses into the ns region. For pulses of that duration, typical optical damage thresholds are as high as 40 $J/cm^2$ for uncoated silica optics to as low as several $J/cm^2$ for anti-reflection coatings. Other limits may set in from nonlinear effects in the laser material.

If we consider laser materials suited for high-energy, ps and shorter-pulse CPA systems, there are several criteria:

The gain linewidth must be sufficiently large to allow amplification for the desired pulsewidth. This criterion is more stressing than for simple mode-locked pulse generation since there is a large amount amplification required to take the typical 10s of nanoJoules (nJ) pulse energy from a mode-locked laser to the J and higher level. High amplifications act to narrow the effective bandwidth of the laser material through gain narrowing, the result of the gain spectral function being raised to some higher power, depending on the required amplification.

The saturation fluence must be low enough to allow good extraction of energy stored in the laser medium before optical damage to the laser material or associated optics. While multi-passing of the extraction beam can improve extraction efficiency, this also requires that the material have sufficient gain bandwidth to overcome the gain narrowing that becomes more problematic as the number of passes increases. For saturation fluences above 10 $J/cm^2$ efficient extraction is problematic.

The laser material must be capable of being optically pumped with good conversion of pump energy into stored energy. Until the last decade, the only practical, affordable pump source for high-energy systems was flashlamps or pump lasers based on flashlamps. Attached to this requirement is that the pump power must be delivered in a time comparable to the storage time, to obtain a high stored energy.

Given the need to increase, at high energies, the area of the laser beam doing extraction, the laser material has to be able to be grown, in the case of crystals, or fabricated, in the case of glasses, in sufficiently large size to accommodate the area of the extraction beam.

There must exist techniques to avoid, at large material sizes, the inability to store energy due to (1) spurious laser operation in the material due to formation of laser cavities based on internal reflections inside the material or (2) excessive optical gain, in a direction along that of the gain or, for large beam sizes, along the width of the beam. This high gain leads to ASE that arises from decay of the upper laser level and leads to depletion of stored energy. Unfortunately, the issue of ASE becomes more pronounced for materials with large cross sections and thus low saturation fluences, which otherwise facilitate efficient extraction.

The first two criteria eliminate many of the materials listed in Table B1.1, due to limited bandwidth, too high a value for saturation fluence, or, in a few cases, too low a value. Equation A.2 points out the fundamental relations between storage time, gain cross section (and hence saturation fluence), and linewidth, and one result is the challenge in finding materials that have both large linewidth and a low $E_{sat}$. Other materials that pass the first criteria have, until recently, suffered from poor efficiencies with lamp pumping (notably the Yb- and Ho-doped crystals) since they do not have a multiplicity of high-lying energy levels that overlap with the emission spectra of lamps. As we note in Appendix B3, such materials may emerge as high-peak-power sources in the future with the development of diode and other pumping techniques.

## Petawatt-Class Nd:glass Lasers

### *Background of Nd:glass Lasers*

The glass materials used as hosts for the Nd ion belong to a very large category of optical glasses. In general, glasses are amorphous materials and, in contrast to crystals, have no organized structure that extends past several clusters of atoms. Another property of glass is the presence of a glass transition from a hard to a “rubbery” state as the material temperature is increased to a certain level, but below the point at which the material turns liquid. Transparent glasses are characterized by formers that make up most of the glass, and these are typically oxides of Si, B, Ge, or P, although there are glasses based on metallic-fluoride formers and mixes of oxide and fluoride formers. Other components of the glass, network modifiers, typically alkali-based (e.g., Na and Ca) are added to control specific glass properties. The most widely used glass for photonics is pure silica ($SiO_2$), the basis for optical fibers for telecom and lasers, while common window glass is 72 percent silica mixed in with oxides of Na, Ca, Mg, and Al.

The first Nd:glass laser was demonstrated by Snitzer 1961.[7] The potential to scale glass lasers to high energies has led to their extensive development for ICF, which has funded Nd:glass-laser research since the 1970s. Key requirements of laser glass for ICF, besides desirable laser-spectroscopic, nonlinear-optical, thermal, and mechanical properties, are the ability to fabricate the material in large, optically uniform slabs, which have to be free of impurities and defects that would lead to optical damage in the material.

### *Glass Categories and Manufacture*

The main categories of laser glass are silicate, phosphate, and fluorophosphates. The first glasses used for ICF work were silicates, but at present, phosphate glass (typically $60P_2O_5$ – $10Al_2O_3$ - $30M_2O/MO$, where M stands for a metallic ion) has become the glass category of choice, as it can be fabricated in large sizes free of the metallic inclusions that plague other glasses.[8] Figure 2.1 is a photograph of a large slab of unpolished Nd-doped phosphate glass, shown in a facility developed to provide the size of glass needed in the Lawrence Livermore National Laboratory (LLNL) National Ignition Facility (NIF).

In terms of amplifier performance, Figure B1.5 provides a good illustration of the relation among operating fluence, pulsewidth, and output energy, for the case of the present 1053-nm NIF final amplifier stage, which operates with a square beam cross section of 37.2 cm and a double-pass configuration.[9] At short pulsewidths, energy limits come about from nonlinear effects in the glass, which lead to the generation of intensity peaks in the beam and optical damage to the material, while at long pulsewidths the limit is from the available input energy to the amplifier.[10] The reduction in allowable output energy with shortening pulsewidth illustrates why the CPA technique is key to generating PW-class laser systems. For several-ns-duration pulses the amplifier operates efficiently, at 2-3x the Nd:glass saturation fluence. As another example, the Laboratory for Laser Energetics (LLE) Omega system runs conservatively with a final stage, single-pass amplifier fluence of up to 3.6 J/cm$^2$ with temporally shaped, 0.1 to 4-ns pulses.

The high operating fluences used at the NIF and in other facilities are the result of substantial development of polishing and coating technology over several decades that has allowed relatively damage-free operation at increasingly higher levels. The NIF system runs with fluences on the UV-wavelength optics that do lead to occasional damage, but includes techniques to mitigate the effects of localized damage and reduce further growth of damaged regions, as well as means to easily service components when the damaged regions grow to the point that the optics are unusable.

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[7] E. Snitzer, 1961, Optical maser action of Nd3+ in a barium crown glass, *Phys. Rev. Lett.* 7: 444.

[8] J.H. Campbell, J. S. Hayden, and A. J. Marker, 2011, High-power solid-state lasers from a laser glass perspective, *International Journal of Applied Glass Science* 2(1): 3-29.

[9] C.A. Haynam, P. J. Wegner, J. M. Auerbach, M. W. Bowers, S. N. Dixit, G. V.
Erbert, G. M. Heestand, et al., 2007, National Ignition Facility laser performance status, *Appl. Opt.* 46(16): 3276-3303.

[10] C.A. Haynam, et al., 2007, National Ignition Facility laser performance status.

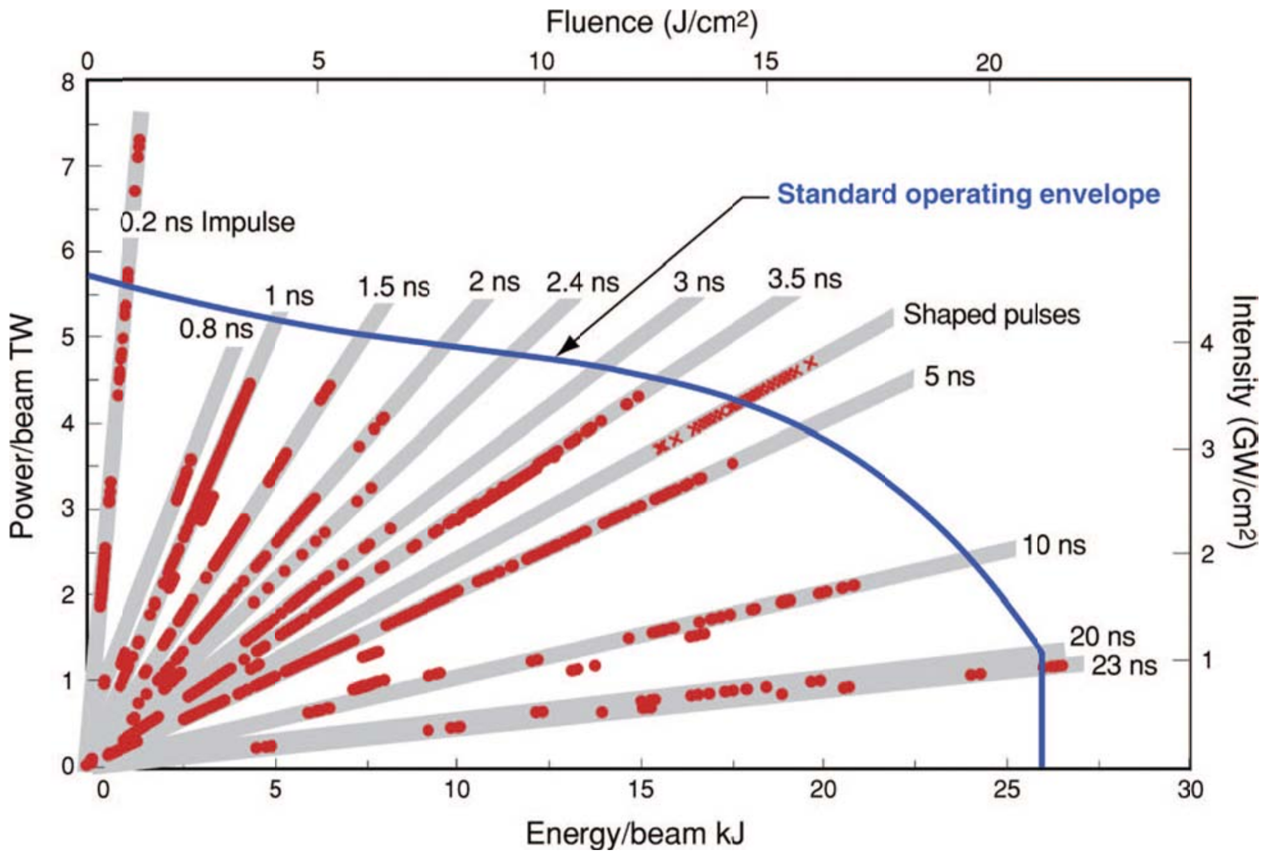


**FIGURE B1.5** Performance of the NIF phosphate-glass final-stage amplifier chain for various input pulsewidths, illustrating the influence of pulsewidth on allowable amplifier operating fluence. "Shaped pulses" are the particular waveform chosen for the ICF application. SOURCE: C.A. Haynam, P. J. Wegner, J. M. Auerbach, M. W. Bowers, S. N. Dixit, G. V. Erbert, G. M. Heestand, et al., 2007, National Ignition Facility laser performance status, *Appl. Opt.* 46(16): 3276-3303.

***Glass Thermal Limitations***

The many favorable properties of glasses for high-energy lasers are accompanied by a significant limitation. Due to the lack of long-range structure, glass has poor thermal conductivity, as phonons that transport heat in electrically insulating materials like glasses cannot travel far without being scattered. The conductivities of common laser glasses are about 25x lower than for YAG, a common laser host, and about 50x lower than sapphire. In the process of heat generation in the laser that is a natural outcome of the pumping-lasing process, the flow of heat out of the material creates a temperature gradient that in turn creates optical distortion, through the material change of refractive index with temperature. In addition, the stress in the material from the gradient (due to differential thermal expansion) leads to optical distortion from the stress-optic effect, primarily the creation of birefringence that depolarizes the linearly polarized light that is required in systems needed to drive nonlinear optics or work efficiently with grating compressors. Ultimately, large thermal gradients create enough stress to fracture the material.

In comparing laser materials, the thermal shock parameter, $R_T$, provides an indication of the ability of a given material to handle a high thermal load without fracturing, and is given by the relation:

$$R_T = \kappa \sigma_T (1 - \nu) / (\alpha E) \qquad (A.4)$$

where $\kappa$ is the thermal conductivity, $\sigma_T$ is the tensile strength of the material, $\nu$ is the material Poisson ratio, $\alpha$ is the thermal expansion coefficient, and E is the Young's modulus. The only parameter not purely intrinsic to a material is the tensile strength, which can vary depending on the nature of the surface finish of a material. (Fracture can start at a location of a"flaw"or"micro-crack"on the surface.)

While the exact amount of thermal load a laser material can handle depends on the geometry of the system, the value is proportional to $R_T$ and thus the quantity does provide a way to compare different materials under the same conditions. While glasses can be engineered to have a low thermal expansion coefficient (pure silica glass and zerodur are examples), those glasses do not make good hosts for high concentration levels of rare-earth ions. The low thermal conductivity and resultant low thermal shock parameter of laser glasses remains a major limit to their average-power output. Typical laser glasses have values of the thermal shock parameter in the 40-140 W/m range, while crystal hosts such as YAG and sapphire have values of 1,450 and 3,400, respectively.[11]

The problems of poor thermal conductivity in glass are magnified by the large material volumes required for high energies, which lead to relatively long paths for heat flow and thus large temperature gradients. High-energy systems, to date, mainly operate at such low pulse rates (several per min to per day) that heat in the glass material can be fully removed before the next pulse is generated, and thus long-term gradients do not develop. (We also discuss later how higher pulse rates in glass lasers have been enabled by diode-laser pumping and/or advanced thermal-management techniques.)

Early glass lasers, like other solid-state lasers, were fabricated in the shape of rods, well matched to the cylindrical geometry of pump lamps, but also subject to major thermo-optic distortion since the heat flow, and hence temperature gradient, is perpendicular to the laser beam. The beam experiences different optical paths depending on the point in the beam cross section, as well as stress-induced birefringence. High-energy glass laser designs evolved to use relatively thin, multiple disks, designed with flashlamp illumination to be uniformly pumped. In that design the thermal gradient is primarily along the laser beam, and thus all parts of the beam experience nearly the same optical path. The ultimate limitations due to thermal fracture remain the limit to pulse rate and hence laser average power.

## Petawatt Glass System Examples

At present there are a number of PW-class, Nd:glass-based systems worldwide, as shown in Table 4.2 from Chapter 4. We present details on a selected few of these.

### *First Petawatt Laser*

The first PW laser system employed CPA technology and included a Ti:sapphire mode-locked laser at 1,054 nm, with output pulses stretched to about a 3-ns pulsewidth, Ti:sapphire pre-amplifier stages, Nd:glass rod amplifiers, and, at high energies, disk amplifiers based on phosphate glass.[12] It was constructed at LLNL, crossed the PW-peak-power threshold in 1996 and by 1998 had reached 1.5 PW of peak power, with 660 J of energy in a 440-ps pulse. For this system one key technology was large-aperture, flashlamp-pumped, disk-geometry amplifiers, as shown in Figure B1.6, developed primarily for applications to ICF studies and incorporated in the NOVA laser, the fore-runner to the present NIF system. Such amplifiers convert about 1-1.5 percent of the electrical energy input to the lamps into stored energy in the laser medium. The large size of the glass disks in NOVA limited operation to 6 firings/day. The system was de-commissioned in 1999 to make room for the present NIF laser system.

A key part of the LLNL PW-laser effort involved development of techniques to fabricate large-diameter optical gratings, needed to compress the high-energy stretched pulse and not suffer from optical damage. The system employed LLNL-developed, 94-cm-diameter gratings, which represented a major

[11] W.F. Krupke, 1983, Insulator materials in high power lasers for inertial fusion: Present and future, *MRS Proceedings* 24: 401;W.F. Krupke, 1999, Materials for lasers and nonlinear optics, in *Advances in Lasers and Applications* (D.M. Finlayson and B. Sinclair, eds.), CRC Press.

[12] M.D. Perry, D. Pennington, B. C. Stuart, G. Tietbohl, J. A. Britten, C. Brown, S. Herman, et al., 1999, Petawatt laser pulses, *Opt. Lett.* 24(3): 160-162.

advance in grating-fabrication technology.[13] Figure 2.2 shows one of the gratings mounted in the compressor system, which, as with other high-peak-power systems, must operate in a vacuum to avoid air breakdown by the pulse. The LLNL metallic gratings could operate reliably at fluences of 0.33 J/cm$^2$.[14] Large-area gratings remain a key technology component to any CPA-based systems used at the PW level.

**FIGURE B1.6** Photograph of one NOVA amplifier stage (operating with a 31.5-cm-diameter beam) showing two Nd:glass disks and (behind them,) one (of two) banks of multiple xenon flashlamps. SOURCE: Commander-pirx, licensed under Creative Commons Attribution-Share Alike 3.0 Germany, https://commons.wikimedia.org/w/index.php?curid=15533028.

***Texas Petawatt Laser***

Of interest is the so-called "Texas Petawatt Laser," at the University of Texas at Austin, which employs a combination of technologies to produce a relatively short pulsewidth (130 fs) for a Nd:glass-based system. The system diagram (Figure B1.7) shows that the Nd:glass amplifier stages use a mix of silicate and phosphate glass, which in combination provide a broader amplifier spectral bandwidth than possible with a single type of glass host.[15] Figure B1.2 shows the effect of the glass former on the spectrum of the laser gain cross section. In general, silicate glasses present a larger crystal field to the Nd ion, leading to a larger splitting of the lower (multiple) energy levels of the laser transition, and thus a broader linewidth, shifted somewhat towards longer wavelengths compared to the phosphate glasses. As with the first PW-level laser at LLNL, the system employs a final stage, phosphate-glass disk amplifier based on the NOVA stage shown above.

Another important design feature of the system, now becoming a common feature of PW-class lasers, is the use of a high-gain, broad-linewidth optical parametric amplifiers (OPAs), both for the

[13] M.D. Perry, "Crossing the Petawatt Threshhold," Lawrence Livermore National Laboratory, December 1996, https://str.llnl.gov/str/Petawatt.html.

[14] M.D. Perry, et al., 1999, Petawatt laser pulses.

[15] E.W. Gaul, M. Martinez, J. Blakeney, A. Jochmann, M. Ringuette, D. Hammond, T. Borger, et al., 2010, Demonstration of a 1.1 petawatt laser based on a hybrid optical parametric chirped pulse amplification/mixed Nd:glass amplifier, *Appl. Opt.* 49(9): 1676-1681.

Ti:sapphire-laser-generated mode-locked pulse as well as for the stretched pulse. For the latter, the devices are referred to as optical parametric chirped-pulse amplifiers (OPCPAs). We discuss the technology of parametric amplifiers in Appendix B2 in reference to their application as both preamplifiers and as the final stage amplifiers in PW-class systems. The devices provide a broad-bandwidth, high-energy input to the glass amplifier stages, which operate with a total gain of less than 200, reducing the effect of gain narrowing. Another feature of the system is the use of a "Dazzler," the trade name for an acousto-optic based device that provides control of the phase and amplitude distribution of the frequency spectrum generated by the mode-locked laser. Adjustment of this spectrum allows better control of the output of the system, by correcting for distortions that act to broaden the compressed pulsewidth. The net combined gain with the phosphate and silicate glasses supports an output bandwidth for the Texas Petawatt of 13 nm, centered at 1,057 nm, allowing compression to the 130-fs-pulsewidth region. The system pulse rate is 1 per hour.

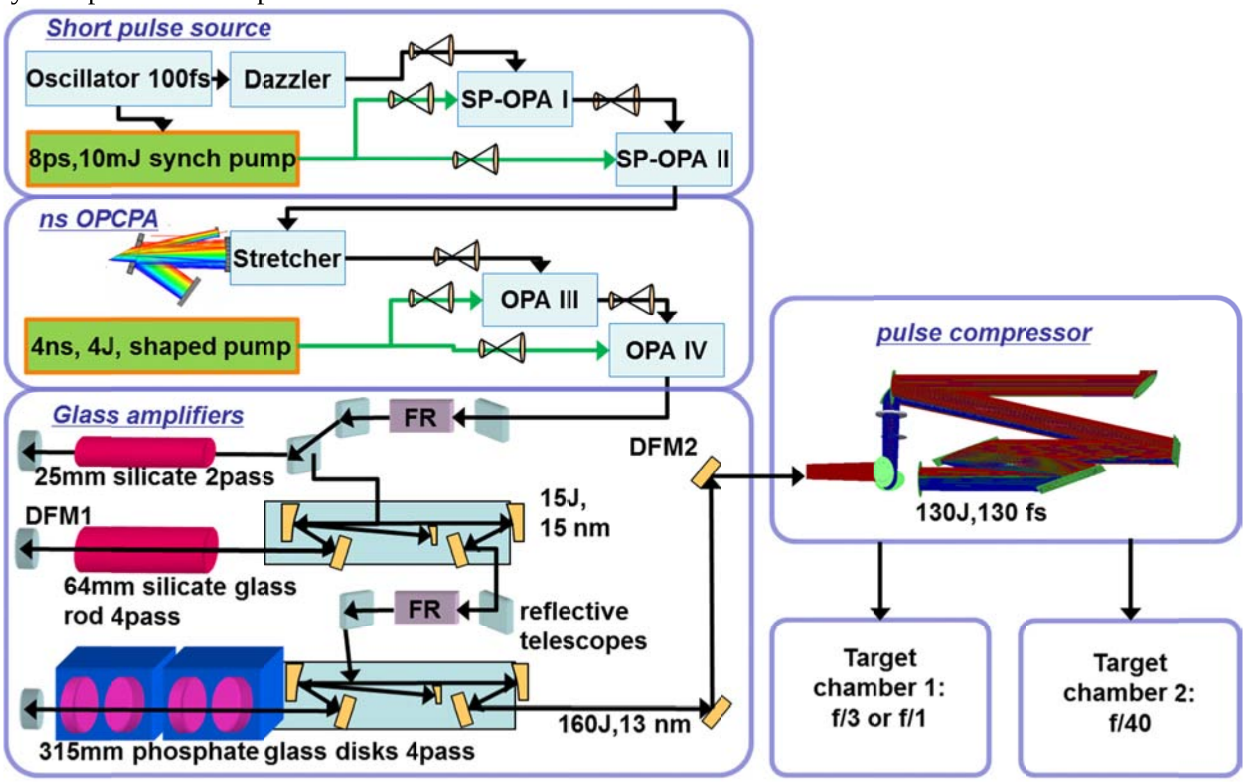


**FIGURE B1.7** Optical diagram of Texas Petawatt laser design. SOURCE: T. Ditmire, University of Texas at Austin, "A Path Towards an Exawatt Laser," presentation to the committee on May 10, 2016.

In Appendix B3 we discuss the outlook for Nd:glass PW systems, where we show how replacement of flashlamps with diode-laser pumps, combined with advance cooling techniques can increase the system pulse rate, and the use of mixed-glass approaches, and possibly new glass materials can lead to shorter pulses.

## Petawatt-Class Ti:sapphire Lasers

### *Background of Ti:sapphire Lasers*

Beyond the clear difference in laser spectroscopic properties, compared to glass host materials the sapphire host crystal can handle a much higher thermal load, and thus can operate at a much higher average power. As noted above, the thermal shock parameter for the material is about 25-80x higher than for laser glasses.

The shorter pulses generated by Ti:sapphire amplifier systems (15-30 fs) allow at least 6x lower energies to reach the PW level compared to Nd:glass systems. Laser-based pumping of Ti:sapphire, due to the short storage time of the material, is the universal approach to high-power system operation. At present, commercial "tabletop" Ti:sapphire oscillator-amplifier systems are available approaching the TW/pulse level (30 mJ in 30-40 fs), at rates as high as 1 kHz, with custom systems at PW-level powers advertised as available from two French-based companies, Thales and Amplitude Technologies. The general approach to building the higher-energy "custom" systems is to employ multiple identical pump lasers, each of which is engineered to operate at an energy and average power limited by the choice of the laser technology, at this writing based on either lamp-pumped Nd:YAG or Nd:glass lasers. Energy- and average-power scaling is done by adding more pump lasers, up to technical limits set by ASE, thermal effects in the Ti:sapphire final stage amplifier, or practical limits set by funding. The alternative is to employ a high-energy, single-stage Nd:glass-laser based pump, with the limits to average power then set by the performance of the pump. In the following we show examples of both approaches.

**Berkeley Lab Laser Accelerator**

The Berkeley Lab Laser Accelerator (BELLA) is unique, at present, in that it operates at a > 1 PW power level with a pulse rate as high as 1/second. Of interest is that it was constructed by a commercial laser supplier, Thales Optronique (Elancourt, France), rather than by a National Laboratory or an academic institution, and was claimed to be the first "commercial" PW laser. Figure B1.8 shows a schematic of the system, with many of the components labeled with commercial trade names. Details of the system have been published,[16] and we briefly summarize them here to point out important PW-system technologies of general interest. The configuration in Figure B1.8 is referred to as a "double CPA."

800-nm-centered, < 10-fs-duration, 100-nm-bandwidth pulses from a mode-locked Ti:sapphire laser are initially stretched to 150 fs, amplified, by about $2 \times 10^5$, through use of a highly multipass (regenerative) Ti:sapphire amplifier, where gain-narrowing reduces the pulse bandwidth to 35 nm, then recompressed and passed through a cross-polarized wave (XPW) element. The latter is used to minimize energy before the main pulse in time (prepulse), i.e., to improve, in the initial stages of the system, the so-called "contrast ratio" of the pulse. Prepulse energy is typically generated by ASE in the regenerative amplifier and also arises from incomplete suppression of other pulses emerging from the high-pulse-rate mode-locked source laser. For many scientific applications, particularly interaction with solid targets and plasmas, any energy arriving before the main pulse can ionize or otherwise perturb the target and modify the interaction. In XPW , a crystal, or two, (typically $BaF_2$) is placed between two crossed polarizers and the pulse to be improved in contrast is focused through the input polarizer onto the crystal.[17] The third-order nonlinear response of the crystal leads to the generation of a beam in the crystal with an orthogonal polarization, which passes through the output polarizer. Since the transmitted pulse energy depends on the cube of the pulse intensity, lower-energy (pre-pulse) light is significantly attenuated. An added benefit of the XPW element is the nonlinear interaction adds some bandwidth back to provide shorter pulse. For the BELLA system, the use of XPW increased the pulse contrast ratio by about 4-5 orders of magnitude to the present operating level of about $1 \times 10^{-10}$, for energy contained in a 1-ns time around the main pulse.

The second CPA system employs pulse stretched to the ns level and a series of staged Ti:sapphire amplifiers, all pumped by doubled Nd:YAG lasers. Thales developed an advancement in this technology

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[16] F. Lureau, S. Lauxa, O. Casagrandea, C. Radiera, O. Chalusa, F. Caradeca, and C. Simon-Boissona, 2012, High energy 1 Hz Titanium Sapphire amplifier for PetaWatt class lasers, in *Solid State Lasers XXI: Technology and Devices* (W. A. Clarkson and R. K. Shori, eds.), Proc. of SPIE, Vol. 8235, doi: 10.1117/12.908127.

[17] A. Jullien, O. Albert, F. Burgy, G. Hamoniaux, J-P. Rousseau, J-P. Chambaret, F. Augé-Rochereau, et al., 2005, 10−10 temporal contrast for femtosecond ultraintense lasers by cross-polarized wave generation, *Opt. Lett.* 30(8): 920-922.

through use of 25-mm-diameter, Nd:YAG rod amplifiers, which facilitated construction of pump lasers that generate 14 J of green pulse energy at a 1-Hz rate. Eight of these sources are used to pump the final, two-pass Ti:sapphire amplifier, which uses a 12-cm-diameter crystal and a 7-cm-diameter pump/extraction beam. For a total of 112 J of pump energy, about 60 J is output (with 39 J extracted) at 800 nm. The compressor employs "commercial" 48.5 x 30-cm, gold-coated diffraction gratings manufactured by Horiba Jobin-Yvon in France. At present the system, a photograph of which appears in Figure 2.3, operates at the 40 J output level with a 30-ps pulse, for a peak power of > 1.3 PW.

While Ti:sapphire systems can operate at lower energies to reach the PW level compared to Nd:glass, the larger gain cross section of the gain medium presents an ASE challenge, notably in the large-diameter disk-configuration final stages where the gain transverse to the extraction beam can lead to significant losses in stored energy and/or parasitic oscillations arising from reflections at the disk edges. In high-energy glass lasers the outer edges of the disks are clad in an index-matched glass doped to absorb the relatively narrow-linewidth emission around 1,050 nm. In Ti:sapphire the challenge is heightened by the large refractive index of the host, the scarcity of suitable index- and thermal-expansion-matched solid materials, and the broad bandwidth of the emission. For BELLA, Thales surrounded the Ti:sapphire disk edge with an index-matched liquid, with a broad-band absorber dye dissolved in the liquid, and water-cooled the liquid to allow operation of the laser at a 1-Hz rate.[18]

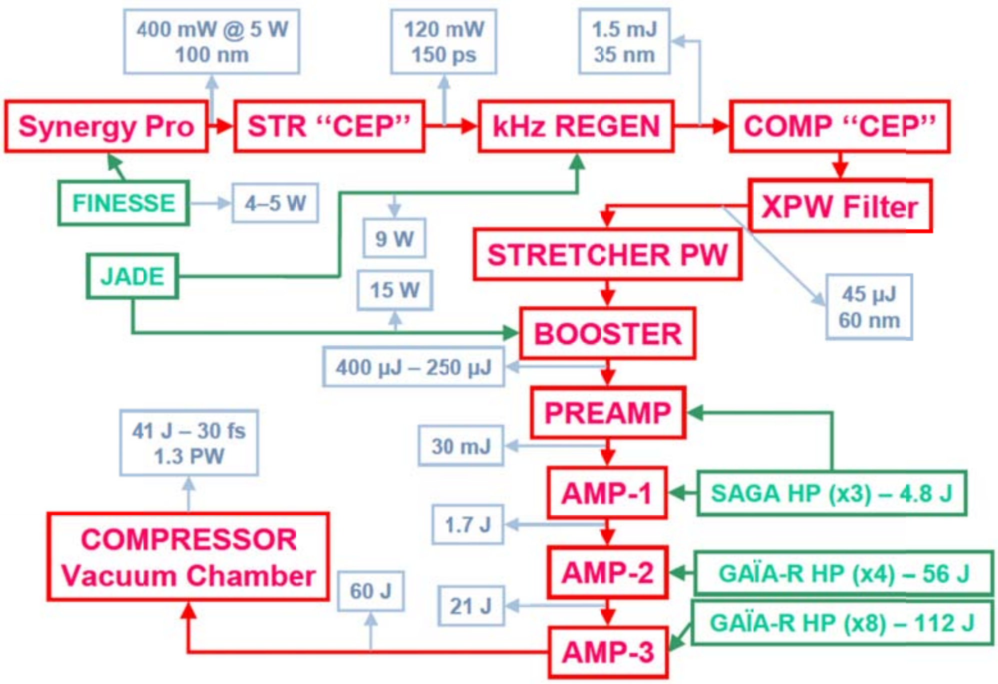


**FIGURE B1.8** Optical diagram of BELLA Nd:YAG-laser pumped PW-class Ti:sapphire system. SOURCE: F. Lureau, S. Lauxa, O. Casagrandea, C. Radiera, O. Chalusa, F. Caradeca, and C. Simon-Boissona, 2012, High energy 1 Hz Titanium Sapphire amplifier for PetaWatt class lasers, in *Solid State Lasers XXI: Technology and Devices* (W. A. Clarkson and R. K. Shori, eds.), Proc. of SPIE, Vol. 8235, doi: 10.1117/12.908127.

### Shanghai Institute of Optics and Fine Mechanics (SIOM): Ti:sapphire

[18] S. Laux, F. Lureau, C. Radier, O. Chalus, F. Caradec, O. Casagrande, E. Pourtal, et al., 2012, Suppression of parasitic lasing in high energy, high-repetition rate Ti:sapphire laser amplifiers, *Opt. Lett.* 37(11): 1913-1915.

At present, a high-peak-power Ti:sapphire laser (2 PW, 53.2 J in 26 fs) has been operated at SIOM, employing a single-beam Nd:glass laser as the pump source.[19] In addition, a 5.3-PW system pumped by two beams has recently become operational.[20] Figure B1.9 is a simplified schematic of the 2-PW system, while Figure B1.10 shows the 5.3-PW system design. As with the BELLA laser, the SIOM systems employ a XPW element, leading to a claimed contrast ratio of 1.5 x $10^{-11}$ in the period of 100 ps before the main pulse.[21] After the high-contrast front end, the pulse passes through a series of amplification stages to the final amplifier.

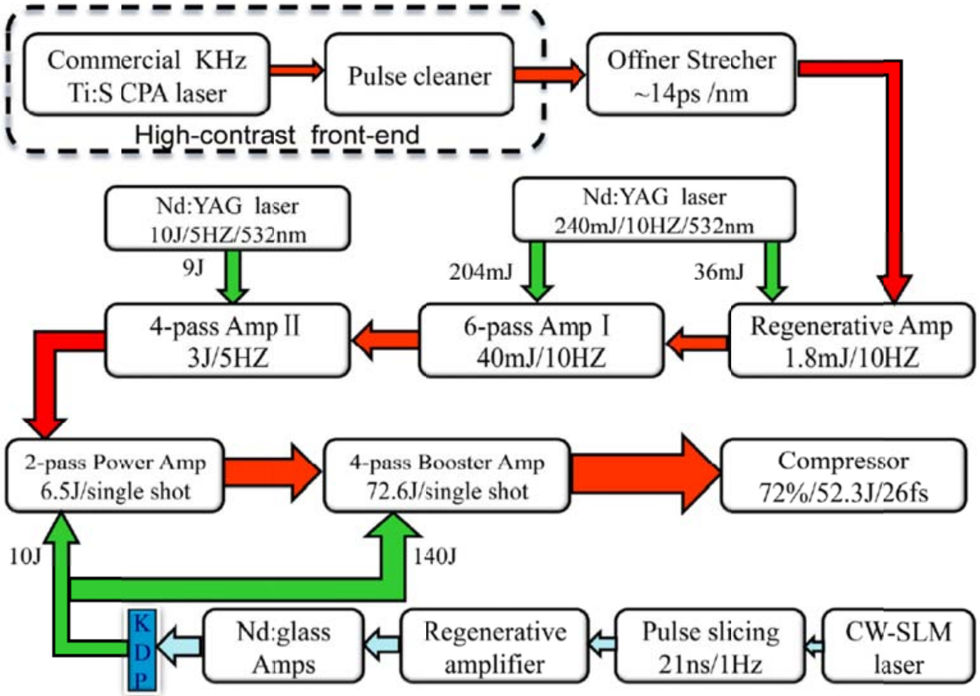


**FIGURE B1.9** Optical diagram of 2-PW Ti:sapphire laser operated at the Shanghai Institute of Optics and Fine Mechanics (SIOM). SOURCE: Y. Chu, X. Liang, L. Yu, Y. Xu, L. Xu, L. Ma, X. Lu, et al., 2013, High-contrast 2.0 Petawatt Ti:sapphire laser, *Opt. Exp.* 21(24): 29231-29239.

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[19] Y. Chu, X. Liang, L. Yu, Y. Xu, L. Xu, L. Ma, X. Lu, et al., 2013, High-contrast 2.0 Petawatt Ti:sapphire laser, *Opt. Exp.* 21(24): 29231-29239.

[20] Y. Chu, Z. Gan, X. Liang, L. Yu, X. Lu, C. Wang, X. Wang, et al., 2015, High-energy large-aperture Ti:sapphire amplifier for 5 PW laser pulses, *Opt. Lett.* 40(21): 5011-5014.

[21] Y. Xu, X. Guo, X. Zou, Y. Li, X. Lu, C. Wang, Y. Liu, et al., 2013, Pulse temporal quality improvement in a petawatt Ti:sapphire laser based on cross-polarized wave generation, *Opt. Commun*. 313: 175–179.

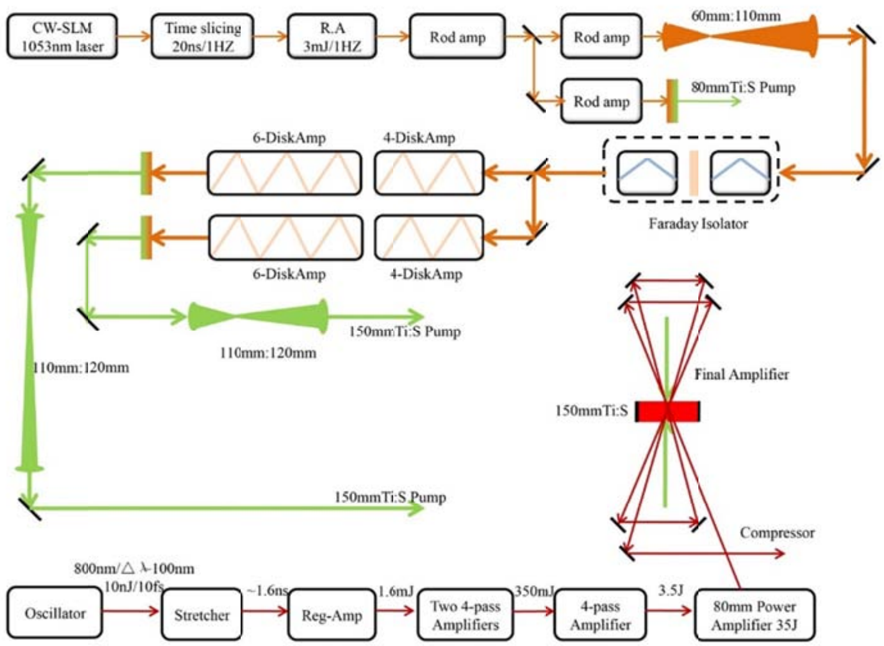


**FIGURE B1.10** Optical diagram of 5.3-PW Ti:sapphire laser operated at SIOM. SOURCE: Y. Chu, Z. Gan, X. Liang, L. Yu, X. Lu, C. Wang, X. Wang, et al., 2015, High-energy large-aperture Ti:sapphire amplifier for 5 PW laser pulses, *Opt. Lett.* 40(21): 5011-5014.

The final amplifier design in both the 2-PW and 5.3-PW systems employs several techniques to minimize the effects of ASE. Figure B1.11 shows a schematic representation of the final amplifier design with pumping and extraction approaches illustrated.

As with the BELLA laser, the Ti:sapphire disks use a cladding consisting of an index-matching liquid containing an IR-absorbing dye. The most effective ASE suppression comes about through a technique referred to as extraction during pumping (EDP),[22] which makes use of the timing of multiple extraction passes through the amplifier to control the excited-state population in the laser material. EDP is only available to ns-pulse-pumped lasers such as Ti:sapphire. The final amplifiers in the two SIOM systems have four-pass designs, with delays set by propagation distances for the extraction beams, as shown in Figure B1.11. In addition, for the 5.3-PW system, the two pump beams, directed on each surface of the disk, are delayed with respect to each other. The extraction process, rather than starting when all the pump energy has been accumulated in the gain medium, is timed to extract some of the stored energy at different times during the pumping process. The timing of the two pump pulses also helps to manage the peak stored energy in the 5.3-PW system. This reduces the maximum transverse gain to predicted values, respectively, of around 800 and 1,750 for the 82-mm-diameter beam in the 2-PW system and the 120-mm-beam in the 5.3 PW system. The conversion efficiencies of pump to output energy for the 2 PW laser were 47 percent (72.6 J output before compression) and 50 percent for the 5 PW system, which

[22] V. Chvykov, and K. Krushelnick, 2012, Large aperture multi-pass amplifiers for high peak power lasers, *Opt. Commun*. 285(8):21342136; V. Chvykov, V. Yanovsky, S-W. Bahk, G. Kalintchenko, and G. Mourou, 2003, paper CWA34 presented at the Conference on Lasers and Electro-Optics, Baltimore, Md., June 1–6, OSA Technical Digest.

generated 192 J of energy. By using 65-cm X 37.5-cm gratings, the SIOM group has obtained 24-fs, 5.3-PW pulses (127 J), in a ~300mm laser beam.[23]

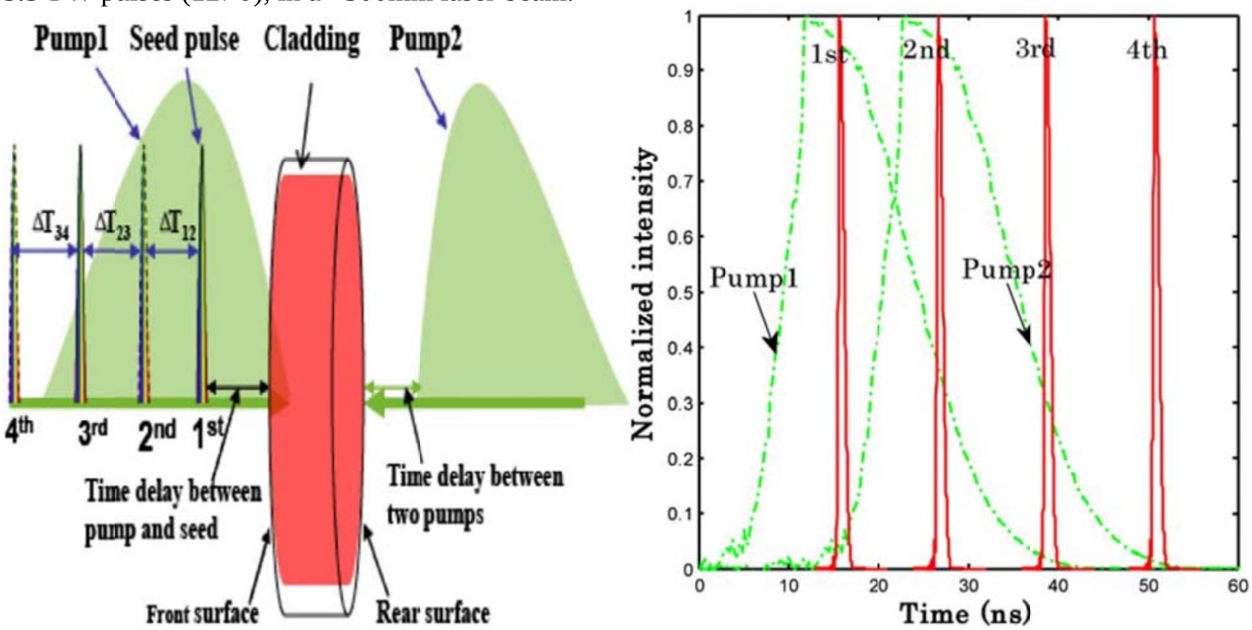


**FIGURE B1.11** Schematic of EDP scheme used in SIOM final amplifiers. SOURCE: Y. Chu, Z. Gan, X. Liang, L. Yu, X. Lu, C. Wang, X. Wang, et al., 2015, High-energy large-aperture Ti:sapphire amplifier for 5 PW laser pulses, Opt. Lett. 40(21): 5011-5014.

At present there are a number of 0.1 PW and higher Ti:sapphire-based systems worldwide, as shown in Table 3.3 in Chapter 3. We return to a discussion of this technology in Appendix B3 in terms of future advances.

[23] R. Li, L. Yu, Z. Gan, C. Wang, S. Li, Y. Liu, X. Liang, et al., 2016, "Development of a Super Intense Laser Facility at Shanghai," presentation at IZEST Conference Extreme Light Scientific and Socio-Economic Outlook, Paris, Nov. 25-29.

# APPENDIX B2. NONLINEAR OPTICS AND OPTICAL PARAMETRIC CHIRPED-PULSE AMPLIFICATION BACKGROUND

The discovery and development of lasers quickly allowed the related development of nonlinear optics, a field that could be predicted in theory but required the intensity produced by lasers to transition to a demonstration and then real applications.

Light entering an insulating material interacts with the electrons and atomic vibrations through a variety of processes. It can be absorbed by creating a vibration or promoting an electron to a higher energy level. Barring that, light creates a displacement of electrons and atoms, for low light intensities, in almost entirely a linear proportion to the electric field of the light. The linear term for polarization has the effect of making light propagate through the material at a slower speed than in a vacuum which varies with wavelength $\lambda$, where the speed is $c/n$, with $c$ the vacuum speed of light and $n$ the refractive index of the material. At higher intensities, the accurate modeling of the displacement, or polarization, requires the inclusion of terms that include the square, cube, and higher-orders of the electric field.

Specifically, the presence of polarization proportional to the square (second-order nonlinearity) of the electric field of the light permits generation of a polarization resulting from the product of two electric fields. This leads to several possibilities. If the two fields are the same frequency, the nonlinear polarization created has a component that is at twice the frequency of the light. This creates light at the “second harmonic” of the two fields, or equivalently, half the wavelength. Another possibility is that two fields can be different frequencies, and here there can be light created at either the difference in frequencies or at the sum of the two frequencies.

Second-order nonlinearity, for one incident beam of light, means that a material polarization is established in a direction that is the same whether the light electric field is positive or negative. Consider setting up a vector inside the material pointing in a certain direction. If this vector is flipped into exactly the reverse direction, and the material appears to the vector to have the same structure, the material is said to have inversion symmetry. For such materials (glass is a good example, but many crystals have this as well), the material will not have a second-order nonlinearity, as there can be no preferred polarization that follows the square of the electric field. Only crystals that lack inversion symmetry can have a non-zero second-order nonlinearity.

The processes of harmonic generation and mixing we describe can be modeled classically using Maxwell’s equations with the nonlinear polarization added in to the customary linear polarization terms for light propagation in a material. Solutions of these equations with two light waves show, in one solution, how two frequencies can generate light at the sum frequency, the intensity of which can increase as the waves propagate in the material, with a loss of energy at the two frequencies. The same general equations show another solution where light at one frequency can generate light at two lower frequencies, provided the sum of the two new frequencies is equal to that of the original frequency. (The sum requirement follows from energy conservation, and from the viewpoint of quantum theory, the sum of the energies of the two new photons must equal that of the original photon.) The latter process, with nomenclature carried over from early work with microwave technology, is called optical parametric generation (OPG) or, when at least one of the lower frequencies is also present in the beam incident on the material, optical parametric amplification (OPA). When an optical cavity is used to provide feedback at the signal or idler wavelength (or both), the device is called an optical parametric oscillator (OPO). The incident power at the high frequency is called the pump, the higher of the two frequencies generated or amplified is the signal, and the lower the idler. Energy conservation requires that the power conversion of pump to signal and pump to idler is given by the ratio of the signal to pump and idler to pump frequencies, often referred to as the Manley-Rowe relation, which was derived from early work at radio frequencies.

The same equations show that to produce appreciable amounts of amplification as the light travels through the material, all the electric fields of the light waves involved need to maintain a constant phase relationship. If they do not, power conversion into the signal and idler flows backwards into the pump, then back to the signal and idler, in a periodic fashion through the material. As a result, it is impossible to obtain significant amplification. The process of arranging the three interacting frequencies to stay in phase is called, fittingly, phase-matching. The phase change per length of material at a given frequency $\nu$, $k(\nu)$, is given by

$$k(\nu) = 2\pi n(\nu)\nu/c , \qquad \text{(B.2a)}$$

where $n(\nu)$ is the refractive index at the frequency and $c$ is the speed of light (in vacuum). In terms of the wavelength $\lambda$ corresponding to the frequency above, Equ. 3.1.5 can be re-written

$$k(\lambda) = 2\pi n(\lambda)/\lambda \qquad \text{(B.2b)}$$

For the parametric process, phase-matching requires

$$k_p = k_s + k_i , \qquad \text{(B.3)}$$

where the subscripts $p$, $s$, and $i$ refer to the pump, signal, and idler, respectively.
If the refractive index of the material was a constant, then phase-matching would happen automatically given the other requirement for conservation of energy, but in all conventional materials the index varies with wavelength due to refractive dispersion. Typically, at visible and near-infrared wavelength it decreases with wavelength. To overcome this, one can utilize birefringent crystals, which show a difference in refractive index depending on the polarization (i.e., the direction of the electric field) of light and the direction of propagation with respect to the crystal orientation. Birefringent phase-matching is the most common technique, although the development of artificially structured materials has allowed another variety, called quasi-phase matching.

The simplest birefringent crystal is uniaxial, that is, there is an “optic axis” in the material along which the refractive index experienced by the light in that direction is independent of its polarization. Light going along any other direction experiences a refractive index that is polarization dependent, where the difference in refractive index between different polarizations depends on the specific direction of propagation. By making use of this dependency, one can achieve phase-matching for the three wavelengths through the proper choice of polarizations for light at each wavelength. One simple case would be the pump polarized parallel and the signal and idler perpendicular to the optic axis, a scheme referred to as “Type I” phase-matching, for the case of crystals (called positive uniaxial) where the index for a given wavelength is higher for the perpendicular polarization. If it is lower (negative uniaxial), then one can reverse the polarizations of the pump, signal, and idler.

The requirement that a crystal be birefringent and also lack inversion symmetry greatly limits the number of materials that can be used for parametric processes. Further limits are set by other practical considerations, such as crystal quality, absorption at all the wavelengths involved, freedom from photochemical degradation at high light intensities, high optical-damage threshold, and, for use with high energies, ability to be grown in large sizes. The number of crystals suited for harmonic and parametric generation at high powers and energies, after about 60 years of development efforts, remains in the single digits.

One class of crystals, first used as acoustic transducers, and predating the development of lasers, are members of the KDP ($KH_2PO_4$) family. They are composed of compounds of alkali metals with light or heavy (hydro, deutero) water and oxides of phosphate or arsenate. Motivated by application to harmonic generation in ICF sources, several groups developed technology to grow nearly meter-aperture KDP and an isomorph, DKDP or $KD^*P$, where almost all the hydrogen is replaced by deuterium. Two other materials, $\beta$-$BaB_2O_4$ (BBO) and $LiB_3O_5$ (LBO), first synthesized in China in the 1970s, have found widespread use in commercial parametric-based light sources. They are relatively robust crystals mechanically, with high optical damage thresholds, a wide transparency range, and in the case of LBO, a very low level of optical absorption. Another borate material, $YbCa_4O(BO_3)_3$ (YCOB) has also been used for some systems needing a large-aperture crystal.

One important point about parametric amplifiers is, in contrast to amplifiers based on stimulated emission, there is no energy storage in the nonlinear material. Gain is only present when the pump is on and is proportional to the pump intensity. For the time the pump is on one can obtain very high gains with high-peak-power pump pulses, as high as $10^{12}$ and sufficient to build up a substantial signal and idler power with only the photon-level thermal noise background as input. Unlike lasers, there is no spontaneous emission background around the pulse in time, and the nature of phase-matching results in gain that is only in the general direction of the pump beam. Thus, scaling to large pump-beam sizes can be done without limits set by gain transverse to the beam. Also, unlike lasers, in the absence of any background absorption in the crystal, or absorption-inducing nonlinear effects in the material, the parametric process does not create any heat. All the incident energy is converted into light at other wavelengths.

### Parametric Amplification of Broad-Spectrum Pulses

The advantages we have just outlined for parametric processes suggest they could be used for high-intensity generation of light, if a suitable high-energy pump laser is available. The other criterion is that the parametric gain has sufficient bandwidth to amplify an ultrashort pulse. If one utilizes a narrow-band pump laser, the bandwidth of an OPA is determined by how rapidly the phase-matching condition deviates from the condition set by equation B.3 as the signal frequency changes. Consider what happens to this condition as the signal frequency deviates by an amount $\Delta\nu$ from the value at which phase-matching occurs. From energy conservation, the idler must deviate by $-\Delta\nu$, and we can approximate the new phase-matching requirement by the equation

$$k_p = k_s + (dk_s/d\nu)\Delta\nu + k_i - (dk_i/d\nu)\Delta\nu \ . \qquad \text{(B.4)}$$

We can write the derivatives as

$$dk_s/d\nu = 2\pi/v_s \quad \text{and} \quad dk_i/d\nu = 2\pi/v_i \ , \qquad \text{(B.5)}$$

and thus

$$k_p = k_s + k_i + 2\pi\,\Delta\nu\,(1/v_s - 1/v_i) \ , \qquad \text{(B.6)}$$

where $v_s$ and $v_i$ are the "group velocities" for the signal and idler waves, respectively. These quantities describe the velocity of the peak position of a short pulse of light (centered at the frequency of the signal or idler) as it travels through the crystal. In the absence of any refractive dispersion this velocity would be the same as the velocity of a continuous wave of light at that frequency, but with dispersion the different frequency components that make up the pulse travel at slightly different speeds. The effect of this makes the peak of pulse move at a different speed. The physical interpretation of equation B.6 is that the broadest bandwidth amplification arises when the group velocities of the signal and idler beams are matched, i.e., the pulses travel together through the nonlinear crystal.

For Type I phase-matching it is possible to have "degenerate" parametric amplification, where the signal and idler frequencies are the same. In that case group velocities for signal and idler waves are the same, the third term in equation B.6 vanishes, and phase-matching is maintained independent of the frequency change in the signal. This leads, in theory, to an infinite bandwidth, but in actuality the approximation of equation (B.4) is no longer valid and higher-order derivatives need to be considered. Nevertheless, the bandwidth does become large, and early work to use parametric gain to amplify short pulses employed systems operating around the degenerate point.

Experiments in the 1990s involving parametric amplifiers driven by ultrashort pulses demonstrated that a more complicated type of phase-matching could lead to even larger bandwidths than found with degenerate phase-matching.[24] Figure B2.1 illustrates "non-collinear" phase-matching, where

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[24] V. Krylov, A. Kalintsev, A. Rebane, D. Erni, and U. P. Wild, 1995, Noncollinear parametric generation in LiIO3 and b-barium borate by frequency-doubled, femtosecond Ti:sapphire laser pulses, *Opt. Lett* 20(2): 151-153;

the constraint that the pump, signal, and idler beams travel in the same direction is eliminated. The significance of this scheme is that through the right combination of angles, not only is phase-matching possible, but also an excellent matching of group velocities of the signal and idler, well away from the degenerate case. An important point is that when amplifying a broad-bandwidth signal beam the angle for the idler wave can and does vary to facilitate phase-matching for the different frequency components in the signal. This degree of freedom is not available for collinear phase-matching.

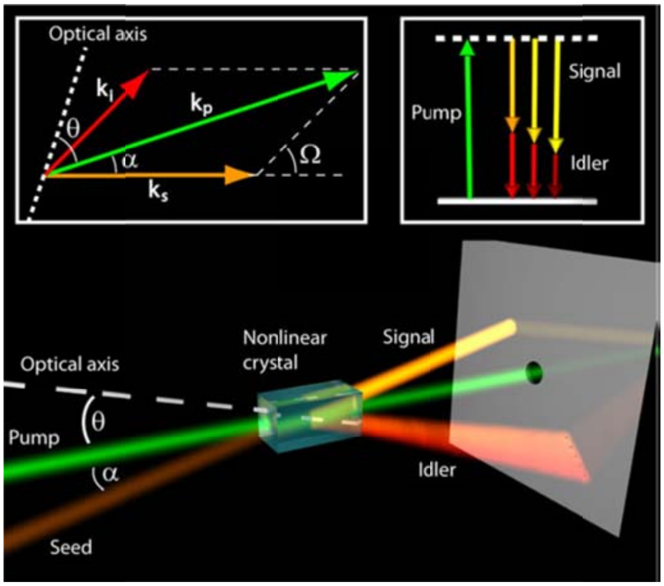


**FIGURE B2.1** *Schematic of non-collinear phase-matching scheme for large-bandwidth parametric gain. SOURCE:* S.Witte and K. S. E. Eikema, 2012, Ultrafast optical parametric chirped-pulse amplification, *IEEE J. Sel. Topics Quantum Electron*. 18(1): 296-307.

Figure B2.2 shows calculated gain bandwidths with non-collinear phase-matching for three nonlinear materials, for a variety of pump wavelengths, as well as calculated gains as a function of frequency in $cm^{-1}$. The latter unit is equivalent to a frequency of 30 GHz, and thus gain bandwidths in the 2,500-3,500 $cm^{-1}$ region correspond to 75-100 GHz linewidths, comparable to Ti:sapphire in spectral width. The actual computed gains, on the order of 1,000, have spectral widths, in the 90-120 GHz range, so in contrast to laser media it is possible to have significant amplification without gain narrowing. In fact, analysis of the gain bandwidth set by phase-matching conditions shows that the bandwidth increases with gain. Thus one can obtain high-gain amplification of several-fs pulses.

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Di Trapani, A. Andreoni, G. P. Banfi, C. Solcia, R. Danielius, A. Piskarskas, P. Foggi, et al., 1995, Group-velocity self-matching of femtosecond pulses in noncollinear parametric generation, *Phys. Rev. A* 51(4): 3164-3168.

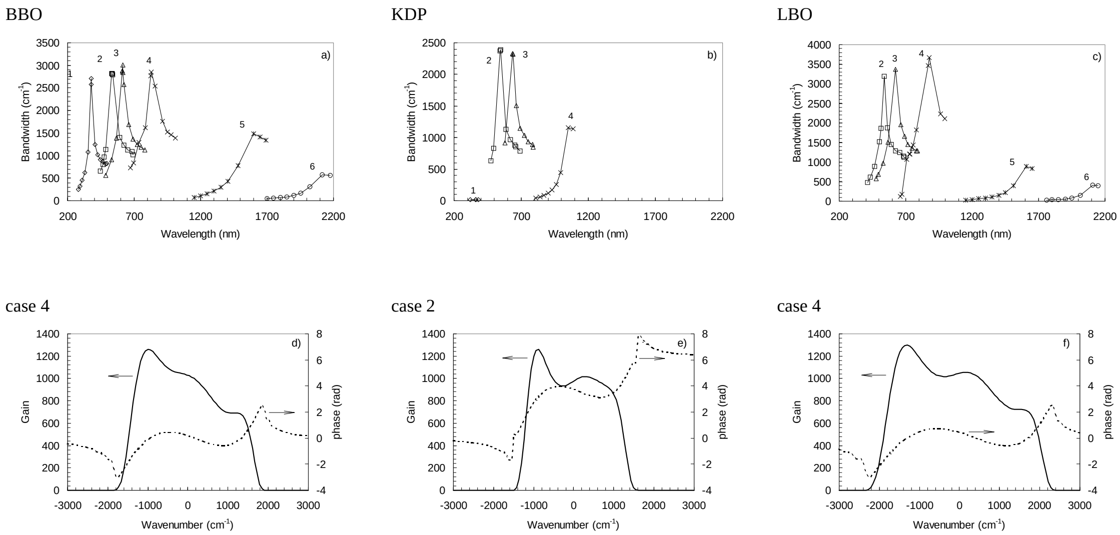


**FIGURE B2.2** (Top curves, a,b,c). Calculated parametric gain bandwidths (FWHM, frequency in cm$^{-1}$) for three materials pumped at different wavelengths, plotted as a function of signal wavelength. Curves labeled 1-6 have pump wavelengths of 249, 351, 400, 526, 800 and 1053 nm, respectively. (Bottom curves, d,e,f) Calculated gain and phase-mismatch plots vs. frequency in cm$^{-1}$ about the signal gain peak for the same materials, for pump wavelengths of 526, 351 and 526 nm, corresponding to center wavelengths of about 800, 500 and 900 nm, respectively. SOURCE: L.N. Ross, P. Matousek, M. Towrie, A.J. Langley, and J.L. Collier, 1997, The prospects for ultrashort pulse duration and ultrahigh intensity using optical parametric chirped pulse amplifiers, Opt. Commun. 144(1-3): 125-133.

## Petawatt-Class Optical Parametric Chirped-Pulse Amplification Systems

### *Russian Optical Parametric Chirped-Pulse Amplification Systems*

The PEtawatt pARametric Laser (PEARL) system, built at the Institute of Applied Physics, Russian Academy of Science in Nizhny Novgorod,[25] utilizes KD*P crystals, which, when pumped at 527 nm, show a gain bandwidth peaked at 910 nm and capable of amplifying 10-15-fs-duration pulses. Figure B2.3 shows a schematic diagram of the system, which employs a 40-fs-pulsewidth, 1,250-nm, mode-locked Cr: $Mg_2SiO_4$ (Cr:Forsterite) laser as a pulse source, stretched to a pulsewidth of 0.6 ns and amplified as an idler by one KD*P OPCPA to generate a 0.5-mJ signal at 910 nm. Another KD*P OPCPA brings the signal energy to 100 mJ, where it is sent into a final KD*P OPCPA stage pumped by 180 J of 527-nm pump energy. The latter, with a 1-ns pulse duration, is derived from a 300 J, Nd:glass (phosphate) system, which was constructed to provide a nearly intensity-uniform, low-divergence pump beam. The final OPCPA amplifier employs a 120-mm-diameter aperture, 80-mm-long crystal, and converts 21 percent of the pump energy into the signal, about 36 percent of the maximum possible based on the Manley-Rowe relation. Subsequent losses in the compressor stage lead to a final output of 24 J in a

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[25] V.V. Lozhkarev, G.I. Freidman, V.N. Ginzburg, E.V. Katin, E.A. Khazanov, A.V. Kirsanov, G.A. Luchinin, et al., 2007, Compact 0.56 Petawatt laser system based on optical parametric chirped pulse amplification in KD*P crystals, *Laser Physics Letters* 4(6): 421.

43-fs pulse, for 0.56 PW of peak power. The system pulse rate is limited to about one per half hour by the Nd:glass pump laser pulse rate.

A less-documented, Nd:glass-pumped system built at the "Luch" Facility at the Russian Federal Nuclear Center- All-Russian Research Institute of Experimental Physics, Sarov, in the "Nizhny Novgorod region," claimed to have reached the 1 PW level with a 100 J-output chirped pulse that was compressed to a 70-fs duration.[26] The final KD*P crystal had a 200 x 200-mm aperture and was pumped by 2.3-ns, 1 kJ green pulse derived from a 2-kJ Nd:glass pulse. Here the pump-to-chirped-signal conversion was around 10 percent.

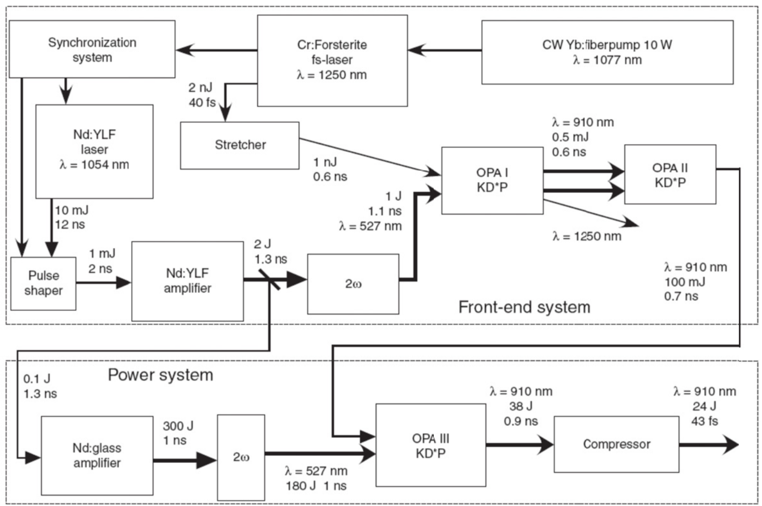


**FIGURE B2.3** PEARL OPCPA-based, 0.56-PW source. SOURCE: V.V. Lozhkarev, G.I. Freidman, V.N. Ginzburg, E.V. Katin, E.A. Khazanov, A.V. Kirsanov, G.A. Luchinin, et al., 2007, Compact 0.56 Petawatt laser system based on optical parametric chirped pulse amplification in KD*P crystals, *Laser Physics Letters* 4(6): 421.

### *Shanghai Institute of Optics and Fine Mechanics (SIOM): Optical Parametric Chirped-Pulse Amplification*

In contrast to the Russian OPCPA work, the SIOM has a reported a 1-PW peak power system employing a large-aperture LBO crystal.[27] The source, as shown in Figure B2.4, employs a Ti:sapphire CPA system to provide a 800-nm-centered, 1.9-ns-duration chirped pulse with as much as 2.25 J of energy. A single OPCPA stage, employing a 100 x 100 mm-aperture, 17-mm-thick crystal, amplifies the CPA signal input to an energy of about 45 J, compressed to 32.6 J of energy with a 32-fs-duration pulse. A Nd:glass laser provides a 2.85-ns pump pulse in the green, in a 84-mm-diameter beam on the LBO crystal. In a series of optimization experiments, the best operating point was for a signal energy of 0.82 J and a pump energy of 170 J, for a 26 percent conversion of pump to chirped-pulse energy and a gain of 55. The conversion was at about 40 percent of the Manley-Rowe limit.

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[26] A.A. Shaykin, G.I. Freidman, S.G. Garanin, V.N. Ginzburg, E.V. Katin, A.I. Kedrov, E.A. Khazanov, et al., 2009, 1 petawatt OPCPA laser in Russia: status and expectations, in *Lasers and Electro-Optics 2009 and the European Quantum Electronics Conference*, June 14-19, Munich, CLEO Europe - EQEC.

[27] L. Yu, X. Liang, L. Xu, W. Li, C. Peng, Z. Hu, C. Wang, et al., 2015. Optimization for high-energy and high-efficiency broadband optical parametric chirped-pulse amplification in LBO near 800 nm, *Opt. Lett*. 40(14): 3412-3415.

The SIOM work exploring combinations of signal input energy and pump pulse energy found issues with so-called “back conversion,” where energy in the signal and idler convert back to pump energy. In principle, with perfect phase-matching, spatially uniform pump and signal-input beams and temporally uniform pump and signal pulses one could convert pump to signal energy up to the Manley-Rowe limit. In practice, none of these conditions can be met, especially phase-matching over a broad spectral range. Back conversion acts as a limit to the efficiency of OPCPA devices, and for the PEARL and SIOM the limit was in the range 36 to 40 percent of Manley-Rowe.

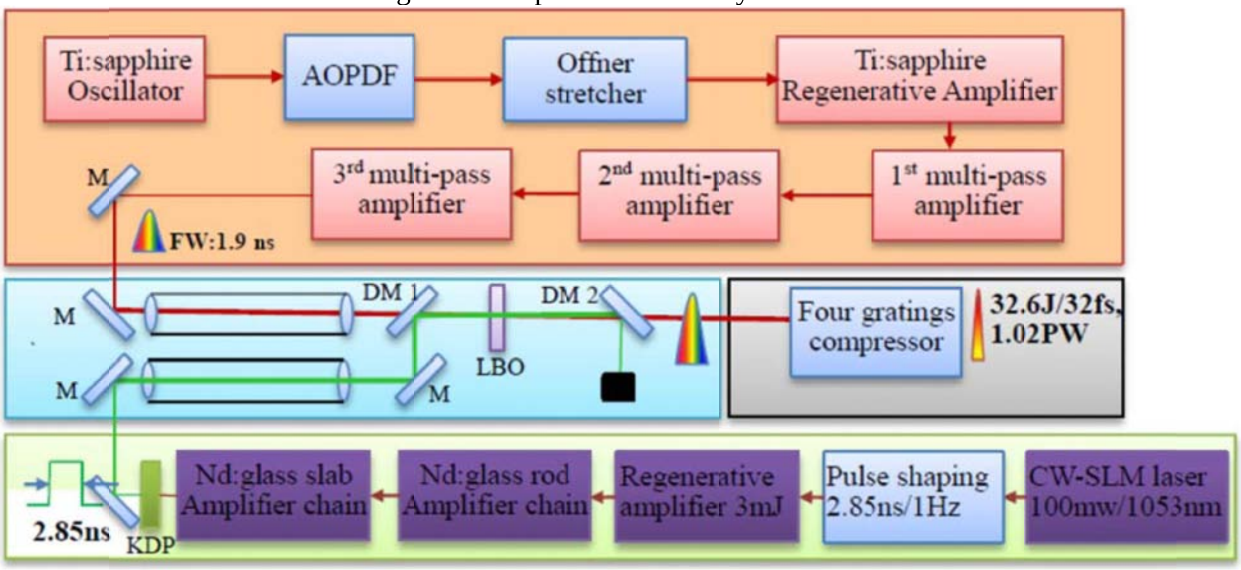


**FIGURE B2.4** 1-PW hybrid, Ti:sapphire CPA/ LBO OPCPA source built at SIOM. SOURCE: L. Yu, X. Liang, L. Xu, W. Li, C. Peng, Z. Hu, C. Wang, et al., 2015, Optimization for high-energy and high-efficiency broadband optical parametric chirped-pulse amplification in LBO near 800 nm, *Opt. Lett.* 40(14): 3412-3415.

# Appendix B3. Enabling technologies

## Laser Diode Pumping Sources

Laser diodes are based on a semiconductor material with a p-n junction, where laser action is obtained by passing electrical current through the junction. First developed in the 1960s, they operated at room temperature as low-power continuous-wave (cw) devices (10's of mW) until the 1980s, when advances in technology allowed power scaling of individual lasers to the 1 W level and fabrication of linear arrays (bars) to the tens-of-W level. Since then there have been steady advances to the point that single devices can operate at >10 W power levels and bars at the 500 W level. These power levels are not in a diffraction-limited laser beam but are nevertheless suited for many applications, notably optical pumping of solid-state lasers. Typical limits to power for single-emitter devices are destruction of the chip surface by optical damage, a limit that varies little whether the devices run cw or in a pulsed mode. For bars the limit is typically excessive temperature rise, and here the peak power available can be increased by running the device in a pulsed format.

The use of diodes for pumping of solid-state gain media has advantages over the use of gas-discharge lamps. Both can convert a high fraction of electrical power into light (60 to 80 percent),[1] but diodes have the following advantages:

A narrow spectral bandwidth that can be tuned, by adjusting the composition of the semiconductor, to pump the upper laser level or slightly higher energy levels directly. This results in less heat left in the laser material compared to lamps, which, especially for near-infrared lasers, pump a multitude of higher-lying energy levels. In addition, lamps produce a large fraction of power that does not pump the laser material at all. Figure B3.1 illustrates this for the case of Nd:YAG.

A narrow spatial beam compared to the incoherent emission in all directions from a lamp, allowing better matching of the pump energy to the desired region in the solid-state gain medium, and thus higher conversion of pump power into laser power for some laser configurations.

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[1] J. H. Goncz and P. B. Newell, "Spectra of Pulsed and Continuous Xenon Discharges," J. Opt. Soc. Am. **56**, 87 (1966). Data showed 65% conversion efficiency from electrical input to light in the 350- to 1100- nm region.; J. Holzrichter, Laser Fusion Program, Semiannual Report, July-December 1973, (UCRL-50021-73-2), Lawrence Livermore National Laboratory, University of California, Livermore, CA, p.44. Data was taken with a wavelength-insensitive calorimeter and a xenon flashlamp, showing as much as 80% conversion of electrical input to radiant energy; Commercial Diode bars operating in the 915-1030-nm wavelength region specify 62% conversion efficiency (II-VI Laser Enterprise BPC/OPC 80W), and 65% at 980 nm for unmounted bars (OSRAM SPL BF98-4-05); P. Crump, G. Erbert, H. Wenzel, C. Frevert, C. M. Schultz, K-H. Hasler, R. Staske, B. Sumpf, A. Maaßdorf, Frank Bugge, Steffen Knigge, and Gunther Trankle, "Efficient High-Power Laser Diodes," IEEE. J. Sel. Topics Quantum Electron. **19**, 1501211 (2013); P. A. Crump, M. Grimshaw, J. Wang, W. Dong, S. Zhang, S. Das, J. Farmer, M. DeVito, L. S. Meng, and J. K. Brasseur, "85% Power Conversion Efficiency 975-nm Broad Area Diode Lasers at -50°C, 76 % at 10°C," in *Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference and Photonic Applications Systems Technologies*, Technical Digest (CD) (Optical Society of America, 2006), paper JWB24.

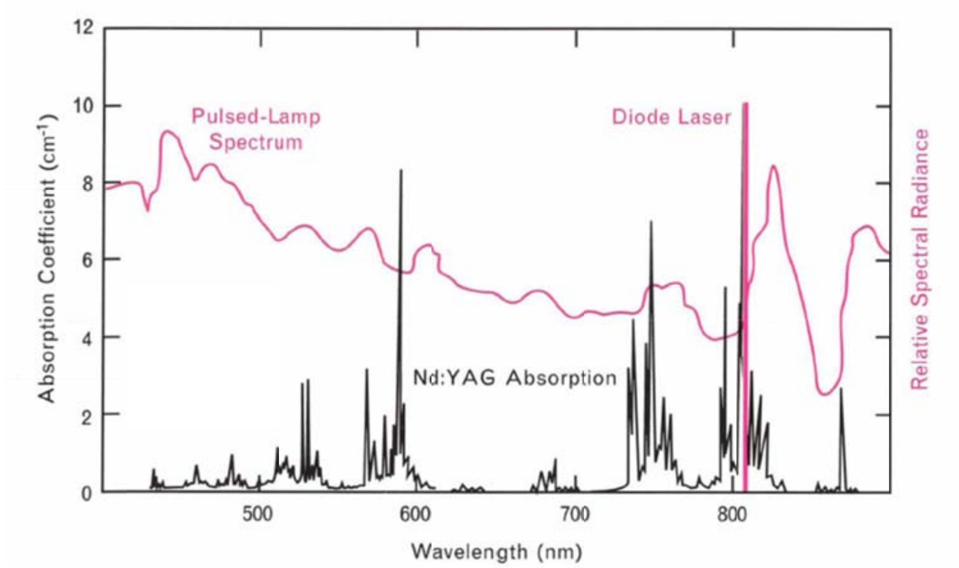


**FIGURE B3.1** Nd:YAG absorption spectrum (left axis) overlapped with spectrum of typical xenon flashlamp and 808-nm diode laser (right axis.) While the diode wavelength falls entirely in an absorption region of the Nd:YAG material, much of the flashlamp output does not overlap with Nd:YAG absorption material. In addition, much of the flashlamp output that is absorbed is by short-wavelength energy levels in Nd:YAG, leading to increased laser material heating. SOURCE:
T.Y. Fan, 1990, Diode-pumped solid-state lasers, *The Lincoln Laboratory Journal* 3(3): 413.

The net result of the use of diodes is a much higher overall electrical efficiency for diode-pumped solid-state lasers, at least an order-of-magnitude, and, for a given power output, a much reduced level of waste heat in the laser material. For Nd:YAG, as an example, waste heat is one-third or less of that with lamps.[2] The ability to deliver diode pump power to the desired gain region in a material is most significant at low powers, where excited volumes are small. For high-energy systems, especially large-aperture Nd:glass lasers, the brightness of diodes is less important, but the higher efficiency in converting electrical power to absorbed pump power, and the lower waste heat, remains an advantage for diodes.

The replacement of cw arc-lamps and pulsed flashlamps by diodes has resulted in a major advance in solid-state laser systems, particularly for industrial applications. The major impediment for high-energy systems has been the cost of diode lasers compared to flashlamps. For example, a typical pulsewidth is about 0.2 ms for a pulsed pumping system with Nd-doped solid-state lasers. For 100 J of diode pump energy this requires a pump source with about 500 kW of peak power, or 1,000 bars with 500 W of power each. Even with diode cost at $1/W, the cost of lamps is still several orders-of-magnitude cheaper, even if at least 10x more energy is needed. Nevertheless, the improved performance with diode pumping can justify the extra expense. We discuss, below, current applications of diode pumping to high-peak-power lasers.

The emergence of high-power diodes has also enabled development of an entirely new class of solid-state lasers based on the rare-earth dopant ytterbium (Yb). The energy-level structure for this ion, which has only 1 electron in the 4f shell, is very simple compared to other rare earths. Referring to Figure B3.2, for the case of Yb:YAG, there is only one main energy level above the ground state, with both absorption and emission taking place around 1,000 nm. Compared to Nd-doped crystals, the Yb-doped absorption and gain linewidths tend to be broader except for those between the lowest-lying ground state

[2] T.S. Chen, V.L. Anderson, and O. Kahan, 1990, Measurements of heating and energy storage in diode-pumped Nd:YAG, *IEEE J. Quantum Electron*. 26(1): 6-8.

and lowest-lying excited state, the "zero-phonon" transition. This is the result of considerable lifetime broadening of the lower levels due to a high scattering rate by phonons. For flashlamp pumping the ion has poor absorption overlap with the broad emission spectrum of flashlamps, and lasers based on the ion did not find any commercial uses due to their low efficiency. This problem was eliminated with diode pumping, with the added advantage that the small difference in pump and laser wavelengths leads to a greatly reduced level of heating compared to 800-nm-region, diode-pumped Nd-doped lasers. As is evident from Figure B3.2, absorption is present at the laser wavelength (making this a so-called 3½-level) laser, so the amount of pump power density needed to achieve gain is higher compared to Nd-doped lasers. This can be overcome with the high pump power densities possible with diode pumping or by cooling the laser material to reduce the population of the lower level and hence the absorption. We discuss more about Yb-doped media in sections below.

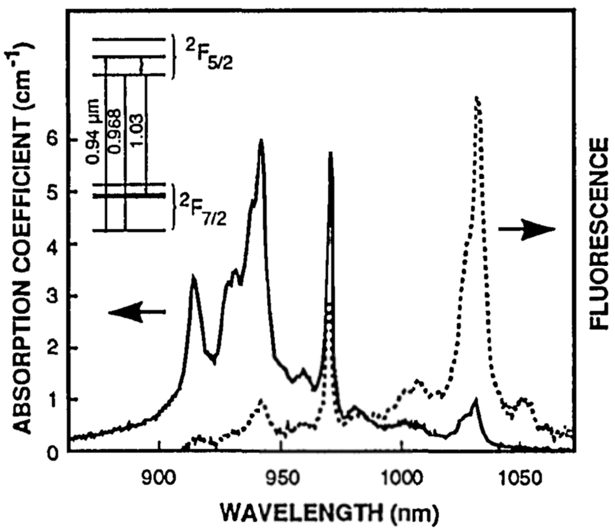


**FIGURE B3.2** Absorption (solid line) and fluorescence (dotted line) spectra for Yb:YAG at room temperature, with energy-level diagram in upper left corner. The "zero-phonon" transition for this material is at 968 nm. SOURCE: P. Lacovara, H. K. Choi, C. A. Wang, R. L. Aggarwal, and T. Y. Fan, 1991, Room-temperature diode-pumped Yb:YAG laser, *Opt. Lett.* 16(14): 1089-1091.

### Thermal Management

For relatively low-energy (1-10 J/pulse), pulsed solid-state lasers with flashlamp pumping, active cooling, typically with flowing water, has long been used to allow modest average powers, in the 10-100-W range. Similar systems with diode pumping can run at much higher powers, at the kW level. With diodes as pump sources other overall systems designs are possible to better handle thermal issues with high cw or quasi-cw operation, notably the thin-disk laser first demonstrated by Giesen[3] and commercialized primarily by Trumpf Inc. (Ditzingen, Germany) and fiber-format lasers, which now can produce the highest cw powers of any commercial solid-state laser. Neither of these designs can operate with single apertures large enough for PW-class lasers, at least those with 10-fs and longer pulses.

For PW-level, high-energy systems, which have been, with the exception of BELLA, based on flashlamp-pumped Nd:glass, the pump laser has relied on passive air cooling for the laser material as well as the flashlamps. The firing of the next shot has to wait until components have returned to ambient

[3] A. Giesen, H. Hugel, A. Voss, K. Wittig, U. Brauch, and H. Opower, 1994, Scalable concept for diode-pumped high-power solid-state lasers, *Appl. Phys. B* 58(5): 363-372.

temperature. This is also true of ICF drivers, but the OMEGA system does water-cool the lamps and thus can run at a higher shot rate than similar systems.[4]

The challenge in more aggressive cooling of high-energy lasers arises from the large volumes of laser material needed for high-energy operation. Figure B3.3 and Figure B3.4 show two approaches used for large-aperture designs, involving flowing a coolant between a series of relatively thin disks of laser material. The first employs rapid flow of helium gas through the disks, which was demonstrated at LLNL with the Mercury laser[5] and is being used in the LLNL HAPLS Ti:sapphire laser, described in more detail below. Effective operation with the gas is aided in these by the lower heat loads from diode-laser pumping. Figure B3.4 shows a design being tested by National Energetics, where liquid cooling (fluorinert) of the disks is employed in flashlamp-pumped systems and allows operation, for 250-J-class amplifiers, at rates of at least 0.1 Hz. Similar thin-disk designs can be used with Ti:sapphire lasers, (see HAPLS, below) although liquid cooling is problematic due to the added spectral dispersion.

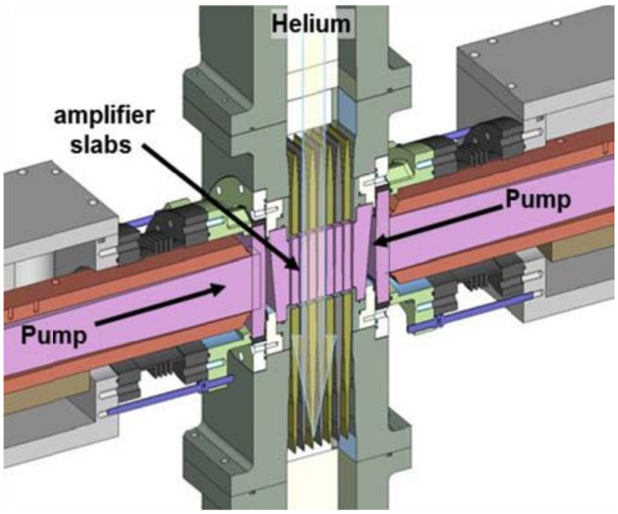


**FIGURE B3.3** Gas-cooled disks design implemented by LLNL in Mercury and HAPLS lasers. SOURCE: A. Erlandson, 2014, "High Energy DPSSL Technology," presented at the ELI-HiLASE Summer School, Aug. 24-29, Prague, Czech Republic, http://www.eli-beams.eu/wp-content/uploads/2013/11/Erlandson_high_energy_class_dpssl_technology.pdf.

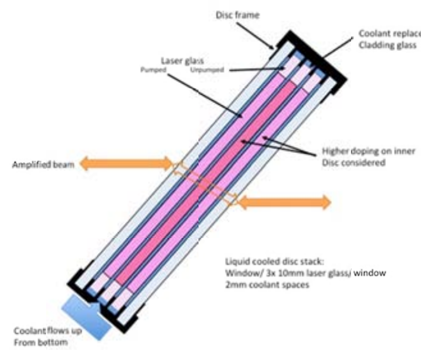


**FIGURE B3.4** Liquid-cooled disks design under investigation by National Energetics. SOURCE: Courtesy of National Energetics, http://nationalenergetics.com/technology/disc-amplifiers/.

With future PW-level systems planned for operation at higher powers, considerations of thermal issues must also be applied to other elements of the system. With OPCPAs, in theory, there should be no heat deposited in the media, but in reality all materials have some level of optical absorption in the bulk of the crystal, as well as absorption due to defects in the surface polish and in the dielectric coatings. The issue is of concern since nonlinear materials in general do not have good thermo-mechanical properties. As an example, the thermal shock parameters of KD*P and BBO are 145 and 39 W/m, respectively, comparable

[4] R. McCrory and C. Verdon, "Collaboration Ignites Laser Advances," Lawrence Livermore National Laboratory, June 1999, https://str.llnl.gov/str/Verdon.html.

[5] A. Erlandson, 2014, "High Energy DPSSL Technology," presented at the ELI-HiLASE Summer School, Aug. 24-29, Prague, Czech Republic, http://www.eli-beams.eu/wp content/uploads/2013/11/Erlandson_high_energy_class_dpssl_technology.pdf.

to laser glasses. Likely some form of gas-based cooling systems similar to that of Figure B3.3 will be needed for high-average-power, high-energy OPCPAs.

Another area of concern for PW-class systems in the future is thermal limits to compression gratings. Present gratings employ metallic coatings, which have some level of absorptive losses. All-dielectric-coating gratings can be made but are challenged in operating over a wide enough bandwidth to compress 30-fs and shorter pulses. Research in this area, applied for example to the HAPLS system described below, is ongoing and proprietary in nature.

### Fiber Geometry

One of the most significant recent developments in solid-state lasers has been the scaling in average power of fiber-geometry lasers, simply called fiber lasers. In general, fiber lasers involve an optical fiber that has a core doped with rare earths. The latter can be optically pumped to produce optical gain and thus laser action. The vast majority of fiber lasers employ silica glass as the major constituent of the fiber, with non-laser dopants such as Ge, Al, and F used to modify the index of the glass and create the index waveguide structures needed for light guiding. With proper control of the index structure in the fiber, one can constrain the beam properties of the fiber laser to a single, diffraction-limited mode, an important advantage for the fiber geometry. Two key developments have enabled power scaling of single-mode fiber lasers.

One is the concept of cladding pumping that allows highly divergent, multimode pump light to be coupled into the single-mode, doped core of an optical fiber.[6] This allows the fiber laser to operate as a brightness converter, specifically taking the multi-mode power from a multitude of diode lasers and converting it into single-mode power. For fiber lasers doped with the rare-earth Yb, the raw optical power conversion from pump to output power can approach 90 percent.

Fibers are essentially rod-geometry solid-state lasers, where the limit on power output (independent of the rod diameter) is given by the fracture-limited heating power per unit length (W/l). This quantity is directly proportional to the thermal shock parameter of equation A.4. For fused silica, which has a very low thermal expansion coefficient, the thermal shock parameter (1,450 W/m) is similar to materials such as YAG, but more importantly, for typical cladding-pumped fiber lasers the length of material used in a laser is in the 1-20-m range, about 1,000x that of typical rod lasers. Thermal fracture has not been an issue for conventional, silica-based fiber lasers.

The second development, mentioned above, has been the steady and significant improvement in the power available from diode lasers. Related to fiber lasers, an associated advance has been in finding ways to efficiently couple the outputs of many diodes into a single multimode fiber that in turn couples light into the cladding of the fiber laser. Present technology has allowed construction of directly diode-pumped fiber lasers that operate with a single fiber and a single mode (i.e., diffraction limited) at multi-kW power levels. Hybrid designs have also been developed that use a collection of lower-power fiber lasers to cladding pump the core of one fiber, and this has allowed further scaling of a single-mode fiber laser to the 10-kW level.[7]

Until recently, thermo-optic distortion of the core region of the fiber from temperature gradients created by laser operation has been small compared to the built-in refractive index structure in the fiber. Thus the beam properties of fiber lasers have been nearly power-independent. Advances in high-power diodes, and also in development of fibers with large single-mode core diameters, have shown that thermal effects can appear as a limit to single-mode power, especially when single-mode core diameters exceed

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[6] E. Snitzer, H. Po, F. Hakimi, R. Tumminelli, and B. C. McCollum, 1988, Double clad, offset core Nd fiber laser, in *Optical Fiber Sensors*, Vol. 2, Optical Society of America, New Orleans.

[7] V. Gapontsev, V. Fomin, and A. Yusim, 2009, Recent progress in scaling high-power fiber lasers at IPG photonics, in *22nd Annual Solid State and Diode Laser Technology Review*, Newton, Mass, July.

about 15 µm. This effect, thermally induced mode instability (TMI),[8] has become the most important limitation to the cw power available from single-mode fiber lasers. The commercial 10-kW fiber laser cited above mitigates TMI through the use of a small difference in pump and laser wavelengths, which minimizes fiber heating.

While the overall electrical efficiencies, high average power, and high beam quality of fiber lasers make them unique as solid-state lasers, the small diameter of the single-mode active core (on the order of 10-100 µm) limits the pulsed, peak-power outputs of individual fiber lasers. The ultimate limit is optical damage, but before that is reached, a variety of unwanted nonlinear optical effects distort the temporal and spectral nature of the pulse. In addition, although the gain-bandwidth of the most favorable fiber laser to date, Yb-doped silica glass (Yb:fiber), could support nominal 20-fs pulses, fiber lasers operate with high gain and are thus subject to substantial gain-narrowing, with the result that amplified pulsewidths for Yb:fibers are typically in the 200-fs and higher range. To date, the highest peak power output from a CPA-technology, single-Yb:fiber system is 3.8 GW (2.2 mJ in 415 fs),[9] achieved through use of an extraordinary fiber having a 108- µm core diameter. In terms of average power, the highest achieved from a single-fiber CPA system is 830 W, for 640-ps pulses at a 78-MHz rate, or 12 MW of peak power.[10] As we discuss in the next section, further energy scaling of ultrafast fiber lasers is possible through beam-combining techniques.

## Beam Combination

When a limit to higher power output (or a shorter pulsewidth) is reached for a certain source technology, one can employ the use of multiple sources to exceed the limit. One extreme example is the NIF system at LLNL, which employs 192 different beams from Nd:glass lasers to irradiate the target. In this case, obtaining both a high energy and a uniform illumination are achieved by the combination of beams. However, to obtain higher focused intensities, this type of "incoherent" combination does not lead to higher beam brightness, i.e., the ability to put more power into a small focal area. For that, multiple sources must be coherently combined, either spatially to get higher brightness or spectrally to produce shorter pulses and hence higher peak powers.

Coherent combining of cw lasers requires precise control over the relative phases of the lasers so that the rapidly varying electric fields of the lasers all peak at the same time as well as overlap in space. This requires lasers to have a stable, single-frequency output as well as a spatial output with a well-defined phase-front and a well-defined polarization. Typical coherently combined lasers might consist of one low-power laser as a stable, single-frequency source, which provides input to an array of amplifiers, the outputs of which are then combined. Given the need to maintain the correct phase relationship amongst the beams, one must hold the path length for light in each amplifier stable to a small fraction of the laser wavelength. Typically this can only be accomplished by an active, path-length control system for each beam. For a narrow-line, single-frequency source, the absolute path length for each amplifier does not have to match that of another amplifier, just the optical phases.

For coherent combining of pulsed lasers there is an added requirement. The absolute path lengths the pulses travel through the amplifiers must be matched enough so that the pulses all arrive at the same time, as well as with the same phase. Clearly, the path matching gets more challenging as the pulses get

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[8] A.V. Smith and J. J. Smith, 2011, Mode instability in high power fiber amplifiers, *Opt. Express* 19(11): 10180-10192.

[9] T. Eidam, J. Rothhardt, F. Stutzki, F. Jansen, S. Hädrich, H. Carstens, C. Jauregui, J. Limpert, and A. Tünnermann, 2011, Fiber chirped-pulse amplification system emitting 3.8 GW peak power, *Opt. Express* 19(1): 255-260.

[10] T. Eidam, S. Hanf, E. Seise, T.V. Andersen, T. Gabler, C. Wirth, T. Schreiber, et al., 2010, Femtosecond fiber CPA system emitting 830 W average output power, *Opt. Lett*. 35(2): 94-96.

shorter. For example, a 30-fs pulse has a length in free space of 9 µm, and any path difference must be a small fraction of this for effective combining.

In the area of pulsed systems, one can also perform spectral combining, where lasers centered at different wavelengths can be combined to produce a broader-bandwidth source, with a shorter pulsewidth, again if the phases of the two lasers can be synchronized to the same degree required for spatial combining.

Much of the recent work in beam combining has involved cw fiber lasers, which can be engineered with both the beam and spectral properties needed for efficient coherent combining. Reported beam-combined results include total powers of 4 kW from 8, spatially overlapped (or "tiled aperture") lasers[11] and 5 kW from 4 lasers combined with a diffractive optic into one beam, so-called "filled aperture" combining.[12] Both systems included an electronic control for the phase of each beam. In the former, feedback control for phase-locking employed the "stochastic parallel-gradient-descent" (SPGD) technique, an algorithm that seeks to maximize combined beam quality by continually dithering the phase of each laser[13] until a desired metric, such as beam quality, is reached. The latter employed the "locking of optical coherence by single-detector frequency tagging" (LOCSET) scheme where each beam has a unique high-frequency phase modulation applied to then determine the needed phase correction for the beam.[14]

In terms of PW-class, intense-laser technology, coherent spatial and/or spectral combination techniques are more challenging. The present technology of Nd:glass-driven systems has such a low pulse rate that any adaptive feedback control for phase is impractical. It is unrealistic to expect that the optical phase path would remain stable enough against environmental changes between pulses to allow optimization of the beam or spectrum. We discuss newer technologies below for high-energy lasers that will allow higher pulse rates, but it remains an open question whether they can be high enough for effective combination.

There have been active efforts to explore beam combination of ultrashort-pulsed fiber lasers, given their high electrical efficiencies, high beam-quality, and high-average-power capabilities. The latter allow operation at high enough pulse rates to enable effective feedback control of beam and/or spectral combining. However, given the mJ-level of pulse energy now available from individual fibers, the absolute numbers of fiber lasers required to reach the PW-peak-power region goes well beyond the current state of the art. That has not prevented proposal of speculative schemes that scale fiber-based systems to the PW peak-power level. In the following we briefly discuss examples of these efforts, showing systems that operate at the state of the art as well as designs that could allow scaling to large energy levels. A recent review of the subject provides more examples and details.[15]

There are two general schemes for spatial beam combining. One is similar to the approach used with cw lasers, where the outputs of multiple amplifiers working with the same input pulse are combined (common pulse). The other is unique to pulsed systems, where multiple pulses, separated in time, are combined into one pulse (divided pulses). The schemes can be combined for energy scaling, and we show how this had led to the highest peak power (35 GW) to date for a fiber-based system with eight fibers.[16] We provide examples of these approaches below.

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[11] C.X. Yu, S. J. Augst, S. M. Redmond, K. C. Goldizen, D. V. Murphy, A. Sanchez, and T. Y. Fan, 2011, Coherent combining of a 4 kW, eight-element fiber amplifier array, *Opt. Lett.* 36(14): 2686-2688.

[12] A. Flores, I. Dajani, R. Holten, T. Ehrenreich, and B. Anderson, 2016, Multi-kilowatt diffractive coherent combining of pseudorandom-modulated fiber amplifiers, *Opt. Eng*. 55(9): 096101.

[13] M.A. Vorontsov and V. P. Sivokon, 1998, Stochastic parallel-gradient-descent technique for high-resolution wave-front phase-distortion correction, *J. Opt. Soc. Am. A* 15(10): 2745-2758.

[14] T.M. Shay, 2006, Theory of electronically phased coherent beam combination without a reference beam, *Optics Express* 14(25): 12188-12195.

[15] M. Hanna, M. Guichard, Y. Zaouter, D. N. Papadopoulos, F. Druon, and P. Georges, 2016, Coherent combination of ultrafast fiber amplifiers, *J. Phys. B: At. Mol. Opt. Phys*. 49(6): 062004.

[16] Marco Kienel et al., "12 MJ KW-Class Ultrafast Fiber Laser System Using Multidimensional Coherent Pulse Addition," *Optics Letters* 41, no. 14 (July 15, 2016): 3343–46, doi:10.1364/OL.41.003343.

In this section we also discuss the use of an enhancement cavity at the output of a system to increase the peak power, which could be considered a form of beam combining.

**Spatial—Common Pulse**

22 GW of peak power has been obtained through the coherent combination of four very-large mode-area (80 µm) Yb:fiber lasers.[17] An optical schematic of the system, Figure B3.5 shows a CPA system, where a common, low-energy, stretched pulse is amplified, spectrally optimized by a spatial-light-modulator-based "Pulse-Shaper" (also seen in Figure B1.7) and split into four beams through polarization-dependent, 50/50 beam splitters. Successive combining, two beams at a time, again with polarization-dependent optics, leads to a common beam that is then compressed. The phase-control scheme, based on a technique developed by Hänsch and Couillaud,[18] senses the combined polarization of the two beams and adjusts the relative phases to maximize the linearly polarized combined power. The system construction took care to match the pulse propagation time for the four beam paths. Measurement of the compressed pulse indicated a 200-fs pulsewidth, with about 16 percent of the total pulse energy outside of the main pulse. The energy contained in the 200-fs pulse was about 5.7 mJ, and, at a 40-kHz rate, the average output power was 230 W.

It is important to recognize an important effect in this and other fiber-laser-based ultrafast systems. Despite the CPA technique, which for this system resulted in 2-ns-duration pulses in the amplifiers, the nonlinear effect of the high peak power on the refractive index and hence the optical phase in the final amplifiers (self-phase modulation, or SPM) was significant, about 5 radians of shift, and thus the phase delay through the amplifiers depended strongly on the pulse peak power. This coupling of power and phase represents an added challenge to control of the beam-combining effectiveness, mapping intensity fluctuations to phase fluctuations and adding to the other environmental perturbations on the phase of the beams to be combined.

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[17] A. Klenke, S. Hädrich, T. Eidam, J. Rothhardt, M. Kienel, S. Demmler, T. Gottschall, J. Limpert, and A. Tünnermann, 2014, 22 GW peak-power fiber chirped-pulse-amplification system, *Opt. Lett.* 39(24): 6875-6878.

[18] T.W. Hänsch and B. Couillaud, 1980, Laser frequency stabilization by polarization spectroscopy of a reflecting reference cavit, *Opt.Commun*. 35(3): 441-444.

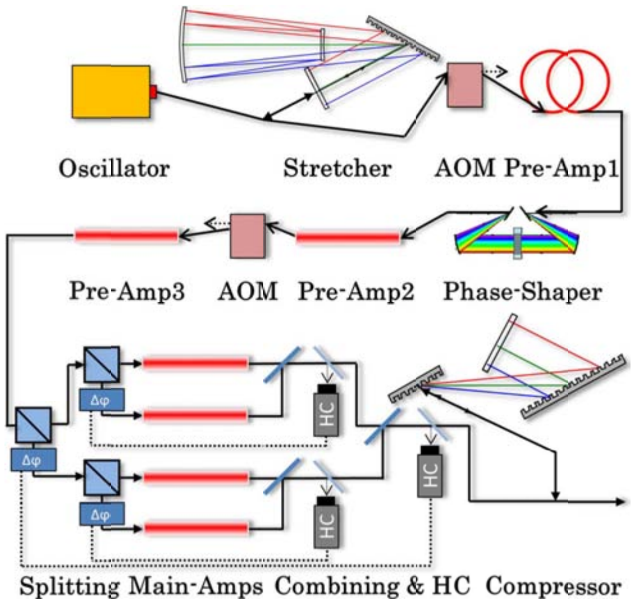


**FIGURE B3.5** Optical schematic of beam-combined, fiber-laser-based, 22-GW peak power source. The AOMs are acousto-optic modulator, used to select pulses produced by the oscillator to reduce the pulse rate from 64 MHz to 40 kHz. HC refers to the Hänsch-Couillaud phase-control system. SOURCE: A. Klenke, S. Hädrich, T. Eidam, J. Rothhardt, M. Kienel, S. Demmler, T. Gottschall, J. Limpert, and A. Tünnermann, 2014, 22 GW peak-power fiber chirped-pulse-amplification system, *Opt. Lett*. 39(24): 6875-6878..

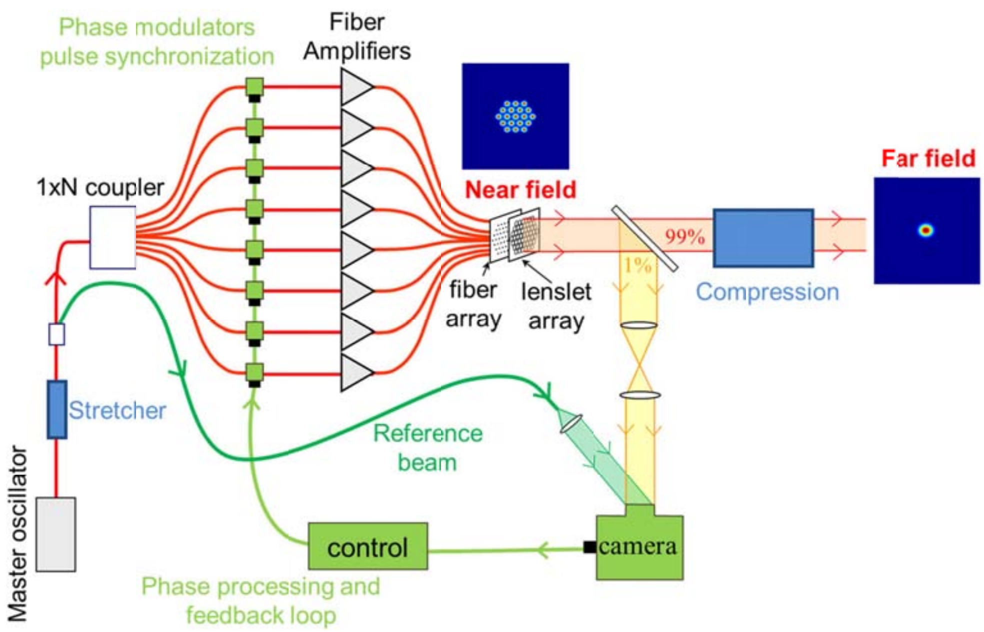


**FIGURE B3.6** Optical schematic of beam-combined, XCAN system design. SOURCE: L. Daniault, S. Bellanger, J. Le Dortz, J. Bourderionnet, ´E. Lallier, C. Larat, M. Antier-Murge, J.-C. Chanteloup A. Brignon, C. Simon-Boisson, and G. Mourou, 2015, XCAN – A coherent amplification network of femtosecond fiber chirped-pulse amplifiers, *Eur. Phys. J. Special Topics* 224(13): 2609-2613.

Another combining scheme (XCAN), developed in collaboration between the Ecole Polytechnique and Thales in France, claims to be scalable to large numbers of fiber amplifiers.[19] Figure B3.6 presents a schematic of the system, which remains at an early stage of actual implementation. The key features of the design are CPA, with pulses stretched to the several-ns length, a “tiled aperture” beam combination, and a camera-based sensor that samples each fiber output before compression, interfered with a common beam derived from the input to the fiber array. The image presented to the camera is a set of spatially distinct interference patterns that can be processed to derive the phase control for each fiber amplifier. The present plan seeks a short-term demonstration of a 61-fiber system with pulse energy of 10 mJ, with 50-kHz pulse rate, 350-fs pulses.

**Spatial—Divided Pulse**

One approach of the divided pulse amplification (DPA) scheme is to split a pulse into a series of replicas in time, not in space, and send them through a common amplifier. After that, one has to implement an inverse process to recombine the replicas into a single pulse. Here there is excellent spatial overlap, and the phase control shifts to that needed to ensure that the pulses recombine in time with the same phase. DPA can be considered as a variant of CPA in that the peak power of the split pulses is reduced, in this case by the number of replicas, and also that the maximum average power of the amplifier is not increased. The major challenge in DPA designs is in gain saturation in the common amplifier, where the gain for each subsequent pulse is smaller and thus the pulses do not match in amplitude (and for large saturation also shape) when they are recombined. This lowers the efficiency of the combination process. To avoid this and run the amplifier in a mode with minimal gain saturation unfortunately lowers the total energy extracted from the amplifier; for fibers, this reduces the overall electrical efficiency. The DPA technique has been employed for ps-duration pulses, where temporal splitting is relatively simple, and can be done, for example, with a set of birefringent crystals, taking advantage of the stable optical path difference in the crystal for orthogonal polarizations.[20] In the example cited, 32 pulse replicas of 2.2-ps pulses were generated and amplified by Yb:fibers, and the design employed the same crystals to both split and recombine the pulses.

For high-energy scaling one needs to employs ns-duration chirped pulses, and here generation of replicas requires free-space optics, with m-level paths to produce enough delay between pulses. In one system separate splitting and combining optics were used to produce 4 pulses, with path-length control provided by a LOCSET control system, and individual control of pulse amplitudes in the optics provided some compensation for gain saturation in the Yb:fiber amplifier.[21] The system generated 380-fs-duration compressed pulses of 1.25 mJ (2.9 GW) at a 30-kHz rate, with a recombination efficiency of 75 percent. A more sophisticated DPA scheme has been proposed but only demonstrated at low powers.[22] In this design, the train of equally time-spaced pulses, to be amplified and then combined, is generated by an electronic system that controls both the amplitude and phase of each pulse. After amplification, the pulses are combined through use of mirror-based interferometers, specifically, a Gires-Tournois (GT) design. A

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[19] L. Daniault, S. Bellanger, J. Le Dortz, J. Bourderionnet, ´E. Lallier, C. Larat, M. Antier-Murge, J.-C. Chanteloup, A. Brignon, C. Simon-Boisson, and G. Mourou, 2015, XCAN – A coherent amplification network of femtosecond fiber chirped-pulse amplifiers, *Eur. Phys. J. Special Topics* 224(13): 2609-2613.

[20] L.J. Kong, L. M. Zhao, S. Lefrancois, D. G. Ouzounov, C. X. Yang, and F. W. Wise, 2012, Generation of megawatt peak power picosecond pulses from a divided-pulse fiber amplifier, *Opt. Lett*. 37: 253.

[21] M. Kienel, A. Klenke, T. Eidam, S. Hädrich, J. Limpert, and A. Tünnermann, 2014, Energy scaling of femtosecond amplifiers using actively controlled divided-pulse amplification, *Opt. Lett*. 39: 1049.

[22] T. Zhou, J. Ruppe, C. Zhu, I-Ning Hu, J. Nees, and A. Galvanauskas, 2015, Coherent pulse stacking amplification using low-finesse Gires-Tournois interferometers, *Opt. Exp*. 23 7442; J. Ruppe, M. Sheikhsofla, S. Chen, H. Pei, J. Nees, R. Wilcox, W. Leemans, and A. Galvanauskas, 2016, “Progress in Coherent Pulse Stacking: A Pathway Toward Compact kHz Repetition Rate LPA Drivers,” 17th Advanced Accelerator Concepts Workshop, Aug. 1-5, Gaylord National Resort, Baltimore. https://indico.syntek.org/event/4/session/15/contribution/234.

set of pulses is injected into one interferometer, which has a round-trip time exactly equal to the pulse spacing. Pulse energies add together, and then a final (extraction) pulse is injected with a different phase but the same energy as that stored in the cavity and acts, through coherent interference, to couple all of the stored energy out in a single pulse. Through the combination of N of these interferometers, as shown in Figure B3.7, it is possible to stack about 2N pulses together, with the understanding that the extraction pulse increases in energy as it passes through the N interferometers. By controlling the individual interferometer input/output mirror reflectivities, it is possible to combine equal-amplitude pulses by control of just the pulse phase, simplifying the design.[23] Another scheme, in Figure B3.8, combines two sets of N interferometers, with the second set having a round-trip time 2N times as long as the first. This "multiplexing" scheme can combine about $(2N)^2$ pulses. To date, researchers[24] have stacked nine low-energy pulses by four cascaded GT interferometers with a pulse-energy increase of 7, and 16 dB of contrast between the main pulse and other pulses. In a multiplex design of four interferometers and one long-path interferometer, the same group combined 27 pulses.

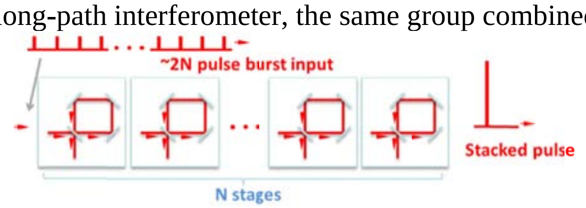


FIGURE B3.7 Pulse-combining design based on sequential pulse stacking by GT interferometers. SOURCE: J. Ruppe, M. Sheikhsofla, S. Chen, H. Pei, J. Nees, R. Wilcox, W. Leemans, and A. Galvanauskas, 2016, "Progress in Coherent Pulse Stacking: A Pathway Toward Compact kHz Repetition Rate LPA Drivers," 17th Advanced Accelerator Concepts Workshop, Aug. 1-5, Gaylord National Resort, Baltimore. https://indico.syntek.org/event/4/session/15/contribution/234..

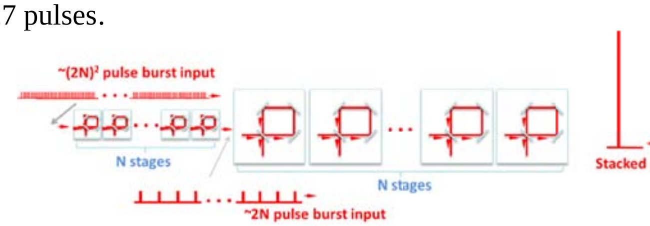


FIGURE B3.8 Pulse-combining design based on sequential pulse stacking and multiplexing by GT interferometers. SOURCE: J. Ruppe, M. Sheikhsofla, S. Chen, H. Pei, J. Nees, R. Wilcox, W. Leemans, and A. Galvanauskas, 2016, "Progress in Coherent Pulse Stacking: A Pathway Toward Compact kHz Repetition Rate LPA Drivers," 17th Advanced Accelerator Concepts Workshop, Aug. 1-5, Gaylord National Resort, Baltimore. https://indico.syntek.org/event/4/session/15/contribution/234.

This stacking design promises scaling to a large number of pulses and allows control of gain saturation in the amplifier through individual control of the pulse amplitude sent into the amplifier. A major challenge for future high-energy applications is in obtaining a sufficiently high pulse-contrast ratio.

**Spatial—Combined Approaches**

The highest pulse energy to date (12 mJ, before compression) from a fiber-laser-based, femtosecond-class source has been obtained through a combination of spatial and temporal beam combining.[25] Figure B3.9 shows a schematic of the system, whose delay lines splits the 1.3-ns stretched pulse into 4 pulses, each of which is adjusted to correct for gain saturation in the final amplifiers. As with the system in Figure B3.5, polarization optics spatially split the beam into 8 channels, which are then spatially recombined with polarization-based optics and then temporally combined with optical delay lines. For phase control the system combines HC and LOCSET control. The combined average power

[23] J. Ruppe, et al., 2016, "Progress in Coherent Pulse Stacking."
[24] J. Ruppe, et al., 2016, "Progress in Coherent Pulse Stacking."
[25] M. Kienel, M. Muller, A. Klenke, J. Limpert, and A. Tünnermann, 2016, 12 mJ kW-class ultrafast fiber laser system using multidimensional coherent pulse addition, *Opt. Lett*. 41(14): 3343-3346.

was 700 W and the estimated peak power after compression was 35 GW in a 262-fs pulse, to date the highest peak power from a fiber-based source.

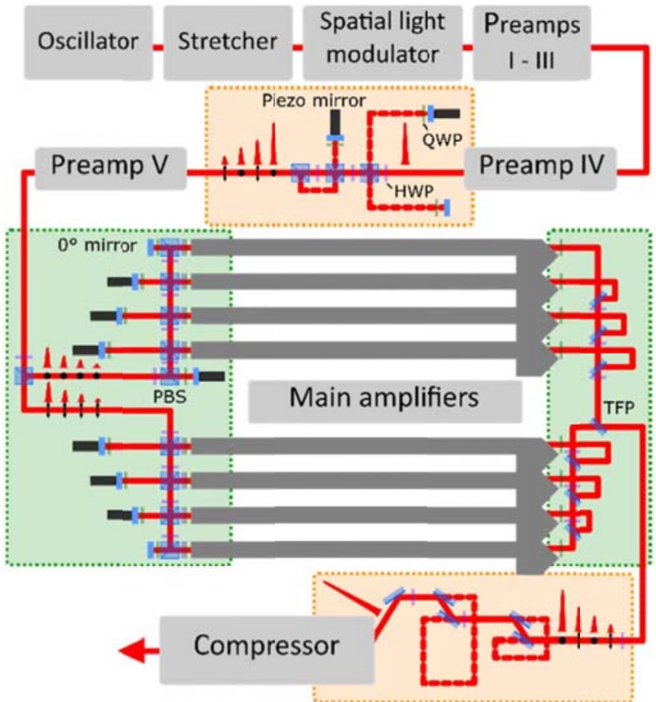


**FIGURE B3.9** Optical schematic of CPA system combining both spatial and temporal beam combining.

**Spectral**

Spectral beam combining facilitates generation of shorter pulses than possible from a single type of source, whether a laser medium or an OPA. As with spatial combining, precision phase control of the combined sources is needed to generate a stable and reproducible pulse. When combined with high-energy amplification, the technique promises generation of PW-class peak powers for the lower pulse energies.

In pioneering low-energy work,[26] pulses from a broad bandwidth Ti:sapphire mode-locked laser acted as seed sources for two OPCPAs. One, pumped by a doubled Nd:YLF laser at 523 nm, provided amplification centered around 870 nm for input directly from the seed source. The other, pumped by the same laser at 1,047 nm, amplified a 2,150-nm-centered signal derived from difference-frequency generation with the Ti:sapphire pulse spectrum. When outputs of the two OPCPAs were coherently combined, they generated a complex pulse with an estimated duration of 0.8 cycles, centered at 1,260 nm, or approximately 3.3 fs in duration. A balanced optical cross correlator (BOC), the optical equivalent of a balanced microwave phase detector,[27] provides the feedback signal needed to maintain a stable phase relationship between the pulses.

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[26] S.W. Huang, G. Cirmi, J. Moses, K-H. Hong, S. Bhardwaj, J. R. Birge, L-J. Chen, I. V. Kabakova, E. Li, B. J. Eggleton, G. Cerullo and F. X. Kartner, 2012, Optical waveform synthesizer and its application to high-harmonic generation, *J. Phys. B: At. Mol. Opt. Phys*. 45: 074009.

[27] T.R. Schibli, J. Kim, O. Kuzucu, J. T. Gopinath, S. N. Tandon, G. S. Petrich, L. A. Kolodziejski, J. G. Fujimoto, E. P. Ippen, and F. X. Kaertner, 2003, Attosecond active synchronization of passively mode-locked lasers by balanced cross correlation, *Opt. Lett*. 28(11): 947-949.

A more recent and ambitious attempt at spectral beam combining has been ongoing at the Max Planck Institute of Quantum Optics (MPQ) in Garching, Germany. An example of this concept,[28] in Figure B3.10, as part of "Third-generation femtosecond technology," makes use of three OPCPAs pumped by the fundamental, second, and third harmonics of a Yb:YAG laser system. They are seeded by a three-octave spanning seed source based on a high-power, Yb:YAG mode-locked laser combined with a variety of nonlinear pulse compression and spectral broadening techniques to produce a phase-coherent pulse with a spectrum from 450-2,700 nm. The three OPCPAs each amplify a different portion of this spectrum, and can, with proper control of phasing, be (theoretically) combined in output to generate pulses as short as 1.7 fs. The OPCPA pumps are derived from high-average-power, ps-duration thin-disk sources, developed initially for applications to industrial materials processing and could allow kHz-rates for pulses. At present, the efforts at MPQ are in the development phase to turn the concepts in Figure B3.10 into a working reality.

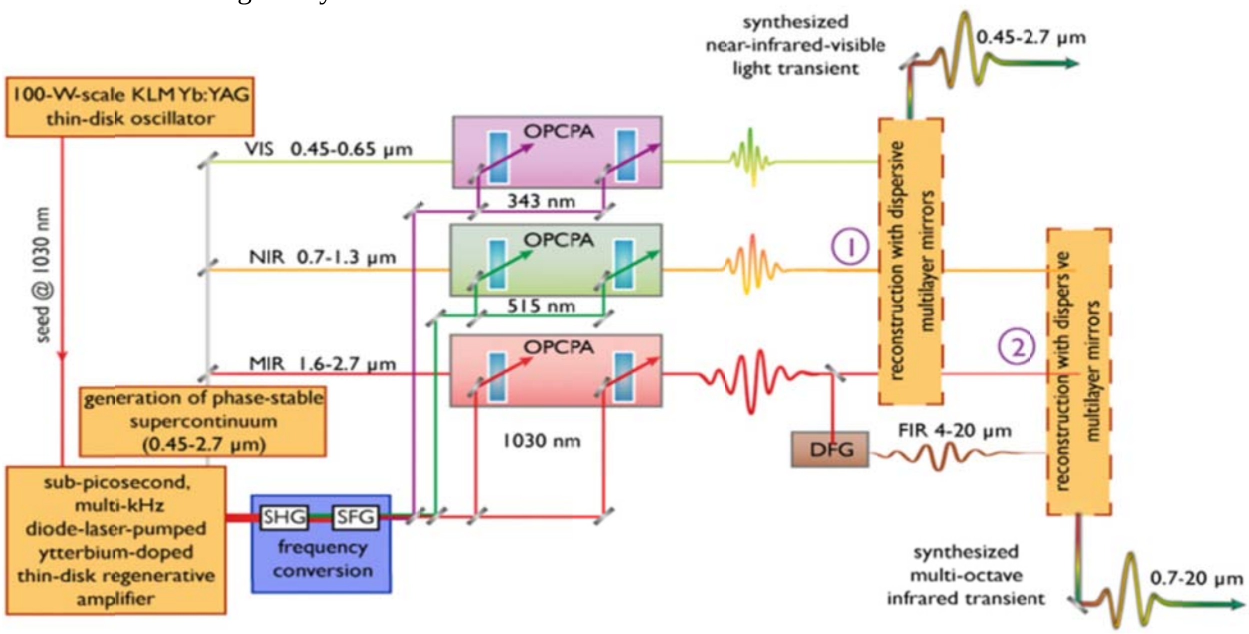


**FIGURE B3.10** Optical design of "Third generation" femtosecond source. SOURCE: H. Fattahi, H. Barros, M. Gorjan, T. Nubbemeyer, B. Alsaif, C. Teisset, M. Schultze, et al., 2014, Third-generation femtosecond technology, *Optica* 1(1): 45-63.

With regard to fiber lasers, the Yb:fiber lasers, due to gain-narrowing, operate with CPA pulsewidths at least order-of-magnitude higher than their gain linewidths could support. Dividing the input pulse spectrum into several spectral regions can allow Yb:fiber lasers to produce shorter pulses. In one low-power demonstration,[29] a broadband input source was split into two spectral bands, which peaked at 1,026 and 1,040 nm, and each was input to a Yb:fiber CPA and then combined, with phase control on one beam provided to lock the phases. Here the interference between the two beams provided a sensing signal through high-frequency modulation of the phase. The combined pulsewidth was 130 fs.

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[28] H. Fattahi, H. Barros, M. Gorjan, T. Nubbemeyer, B. Alsaif, C. Teisset, M. Schultze, et al., 2014, Third-generation femtosecond technology, *Optica* 1(1): 45-63.

[29] F. Guichard, M. Hanna, L. Lombard, Y. Zaouter, C. Hönninger, F. Morin, F. Druon, E. Mottay, and P. Georges, 2013, Two-channel pulse synthesis to overcome gain narrowing in femtosecond fiber amplifiers, *Opt. Lett*. 38(24): 5430-5433.

**External Cavity Peak Power Enhancement**

Pulses repetitively injected into an external, low-loss resonator, if synchronized with the resonator round-trip time, can build up in peak power through additive combination, or "pulse stacking," which can be viewed as a variation on the technique of divided pulse amplification. For fiber lasers, pulse stacking allows the device to operate with relatively low-energy pulses at a high pulse rate—a favorable operating condition for this technology. The key to extraction of the enhanced-power pulse for use outside of the resonator is the insertion of a fast, low-loss optical switch inside the resonator that diverts the pulse out in a time short compared to the cavity round-trip time. A recent theoretical design[30] postulated a stacking of 666 pulses to enable scaling of one spatially combined, 16-channel CPA (0.18 mJ per pulse per amplifier) running at a 10 MHz pulse rate to an energy of 1.3 J/pulse at 15 kHz. With compression of the resultant pulse to 300 fs, the peak power could be 3 TW. The key technology to be developed is the required fast and low-loss optical switch inside the resonator that could handle such a high pulse energy/power.

**Pulse Compression**

A variety of pulse-compression techniques are under investigation, particularly for fiber lasers, which, even with CPA techniques, are challenged to produce pulses shorter than 100 fs. Many of these compression schemes, employing solid-core fibers, gas-filled hollow-core photonic-crystal fibers or gas-filled capillary tubes, involve a nonlinear process, such as self-phase-modulation, to add additional bandwidth and frequency chirp to the pulse, combined with spectral dispersion that compresses the pulse to a smaller pulsewidth than at the input. All do lead to some loss of pulse energy. In general, these schemes do not have the aperture needed to reach or even approach the PW regime, with the exception of the thin-film compressor we reference below. We describe several potentially large-aperture techniques that are under deployment, development, or consideration.

**Tiled Gratings**

The desire to further scale the energy of intense-laser sources creates a challenge for fabrication of the large-area gratings (e.g., Figure 2.2) needed to avoid optical damage in the grating-based compressor stages of CPA systems. One approach to reach larger energies is to use multiple (tiled) gratings, essentially a form of coherent spatial beam combination. The technique requires the same level of alignment, path-length, and phase control applied to coherent beam-combining. In this case the control requirements are somewhat easier, as one does not have to contend with the large path lengths and environmental changes present in amplifier systems. In principle, the feedback system control system can function effectively even with low-pulse-rate sources. Figure B3.11 shows the mechanical design of one three-grating tiled compressor system[31] that is equivalent, in theory, to a 1.41-m aperture grating. Two of the gratings have a linear position control as well as tip, tilt, and rotation controls that assemblers can adjust, using laser-based, interferometic measurements to achieve suitable alignment of all three gratings.

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[30] S. Breitkopf, T. Eidam, A. Klenke, L. von Grafenstein, H. Carstens, S. Holzberger, E. Fill, et al., 2014, A concept for multiterawatt fibre lasers based on coherent pulse stacking in passive cavities, *Light: Science & Applications* 3: e211.

[31] J. Qiao, A. Kalb, M. J. Guardalben, G. King, D. Canning, and J. H. Kelly, 2007, Large-aperture grating tiling by interferometry for petawatt chirped-pulse–amplification systems, *Opt. Exp.* 23(15): 9562-9574.

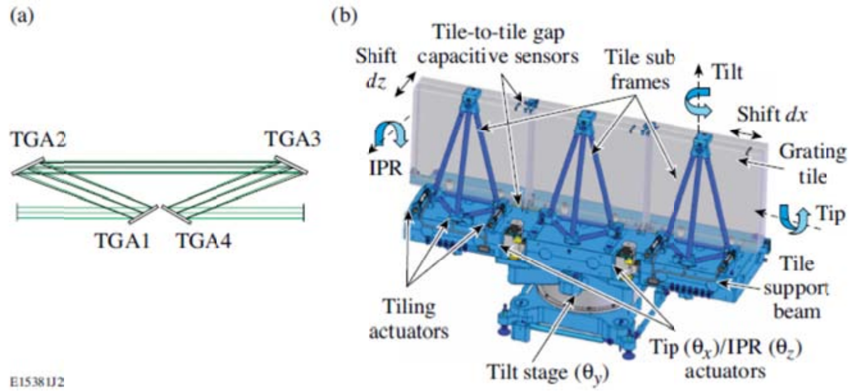


**FIGURE B3.11** Mechanical design of tiled-grating system for three 0.47-m × 0.43-m gratings, used with OMEGA-EP system at the Laboratory for Laser Energetics. SOURCE: J. Qiao, A. Kalb, M. J. Guardalben, G. King, D. Canning, and J. H. Kelly, 2007, Large-aperture grating tiling by interferometry for petawatt chirped-pulse–amplification systems, *Opt. Exp*. 23(15): 9562-9574.

**Raman Compressors**

Plasma-based compressors were proposed[32] in 1999 as an alternative to gratings for pulse compression and as a means to reach multi-MJ, exawatt ($10^{18}$ W) pulses needed for applications such as fast-igniter fusion. A plasma is gas-like state of matter consisting of free electrons and an equal number of positively charged ions, which can be sustained by applying a suitable electric field to a cell containing a gas. In principle, plasmas can survive source intensities higher than solid materials, particularly gratings. The most promising plasma-based compressor scheme uses stimulated plasma Raman scattering, which is a type of parametric process similar to OPAs. Here the interaction involved is with light and longitudinal electronic oscillations in the plasma. The oscillations arise from the restoring force between ions and electrons when the incoming light acts to separate the equilibrium locations of electrons and ions and create spatial regions that have a net charge. In the Raman process, light at a (signal) frequency equal to the difference between that of a “pump” source and that of the electron plasma oscillation frequency can be amplified.

Figure B3.12 shows a conceptual timing diagram of a plasma Raman compressor. In the top of the figure, a high-energy, long-pulse pump beam, moving from left to right in the plasma, encounters a low-energy, short-duration seed pulse at the signal frequency, moving in the opposite direction. The bottom of the figure represents a later point in time when the amplified seed pulse becomes large enough in energy to remove a large fraction of the pump energy, essentially compressing a portion of the pulse energy into roughly the same duration as that of the seed.

[32] V.M. Malkin, G. Shvets, and N. J. Fisch, 1999, Fast compression of laser beams to highly overcritical powers, *Phys. Rev. Lett*. 82: 4448.

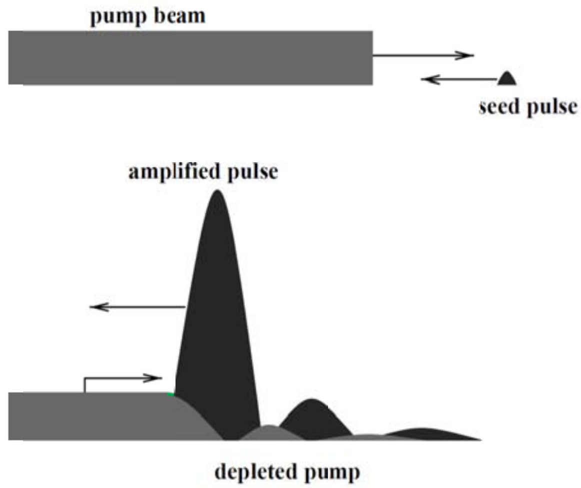


**FIGURE B3.12** Simplified timing and energy-flow diagram for Raman-based pulse compression. SOURCE: V.M. Malkin, G. Shvets, and N. J. Fisch, 1999, Fast compression of laser beams to highly overcritical powers, *Phys. Rev. Lett.* 82: 4448.

While the fundamental concept of Raman pulse compression is simple, modeling of all of the nonlinear interactions in the plasma is highly complex and computer intensive. While some work has investigated 1,000x compression of ps-duration pulses to the fs level, other studies claim that ns-duration pulses can be similarly compressed, with 60 percent efficiency, into the ps regime.[33] Since the initial proposal, extensive research efforts (primarily theoretical) have identified a variety of processes that complicate efficient compression[34] and recent models suggest that the parameter space for efficient compression is narrow.[35] The latter work proposed a system that would compress a 25-ps pulse at 800 nm to about 25 fs, with 35 percent efficiency. To date, laboratory efforts[36] have led to generation of 60 GW of peak power in a 50 fs pulse, with a 20-ps pump and low (6.4 percent) conversion efficiencies. Work at the Laboratory for Laser Energetics is planned to explore much higher energy and power regimes[37] with a high-energy, Nd:glass, ps-duration pump laser at 1,053 nm.

One area of interest for this technology is in the compression of shorter-wavelength sources, where damage-resistant gratings are not available, but here the work to date has been in theory only.

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[33] R. M. G. M. Trines, F. Fiu´za, R. Bingham, R. A. Fonseca, L. O. Silva, R. A. Cairns, and P. A. Norreys, 2011, Production of picosecond, kilojoule, and petawatt laser pulses via Raman amplification of nanosecond pulses, *Phys. Rev Lett*. 107(10): 105002.

[34] V.M. Malkin, Z. Toroker, and N. J. Fisch, 2014, Exceeding the leading spike intensity and fluence limits in backward Raman amplifiers, *Phys. Rev. E* 90(6): 063110.

[35] R. M. G. M. Trines, F. Fiúza, R. Bingham, R. A. Fonseca, L. O. Silva, R. A. Cairns, and P. A. Norreys, 2011, Simulations of efficient Raman amplification into the multipetawatt regime, *Nature Physics* 7: 87-92.

[36] J. Ren, W. Cheng, S. Li, and S. Suckewer, 2007, A new method for generating ultraintense and ultrashort laser pulses, *Nature Phys*. 3:732-736.

[37] J. Bromage, University of Rochester, "Ultra-High Intensity Laser Technology," presentation to the committee on July 14, 2016.

**Thin-Film Compressors**

A more speculative compressor, in this case to take 25-fs-duration pulses into the 2-fs regime, has been proposed[38] based on the use of thin plastic films. The system schematic in Figure B3.13 shows a two-stage design, with a 25-fs pulse passing through a 0.5-mm plastic film (Film1), where self-phase-modulation in the film adds bandwidth and frequency chirp to the pulse. The pulse is then reflected by two mirrors, with deformable surfaces to correct for beam irregularities due to both the input beam and the plastic film, and compressed by a chirped-mirror compressor (Compressor 1) to about 5 fs. The compressed pulse passes through another plastic film, 0.1 mm in thickness, and a similar mirror-compressor scheme to reduce the pulsewidth to about 2 fs.

The proposed design modeled a 27 J, 27 fs (1 PW), 800-nm Ti:sapphire laser with a uniform output beam and a beam diameter of 16 cm. The use of a plastic film allows an inexpensive means of deploying such a thin material over a large diameter. With an assumed efficiency of >50 percent, the compressor achieves a peak power increase of nearly 10x, and the design can be employed with higher-peak-power lasers through suitable area scaling.

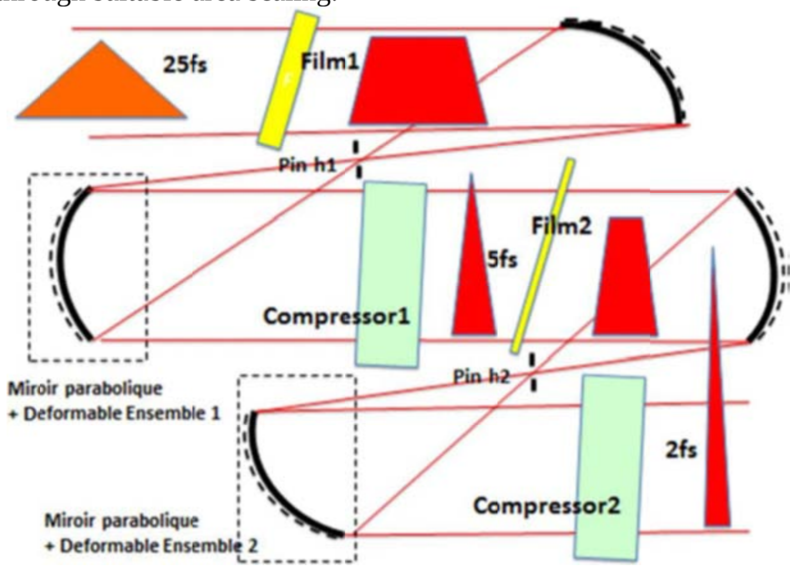


**FIGURE B3.13** *Two-stage, thin-film compressor concept to reach 2-fs pulse durations.* SOURCE: G. Mourou, S. Mironov, E. Khazanov, and A. Sergeev, 2014, Single cycle thin film compressor opening the door to Zeptosecond-Exawatt physics, *Eur. Phys. J. Spec. Top.* 223(6): 1181-1188.

[38] G. Mourou, S. Mironov, E. Khazanov, and A. Sergeev, 2014, Single cycle thin film compressor opening the door to Zeptosecond-Exawatt physics, *Eur. Phys. J. Spec. Top*. 223(6): 1181-1188.

# APPENDIX B4. SYSTEMS UNDER CONSTRUCTION OR CONSIDERATION

We organize this section by the technologies being utilized.

## Nd:glass

### Extreme Light Infrastructure Beamlines, 10 Petawatts

The ELI Beamlines facility in Prague, Czech Republic has ordered a 10-PW-power Nd:glass system, with delivery planned for the end of 2017, from National Energetics in Austin, TX, a spinout company related to the "Texas Petawatt" system described above. The technology is similar in that a mixed-glass high-energy amplifier is combined with an OPCPA front end. In contrast with the earlier system, active cooling of the Nd:glass elements, as illustrated in Figure B3.4 in Appendix 2C, is part of the design, allowing for a claimed pulse rate of one per minute.

Figure B4.1 is a functional block diagram of the system, showing the staging and details of the energetics and pulse/spectral properties, and Figure B4.2 is an optical schematic of the design. The goal is to generate 150-fs-duration pulses and > 1,500 J of compressed energy. The final amplifiers will operate with 30-cm aperture, phosphate Nd:glass slabs.

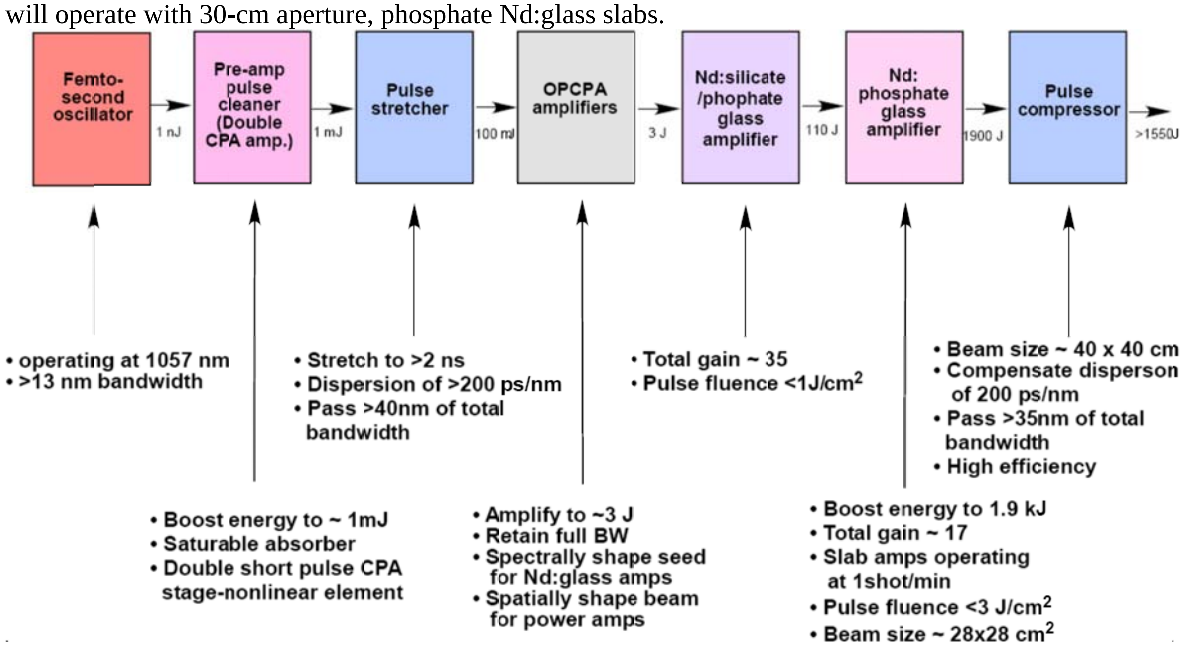


**FIGURE B4.1** Block diagram of 10-PW Nd:glass laser under construction at National Energetics. SOURCE: T. Ditmire, University of Texas at Austin, "A Path Towards an Exawatt Laser," presentation to the committee on May 10, 2016.

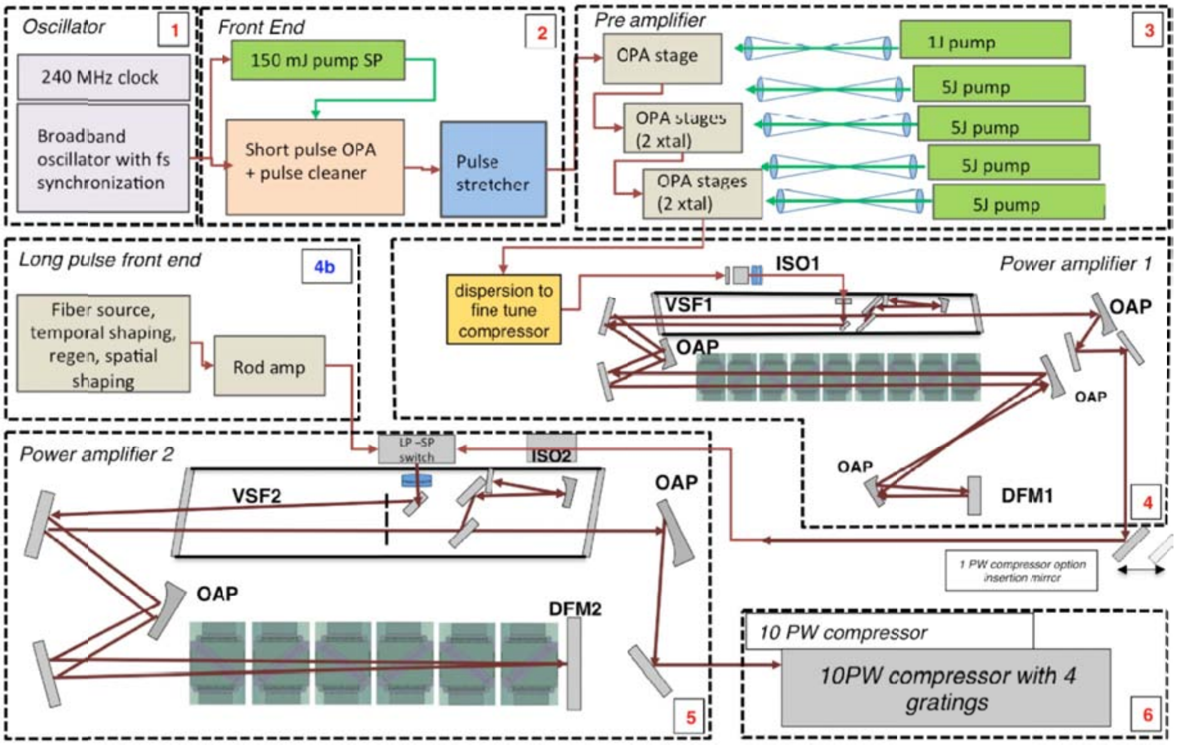


**FIGURE B4.2** Optical schematic of 10-PW Nd:glass laser under construction at National Energetics. NOTE: ISO, optical isolator; VSF, image relay (in vacuum); OAP, off-axis paraboloid mirror; DFM, deformable mirror (for beam phase correction). The Nd:glass amplifier system is comprised of 20-cm-aperture, mixed-glass stages (Power amplifier 1) and 30-cm-aperture, Nd:phosphate glass final amplifier stages (Power amplifier 2). The system includes option for 1-PW pulses derived from Power amplifier 1 as well as "long-pulse" operation from Power amplifier 2. SOURCE: T. Ditmire, University of Texas at Austin, "A Path Towards an Exawatt Laser," presentation to the committee on May 10, 2016.

As of August, 2016, the project had reached a development milestone, in manufacture and testing of one of the 20-cm-aperture, mixed-Nd:glass amplifier stages.

### Laser Ignition Fusion Energy, Lawrence Livermore National Laboratory

LLNL, in considering the future of laser-driven ICF, carried out a design study for a laser capable of driving a fusion-based electrical power plant. We provide some of the study details as they provide guidance on what could be the basis for future designs for Nd:glass lasers and OPCPA systems operating with high rates at the PW level. The designs also have been employed on a smaller scale for the pump laser used in the HAPLS Ti:sapphire laser described below.

The laser requirements for Laser Ignition Fusion Energy (LIFE) called for a megajoule-class, ns-pulse laser that would operate at a pulse rate of 16 Hz. The design concept was based on high-efficiency modules, each operating at 130 kW (8 kJ/pulse) of average power at the fundamental wavelength. As part of the study, researchers[1] did a system overall electrical efficiency trade-off among several diode-pumped solid-state media, with the results plotted in Figure B4.3. The efficiency calculations included the power consumed for cooling in systems operating below ambient temperature. The net result was that Nd:glass could operate with an efficiency comparable to

[1] A.C. Erlandson, S. M. Aceves, A. J. Bayramian, A. L. Bullington, R. J. Beach, C. D. Boley, J. A. Caird, et al., 2011, Comparison of Nd:phosphate glass, Yb:YAG and Yb:S-FAP laser beamlines for laser inertial fusion energy (LIFE), *Opt. Mat. Exp*. 1(7): 1341-1352.

crystalline media. The medium has the advantage that it has been well developed and is available in large sizes, in contrast to Yb:S-FAP and, to a lesser extent, Yb:YAG.

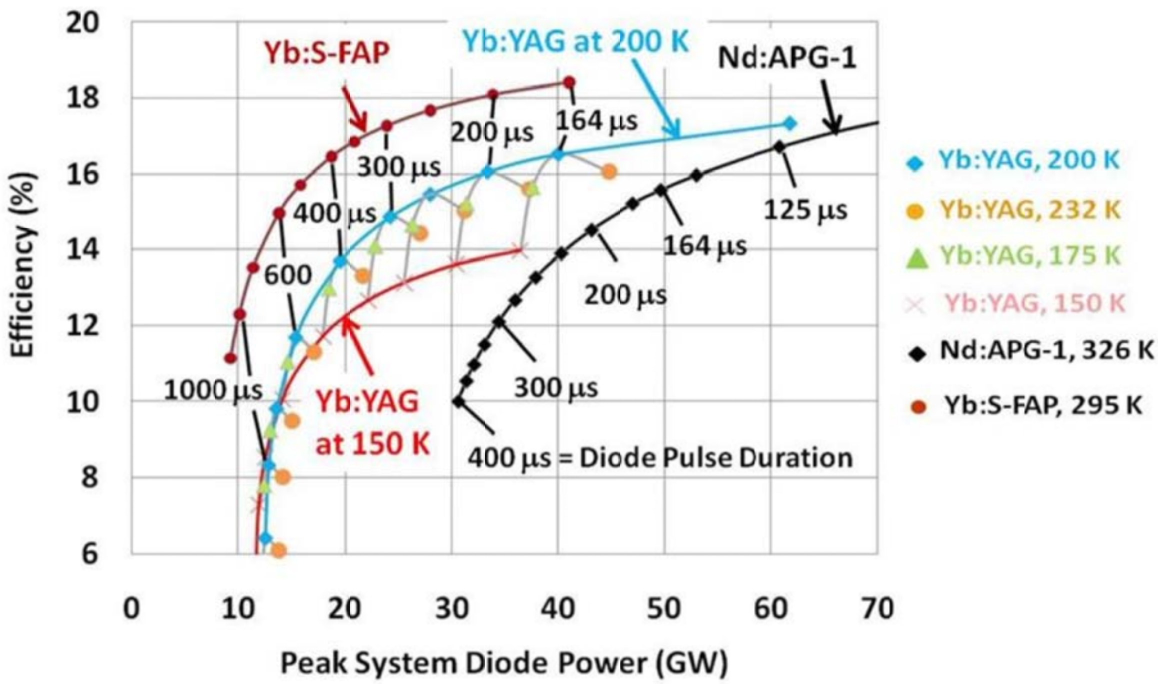


**FIGURE B4.3** Projected LIFE laser system electrical efficiency versus total diode pump peak power for different diode-pumped laser media, with different pump pulsewidths. Calculations for Yb:YAG include operation at several media temperatures. SOURCE: A.C. Erlandson, A.C., S. M. Aceves, A. J. Bayramian, A. L. Bullington, R. J. Beach, C. D. Boley, J. A. Caird, et al., 2011, Comparison of Nd:phosphate glass, Yb:YAG and Yb:S-FAP laser beamlines for laser inertial fusion energy (LIFE), *Opt. Mat. Exp*. 1(7): 1341-1352.

### Ti:sapphire

#### High-Repetition-Rate Advanced Petawatt Laser System, Extreme Light Infrastructure Beamlines

As with National Energetics, LLNL is under contract to design, build, and deliver a PW-class laser system to the ELI Beamlines facility. The High-Repetition-Rate Advanced Petawatt Laser System (HAPLS) is based on a 1-PW, Ti:sapphire laser pumped by a 10-Hz, diode-pumped Nd:glass laser, with a design building on prior work at LLNL on high-pulse-rate, high-energy diode-pumped lasers, including the LIFE design discussed above. A rendition of the system appears in Figure B4.4 and includes a Nd:glass pump laser with the capability for 200 J/pulse of fundamental energy. A key component of the system is an 800-kW pulsed, 888-nm-wavelength diode-laser array, shown in Figure B4.5, developed by Lasertel Inc. (Tucson, AZ) and driven by LLNL-developed pulse-power electronics[2] that provide 300-µs-duration pulses with 75 percent efficiency in delivering electrical power to the diodes. For some perspective, the array is claimed to be the largest peak-power diode-laser system ever developed. Four of these arrays are used, for a total maximum pump energy of 960 J. The Nd:glass slabs are cooled by the flowing He-gas design in Figure B3.3, with a similar design used for the Ti:sapphire crystals. The planned operating point for 1 PW of compressed peak power

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[2] E.S. Fulkerson, S. Telford, R. Deri, A. Bayramian, R. Lanning, E. Koh, K. Charron, and C. Haefner, 2015, Pulsed power system for the HAPLS Diode Pumped Laser System, in *Proceedings of the IEEE Pulsed Power Conference (PPC),* Austin, May 31-June 1.

(30 J in 30 fs) is 42 J of energy from the Ti:sapphire laser with 107 J of green pump energy and 140 J of fundamental pump energy. At 10 Hz the system would operate the Ti:sapphire laser at the highest average power ever attained from the material.

As of December 2016, the system had operated with the pump laser at an intermediate milestone of >100 J of fundamental energy, 75 percent conversion to the second harmonic, and operation of the Ti:sapphire source with < 30 fs pulsewidth.[3]

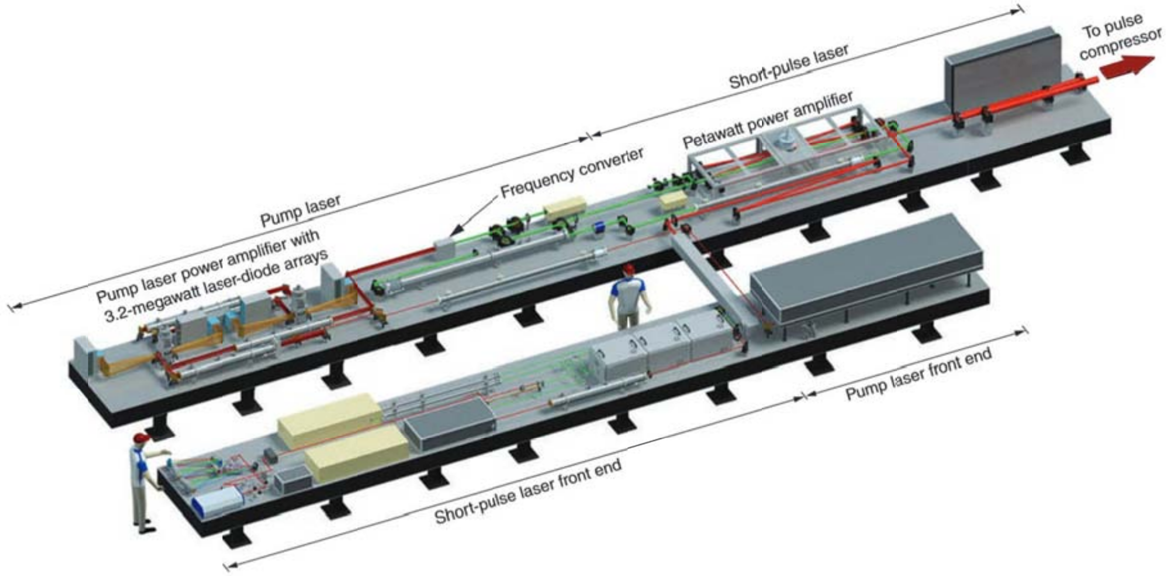


**FIGURE B4.4** Computer-aided design rendition of LLNL HAPLS Ti:sapphire system. SOURCE: Lawrence Livermore National Laboratory, 2014, "Lighting a New Era in Scientific Discovery," *https://str.llnl.gov/content/pages/january-2014/pdf/01.14.1.pdf*.

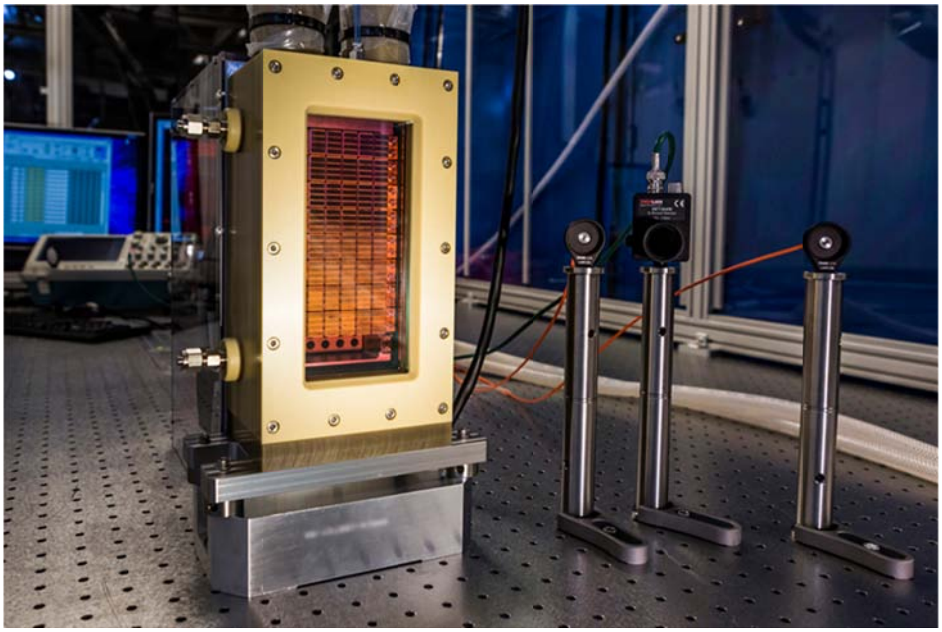

**FIGURE B4.5** Photograph of one of four, 800-kW diode-laser array used in the HAPLS pump laser. SOURCE: Courtesy of Lawrence Livermore National Laboratory.

[3] Lawrence Livermore National Laboratory, "Petawatt Laser System Passes a Key Milestone," January 22, 2016, https://www.llnl.gov/news/petawatt-laser-system-passes-key-miestone.

**High Field-Petawatt, Extreme Light Infrastructure-Attosecond Pulse Light Source**

In contrast to the HAPLS system, the ELI-ALPS facility in Szeged, Hungary was scheduled obtain a 10-Hz, 2-PW Ti:sapphire laser that employs flashlamp-pumped pump lasers, for the so-called HF PW System.[4] A schematic of the system appears in Figure B4.6. The device, to be built by Amplitude Technologies (Lisses, France) in cooperation with their subsidiary, Continuum (San Jose, CA), would include newly designed pump lasers providing 60 J of energy from a single beam.[5] Also in contrast with the HAPLS system, the design would seek to operate with 17-fs-duration pulses, thus requiring 34 J of pulse energy, compared to the 30 J design for the LLNL system. The front end of the system would be based on a high-contrast, OPCPA design.

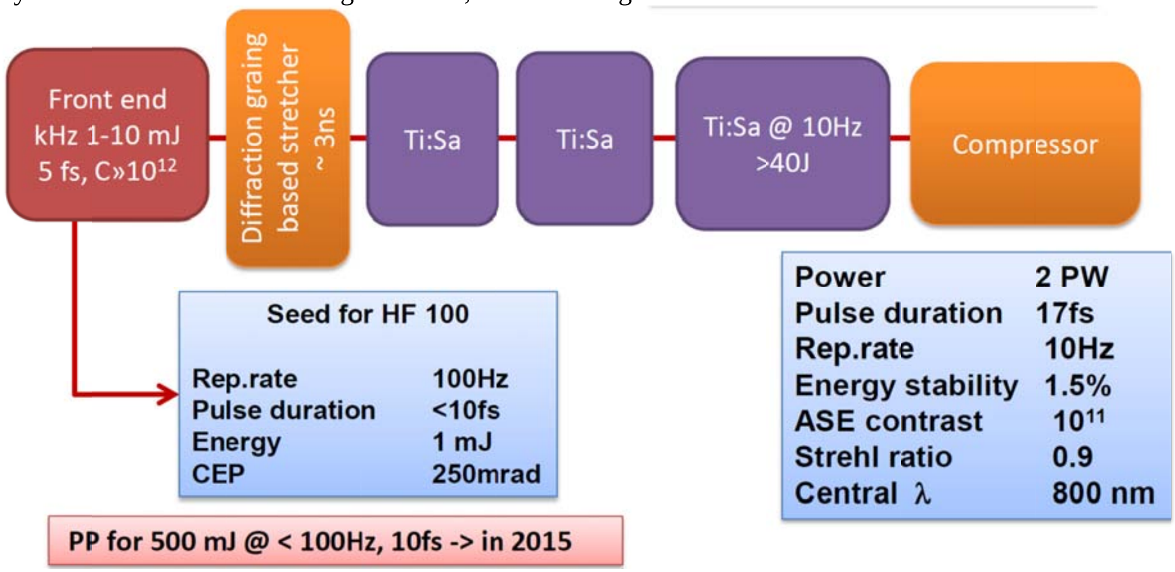


**FIGURE B4.6** Optical schematic for proposed 2-PW, 10-Hz Ti:sapphire laser that would be supplied to ELI-ALPS in Hungary, along with key system specifications. The system would also provide 1-mJ, < 10 fs pulses at a 100-Hz rate for other experiments. SOURCE: K. Osvay, 2015, "The ELI attosecond light pulse source," http://www.eli-alps.hu/sites/default/files/tangows/20150224-0945-ELI-ELIALPS-General-KarolyOsvay.pdf.

In a recent update on the HF-PW system,[6] it now appears that the specifications of the final stages of the HF-PW system are uncertain, with one possibility being a Ti:sapphire system providing 40 J in < 15 fs pulses at a 5-Hz rate, or an OPCPA system at 10 J in < 8 fs at a 10-Hz-rate, but "the parametric superfluorescence contrast and substantial level of laser command control has to be yet demonstrated for PW OPA stages."[7]

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[4] K. Osvay, 2015, "The ELI attosecond light pulse source," http://www.eli-alps.hu/sites/default/files/tangows/20150224-0945-ELI-ELIALPS-General-KarolyOsvay.pdf.

[5] P.M. Paul, F. Falcoz, E. Gontier, S. Branly, L. Vigroux, and G. Riboulet, 2016, Towards high repetition rate ultra-intense lasers, latest developments at Amplitude Technologies, in *Proceedings High-Brightness Sources and Light-Driven Interactions*, Long Beach, California, March 20-22, Optical Society of America.

[6] Extreme Light Infrastructure, "ELI-ALPS Research Facilities," http://www.eli-alps.hu/?q=en/02_Parameters, accessed January 27, 2017.

[7] Extreme Light Infrastructure, "ELI-ALPS Research Facilities."

### Center for Relativistic Laser Science, Korea

At the Center for Relativistic Laser Science (CoReLS) in Gwangju, Korea, a 4-PW Ti:Sapphire has recently been operated at a 0.1 Hz pulse rate.[8] The system is an upgrade to a 1.5 PW source at the facility, with an added Ti:sapphire “booster” amplifier pumped by 180 J/pulse (green), Nd:glass-based system, delivering 112 J of energy with a 34-J input, for an efficiency of 47 percent. To narrow the system pulsewidth, developers employed a spectrally optimized OPCPA-based seed laser and were able to obtain a compressed pulsewidth of 19.6 fs, with 83 J of energy. The system is in the commissioning stage and is slated to become available for experiments in the near term.

### Extreme Light Infrastructure-Nuclear Physics, 10 Petawatts, Romania

At the ELI-NP facility in Magurele, Romania, Thales Optronique (Elancourt, France) is currently set to install two 10-PW Ti:sapphire systems, pumped by a bank of flashlamp-pumped Nd:glass lasers operating at 1 pulse/minute. A schematic of the combined systems appears in Figure B4.7, including additional, higher-pulse-rate beamlines for other experiments. The system front-end design appears in Figure B4.8, showing a hybrid scheme with a Ti:sapphire mode-locked oscillator and CPA stages, followed by a compressor, XPW stage, another stretcher, to the 20-ps level, and a high-gain OPCPA stage pumped by pump source whose pulse is derived from the Ti:sapphire oscillator.[9] The front end produces 10.5-mJ, 20-ps pulses at a 10-Hz rate, with a pulse contrast of $10^{12}$ in a 100-ps window around the main pulse and a bandwidth of 70 nm. This output is stretched to the ns level and injected into a series of Ti:sapphire amplifiers, shown in Figure B4.7, to reach the final design energy of 280 J, which yields a projected compressed energy of 210 J in 21 fs.

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[8] S.K. Lee, J. H. Sung, H. W. Lee, J. Y. Yoo, and C. H. Nam, 2016, “0.1 Hz Sub-20 fs 4 PW Ti:Sapphire Laser,” presented at Seminar 4, Annual International Laser Physics Workshop, Yerevan, Armenia, July 11-15, http://www.lasphys.com/workshops/abstracts/files/2016/99/ff/0c/fef86f98c626380d3544758d06/abstract.pdf.

[9] F. Lureau, 2015, “High Power Laser System (HPLS),” in *ELI-NP Science Program and Instruments Technical Design Reports*, Magurele, Romania, February 18-20, http://www.eli-np.ro/indico/getFile.py/access?contribId=2&resId=0&materialId=slides&confId=22.

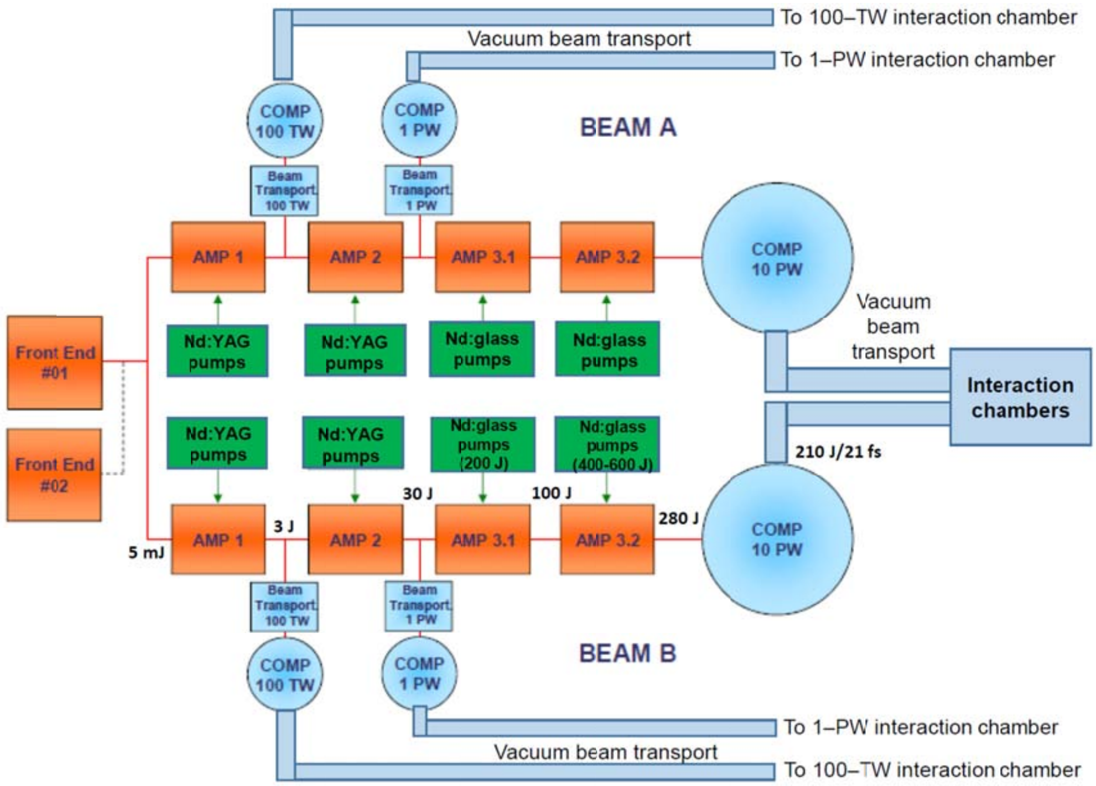


**FIGURE B4.7** *Optical schematic for two 10-PW Ti:sapphire lasers to be supplied to ELI-NP in Romania. The system will also provide 100 TW (10 Hz) and 1 PW (1 Hz) beamlines. SOURCE:* R. Dabu, 2014, "High power laser system (HPLS) at ELI-NP," presented at ELI Beamlines Summer School, Aug. 24-29, Prague, Czech Republic, http://www.eli-beams.eu/wp-content/uploads/2013/11/Dabu_high_power_laser_system_at_eli-np.pdf.

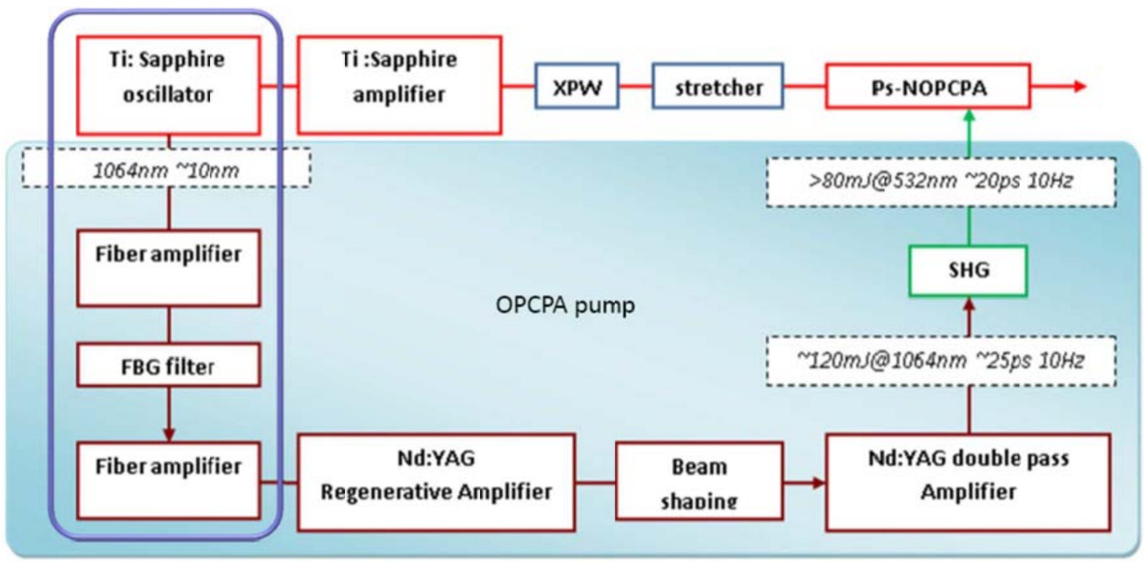


**FIGURE B4.8** Hybrid Ti:sapphire, OPCPA front end for ELI-NP system. SOURCE: F. Lureau, 2015, "High Power Laser System (HPLS)," in *ELI-NP Science Program and Instruments Technical Design Reports*, Magurele, Romania, February 18-20, http://www.eli-np.ro/indico/getFile.py/access?contribId=2&resId=0&materialId=slides&confId=22.

The initial high-energy Ti:sapphire amplifier stages utilize flashlamp-pumped Nd:YAG lasers similar to those used in the BELLA system described above. The final Nd:glass amplifiers are pumped by as many as eight "ATLAS" 100-J (527-nm) Nd:glass lasers. Figure B4.9 shows photograph of one completed ATLAS system, while Figure B4.10 shows a drawing of the complete system as it will be installed at ELI-NP. The ELI-NP 10 PW laser is scheduled for operational status in 2018.


**FIGURE B4.9** Photograph of ATLAS flashlamp-pumped Nd:glass laser providing 100 J of 527-nm energy at a pulse rate of 1/minute. SOURCE: F. Lureau, 2015, "High Power Laser System (HPLS)," in *ELI-NP Science Program and Instruments Technical Design Reports*, Magurele, Romania, February 18-20, http://www.elinp.ro/indico/getFile.py/access?contribId=2&resId=0&materialId=slides&confId=22.

**FIGURE B4.10** Computer rendition of 10-PW system to be installed at ELI-NP. SOURCE: F. Lureau, 2015, "High Power Laser System (HPLS)," in *ELI-NP Science Program and Instruments Technical Design Reports*, Magurele, Romania, February 18-20, http://www.eli-np.ro/indico/getFile.py/access?contribId=2&resId=0&materialId=slides&confId=22.

## APOLLON, France

The Apollon laser, under construction at l'Orme des Merisiers, Saclay, France, is also slated to generate 10 PW of peak power, but as of September 2015 was funded for 5 PW.[10] The design pulsewidth of 15 fs is slightly shorter than the 21-fs pulse for the ELI-NP system. Figure B4.11 shows a diagram of the Apollon front end. As with the ELI-NP system an OPCPA design is employed to amplify the output of the Ti:sapphire mode-locked source, but in this case a 1,030-nm part of the oscillator spectrum is amplified in a Yb:fiber, stretched to 1.5 ns, amplified to 2 mJ in a Yb:KYW regenerative amplifier and further amplified in a Yb:YAG thin-disk regenerative amplifier to 150 mJ. The 15 ps compressed pulse is doubled to about 80 mJ of energy and pumps a BBO OPCPA. A Ti:sapphire CPA system after the oscillator provides 1.5 mJ, 25-fs pulses which drive a XPW stage to provide high contrast (> $10^{13}$), the output of that is stretched to 6 ps and provides the input to the OPCPA stage.[11] The mJ-level OPCPA output pulse is then set to amplified further to provide an input to the high-energy Ti:sapphire amplifier chain.[12] The use of diode-pumping for all of the lasers in the front-end enables a 100-Hz pulse rate, an aid to the use of diagnostics and feedback controls that provide for a high-stability seed source, even when the entire system runs at a much lower rate.

Figure B4.12 shows the entire system block diagram, indicating that the OPCPA front end will provide 30-mJ, 1-ns-duration pulses with a theoretical bandwidth supporting <10-fs pulses, although the overall system is designed for 15 fs compressed pulses. The Nd:glass, liquid-cooled pump lasers, built by Continuum and National Energetics, will run at a rate of 1/minute, and are specified to generate a total of 800 J of green energy for the final three stages of Ti:sapphire amplifiers. The last amplifier with utilize 17.5-cm-diameter Ti:sapphire crystals, with a pumped diameter of 15 cm. Compression gratings for the system, supplied by LLNL, measure 91 x 45.5 cm.

At present, the Apollon laser is scheduled to be available for experiments in 2018.

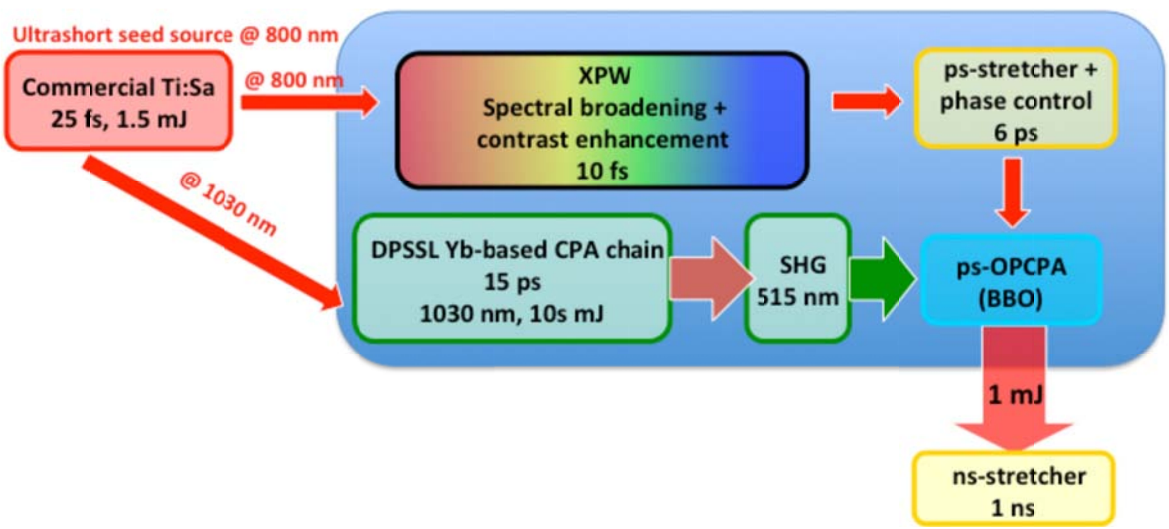


**FIGURE B4.11** Block diagram for a portion of the Apollon front end. SOURCE: D.N. Papadopoulos, P. Ramirez, A. Pellegrina, N. Lebas, C. Leblanc, G. Chériaux, J. P. Zou, et al., 2015, "High-contrast 10-fs OPCPA-based Front-End for the Apollon-10PW laser," paper ATu4A.3in *Advanced Solid State Lasers,* OSA Technical Digest.

[10] Ecole Polytechnique, "Birth of Apollon, the most powerful laser worldwide," September 30, 2015, https://www.polytechnique.edu/en/content/birth-apollon-most-powerful-laser-worldwide?language=en.

[11] D.N. Papadopoulos, P. Ramirez, A. Pellegrina, N. Lebas, C. Leblanc, G. Chériaux, J. P. Zou, et al., 2015, "High-contrast 10-fs OPCPA-based Front-End for the Apollon-10PW laser," paper ATu4A.3 in *Advanced Solid State Lasers*, OSA Technical Digest.

[12] J.P. Zou, C. Le Blanc, D.N. Papadopoulos, G. Ch´eriaux, P. Georges, G. Mennerat, F. Druon, et al., 2015, Design and current progress of the Apollon 10 PW project, *High Power Laser Science and Engineering* 3:e2.

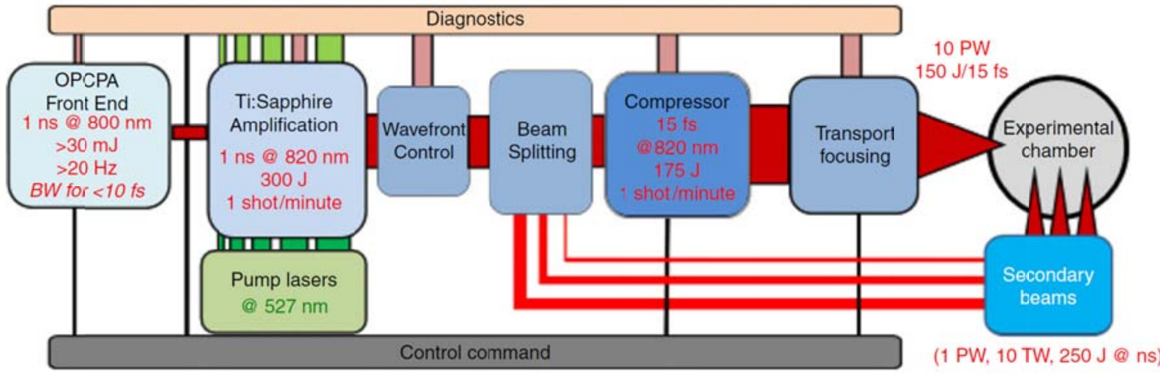


**FIGURE B4.12** Block diagram for entire Apollon 10-PW Ti:sapphire laser. SOURCE: J.P. Zou, C. Le Blanc, D.N. Papadopoulos, G. Ch´eriaux, P. Georges, G. Mennerat, F. Druon, et al., 2015, Design and current progress of the Apollon 10 PW project, *High Power Laser Science and Engineering* 3:e2.

### 10 Petawatts at the Shanghai Institute for Optics and Fine Mechanics

Presently under consideration at the Shanghai Institute for Optics and Fine Mechanics (SIOM) is a 10-PW source that employs a Ti:sapphire stage as the final amplifier.[13] The device would be installed at the Superintense Ultrafast Laser Facility (SULF) at SIOM. The notional design would utilize two 527-nm, 500-J, 10 ns pump beams from Nd:glass lasers, arranged to provide four separate time-delayed pumps in a design similar to that in Figure B1.11. The amplifier would provide a gain of 10 and generate about 500 J of energy with a 1.5-ns pulse before compression. Based on the 5.3-PW laser now at SIOM, the system pulsewidth would be about 24 fs, requiring a minimum of 240 J of compressed energy to reach the 10-PW level. The major issue to be resolved is whether the required gain and stored energy can be achieved before parasitic losses arise in the amplifier.

### Optical Parametric Chirped-Pulse Amplifiers

### 10 Petawatts at the Shanghai Institute for Optics and Fine Mechanics

Also under consideration at the Shanghai Institute for Optics and Fine Mechanics (SIOM) is a 10-PW source that would employ an OPCPA stage as the final amplifier, also for use in SULF at SIOM. Figure B4.13 is a diagram of the system design, which employs a Ti:sapphire-based source, similar to the SIOM 2- and 5.3-PW systems described above, to reach the 50-J energy level. In order to achieve the 10-PW output power, two materials are under investigation for the final, 800-nm-region OPCPA stage, LBO and YCOB. (KD*P does not have a high-enough bandwidth for operation in this wavelength range.) The ultimate choice may depend on the ability to grow either material with a sufficiently large aperture to handle the 2-kJ, 527-nm pump beam derived from a Nd:glass laser. The system projected optical-optical efficiency of 25 percent will yield a 500-J pulse, compressed to produce a 300-J, 30-fs output pulse. Issues to be resolved before this choice would be made, besides obtaining the OPCPA crystal, are whether the desired OPCPA efficiency can be realized.

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[13] R. Li, L. Yu, Z. Gan, C. Wang, S. Li, Y. Liu, X. Liang, et al., 2016, “Development of a Super Intense Laser Facility at Shanghai,” presentation at IZEST Conference Extreme Light Scientific and Socio-Economic Outlook, Paris, Nov. 25-29.

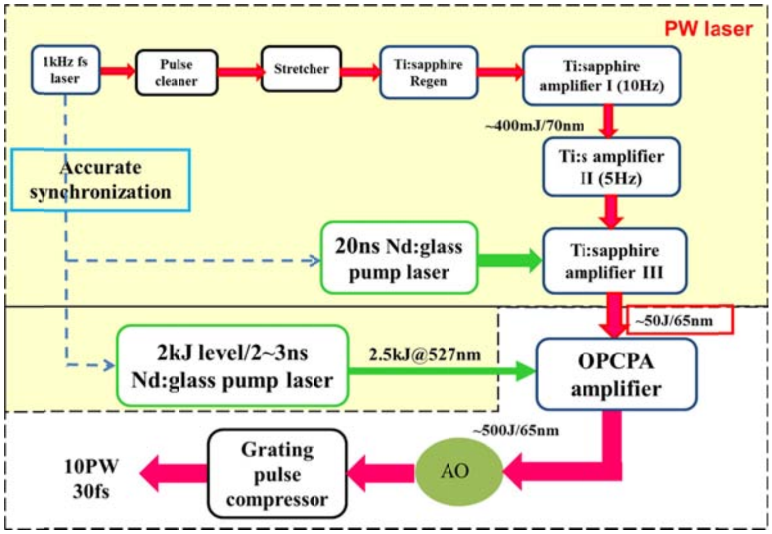


**FIGURE B4.13** Optical schematic of 10 PW OPCPA-final-amplifier system under consideration at the Shanghai Institute for Optics and Fine Mechanics (SIOM). SOURCE: R. Li, "New progress towards a 10PW Laser Facility "SULF" at Shanghai," presentation to the committee on February 29, 2016.

### Vulcan 20 Petawatts, UK

The Central Laser Facility (CLF) at the Rutherford Appleton Laboratory, in Oxford, UK, has had several high-peak-power systems in operation, including a flashlamp-pumped Nd:glass laser (Vulcan) with a CPA option that can generate 1 PW (500 J in 500 ps) at a pulse rate of 1 shot every 20 minutes.[14] Of interest to the CPA option is the early and pioneering use of OPCPA technology to provide the front end for the system. The CLF also has a Nd:glass-pumped Ti:sapphire laser (Gemini) that has two output beams, each capable of 15 J in 30-fs pulse (0.5 PW) at a pulse rate of one shot every 20 seconds.

For over a decade the CLF has been engaged in the development of an OPCPA-based source that would utilize the Vulcan laser as a pump source. The initial effort was intended to generate 10 PW of peak power, as diagrammed in Figure B4.14, and was able to demonstrate the front end of the system, up to the Joule-level with ns pulses. Budgetary constraints put development on hold around 2008. Current plans are underway to eventually reach the 20-PW level.

The design of the system involves the use of large-aperture KD*P crystals, which, when pumped by a doubled Nd:glass laser, have maximum spectral bandwidth when non-collinear phase-matching is set for a central wavelength of 910 nm (see Figure B2.1 and Figure B4.17 below). This is the same technology discussed above for the Russian PW-class OPCPA systems. In order to provide a seed laser at this wavelength, researchers at the CLF developed a unique, Ti:sapphire-pumped, collinear-phase-matched OPCPA-based source[15] that employs a chirped pump (around 400 nm) and synchronized chirped signal (around 714 nm) to maintain phase-matching over a broad wavelength region and generate an idler beam at 910 nm with a bandwidth of > 165 nm, suitable for compression to 15 fs. More recent work has shown how the chirping scheme can be optimized to generate an

[14] C.N. Danson, P.A. Brummitt, R.J. Clarke, J.L. Collier, B. Fell, A.J. Frackiewicz, S. Hawkes, et al., 2005, Vulcan petawatt—design, operation and interactions at 5 × 1020 Wcm−2, *Laser Part. Beams* 23: 87–93.

[15] Y. Tang, I. N. Ross, C. Hernandez-Gomez, G. H. C. New, I. Musgrave, O. V. Chekhlov, P. Matousek, and J. L. Collier, 2008, Optical parametric chirped-pulse amplification source suitable for seeding high-energy systems, *Opt. Lett.* 33(20): 2386-2388.

optimized 910-nm source, stretched to 3 ns and capable of compression to below 20 fs after the final OPCPA amplifier.[16]

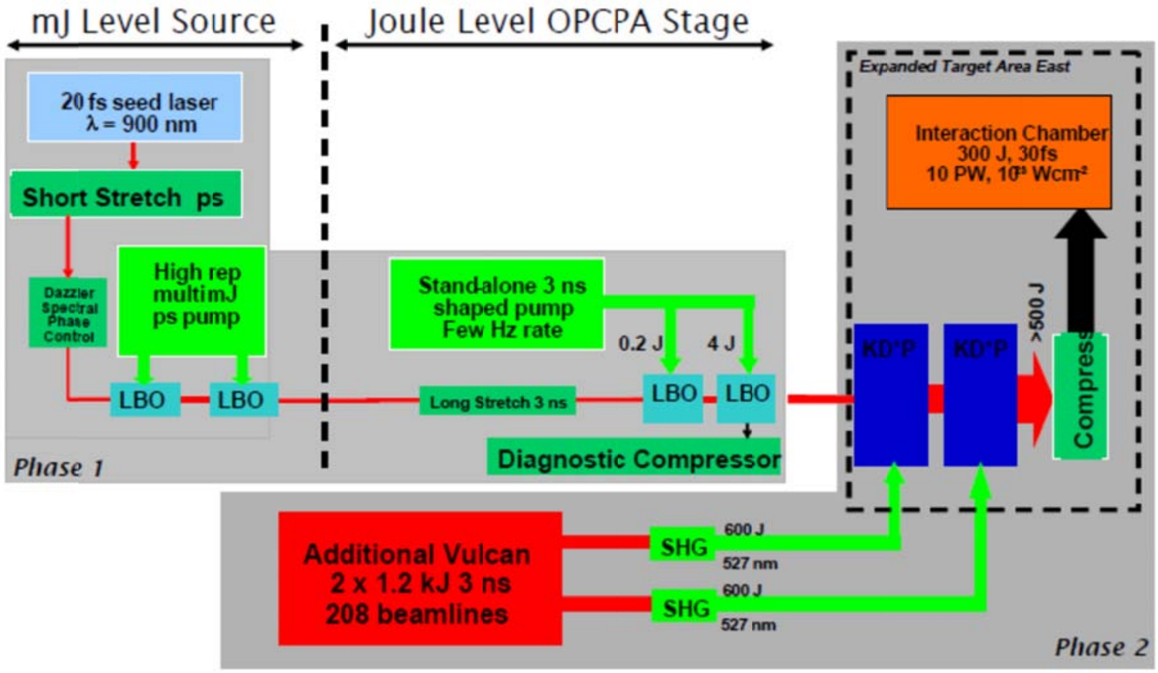


**FIGURE B4.14** Optical schematic of the original Vulcan 10 PW OPCPA-based source, now set to operate at the 20-PW level. SOURCE:

**1, 20, and 50 Petwatts Gekko-EXA**

Since 2009 a group at the Institute of Laser Engineering (ILE), Osaka University, Japan has been discussing development of a high-peak power OPCPA system, with initial discussions suggesting a two-beam source with a total peak power of 200 PW. More recently, a design for a 50-PW, single-beam system has been proposed, along with additional beamlines that generate 1 PW, 10-fs pulses at 100 Hz and 20 PW, 10-fs pulses at 0.01 Hz.[17] The overall design appears in Figure B4.15, and shows a common front end generating < 10-fs pulses, followed by associated low-energy stretchers and amplifiers to provide the signal (center wavelength around 1,053 nm) for the OPCPAs as well as the seed sources for the OPCPA pumps. The 100-Hz-pump system employs diode-pumped, cryogenically cooled Yb:YAG crystals, while the 0.01-Hz system may use either Nd:YAG of Nd:glass, with a split-disk cooling design similar to that in Figure B3.4. The 50-PW beamline employs the existing, Nd:glass-based, Laser for Fast Ignition Experiments (LFEX) at the ILE. In all cases, the final OPCPA stages are based on partially deuterated KDP (p-DKDP) crystals, arranged for slightly non-collinear phase-matching to provide 600-nm gain bandwidths around 1,053 nm.

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[16] A.S. Wyatt, P. Oliveira, A. Boyle, Y. Tang, M. Galimberti, I. N. Ross, I. O. Musgrave, C. Hernandez, and J. Collier, 2015, "Ultra-Broadband Spectral Phase Control in the Vulcan 20PW Upgrade Front End," in *2015 European Conference on Lasers and Electro-Optics*, Munich, June 21-25, Optical Society of America.

[17] J. Kawanaka, K. Tsubakimoto, H. Yoshida, K. Fujioka, Y. Fujimoto, S. Tokita, T. Jitsuno, N. Miyanaga, and Gekko-EXA Design Team, 2016, Conceptual design of sub-exa-watt system by using optical parametric chirped pulse amplification, *Journal of Physics: Conference Series* 688:012044.

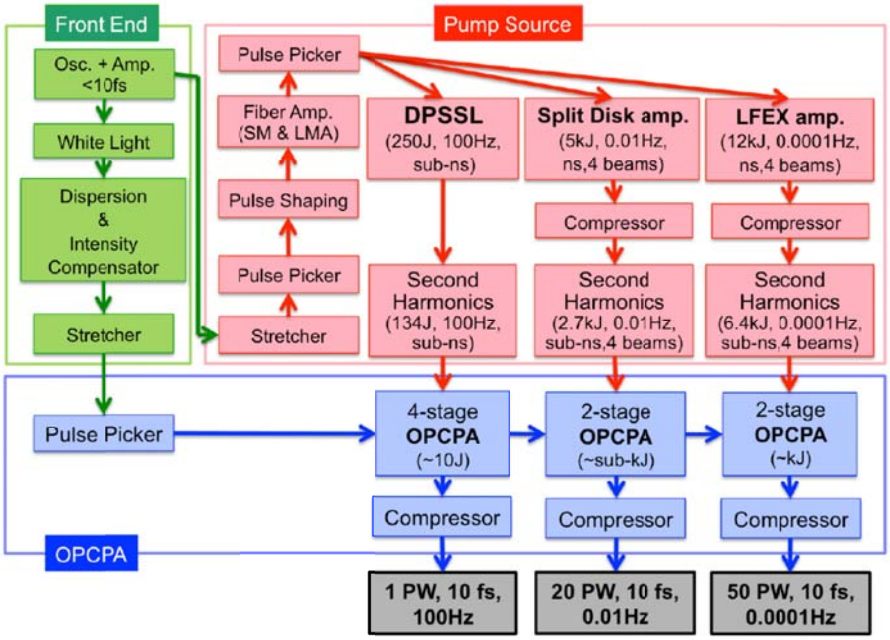


**FIGURE B4.15** Overall proposed design for Gekko-EXA system, showing three beamlines. SOURCE: J. Kawanaka, K. Tsubakimoto, H. Yoshida, K. Fujioka, Y. Fujimoto, S. Tokita, T. Jitsuno, N. Miyanaga, and Gekko-EXA Design Team, 2016, Conceptual design of sub-exa-watt system by using optical parametric chirped pulse amplification, *Journal of Physics: Conference Series* 688: 012044.

### 75-Petawatt Extended Performance-Optical Parametric Amplifier Line, Laboratory for Laser Energetics

LLE has presented a conceptual design to build an OPCPA-based, 75-PW source (EP-OPAL), that would be pumped by the OMEGA EP Nd:glass laser.[18] The latter system, in operation since 2008, has 4 beamlines, each with technology derived the LLNL NIF laser. Each beamline, operating with a 10-ns pulse, can produce 6.5 kJ of 351-nm energy. Two of the beamlines can also run with short pulses, with 2.6 kJ of 10-ps-pulsewidth energy at the fundamental, and up to 1 PW of peak power, 1 kJ of energy with a 1-ps pulsewidth. The system shot rate is one per 105 minutes.[19]

Figure B4.16 is an optical schematic of the proposed EP-OPAL system, which shows that two of the OMEGA-EP beamlines would be employed to provide doubled (527-nm) wavelength pump energy of 6.3 kJ in a 2.5-ns pulse. The final NOPA (really non-collinear OPCPA) stages would employ large-aperture KD*P crystals, in common with the Russian PW OPCPA systems and the proposed Vulcan 20 PW system, discussed above. We show the calculated gain as a function of wavelength for that material in Figure B4.17.

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[18] J. Bromage, University of Rochester, "Ultra-High Intensity Laser Technology," presentation to the committee on July 14, 2016.

[19] S. Morse, "Omega Laser Facility and User Group Overview," presentation to the committee on July 14, 2016.

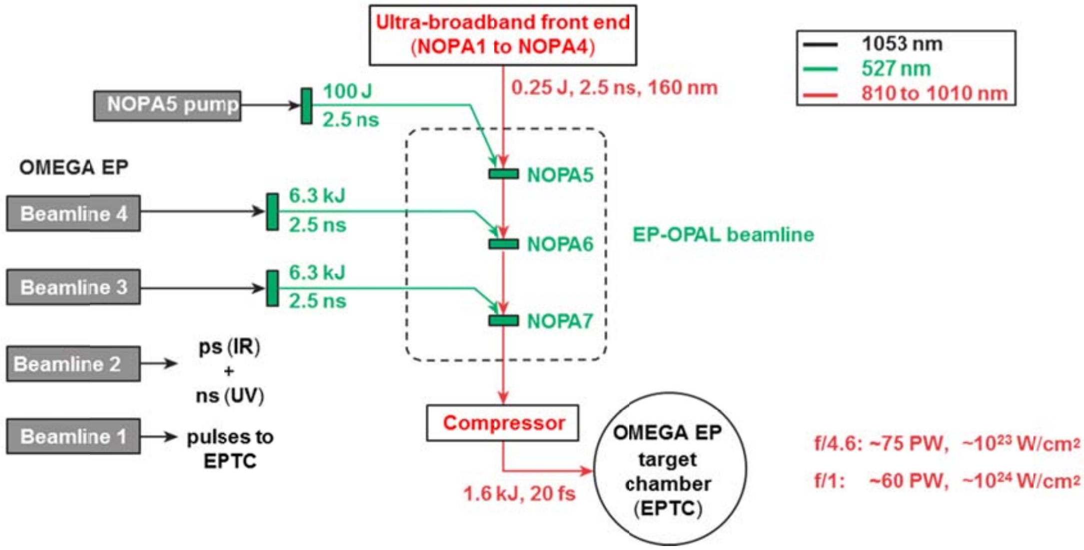


**FIGURE B4.16** Optical schematic of proposed EP-OPAL 75 PW laser at the Laboratory for Laser Energetics (LLE). SOURCE: J. Bromage, University of Rochester, "Ultra-High Intensity Laser Technology," presentation to the committee on July 14, 2016.

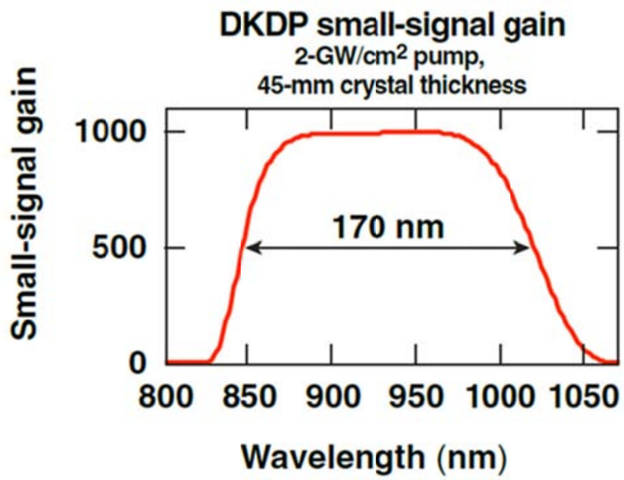


**FIGURE B4.17** Small-signal gain for a DKDP (KD*P) crystal pumped by a doubled Nd:glass laser, for optimized non-collinear phase-matching, with parameters indicated. SOURCE: J. Bromage, University of Rochester, "Ultra-High Intensity Laser Technology," presentation to the committee on July 14, 2016.

LLE has been engaged in preliminary work on a sub-scale system, MTW-OPAL, to test out some of the technologies, and plans to demonstrate that device by 2019, with a goal of 7.5 J in 15 fs.[20] To date, LLE has developed and has operational a high-contrast, ultra-broadband front end (UFE) for the system, the design of which appears in Figure B4.18 below.[21] The source is unique in that the short pulse, providing a broad linewidth in the 810-1010-nm region, is derived from a so-called "white-light continuum" (WLC) which is generated by a fiber-laser pumped crystal. The WLC is subsequently amplified by three, picosecond-pulsewidth-pumped NOPAs, and then stretched to a 1.5-ns pulsewidth for further amplification by OPCPAs. The use of the relatively low-pulse-rate WLC

[20] J. Bromage, 2016, "Ultra-High Intensity Laser Technology."

[21] E.M. Campbell, 2015, "Ultrahigh Brightness Laser Development at the Laboratory for Laser Energetics," presentation at George Washington University, Washington, D.C., December 14. https://physics.columbian.gwu.edu/sites/physics.columbian.gwu.edu/files/downloads/Campbell_LDRS2015.pdf.

makes possible a high pulse-contrast ratio compared to a mode-locked source, where the high pulse rate can make suppression of nearby (in time) pulses a challenge.

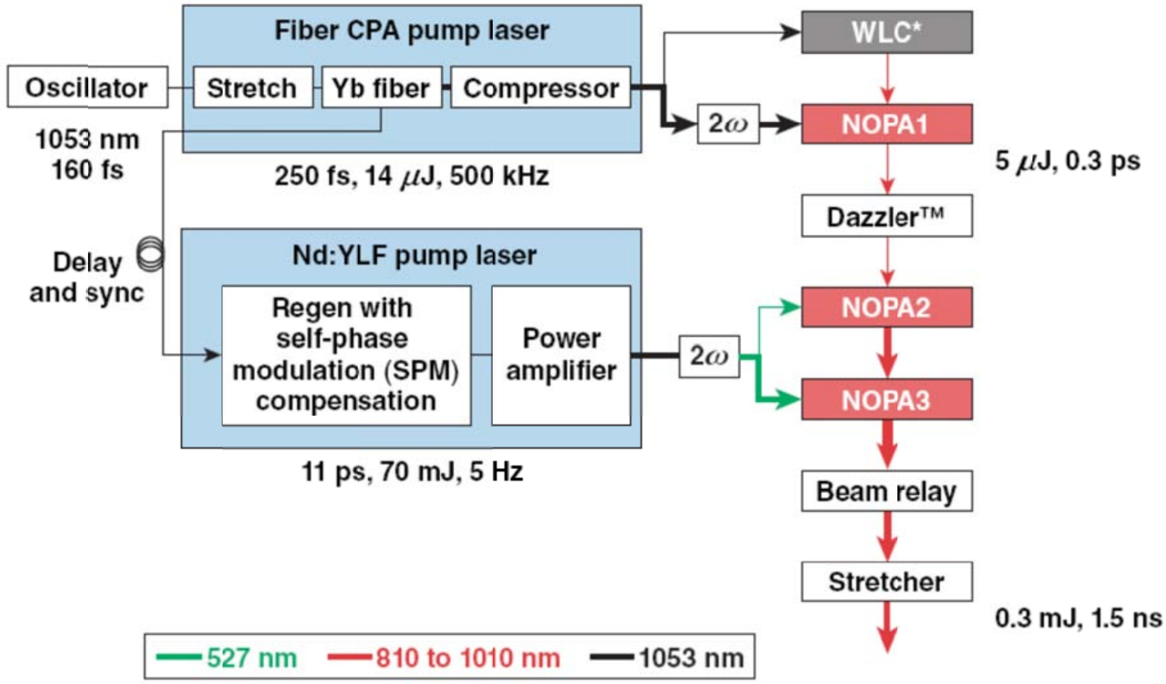


**FIGURE B4.18** Front-end (UFE) system in operation at LLE to be used as driver for OPCPA scaling experiments. System is based on NOPA-amplified, stretched pulses generated by a fiber-laser-driven, "white-light continuum" source. SOURCE: E.M. Campbell, 2015, "Ultrahigh Brightness Laser Development at the Laboratory for Laser Energetics," presentation at George Washington University, Washington, D.C., December 14. *https://physics.columbian.gwu.edu/sites/physics.columbian.gwu.edu/files/downloads/Campbell_LDRS2015.pdf*.

Operation of the eventual EP-OPAL system requires solving a number of technological challenges, including development of gratings with both a large bandwidth and aperture, sufficiently large KD*P crystals, wavefront control for high beam quality and optical coatings needed to handle the large bandwidths and high peak energies.[22]

**Exawatt Center for Extreme Light Studies, 200 Petawatts, Russia**

During the initial stages of planning for what is now the Extreme Light Infrastructure (ELI), presently under construction in Europe at three locations, there was a proposal to develop a "Fourth Pillar" facility in Russia that would include a laser system generating 200 PW of peak power. The program, Exawatt Center for Extreme Light Studies Project (XCELS) proposed to reach this level through the coherent combination of 12 Nd:glass-pumped, KD*P, OPCPA-based sources, as shown in Figure B4.19.[23] The bases for the system were energy-scaled versions of the Russian OPCPAs discussed above, "PEARL" and "Luch." For XCELS a 500-J, 1-ns-stretched pulse source would be split in 12 beams and each beam would be then amplified back to the 500-J level, compressed to 400 J in 25 fs and then coherently combined at the target. As we have noted, such coherent combination

[22] J. Bromage, 2016, "Ultra-High Intensity Laser Technology."

[23] A.G. Litvak, E.A. Khazanov, and A.M. Sergeev, 2013, Exawatt Center for Extreme Light Studies Project (XCELS), https://gargantua.polytechnique.fr/siatel-web/linkto/mICYYYSJkYY6.

would present a major control challenge given the expected low pulse rate of the system. The future status of XCELS is uncertain given a variety of monetary and political challenges.

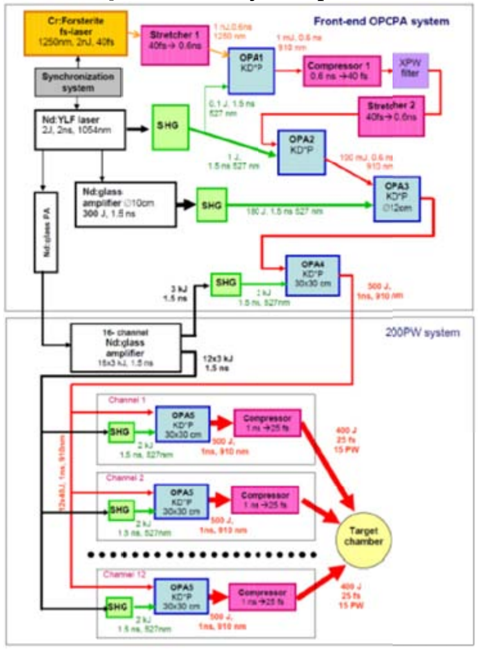


**FIGURE B4.19** Optical schematic of proposed 200-PW XCELS system. SOURCE: A.G. Litvak, E.A. Khazanov, and A.M. Sergeev, 2013, Exawatt Center for Extreme Light Studies Project (XCELS), https://gargantua.polytechnique.fr/siatel-web/linkto/mICYYYSJkYY6.

### Shanghai Institute for Optics and Fine Mechanics, 100-Petawatts

We note that recently the SIOM has proposed to build a 100-PW source (1,500 J in 15 fs), presumably OPCPA-based, as part of a facility called the Station of Extreme Light Science (SEL) at X-ray FEL, where the possibility of combining the source with a X-ray FEL will provide a unique experimental capability.[24]

### Yb-doped Materials

As discussed in Appendix 2C, the development of diode pumping opened a variety of new approaches to the operation of solid-state lasers and a whole class of laser materials based on the rare-earth dopant Yb. With relation to PW-class lasers, a direct system similar to Nd:glass or Ti:sapphire is a challenge, as an examination of Table 2.1 indicates. While Yb-doped, large-bandwidth materials have favorable storage times, extraction of the stored energy faces the problem of a relatively high saturation fluence, especially for materials with a large bandwidth. The use of multi-passing to overcome the high fluence then makes short-pulse operation problematic, due to gain narrowing.

We discuss below two systems under construction that are attempting to reach PW levels directly from the diode-pumped Yb-doped media. We follow with descriptions of high-energy Yb-doped ns-duration lasers, which can be employed as pumps for OPCPA (or Ti:sapphire) systems as an alternative to Nd-doped lasers.

### POLARIS (glass)

The POLARIS (Petawatt Optical Laser Amplifier for Radiation Intensive Experiments) in operation at the Helmholtz Institute in Jena, Germany, employs a mix of diode-pumped Yb:glass and

[24] R. Li, L. Yu, Z. Gan, C. Wang, S. Li, Y. Liu, X. Liang, et al., 2016, "Development of a Super Intense Laser Facility at Shanghai," presentation at IZEST Conference Extreme Light Scientific and Socio-Economic Outlook, Paris, Nov. 25-29.

Yb:$CaF_2$ media as amplifiers.[25] The Yb:glass media are used for all but the final stage of the system because of their large gain bandwidth, but this does lead to a limited pulse rate of 0.02 Hz even with diode pumping. A schematic of the system, in Figure B4.20, shows a double-CPA design, where pulses from a mode-locked Ti:sapphire laser at 1,030 nm are stretched to 20 ps, regeneratively amplified, compressed, and then passed through an XPW stage for contrast enhancement. After that, the pulses are stretched to the ns region and passed through a series of regenerative and multi-pass amplifiers, with the final stage a 17-pass, Yb:$CaF_2$ amplifier that generates 54 J of energy. This stage employs a 6.5-cm-diameter, 3.4-cm thick crystal and is pumped by 1.2 kJ (120 diode arrays) of diode energy at 940 nm, delivered in a 4-ms-duration pulse. The extracted energy represents an optical efficiency of 4.5 percent. Due to the limited aperture of the available compression gratings, only a fraction of the pulse energy has been compressed, yielding a 16.7 J, 98-fs, pulse, or 0.17 PW. Future system improvements may yield peak powers closer to the PW level. The system pulse contrast from background ASE is estimated to be 7 x $10^{13}$.

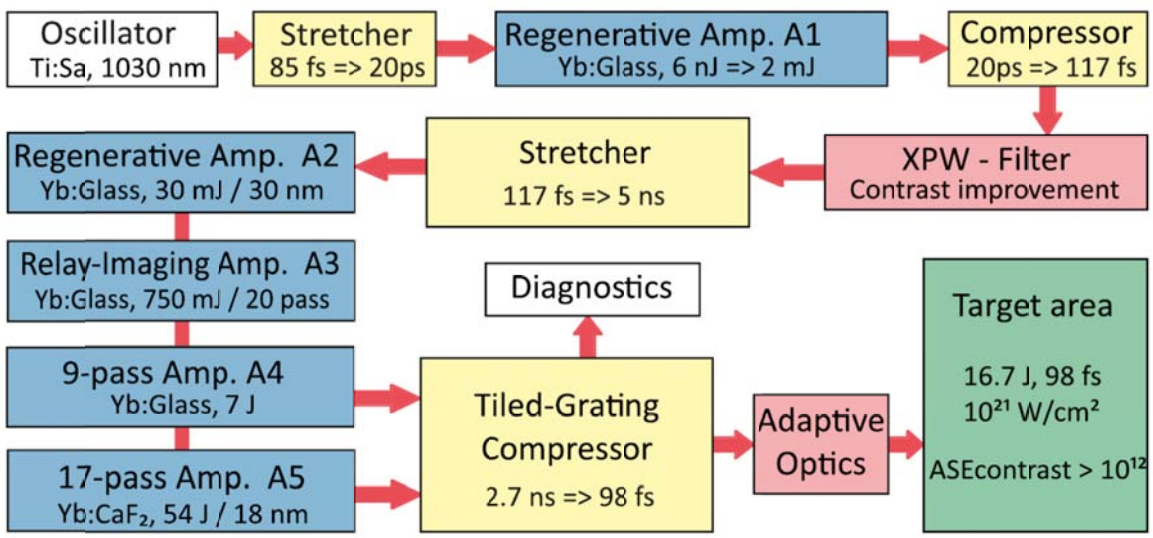


**FIGURE B4.20** Optical schematic of POLARIS mixed Yb-doped media system at the Helmholtz Institute in Jena. The limited aperture available for the compression gratings has kept the compressed energy at under 17 J as of this writing. SOURCE: M. Hornung, H. Liebetrau, S. Keppler, A. Kessler, M. Hellwing, F. Schorcht, G. A. Becker, M. Reuter, J. Polz, J. Körner, J. Hein, and M. C. Kaluza, 2016, 54 J pulses with 18 nm bandwidth from a diode-pumped chirped-pulse amplification laser system, *Opt. Lett*. 41(22): 5413-5416.

**PENELOPE ($CaF_2$)**

Under construction at the Helmholtz-Centre Dresden-Rossendorf (HZDR) in Germany is the PEnELOPE (Petawatt, Energy-Efficient Laser for Optical Plasma Experiments) system.[26] The staging of the system is diagrammed in Figure B4.21 and shows a series of regenerative and multipass amplifiers, with roughly a 10x increase in energy between stages. The 60-fs, diode-pumped Yb:KGW oscillator pulse is stretched to 3 ns, with a 50-nm bandwidth, and followed by thin-disk (active-

[25] M. Hornung, H. Liebetrau, S. Keppler, A. Kessler, M. Hellwing, F. Schorcht, G. A. Becker, M. Reuter, J. Polz, J. Körner, J. Hein, and M. C. Kaluza, 2016, 54 J pulses with 18 nm bandwidth from a diode-pumped chirped-pulse amplification laser system, *Opt. Lett.* 41(22): 5413-5416.

[26] M. Siebold, F. Roeser, M. Loeser, D. Albach, and U. Schramm, 2013, “PEnELOPE - a high peak-power diode-pumped laser system for laser-plasma experiments,” in *High-Power, High-Energy, and High-Intensity Laser Technology; and Research Using Extreme Light: Entering New Frontiers with Petawatt-Class Lasers*, (J. Hein, G. Korn, L.O. Silva, eds.), Proc. of SPIE Vol. 8780, 878005; Helmholtz-Zentrum Dresden-Rossendorf, “PEnELOPE,” February 6, 2016, https://www.hzdr.de/db/Cms?pNid=2098.

mirror) amplifiers to the 1-J level. The final two, 12-pass stages employ He-gas-cooled disks (4 per stage) with sizes of 5.5 and 11 cm, respectively, cooled to the 200-300 K range, and operate with diode pulsewidths in the 1.5-4-ms region. Thus the final stage of the system, with 1.2 MW of diode peak pump power, will utilize a pump energy of 1.8-5 kJ, leading to optical efficiencies well below 10 percent. Operation at the 0.1-PW level (15 J in 150 fs) at a 10-Hz rate is scheduled for 2016, while the PW-level system at 10x the energy and a 1-Hz rate is planned for 2017.[27]

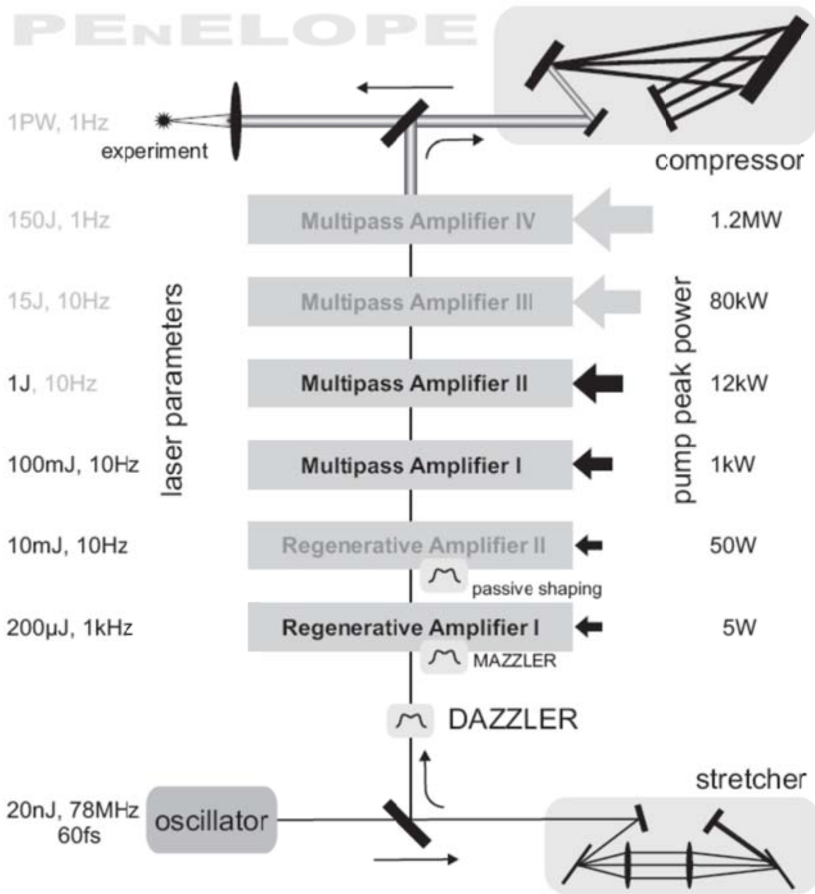


**FIGURE B4.21** Diagram of PEnELOPE Yb:$CaF_2$-based system under construction at the HZDR in Dresden, Germany. Items with black text and arrows were in operation in 2013. Full system operation is planned for 2017. SOURCE: M. Siebold, F. Roeser, M. Loeser, D. Albach, and U. Schramm, 2013, “PEnELOPE - a high peak-power diode-pumped laser system for laser-plasma experiments,” in *High-Power, High-Energy, and High-Intensity Laser Technology; and Research Using Extreme Light: Entering New Frontiers with Petawatt-Class Lasers*, (J. Hein, G. Korn, L.O. Silva, eds.), Proc. of SPIE Vol. 8780, 878005.

### High-Energy, ns-pulse Yb:YAG Lasers

High-energy, ns-pulse, diode-pumped Yb:YAG lasers can provide an alternative to various Nd-doped lasers as pumps for both Ti:sapphire lasers and OPCPAs. In Figure B4.3 we show an efficiency comparison for a particular ns-pulse application, MJ-energy driving of ICF, that shows favorable operation for Yb:YAG lasers with cooling to below room temperature, and indicates that the

[27] P. Michel, 2016, ELBE Center for High-Power Radiation Sources, *Journal of Large-Scale Research Facilities* 2: A39.

diode-peak power (and hence cost) to reach a certain energy would be less than for Nd:glass. For more modest energies the requirements for large-diameter Yb:YAG crystals is relaxed to levels now attained through ceramic fabrication techniques.

The Diode Pumped Optical Laser for Experiments (DiPOLE) system under development at the CLF, Rutherford Laboratory,[28] intended for eventual application in the L2 Beamline at ELI Beamlines in Prague, utilizes a He-gas-cooled final stage based on ceramic Yb:YAG. Figure B4.22 shows the details of this stage, which contains six, 0.85-cm thick, square-shaped ceramic gain media slabs, with a central 10-cm square, Yb-doped YAG region surrounded by a 1-cm-wide, Cr-doped YAG absorptive cladding for ASE suppression. To date, with gas cooling at 175 K, the system has generated a 10-ns output pulse with 107 J of energy. The pulse rate was limited to 1 Hz by issues with the cooling system, but the goal is 10-Hz operation, and cooling to 150 K. The two 940-nm diode pump source produced a total of 506 J in a 1.2-ms-pulse, for an optical efficiency of 21 percent.

In principal, as an OPCPA pump (doubled), the DiPOLE laser could be the basis for an overall PW-class system, with a 20-J, 20-fs pulse output from the OPCPA.

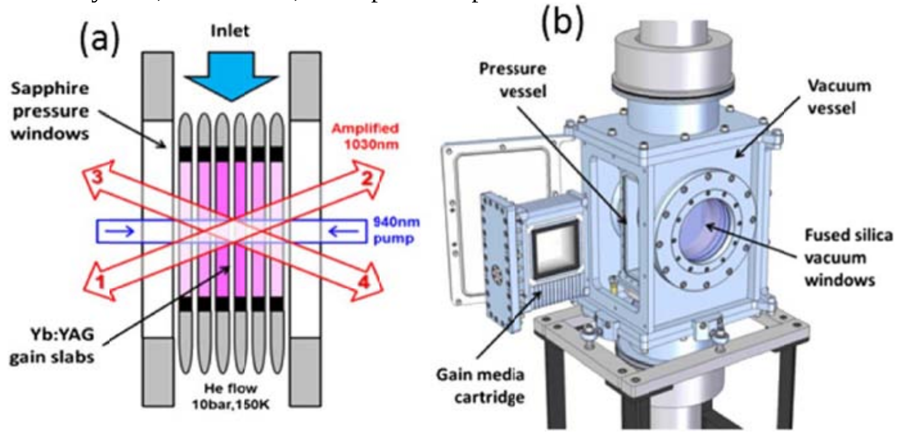


**FIGURE B4.22** Detail of cooling and pumping design for DIPOLE 100-J Yb:YAG final amplifier stage, with optics/cooling arrangement on the left and mechanical design on the right. SOURCE: S. Banerjee, P. D. Mason, K. Ertel, P. J. Phillips, M. De Vido, O. Chekhlov, M. Divoky, et al., 2016, 100 J-level nanosecond pulsed diode pumped solid state laser, *Opt. Lett*. 41(9): 2089-2092.

In other, similar work, Hamamatsu Photonics K.K., in Shizuoka, Japan, has reported on a 55 J, cryogenically cooled (105 K) Yb:YAG laser with 55 J of pulse energy at a low rate. The diode-pump produced 450 J of energy in a 1 ms pulse, and produced an estimated stored energy of 170 J. Further development of this system is underway, for both scientific and industrial applications.[29]
As a reminder, we note from above the intent at the ILE in Japan to construct a 1-PW (10 J in 10 fs) OPCPA-based source running at 100 Hz, based on a 250-J/pulse, cryogenically cooled, ns-pulse, diode-pumped Yb:YAG laser, doubled to 134 J/pulse and driving a multi-stage OPCPA to produce the desired peak power.

### Fiber Geometry
### International Coherent Amplification Network

The International Coherent Amplification Network (ICAN) was a highly publicized conceptual design for a Yb:fiber-based, PW-class system. Motivated by a desire to drive next-

[28] S. Banerjee, P. D. Mason, K. Ertel, P. J. Phillips, M. De Vido, O. Chekhlov, M. Divoky, et al., 2016, 100 J-level nanosecond pulsed diode pumped solid state laser, *Opt. Lett.* 41(9): 2089-2092.

[29] T. Sekine, Y. Takeuchi, T. Kurita, Y. Hatano, Y. Muramatsu, Y. Mizuta, Y. Kabeya, Y. Tamaoki, and Y. Kato, 2016, “High Gain, High Efficiency Cryogenic Yb:YAG Ceramics Amplifier for Several Hundred Joules DPSSL,” in *Lasers Congress 2016,* Optical Society of America.

generation particle accelerators, the ICAN design (Figure B4.23) called, in one publication,[30] for a 30-J/pulse, 30-fs output at kHz" rates, but a later publication discussed goals of >10 J per pulse, a >10 kHz pulse rate with pulses of 100–200 fs duration.[31] The longer pulsewidth in the later publication recognizes that, with the properties of Yb:fibers, a 30-fs pulse would require spectral beam combination in addition to spatial combination. Given the notional design of 1 mJ/fiber, the system requires > 10,000 fiber lasers to meet the output-energy requirements.

[30] T. Tajima, W. Brocklesby, and G. Mourou, 2013, ICAN: The next laser powerhouse, *Optics & Photonics News* 24(5): 36-43.
[31] G. Mourou, W. Brocklesby, T. Tajima, and J. Limpert, 2013, The future is fibre accelerators, *Nature Photonics* 7: 258-261.

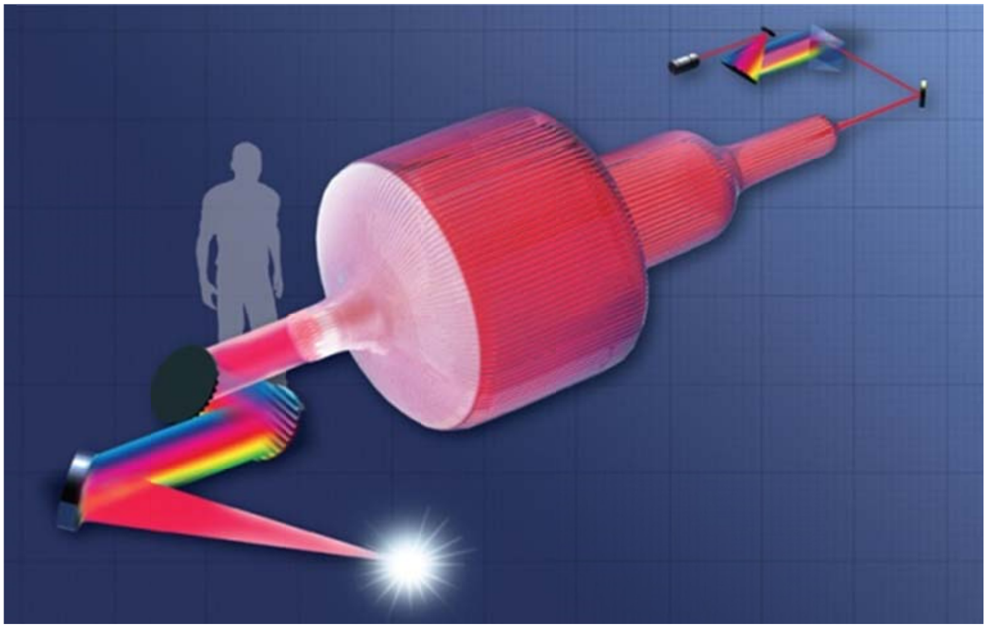

**FIGURE B4.23** Design of the ICAN laser at IZEST. Image credit: Phil Saunders/spacechannel.org.

There are several major challenges for the ICAN concept, which are evident from our discussion, in Appendix 2C, of experimental results to date with fiber lasers.

The number of required lasers is several orders of magnitude beyond the number of sources that have been coherently combined to date. This issue can be mitigated by cascading the combining process (i.e., combine 10 lasers, then combine the combined laser, etc.) but it still represents a major control challenge.

For pulsewidths in the 100-fs range, the path lengths for all the fibers require matching at the 30-µm level.

Even at the mJ level for a chirped pulse, for conventional fibers there is a strong coupling, due to nonlinear optical effects, between the phase delay in the fiber and the pulse intensity, adding in the need to match and control the energy out of each fiber.

Obtaining a high pulse contrast is problematic, as ASE is a major issue with fiber lasers and there is no evident technique in ICAN to suppress ASE to the levels required by many applications. At present, development of the ICAN concept has evolved into the XCAN effort discussed above.

## Free-Electron Lasers

While we have considered PW-level laser-based sources for generation of high intensities, another approach to reaching high intensities is to greatly shorten the wavelength of the source to allow much tighter focusing and enable high intensities without requiring PW-level powers. Free-electron lasers can provide a source of short-wavelength (e.g., X-rays), coherent radiation, and in addition could produce significantly shorter pulses than conventional lasers. To date, they have produced pulses on the order of 10 fs, with pulse energies on the order of 1 mJ, and focal spot sizes on the order of 100 nm.  These numbers imply a combined peak power of $10^{21}$ W/cm$^2$.

### SASE-driven X-ray Free-Electron Lasers

FELs were originally conceived as broadly tunable lasers in the infrared and visible[32] but came into their own with the realization that they could operate as ultra-high power X-ray laser sources without requiring mirrors or a stable recirculating optical cavity. This principle, known as self-amplified stimulated emission (SASE),[33] comes about because the relativistic electron gain medium travels along with the radiation it produces. Therefore the lasing requirement for a long gain-length product, which is ordinarily achieved by recirculating the light with mirrors, can instead be accomplished without mirrors by simple linear co-propagation of the light and the electrons. SASE led to the development of today's class of uniquely valuable, high-powered, X-ray free-electron laser light sources such as the U.S. Department of Energy's LCLS, first commissioned at SLAC.[34] Current-generation FELs have approximately one billion times higher power than the synchrotrons they replaced, and thus are far and away the most intense X-ray laser sources available. These currently operate at photon energies up to about 10 keV, with peak power up to 50 GW, demonstrated focused intensities of $10^{20}$W/cm$^{2}$,[35] and pulse lengths from 100 fs down to less than 1 fs. They have led to some unique science, including science in high-intensity areas that will be discussed later in this report.

[32] L.R. Elias, M. Fairbank, J. M. J. Madey, H. A. Schwettman, and T. I. Smith, 1976, Observation of stimulated emission of radiation by relativistic electrons in a spatially periodic transverse magnetic field, *Phys. Rev. Lett.* 36: 717.

[33] R. Bonifacio, C. Pellegrini, and L. M. Narducci, 1984, Collective instabilities and high-gain regime in a free electron laser, *Opt. Commun*. 50: 373.

[34] P. Emma, R. Akre, J. Arthur, R. Bionta, C. Bostedt, J. Bozek, A. Brachmann, et al., 2010, First lasing and operation of an angstrom-wavelength free-electron laser, *Nature Photonics* 4(9): 641–647.

[35] H. Mimura, H. Yumoto, S. Matsuyama, T. Koyama, K. Tono, Y. Inubushi, T. Togashi, et al., 2014, Generation of 1020 W cm−2 hard x-ray laser pulses with two-stage reflective focusing system, *Nature Communications* 5: 3539.

**TABLE B4.1** Characteristics of Hard X-ray Free-Electron Laser in Operation or under Construction (identified by the *)

| | LCLS | SACLA | European X-FEL* | Korean-X-FEL* | Swiss X-FEL* | LCLS-II Cu RF* |
|---|---|---|---|---|---|---|
| **Electron energy (GeV)** | 2.15–15.9 | 5.2–8.45 | 8.5–17.5 | 4–10 | 2.1–5.8 | 2.5–15 |
| **Wavelength range (nm)** | 0.11–4.4 | 0.275–0.063 | 5.1–0.04 | 0.6–0.1 | 7–0.1 | 1.2–0.05 |
| **X-ray pulse energy (mJ)** | 1–3 for $0.1<\lambda<1.5$ | 0.2–0.4 for $0.08<\lambda<0.275$ | 0.67–8.5 for $0.04<\lambda<5.1$ | 0.81–1 for $0.1<\lambda<0.6$ nm | 0.5–1.3 for $0.1<\lambda<7$ | 1–4.5 for $0.05<\lambda<0.4$ |
| **Pulse duration, rms (fs)** | 5–250 for $0.1<\lambda<1.5$ | 4.3 for $0.08<\lambda<0.275$ | 1.68–107 for $0.04<\lambda<5.1$ | 8.6–26 for $0.1,\lambda<0.6$ nm | 2–20 for $0.1<\lambda<7$ | 5–50 |
| **Linewidth, rms (%) SASE** | 0.5–0.1 for $0.1<\lambda<1.5$ | 0.11–0.37 for $0.08<\lambda<0.275$ | 0.02–0.25 for $0.04<\lambda<5.1$ | 0.15–0.18 for $0.1<\lambda<0.6$ nm | 0.06–0.4 for $0.1<\lambda<7$ | 0.2–0.1 |
| **Linewidth, rms (%) seeded** | 0.01–0.005 for $0.1<\lambda<1.5$ | 0.01–0.03* $0.08<\lambda<0.275$ | 0.04–0.005 for $0.04<\lambda<5.1$ | 0.002–0.002 for $0.1<\lambda<0.6$ nm | 0.01–0.002 for $0.1<\lambda<7$ | 0.02 |

**TABLE B4.2** Characteristics of Soft X-ray Free-Electron Lasers Operating and under Construction

| | FLASH | Fermi FEL-1 | Fermi FEL-2 | LCLS-II SXR Und* | LCLS-II HXR Und* |
|---|---|---|---|---|---|
| **Electron energy (GeV)** | 0.35–1.25 | 1.0–1.5 | | 3.6–4.0 | 3.3–4.0 |
| **Wavelength range (nm)** | 52–4.2 | 100–200 | 20–4 | 6–1.0 | 1.2–0.25 |
| **X-ray pulse energy (mJ)** | 0.2@$\lambda$max,0.5@$\lambda$min | 0.3@$\lambda$max, 0.1@$\lambda$min | 0.1@10.8 nm, 0.01@$\lambda$min | 0.9@$\lambda$max, 0.4@$\lambda$min | 1.1@$\lambda$max, 0.02@$\lambda$min |
| **Pulse duration, rms (fs)** | 15–100@$\lambda$max, 15–100@$\lambda$min | Depending on seed pulse duration and harmonic order, typically 40–100 | | 6–50 | 6–50 |
| **Linewidth, rms (%) SASE** | 0.2@$\lambda$max, 0.15@$\lambda$min | | | 0.1 | 0.2–0.05 |
| **Linewidth, rms (%) seeded** | $5\times10^{-4}$–$10^{-3}$ | 0.06@$\lambda$max, 0.03@$\lambda$min | 0.06 @ 10.8 nm, 0.02 @ 5.4 nm, 0.04@$\lambda$max | 0.02 | … |

NOTE: LCLS-II has two undulators for soft x ray (SXR) and hard x ray (HXR).

The general characteristics of X-ray pulses can be summarized as follows:
Pulse energy hundreds of $\mu$J to a few mJ.
Linewidth in SASE mode about $10^{-3}$, order of magnitude of the FEL parameter $\rho$, about 10 times smaller than SASE when using self-seeding.
Pulse duration from a few to about 100 fs.
About $10^{3}$ photons/electron, at 1 Å, compared to about $10^{-2}$ for spontaneous radiation, more at longer wavelengths.

### Free Electron Laser Basic Concepts and Technology

Free-electron lasers use relativistic electrons as a gain medium. Their principle of operation is resonant stimulated synchrotron radiation by electrons that are wiggling in a periodical magnetic field array called an undulator, as shown in Figure B4.24.[36] The resonant wavelength is equal to the slippage length between wiggling electrons in an undulator and the radiation they emit over one wiggle period. The gain at this resonant wavelength is due to the phenomenon of microbunching, in which the emitted radiation acts back on the resonant wiggling electrons to increase the orbit length of some and decrease the orbit length of others until they are driven into density modulations at the resonant wavelength. Electrons that wiggle together emit their synchrotron radiation in phase, so that when the bunching is sufficient to overcome the spontaneous synchrotron emission the beam can efficiently convert electron kinetic energy to coherent light.[37] The quantum description of this shows that it is in fact the same stimulated emission phenomenon as lasing at optical frequencies. In a typical FEL, the number of photons produced per electron is on the order of 1,000.

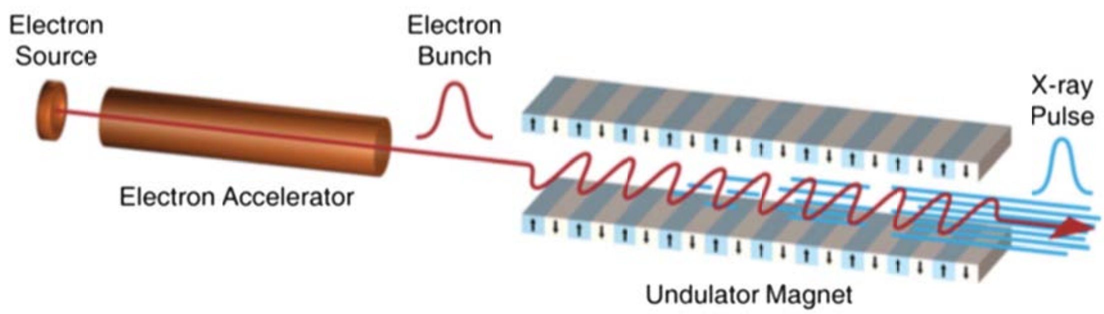


**FIGURE B4.24** Main components of a free-electron laser. A relativistic electron bunch travels through an undulator, where synchrotron radiation emitted by the electrons induces micron-scale bunch-density modulations (microbunching) after several thousand wiggles. This leads to lasing. The mechanism is called self-amplified stimulated emission. The X-ray photon wavelength is on the order of the undulator period divided by the square of the relativistic γ factor. Permanent magnet undulator periods are several centimeters, so X-ray lasers require electron beam energies on the order of 10 GeV (γ of 20,000). This sets the scale of the machine. Conventional radio-frequency driven 10 GeV accelerators are on the order of several hundred meters to over a kilometer in length. SOURCE: C. Pellegrini, A. Marinelli, and S. Reiche, 2016, The physics of X-ray free-electron lasers, *Reviews of Modern Physics* 88(1): 015006.

### *High-Intensity Free-Electron Lasers and Scaling of the Fundamental Intensity Limit*

The spectral intensity of a conventional laser beam is expressed as the [energy/area-time-bandwidth]. The equivalent figure of merit popularly employed for X-ray sources is the six-dimensional $(d^3x)(d^3k)$ phase space density measure called the spectral brightness or the spectral brilliance and is expressed in units of [photons/mm$^2$-mr$^2$-second-0.1%bandwidth]. Figure B4.25 shows the brightness of some current FELs in these units. When expressed as a phase space volume it becomes clear that there is a *maximum possible intensity*, which is defined by the product of the diffraction limit and the Fourier transform limit for any laser pulse with a given number of photons.[38]

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[36] J.M.J. Madey, 1971, Stimulated emission of Bremsstrahlung in a periodic magnetic field, *J. Appl. Phys*. 42: 1906-1913; C. Pellegrini, A. Marinelli, and S. Reiche, 2016, The physics of x-ray free-electron lasers, *Rev. Mod. Phys*. 88(1): 15006.

[37] L.R. Elias et al., 1976, Observation of stimulated emission.

[38] A.E. Siegman, 1986, *Lasers*, Revised edition, University Science Books, Mill Valley, Calif.

For $N$ photons of energy $\hbar\omega$ in a diffraction-limited Gaussian beam (FELs typically have this) and with temporal width $\sigma_t$ and spectral width $\sigma_\omega$ the fundamental intensity limit is given by:

$$B = \frac{N\hbar\omega}{(\lambda/2)^2\, 2\pi\sigma_t\,\sigma_\omega/\omega} \xrightarrow[limit]{transform} \frac{4N\hbar\omega^2}{\pi\lambda^2} = \frac{8(N\hbar\omega)c}{\lambda^3}$$

This equation is written to emphasize that Gaussian laser beams have an intensity that scales with wavelength as $\lambda^{-3}$ for a constant energy, and as $\lambda^{-4}$ for a constant photon number, thus favoring X-ray FELs over optical frequency lasers for high-intensity sources. For the present, however, current sources such as LCLS are not Fourier transform limited at the highest energy levels, and also the technology of X-ray mirrors prevents focusing to waists on the order of the wavelength,[39] and so the highest focused intensity for an X-ray FEL is far below this limit. Measured intensities are in the range of $10^{20}$ W/cm$^2$, which is below the highest intensity available with optical frequency lasers.[40]

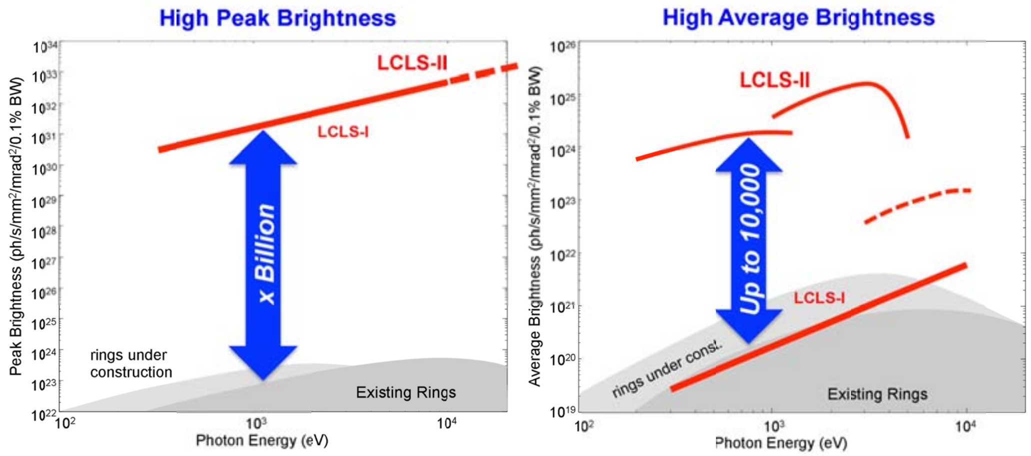


**FIGURE B4.25** FELs provide both highest peak power and highest average power for any laser pulses in the photon energy range above 10eV (VUV to X ray photon energies). Their power is approximately independent of photon energy in this range. For lasers that are operating or under construction, the peak power ranges up to 50 GW (1mJ in 20 fs) and the average power is in the range of several hundred watts (1 mJ pulses at repetition frequencies up to 1 MHz). The figure shows how the peak and average power of an FEL compares to a synchrotron at the same photon energy. SOURCE: Data is from SLAC Report No. LCLSII-1.1-DR-0001-R0, 2014.

### *Average Power*

The current average power for these sources is on the order of fractions of a watt (millijoules at 120 Hz), but this will change with the commissioning in the next decade of X-ray FELs based on continuous superconducting linear accelerators. These sources will have average X-ray powers approaching a kilowatt (see Figure B4.2 for details).

### *Transform-limited Pulse Generation*

Several methods are under active development to generate transform-limited pulses in X-ray FELs and overcome this major impediment to the highest intensity operation of SASE-based

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[39] H. Yumoto, H. Mimura, S. Matsuyama, H. Hara, K. Yamamura, Y. Sano, K. Ueno, et al., 2005, Fabrication of elliptically figured mirror for focusing hard x-rays to size less than 50nm, *Rev. Sci. Instrum.* 76(6): 63708.

[40] H. Mimura, et al., 2014, Generation of 1020 W cm−2 hard x-ray laser pulses.

devices.[41] There is no intrinsic limit to the gain bandwidth in a free-electron-based gain medium, so in addition transform limited pulses could be extremely short. Attosecond and even sub-attosecond *zeptosecond* pulse lasers have been proposed.[42]

In order to generate transform-limited pulses, the electron beam can be manipulated to have only sufficient quality to lase on a single SASE gain spike.[43] Self-seeding is another method, where an initial SASE FEL is filtered to produce a transform-limited energy slice, which is subsequently amplified to saturation in a downstream section of the undulator.[44] Several methods that employ an upstream laser to co-propagate with the electron beam in order to condition its momentum distribution, thereby seeding the microbunching process. These include as examples, harmonic multiplication (HGHG methods),[45] the beam echo effect (EEHG),[46] and direct injection of harmonics.[47]

### *Attosecond and Zeptosecond Pulses*

Since the gain bandwidth in a FEL is effectively unlimited there are also many methods proposed and some demonstrated for attosecond pulses or shorter. Most of these are based on using lasers upstream from the undulator to co-propagate with and thereby condition the electron bunch in advance.[48] Methods to measure sub-femtosecond pulses have also been reported.[49] There have even been serious recent attempts to lay the path toward zeptosecond pulses.[50]

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[41] E. Hemsing, G. Stupakov, D. Xiang, and A. Zholents, 2014, Beam by design: Laser manipulation of electrons in modern accelerators, *Reviews of Modern Physics* 86(3): 897–941.

[42] M. Ferrario, J. B. Rosenzweig, L. Serafini, D. J. Dunning, B. W. J. McNeil, and N. R. Thompson, 2014, Proceedings of the workshop 'Physics and Applications of High Brightness Beams: Towards a Fifth Generation Light Source' Towards Zeptosecond-Scale Pulses from X-Ray Free-Electron Lasers, *Phys. Procedia* 52: 62-67.

[43] S. Reiche, P. Musumeci, C. Pellegrini, and J. B. Rosenzweig, 2008, Development of ultra-short pulse, single coherent spike for SASE X-Ray FELs, *Nucl. Instrum. Methods Phys. Res. Sect. -Accel. Spectrometers Detect. Assoc. Equip* 593(1-2): 45-48; J.B. Rosenzweig, D. Alesini, G. Andonian, M. Boscolo, M. Dunning, L. Faillace, M. Ferrario, et al., 2008, Generation of ultra-short, high brightness electron beams for single-spike SASE FEL operation, *Nucl. Instrum. Methods Phys. Res. Sect. -Accel. Spectrometers Detect. Assoc. Equip* 593 (1–2): 39–44.

[44] J. Amann, W. Berg, V. Blank, F.-J. Decker, Y. Ding, P. Emma, Y. Feng, et al., 2012, Demonstration of self-seeding in a hard x-ray free-electron laser, *Nat. Photonics* 6(10): 693-698; D. Ratner, et al., 2015, Experimental demonstration of a soft x-ray self-seeded free-electron laser, *Physical Review Letters* 114(5): 054801; A. A. Lutman, F.-J Decker, J. Arthur, M. Chollet, Y. Feng, J. Hastings, Z. Huang, et al., 2014, Demonstration of single-crystal self-seeded two-color x-ray free-electron lasers, *Physical Review Letters* 113(25): 254801.

[45] L. H. Yu, 1991, Generation of intense UV radiation by subharmonically seeded single-pass free-electron lasers, *Physical Review A* 44(8): 5178–5193.

[46] G. Stupakov, 2009, Using the beam-echo effect for generation of short-wavelength radiation, *Physical Review Letters* 102(7): 074801.

[47] T. Popmintchev, M.C. Chen, P. Arpin, M.M. Murnane, and H.C. Kapteyn, 2010, The attosecond nonlinear optics of bright coherent x-ray generation, *Nature Photonics* 4(12): 822–832.

[48] A. A. Zholents and G. Penn, 2005, Obtaining attosecond x-ray pulses using a self-amplified spontaneous emission free electron laser, *Physical Review Special Topics - Accelerators and Beams* 8(5): 050704; Y. Ding, Z. Huang, D. Ratner, P. Bucksbaum, and H. Merdji, 2009, Generation of attosecond x-ray pulses with a multicycle two-color enhanced self-amplified spontaneous emission scheme, *Physical Review Special Topics - Accelerators and Beams* 12(6): 060703.

[49] N. Hartmann and J.M. Glownia, 2016, X-ray photonics: Attosecond coherent control at FELs, *Nature Photonics* 10(3): 148–50; N Hartmann, W. Helml, A. Galler, M. Bionta, J. Grünert, S. Molodtsov, K. Ferguson, et al., 2014, Sub-femtosecond precision measurement of relative x-ray arrival time for free-electron lasers, *Nature Photonics* 8: 706-709.

[50] M. Ferrario et al., 2014, Proceedings of the workshop.

### *Multi-Terawatt Free-Electron Lasers*

The intrinsic efficiency of a SASE-based FEL is the ratio of the photon to electron total pulse energy. At LCLS one 250 pC ($1.56 \times 10^9$) 15 GeV electrons possess 250 mJ of kinetic energy, which is converted into several mJ of 10 keV laser radiation, so the efficiency is approximately one percent. The limit is due to the loss of the resonance condition when the electrons lose energy and their oscillating orbits shift in the undulator. This could be compensated by changing the period of the undulator to maintain resonance at the same lasing wavelength. Recent studies of undulator tapering predict that extraction efficiencies could be raised to as much as 12 percent, which would then yield a hard X-ray FEL with a power of several terawatts.[51]

[51] C. Emma, K. Fang, J. Wu, and C. Pellegrini, 2016, High efficiency, multiterawatt x-ray free electron lasers, *Phys. Rev. Accel. Beams* 19(2): 20705.

# C

# Suppelemental information on the International Community

## APPENDIX C1. USER COMMUNITY SEARCH

### Search Terms

TS=((Gemini AND High Power laser) OR (Vulcan AND laser) OR (NOVA AND High power lasers) OR (high power laser AND titan) OR (high power laser AND gekko xii) OR (high power laser AND z-petawatt) OR (high power laser AND texas petawatt laser) OR (high power laser AND PHELIX) OR (high power laser AND orion) OR (high power laser AND omega EP) OR (high power laser AND PETAL or LMJ or Laser Mega Joule) OR (high power laser AND LFEX) OR (high power laser AND NIF arc) OR (high power laser AND (SG-ii-u OR Divine Light OR Shenguang)) OR (high power laser AND (APOLLON OR ELI)) OR (high Power Laser AND (PENELOPE OR POLARIS)) OR (High power laser AND NIF AND National Ignition Facility) OR (high power laser AND (laser mega Joule OR (LMJ and CEA))) OR (high power laser AND UFL-2M) OR (laser AND TARANIS) OR (High power laser AND (ICAN OR IZEST)) OR (high power laser AND (ELI-L3 OR HAPLS)) OR (Petawatt laser AND VEGA) OR (High Power laser AND CETAL) OR (High Power Lasers AND J-Karen) OR (High Power Lasers AND (DRACO OR Pulsar PW)) OR (High Power Lasers AND (PULSER i OR Pulser ii)) OR (PW Laser AND BELLA) OR (High Power Lasers AND Diocles) OR (High Power Lasers AND laserix) OR (High Power Lasers AND SCAPA) OR (High Power Lasers AND ALLS) OR (High Power Lasers AND XL-iii) OR (High Power Lasers AND SIOM) OR ((High energy density laser) OR (High intensity laser acceleration) OR (High intensity laser plasma)OR (High intensity laser generated) OR (High intensity short pulse)))

The search was carried out using the Web of Science and its built-in analytics tools. The collected data was then exported and organized into the graphs and plots shown within the review. The search terms used are the high power laser systems combined with AND terms to extract only the papers related to the pettawatt-class laser systems; for example, a search for “Vulcan” returns 2,141 publications, but this contains many papers using Vulcan to describe carbon, whereas “Vulcan AND laser” returns only 160 publications. The search is extended for all laser systems using OR statements. If a publication mentions more than one laser system, the record is only counted once using the OR statement to combine search terms. However, when searching for the laser systems by name, many publications were not identified and so the search was extended to include terms to describe the common experiments conducted on these systems such as high intensity laser acceleration, high intensity laser plasma, etc. It is expected that there are more publications than are captured within this; however, it is believed that this search should represent a fair reflection of the publications in the field of pettawatt laser science. Finally, the initial search was completed in October 2016.

There are 96 countries who published work on high power laser from the 1970s to now; however, several of these should be combined, i.e., Northern Ireland, Wales, Scotland, and England should ideally be represented as a single country (UK). A more accurate total of countries publishing work on high power lasers is 91.

**TABLE C.1** Top 20 Organizations publishing in the area of High Intensity Laser Science

| Organizations | Records | % of 21,576 |
|---|---|---|
| **LAWRENCE LIVERMORE NATL LAB** | 762 | 3.532 |
| **RUSSIAN ACAD SCI** | 707 | 3.277 |
| **CHINESE ACAD SCI** | 666 | 3.087 |
| **OSAKA UNIV** | 515 | 2.387 |
| **CEA** | 413 | 1.914 |
| **ECOLE POLYTECH** | 343 | 1.59 |
| **UNIV MICHIGAN** | 324 | 1.502 |
| **UNIV ROCHESTER** | 305 | 1.414 |
| **UNIV LONDON IMPERIAL COLL SCI TECHNOL MED** | 292 | 1.353 |
| **RUTHERFORD APPLETON LAB** | 290 | 1.344 |
| **QUEENS UNIV BELFAST** | 256 | 1.187 |
| **LOS ALAMOS NATL LAB** | 252 | 1.168 |
| **UNIV CALIF BERKELEY** | 247 | 1.145 |
| **UNIV TOKYO** | 215 | 0.996 |
| **USN** | 196 | 0.908 |
| **UNIV OXFORD** | 191 | 0.885 |
| **UNIV JENA** | 186 | 0.862 |
| **MOSCOW MV LOMONOSOV STATE UNIV** | 179 | 0.83 |
| **MIT** | 174 | 0.806 |

**TABLE C.2** Top 15 Organizations-Enhanced*[a]

| Organizations-Enhanced | Records | % of 21,576 |
|---|---|---|
| **UNITED STATES DEPARTMENT OF ENERGY DOE** | 1677 | 7.773 |
| **CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS** | 1046 | 4.848 |
| **CEA** | 1022 | 4.737 |
| **RUSSIAN ACADEMY OF SCIENCES** | 999 | 4.63 |
| **LAWRENCE LIVERMORE NATIONAL LABORATORY** | 945 | 4.38 |
| **CHINESE ACADEMY OF SCIENCES** | 824 | 3.819 |
| **UNIVERSITY OF CALIFORNIA SYSTEM** | 768 | 3.56 |
| **UNIVERSITE PARIS SACLAY COMUE** | 666 | 3.087 |
| **OSAKA UNIVERSITY** | 516 | 2.392 |
| **ECOLE POLYTECHNIQUE** | 514 | 2.382 |
| **MAX PLANCK SOCIETY** | 487 | 2.257 |
| **STFC RUTHERFORD APPLETON LABORATORY** | 391 | 1.812 |
| **UNITED STATES DEPARTMENT OF DEFENSE** | 355 | 1.645 |
| **PIERRE MARIE CURIE UNIVERSITY PARIS 6** | 355 | 1.645 |
| **CZECH ACADEMY OF SCIENCES** | 334 | 1.548 |

*Combined with other results which appear to be same institute, i.e., change of name or same postcode given.

# D

# Medical Applications of Lasers

Preliminary experiments in vitro and in vivo have indicated that a number of medical applications of the secondary particle and photon sources induced by high-intensity short-pulse lasers may become practical. Following is a summary of some of these applications.

## Appendix D1 Imaging with Hard X-Rays

Ultra-high-intensity laser interaction with solid and liquid targets can induce bright point-like sources of hard X-rays. Such sources can produce high resolution, high contrast X-ray transmission images through samples of interest. Phase-contrast imaging is also enabled by the spatial coherence of the X-rays generated by these sources. These features cannot be achieved with ordinary X-rays emitted from tubes.

### D1.1 Phase-Contrast In-Line Imaging and X-ray Computed Tomography

An international study used Canada's Advanced Laser Light Source with 200 TW ultra-high-contrast pulses (5 J, 28 fs, 10 Hz repetition rate) to generate hard X-rays to make phase-contrast images of biological objects.[1]

Experiments have been under way to investigate the feasibility of phase-contrast imaging of tumors in an in-line geometry and proton acceleration for irradiation of tumors by protons, with the same laser producing both the X-ray imaging and the proton acceleration. Early experiments demonstrated that both single-shot phase-contrast imaging and proton acceleration to 12 MeV could be achieved with the same ultrafast laser.

In-line X-ray phase-contrast imaging provided improved density resolution imaging with applications in soft tissue biomedical imaging; it requires an X-ray source with a very small effective size so as to be spatially coherent. In 2005 a laser-based hard X-ray source was first demonstrated to produce high quality in-line phase-contrast imaging with a single pulse. Different parts of the X-ray wave diffracted by the sample interfere with each other and provide the in-line phase contrast imaging. Multiple pulses can create multiple images that have been extended to micro-tomography of a bee, showing details not seen before.[2]

Quantitative phase-contrast micro-tomography from a compact laser-driven X-ray source was reported in 2015 by a group from Germany using their ATLAS laser, which generated X-rays at 8.8 keV by betatron radiation from laser wakefield-accelerated electrons. The 60 TW pulses delivered 1.6 J of energy in 28 fs, with peak intensity of $10^{19}$ W/cm$^2$. Electrons from the plasma are trapped into this wave by wavebreaking and accelerated to relativistic energies around 200–400 MeV. The raw phase-contrast image exhibited edge enhancement, although there were no optical elements between the source and the detector; Fresnel diffraction caused the images. A single edge-enhanced image is, itself, useful to produce

[1] S. Fourmaux, S. Corde, K. Ta Phuoc, S. Buffechoux, S. Gnedyuk, A. Rousse, A. Krol, and J.C. Kieffer, 2011, Initial steps towards imaging tumors during their irradiation by protons with the 200TW laser at the Advanced Laser Light Source facility (ALLS), *Proc. of SPIE* 8079: 80791I-1.

[2] R. Toth, J.C. Kieffer, S. Fourmaux, T. Ozaki, and A. Krol, 2005, In-line phase-contrast imaging with a laser-based hard x-ray source, *Rev. Sci. Instrum*. 76: 083701.

high-resolution features in the presence of poor absorption contrast.[3] Researchers at Imperial College in London have a program to produce a bright $\mu$m-sized source of *hard* synchrotron X-rays (critical energy *Ecrit* > 30 keV) based on the betatron oscillations of laser wakefield-accelerated electrons using their Astra-Gemini laser facility.[4] The potential of this source for medical imaging was demonstrated in 2015 by performing micro-computed tomography of a human femoral trabecular bone sample, allowing full 3D reconstruction to a resolution below 50 $\mu$m. The pulses were 40 fs long and 11 J was delivered to the target and focused with a parabolic mirror, with a peak intensity ~$1.8 \times 10^{19}$ $Wcm^{-2}$. With high peak brightness, each image is recorded with a single exposure, reducing the time required for a full tomographic scan. These properties make this an interesting laboratory source for many tomographic imaging applications.

Diagnosis and treatment of osteoporosis requires knowing their microstructure, which cannot be seen in regular radiography. The small-scale structure of bone requires 3D imaging with at least 100 $\mu$m spatial resolution. X-ray computed micro-tomography ($\mu$CT) is now the leading method for determining the internal microstructure of human bone. It requires, however, higher beam energy to be medically relevant. By using wakefield acceleration to near-GeV levels, the X-ray spectrum and brightness were sufficient for single-shot bone imaging while maintaining the advantageously small X-ray source size.

## Appendix D2 Laser-Accelerated Hadron Beams for Cancer Therapy

Hadron ion beams (i.e., protons and heavier ions) are preferred in the radiotherapy of malignant tumors, compared to widely used X-rays or electrons, because they show little spatial scattering and their kinetic energy is deposited primarily near the end of their trajectory. Compared to X-rays or high-energy electron beams, a high-energy hadron beam more precisely irradiates tumors with considerably smaller deposition in surrounding healthy tissue. The existing accelerator technology for high-energy ion beams, cyclotrons, and synchrotrons, plus the beam transport technology and radiation shielding, is complex, very costly, and available only in a few large-scale facilities. The demand for more compact, flexible, and less costly high-gradient acceleration and beam transport techniques is, however, evident.
High-intensity laser-driven ion beams have been suggested as a potential alternative to conventional ion accelerators for radiotherapy. When a laser pulse with intensity above $10^{18}$ $W/cm^2$ interacts with a thin foil target in vacuum, a strong electrostatic field exceeding 1 TV/m is generated at the downstream surface, which can surpass the ion-acceleration field typical of conventional accelerators by six orders of magnitude. A unique feature of laser acceleration is the extremely high peak current attributed mostly to the short duration of a single proton bunch.

Global research is under way, with the hope that laser-accelerated proton beams can become the dominant technology for proton radiotherapy. However, this goal is still a long way off: laser-driven hadron accelerators must have medically relevant beam parameters and performance levels suitable for clinical usage.[5] Research toward the practicality of laser-accelerated ion beam therapy for cancer patients is under way in a number of countries.[6]

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[3] J. Wenz, S. Schleede, K. Khrennikov, M. Bech, P. Thibault, M. Heigoldt, F. Pfeiffer, and S. Karsch, 2015, Quantitative X-ray phase-contrast microtomography from a compact laser-driven betatron source, *Nature Communications* 6: 7568.

[4] J.M. Cole, J.C. Wood, N.C. Lopes, K. Pode1, R.L. Abe, S. Alatabi, J.S.J. Bryant, et al., 2015, Laser-wakefield accelerators as hard x-ray sources for 3D medical imaging of human bone, *Scientific Reports* 5: 13244.

[5] K.W.D. Ledingham, P. McKenna, T. McCanny, S. Shimizu, J.M. Yang, L. Robson, J. Zweit, et al., 2004, High power laser production of short-lived isotopes for positron emission tomography, *J. Phys. D: Appl. Phys.* 37(16): 2341.

[6] Countries include Japan (J-KAREN), Germany (Dresden Laser Acceleration Source and CALA [a collaboration between LMU and TUM]), United Kingdom (LIBRA collaboration at TARANIS and the Terawatt

### D2.1 Initial Biological Experiments

In 2009 the first experiments to demonstrate the biological effects of high-current, short-bunch ion beams accelerated by lasers took place in Japan.* The researchers demonstrated that laser-generated proton irradiation causes breaks in the double-strand deoxyribonucleic acid (DNA) of in vitro (living) human lung cancer cells (Fig. D1).[7]

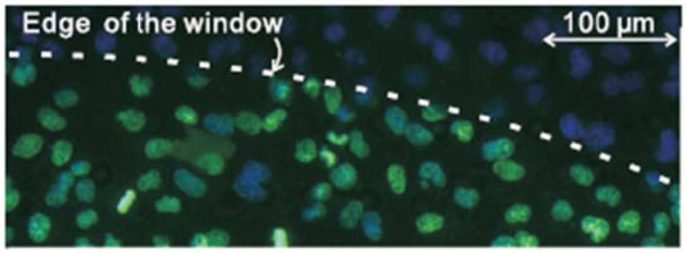


**FIGURE D1** DNA double strand breaks (stained green) after irradiation with laser-accelerated proton beam with energy up to 2.5 MeV. Unaffected nuclei are stained blue.[8] SOURCE: A. Yogo, K. Sato, M. Nishikino, M. Mori, T. Teshima, H. Numasaki, M. Murakami, et al., 2009, Application of laser-accelerated protons to the demonstration of DNA double-strand breaks in human cancer cells, *Applied Physics Letters* 94(18): 181502.

This initial research was followed by groups of researchers in a number of countries to determine the dose dependence and to better understand the biological damage created in tumor cells. A group in Dresden, Germany, formed a collaboration between medical personnel and physicists to study dose-dependent biological damage due to irradiation of in vitro tumor cells with laser-accelerated proton pulses.[9]

### D2.2 Recent Progress Toward Cancer Therapy

Progress in Japan was achieved in 2011 by modifying the previous J-KAREN laser system to produce a monoenergetic proton beamline for laser-generated protons.[10] The experiments were planned to determine the relative biological effectiveness for cell inactivation by laser-accelerated MeV ions of cultured cancer cells from the human salivary gland (HSG cells). Irradiated cells were immediately removed and placed in an incubator for 13 days, after which they were fixed and stained. Any colony consisting of more than 50 cells was counted as a surviving colony. The ratio of *biological* effectiveness

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laser at Queen's University), and the United States (Brookhaven at the Accelerator Test Facility using a $CO_2$ laser and Philadelphia’s Fox Chase Cancer Center).

[7] A. Yogo, K. Sato, M. Nishikino, M. Mori, T. Teshima, H. Numasaki, M. Murakami, et al., 2009, Application of laser-accelerated protons to the demonstration of DNA double-strand breaks in human cancer cells, *Applied Physics Letters* 94(18): 181502.

[8] A. Yogo, K. Sato, M. Nishikino, M. Mori, T. Teshima, H. Numasaki, M. Murakami, et al., 2009, Application of laser-accelerated protons to the demonstration of DNA double-strand breaks in human cancer cells, *Applied Physics Letters* 94(18): 181502.

[9] S.D. Kraft, C. Richter, K. Zeil, M. Baumann, E. Beyreuther, S. Bock, M. Bussmann, et al., 2010, Dose-dependent biological damage of tumour cells by laser-accelerated proton beams, *New J. Phys.* 12: 085003.

[10] A. Yogo, T. Maeda, T. Hori, H. Sakaki, K. Ogura, M. Nishiuchi, A. Sagisaka, et al., 2011, Measurement of relative biological effectiveness of protons in human cancer cells using a laser-driven quasimonoenergetic proton beamline, *Applied Physics Letters* 98: 053701.

in killing cells of a laser-generated proton beam was compared to 4 MeV X-rays from a clinical Linac, given the same amount of absorbed energy. The proton beam was slightly more effective in killing cancer cells than the X-rays by a ratio of 1.2.

Laser-accelerated protons have the unique characteristic of being deposited in bunches at very high intensity. Several experiments have compared laser-accelerated protons with conventionally accelerated protons. The experiments irradiate living tumor cell cultures, determine their killing rates, and compare them with the rates of conventionally accelerated proton beams.[11]

The UK has been carrying out similar research through a UK-wide consortium called Laser Induced Beams of Radiation and Applications (LIBRA). Its aim has been also to develop laser-driven ion sources with a particular focus on biomedical applications, noting that particularly high-profile application for laser-driven ion beams is particle therapy for cancer treatment. The LIBRA program, centered at The Queen's University of Belfast, realized that practical systems will require significant improvements from the performance of today's laser-driven accelerators.[12]

The next year, in a collaboration with University of Birmingham and its hospital as well as the Ion Beam Centre at University of Surrey, the same researchers studied proton irradiation and the biological effect of proton irradiation on human V79 cells and compared it to data obtained with the same cell line irradiated with an X-ray source with peak 225 kV energy conventionally accelerated protons. They saw a similar relative biological effectiveness in killing cells as was seen in Japan: the Relative Biological effectiveness was 1.4, which means the protons were 40 percent more likely to kill cells at the same dose rate than the X-rays.[13]

Recent research in Munich with the 200 TW ARCTURUS laser system at the University of Düsseldorf, Germany, found that laser-accelerated proton bunches might provide a real advantage over the longer synchrotron pulses. Their studies suggest that, while the biological effectiveness of laser-accelerated protons and conventionally accelerated protons are roughly equal with regard to double strand breaks in DNA and tumor cell killing, they have found that laser-accelerated proton pulses apparently produce less immediate nitroxidative stress.

### D2.3 Consortia Working on Laser-Accelerated Proton Beams for Cancer Therapy

While these experiments were carried out and reported, research consortia have been formed and funded throughout Europe to investigate the clinical future of proton irradiation, particularly with femtosecond bunches of protons, with technology originating from mode-locked Ti-sapphire lasers.

Clinical trials using proton and carbon beams are under way in several countries with traditional cyclotron and synchrotron accelerators. One of the chief obstacles to wide-scale use of particle-based therapy, however, is the large cost of the accelerators. For example, the Heavy Ion Medical Accelerator in Chiba, Japan, had a construction cost of almost 300 million dollars, but it can treat only 200 patients a year—a small fraction of cases that could benefit from this form of cancer therapy. Motivated by a desire to reduce the size and cost of radiotherapy facilities, researchers in Japan are setting out to combine a 100 TW, 20 fs laser with a special purpose pulsed synchrotron that will accelerate carbon ions. The ultimate goal of this effort is to produce a device that can be installed in a hospital, with reductions in size, by an order of magnitude, and in cost, by a factor of five compared with existing devices.

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[11] S. Raschke, S. Spickermann, T. Toncian, M. Swantusch, J. Boeker, U. Giesen, G. Iliakis, O. Willi, and F. Boege, 2016, Ultra-short laser-accelerated proton pulses have similar DNA-damaging effectiveness but produce less immediate nitroxidative stress than conventional proton beams, *Nature Scientific Reports* 6: 32441.

[12] M. Borghesi, S.Kara, R. Prasada, F.K. Kakolee, K. Quinn, H. Ahmed, G. Sarri, et al., 2011, Ion source development and radiobiology applications within the LIBRA project, *Proc. of SPIE* 8079: 80791E-1.

[13] F. Hanton, D. Doria, K.F. Kakolee, S. Kar, S.K. Litt, F. Fiorini, H. Ahmed, et al., 2013, Radiobiology at ultra-high dose rates employing laser-driven ions, *Proc. of SPIE* 8779: UNSP 87791E.

The Technical University of Munich and Ludwig Maximilians University of Munich have jointly built a new 70-million-Euro laser center expanding on their already existing, broad range of research into laser science and technology for applications in the fields of life sciences and medicine. Research at CALA aims at developing laser-based technologies in order to improve the cure rates of cancer patients through a combination of early detection and targeted particle therapy. These technologies also offer the potential for the early detection of other chronic diseases such as osteoarthritis, atherosclerosis, and diffuse lung diseases, which—like cancer—seem to show increasing prevalence. It was initially scheduled to be commissioned in 2016 but has seen some delays.

CALA's plan is first to include brilliant X-rays produced by a compact laser-driven or laser-assisted source to localize the tumor by means of advanced imaging techniques. This procedure, if successfully demonstrated, will allow recognition of the primary tumor at a stage when the probability for metastases is still very low. Secondly, knowing precisely the anatomical site of the tumor offers the prospect of curing the patient with a localized, high-precision, laser-driven radiation and particle therapy. Both parts of the clinical procedure are expected to use the same laser source. The novel techniques hold promise for improving present diagnostic and therapeutic capabilities as well as reducing the socioeconomic cost of combatting several chronic diseases.

In the UK, acceleration to high energies (several tens of MeV/nucleons) has been possible only on large Nd:glass systems, such as the Vulcan laser at RAL, up to hundreds of joules in ps pulses. But they operate only on a single shot basis (i.e., a laser shot every 20 minutes or so). Biomedical applications are expected to require many well-controlled pulses, and most interesting systems are based on Ti:Sapphire technology, which reach high powers by providing smaller amounts of energy (up to a few joules) in pulses a few tens of fs long, and can operate at higher repetition rate. For example, the Gemini system currently operational at RAL delivers laser pulses at 20-second intervals, but emerging laser technologies based on diode pumping of the amplifier media have the potential to deliver within a few years high power pulses with much higher repetition. These high repetition rates will be needed for use in cancer therapy or radioisotope production, and upgrades to simultaneously increase intensity and repetition rates are the direction of their research.

### D2.4 Medical Research Under Extreme Light Infrastructure

The Extreme Light Infrastructure (ELI) project described in Chapter 3 identifies several great challenges in molecular, biomedical, and material sciences of the 21st century:

Measuring the mechanisms of physical and chemical processes at the atomic scale. Controlling electronic processes in matter. In addition to that, nuclear dynamics following the electronic events should represent a subject of control.

Understanding the complexity—efficient methods should be developed to control and investigate various processes in real, i.e., highly complex, systems in the state as they are present in nature.

Nanometer scale imaging of arbitrary objects in their native state, e.g., capturing a living cell at nanometer resolution. Nanometrically resolved dynamics of their responses to various stimuli.

## Appendix D3 Laser-Produced Short-Lived Isotopes for Positron Emission Tomography

The well-known medical procedure positron emission tomography (PET) at present requires the nearby presence of a synchrotron to create the short-lived radioactive sources that provide the positrons. Ultra-intense lasers show promise of creating the necessary radioactive sources, although none have yet been demonstrated to be practical. Initial studies are under way in UK, Japan, and elsewhere. This is one of the justifications for ELI, and studies are under way to investigate the feasibility of this approach.

PET is a powerful medical diagnostic/imaging tool. Many chemical compounds can be labeled with positron emitting isotopes, and their bio-distribution can be determined through PET imaging as a function of time: “Positron emission tomography (PET) is a powerful diagnostic/imaging technique requiring the production of the short-lived positron emitting isotopes $^{11}C$, $^{13}N$, $^{15}O$, and $^{18}F$ by proton irradiation of natural/enriched targets using cyclotrons. The development of PET has been hampered due to the size and shielding requirements of nuclear installations. Recent results show that when an intense laser beam interacts with solid targets, MeV protons capable of producing PET isotopes are generated using a petawatt laser beam. The potential for developing compact laser technology for this purpose is high.”[14] Research in this area is also under way in the UK using the new petawatt arm of the Vulcan Nd : Glass laser at RAL. Esirkepov et al. have discussed the production of mono-energetic protons using layered targets.[15] Some recent calculations at Strathclyde conclude that if quasi-monoenergetic protons replace the present quasi-exponential distribution, then a further significant improvement is possible.

[14] K.W.D. Ledingham, et al., 2004, High power laser production.
[15] Esirkepov et al. [20]

# E

## PETAWATT-CLASS LASERS SUMMARY

This appendix summarizes the state of petawatt-class lasers around the world and is a provided as an informative supplement to Chapter 4.

### E.1 Nd:Glass Petawatt-Class Lasers

The multi-kJ petawatt beamlines have all been primarily built to give advanced x-ray radiography capability to megajoule-class long pulse interaction facilities. They typically operate at a pulsewidth of 10 ps with multi-kJ energy outputs. The beamlines are also used for fast-ignition experiments and as high intensity interaction beams in their own right.

The megajoule-class lasers, although designed to operate in the nanosecond regime, are true petawatt-class facilities due to their enormous scale. The multi-pass technology allows close packing of the beamlines at large aperture, producing a multi-pass stacked laser architecture. They were originally designed jointly between the United States and France for use on NIF and Laser Mégajoule (LMJ)[1] and are now replicated throughout the world.


**FIGURE E.1** Locations of glass-based systems worldwide. SOURCE: J. Collier, Rutherford Central Laser Facility.

[1] J.L. Miquel, 2016, LMJ & PETAL status and first experiments, *J. Phys.: Conf. Ser.* 717(1): 012084.

**TABLE E.1** Summary of the Operational, Under Construction, and Proposed Glass-Based PW-Class Lasers in the World[a]

| System Name | Operating Facility | Location | Energy (J) | Pulsewidth (fs) | Peak Power (PW) | Date Operational | Rep Rate (Hz) |
|---|---|---|---|---|---|---|---|
| **Glass systems** | | | | | | | |
| **Nova** | LLNL | Livermore USA | 660 | 440 | 1.5 | 1996 | Single-Shot |
| **Vulcan** | CLF, STFC | Oxford, UK | 500 | 500 | 1 | 2002 | Single-Shot |
| **GekkoXII** | ILE | Osaka Japan | 420 | 470 | 0.89 | 2003 | Single-Shot |
| **Titan** | LLNL | Livermore USA | 300 | 400 | 0.75 | 2007 | 2/hr |
| **Z-Petawatt** | SNL | Sandia USA | 500 | 500 | 1 | 2010 | Single-Shot |
| **Texas Petawatt Laser** | Univeristy of Texas, Austin | Austin USA | 186 | 167 | 1.11 | 2010 | Single-Shot |
| **PHELIX** | GSI, LLNL,CEA | Darmstadt, Germany | 400 | 350 | 1.14 | 2016 | Single-Shot |
| **SG-II-U (PW)** | SIOM | Shanghai China | 1000 | 1000 | 1 | 2010 | Single-Shot |
| **Orion** | AWE | Aldermaston UK | 500 | 500 | 1 | 2013 | Single-Shot |
| **Omega EP** | LLE, UoRochester | Rochester, USA | 1000 | 1000 | 1 | 2008 | Single-Shot |
| **PETAL** | CEA | Bordeaux France | 3500 | 500 | 7 | 2015 | Single-Shot |
| **LFEX** | ILE | Osaka Japan | 50000 | 10000 | 5 | 2015 | Single-Shot |
| **ELI-Beamlines L4** | ELI | Prague Czech Republic | 1500 | 150 | 10 | 2018 | 1/min |
| **Megajoule lasers** | | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **NIF** | LLNL | Livermore USA | 1.80E+06 | 3.60E+06 | 0.5 | 2009 | Single-Shot |
| **LMJ** | CEA | Bordeaux France | 1.80E+06 | 3.00E+06 | 0.6 | 2020 | Single-Shot |
| **UFL-2M - IR** | IAP RAS | Nizhny Novgorod. Russia | 4.60E+06 | 3.00E+06 | 1.53 | TBD | Single-Shot |
| **SG-IV** | SIOM | Mianyang China | 1.80E+06 | 3.00E+06 | 0.6 | TBD | Single-Shot |

[a]The summary includes PW-class lasers with a peak power > 0.5 PW, which are currently operational, under construction (i.e., funded), or proposed *(i.e.*, unfunded*)*. Aspirational systems for which there is no published design or tender have been omitted.

### E.1.1 Facilities Descriptions

***Europe***

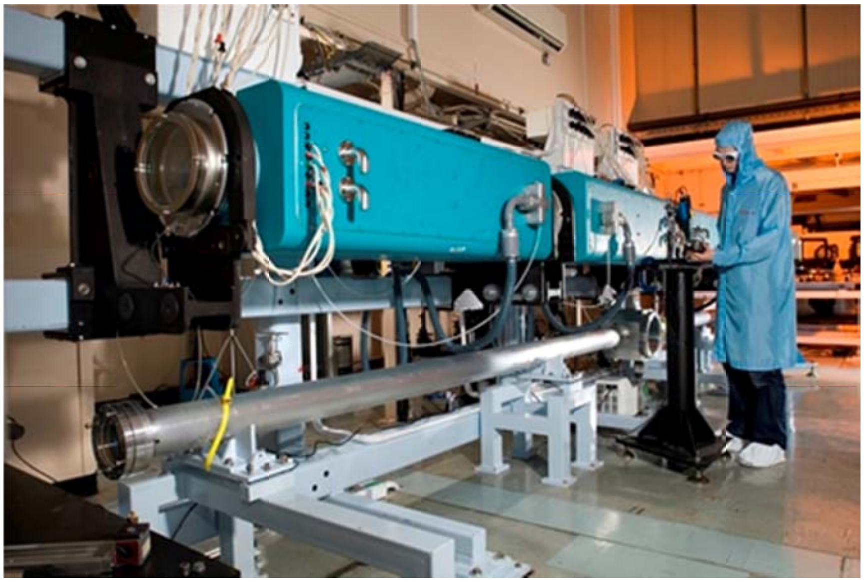

**FIGURE E.2** The amplifiers at the Vulcan laser. SOURCE: Rutherford Central Laser Facility, https://www.clf.stfc.ac.uk

The **Vulcan** laser system[2] has been operational for over 30 years, operating within the petawatt regime since 2002. Having opened to the international plasma physics community 2 years later, currently Vulcan remains the longest-running dedicated user facility at petawatt-class. The system consists of an

[2] C.N. Danson, P.A. Brummitt, R.J. Clarke, J.L. Collier, B. Fell, A.J. Frackiewicz, S. Hancock, S. Hawkes, C. Hernandez-Gomez, and P. Holligan, 2004, Vulcan Petawatt—an ultra-high-intensity interaction facility, *Nuclear Fusion* 44(12): 239–246.

OPCPA front end leading toward a high-power Nd:glass main amplifier. This produces pulses at 500 J in a pulsewidth of 500 fs, an intensity of $10^{21}$ W/cm$^2$ is incident on Vulcan's petawatt target area.

**Orion**[3] became operational in April 2013 at AWE in south England. It is a Nd:glass laser system with a short-pulse petawatt beamline operating within the same regime as Vulcan. In addition to defense research, the facility has also published research in inertial confinement fusion and astrophysics.

Petawatt High Energy Laser for heavy Ion eXperiments (**PHELIX**)[4] was constructed at the Helmholtz Center GSI as a collaboration between LLNL and the Commissariat à l'Energie Atomique (CEA). Currently producing 250 J pulses of 400 fs, a planned upgrade for the laser is designed to deliver pulses of over 1 petawatt at 400 J in 350 fs. The facility is expected to produce high temporal contrast of $10^{-12}$. The upgraded laser is planned to be integrated into the Helmholtz beamline at the Facility for Antiproton and Ion Research (FAIR), providing a high repetition rate ion beam source.[5]

The ELI is currently constructing a beamlines facility in the Czech Republic. **Beamlines L4** is estimated to complete construction in 2018.[6] The goal for this system is to produce 1.5 kJ pulses within 150 fs. At completion, this 10 PW pulse will represent the highest achieved peak power of any glass system. In addition, its projected focussed intensity of $10^{24}$ W/cm$^2$ would be greater than contemporary facilities by at least an order of magnitude.

**LMJ** is currently under construction in CESTA, Bordeaux.[7] The facility, operated by the French Alternative Energies and Atomic Energy Commission (CEA) houses a number of lasers primarily focused on ICF. PETawatt Aquitaine Laser (**PETAL**) functions In addition to the main beamlines. It is able to supply pulses around 1 kJ in the region of 0.5 ps to 10 ps. The beam is designed to work synchronously with the main LMJ beamlines; its primary function will therefore likely be in diagnostics. PETAL was inaugurated in September 2015, producing 1.2 PW pulses at 840 J in 700 fs. It is expected to open to users in 2017. An upgrade for the beamline ultimately aims to increase pulse energy to 6 kJ. Operations combining the LMJ and PETAL are slated for this year.

The main megajoule component of the **LMJ** currently incorporates 22 beamlines divided into 176 beams traveling to the target chamber. There the light is converted into UV via frequency conversion to the third harmonic (3ω- 351 nm). The first operations at the LMJ began in 2014 with now several preliminary campaigns. LMJ is currently in the process of being upgraded—initially to 1.4 MJ operation—using the installed 176 beamlines. The final design of the facility includes 240 long-pulse beams arranged in 30 lines of eight beams. This corresponds to 1.8 MJ on target at 3ω.

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[3] N. Hopps, K. Oades, J. Andrew, C. Brown, G. Cooper, C. Danson, S. Daykin, S. Duffield, R. Edwards, and D. Egan, 2015, Comprehensive description of the Orion laser facility, *Plasma Physics and Controlled Fusion* 57(6): 064002; N. Stuart, T. Robinson, D. Hillier, N. Hopps, B. Parry, I. Musgrave, G. Nersisyan, A. Sharba, M. Zepf, and R. A. Smith, 2016, Comparative study on the temporal contrast of femtosecond mode-locked laser oscillators *Opt. Lett.* 41(14): 3221-3224.

[4] T. Kuehl, 2014, "GSI PHELIX (Petawatt High Energy Laser for heavy-Ion eXperiments)," presented at IZEST–ELI-NP "Extreme Light's New Horizons" Conference, Paris, Sept. 17-19.

[5] Helmholtz Association, 2011, Helmholtz-Roadmap for Research Infrastructures, https://www.helmholtz.de/fileadmin/user_upload/publikationen/pdf/11_Helmholtz_Roadmap_EN_WEB.pdf.

[6] G. A. Mourou, G. Korn, W. Sandner, and J.L. Collier, 2011, *ELI WHITEBOOK*, Berlin, THOSS Media GmbH.

[7] J.L. Miquel, 2016, LMJ & PETAL status and first experiments.

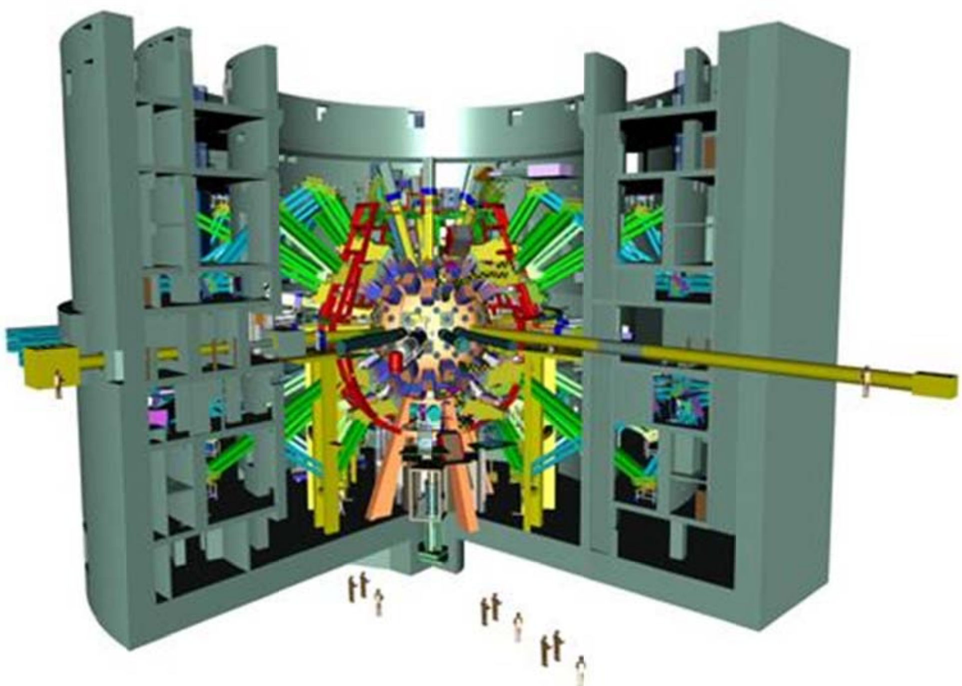

**FIGURE E.3** Design of the interaction chamber based at the LMJ where ignition fusion experiments are performed. SOURCE: Sylvain Girard, Université Jean Monnet

In Russia, there are plans to construct a megajoule facility, **UFL-2M**.[8] The Institute of Applied Physics of the Russian Academy of Science (IAP RAS) based in Nizhny Novgorod, Russia, began construction early in 2012. This facility plans to combine 192 laser beams (of cross-sectional area 400x400 $mm^2$) arranged in 48 beamlines. The facility will deliver 4.6 MJ at 1ω and 2.8 MJ at 2ω (527 nm). This facility, again, is aimed at research surrounding ICF. The peak power of the system, over 1.5 PW, is the greatest of any other planned megajoule facility.

### *North America*

The **Nova** facility[9] was the first petawatt-class laser system to become operational. Based at LLNL, the beamline was capable of delivering 660 J in a 440 fs pulse corresponding to peak powers of 1.5 PW and intensities of $7 \times 10^{20}$ W/$cm^2$. Nova was dismantled in 1999 for the facility to incorporate NIF.

**Titan**[10] is one of the five lasers that make up the Jupiter Laser Facility at LLNL. The Jupiter facility uses several beamlines to investigate laser-matter interaction. Titan is a two beam, petawatt-class laser coupled to a kJ beamline. Recently the front end of the system has been updated to an OPCPA seed

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[8] V.B. Rozanov, S.Y. Gus'kov, G.A. Vergunova, N.N. Demchenko, R.V. Stepanov, I.Y. Doskoch, R. A. Yakhin, and N.V. Zmitrenko, 2016, Direct drive targets for the megajoule facility UFL-2M, *J. Phys.: Conf. Ser.* 688(1): 012095.

[9] M.D. Perry, D. Pennington, B.C. Stuart, G. Tietbohl, J.A. Britten, C. Brown, S. Herman, et al., 1999, Petawatt laser pulses, *Optics Letters* 24(3): 160-162.

[10] P.K. Patel, 2006, “Titan Laser Jupiter Laser Facility,” presented at the Fusion Science Center Meeting, Livermore, Calif., Aug. 28-29.

pulse. Titan's short pulse beamline delivers up to 0.75 PW in a sub-picosecond pulse as well as a 50 J, 2ω option with average contrast to the order of $10^{-5}$.

Many petawatt-class lasers play a heavy role in particle acceleration; this is especially true of the **Z-Petawatt**.[11] This facility uses enhanced photon radiography to study high energy density events created by z-pinch accelerated x-rays. Originally constructed at LLNL but later moved to Sandia National Laboratory (SNL), Z-Petawatt was active at 100 TW in 2008 and reached petawatt-class in 2010. The combination of an OPCPA front end and Nd:phosphate glass amplifiers produces pulses of 500 J within 500 fs.

The **Texas Petawatt** Laser[12] based at the Center for High Energy Density Science at the University of Texas at Austin uses a high energy OPCPA front end with optimized mixed glass to produce shorter pulses than traditional glass petawatt facilities—186 J in 167 fs. The Texas Petawatt has accelerated electrons up to energies of 7 GeV.

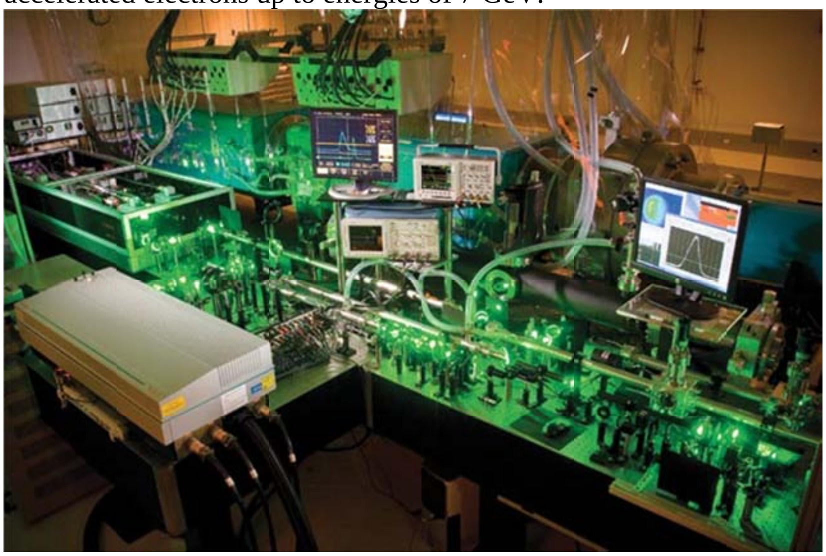

**FIGURE E.4** The Texas Petawatt laser system. SOURCE: Todd Ditmire presentation to the Committee, May 10, 2016

**Omega Extended Performance (EP)**[13] was inaugurated as the first operational multi-kJ petawatt-class facility in 2008 at the Laboratory for Laser Energetics (LLE) at the University of Rochester. The laser was built for development of fast ignition ICF and therefore couples high pulse energy, high intensity and a short pulse length. The facility is based upon four beamlines, two of which operate for short pulses. In combination with the OMEGA beamlines, a highly flexible array of outputs is possible, delivering 1 PW performance at 1 ps and up to 6.5 kJ performance at pulsewidths >10 ps. The output is also configurable to 3ω light.

**NIF**,[14] at LLNL, is dedicated to development of pathways toward commercial ICF. The beamlines were first opened in March 2009, and NIF is currently the only operational megajoule-scale

[11] J. Schwarz, P. Rambo, M. Geissel, A. Edens, I. Smith, E. Brambrink, M. Kimmel, and B. Atherton, 2008, Activation of the Z-petawatt laser at Sandia National Laboratories, *J. Phys.: Conf. Ser.* 112: 032020.

[12] E.W. Gaul, M. Martinez, J. Blakeney, A. Jochmann, M. Ringuette, D. Hammond, T. Borger, et al., 2010, Demonstration of a 1.1 petawatt laser based on a hybrid optical parametric chirped pulse amplification/mixed Nd:glass amplifier, *Appl. Opt.* 49(9): 1676-1681.

[13] D.N. Maywar, J.H. Kelly, L.J. Waxer, S.F.B. Morse, I.A. Begishev, J. Bromage, C. Dorrer, J.L. Edwards, L. Folnsbee, and M.J. Guardalben, 2008, OMEGA EP high-energy petawatt laser: progress and prospects, *Journal of Physics: Conference Series* 112(3): 032007.

[14] L.J. Perkins, R. Betti, K.N. LaFortune, and W.H. Williams, 2009, Shock ignition: A new approach to high gain inertial confinement fusion on the National Ignition Facility, *Phys. Rev. Lett.* 103: 045004; E.I. Moses, J.

facility. The facility delivers 192 40 x 40 beams to target. Since January 2013, NIF has been capable of delivering energy over 1.8 MJ in long pulses of 3.6 ns. This represents pulses of 3ω light at 0.5 PW. Recently, NIF published results claiming positive energy output from fusion interaction.[15,16]

**FIGURE E.5** NIF beamlines. SOURCE: NIF website laser.llnl.gov

### *Asia*

**Gekko XII**[17] was the first petawatt-class system constructed in Asia and has been operational since 2003 at the Institute of Laser Engineering (ILE), University of Osaka, Japan. Consisting of an OPCPA front end and 12 Nd:Glass amplified beamlines produce 2ω ultra-short pulses of 420 J in a 470 fs. Similar to many lasers operating in this application space, Gekko XII primarily researches fast ignition for ICF. An F/7 off-axis parabola was used to focus to target, giving focused intensities of $2.5x10^{19}$ $W/cm^2$ with contrast levels of $1{:}5x10^8$ $W/cm^2$.

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Atherton, L. Lagin, D. Larson, C. Keane, B. MacGowan, R. Patterson, M. Spaeth, B. Van Wonterghem, P. Wegner, and R. Kauffman, 2016, The National Ignition Facility: Transition to a user facility, *Journal of Physics: Conference Series* 688(1); E.I. Moses and the NIC Collaborators, 2013, The National Ignition Campaign: status and progress, *Nuclear Fusion* 53(10): 104020.

[15] R. Betti and O. A. Hurricane, "Inertial-Confinement Fusion with Lasers," *Nature Physics*, May 3, 2016, 435–48, doi:10.1038/nphys3736.

[16] O. A. Hurricane et al., "Fuel Gain Exceeding Unity in an Inertially Confined Fusion Implosion," *Nature* 506, no. 7488 (February 20, 2014): 343–48, doi:10.1038/nature13008.

[17] T. Yamanaka, H. Azechi, Y. Fujimoto, H. Fujita, Y. Izawa, T. Jitsuno, Y. Kitagawa, et al., 2002, "Progress in Direct-Drive Laser Fusion UsingXII/PW Facility," presented at the 19th Fusion Energy Conference, Lyon, France, Oct. 14-19.

Also based at the Gekko XII facility is the laser for fast ignition experiment (**LFEX)**,[18] a mutli-petawatt laser operational at high peak powers. LFEX, in addition to Gekko, makes up the fast ignition realization experiment (FIREX) project for research into fast ignition. The system is currently used in fast x-ray generation. In 2015 it published results of operation at 2 PW, the highest peak power of any system at that time. LFEX is under ongoing upgrades with the final goal of producing 5 PW pulses with an input energy of 50 kJ. The beam is focused to target by a 4 m off-axis parabola. The contrast of the final specification will be to the order of $10^{10}$.

The Shanghai Institute of Optics and Fine Mechanics (SIOM) is responsible for the operation of several petawatt-class lasers. SIOM currently houses the highest power, cumulatively, of any major facility worldwide. The first operational petawatt-class system was **SG-II**,[19] the Shenguang (Divine Light) II high energy facility. SG-II was an eight beam Nd:glass laser facility producing long pulses at an energy of 6 kJ with a 2 kJ option at 3ω. A ninth beamline, commissioned in 2005, was later converted to the **SG-II-U PW**[20] beamline in 2010. In the petawatt regime, SG-II-U outputs 1 kJ pulses in 1 ps. SG-II-U also included the building of a separate 24 kJ, 3ω, 3 ns eight-beam facility. SG-II is currently being refitted as a fully OPCPA system. This will be discussed further in a later section.
SIOM currently plans to begin production of another megajoule laser, **SG-IV**.[21] The system is to be built at the Chinese Academy of Engineering Physics (CAEP) Research Center for Laser Fusion, Mianyang, China. Although the design of the system has not been finalized, it is believed to operate within a similar scale to NIF and LMJ. Design options can be tested on SG-IIIP, a prototype beamline contained within SG-III.

### E.2 Ti:Sapphire Petawatt-Class Lasers

The following section describes in brief the major facilities worldwide that house Ti:Sapphire-based petawatt-class lasers. In recent years, advances in technology have sufficiently reduced the scale and cost of high power Ti:Sapphire lasers such that commercial systems operating up to ~300 TW are within reach of university departments from companies such as Amplitude Technologies and Thales. This section will focus primarily on systems that can deliver > 0.5 PW on target.

[18] H. Azechi and FIREX Project Team, 2016, The status of Fast Ignition Realization EXperiment (FIREX) and prospects for inertial fusion energy, *J. Phys.: Conf. Ser.* 717: 012006.
[19] Z. Lin, X. Deng, D. Fan, and X. Xie, 1999, SG-II laser elementary research and precision SG-II program, *Fusion Engineering and Design* 44(1–4): 61-66.
[20] G. Xu, T. Wang, Z. Li, and J. Zhu, 2008, 1 kJ petawatt laser system for SG-II-U program, *The Review of Laser Engineering* 36(APLS): 1172-1175; T. Wang, G. Xu, Y. Dai, Z. Lin, and J. Zhu, 2011, Recent progress on the PW beamline for SG-II-U laser facility, Pp. 1-2 in *CLEO: 2011- Laser Science to Photonic Applications*, Baltimore, Md., May 1-6.
[21] X.T. He and ICF teams in China, 2016, The updated advancements of inertial confinement fusion program in China, *Journal of Physics: Conference Series* 688: 012029.


**FIGURE E.6** Locations of Ti:S systems worldwide. SOURCE: J. Collier, Rutherford Central Laser Facility.

Ti:Sapphire-based systems are not limited to the single PW level. The highest peak power Ti:Sapphire system in development at present is Apollon, which has recently demonstrated 5 PW peak power with a target of 10 PW.[22] Similarly, SIOM is currently constructing a 10 PW laser also currently operational at 5 PW[23] and the ELI-Nuclear Physics (NP) Facility has commissioned 2 x 10 PW systems commercially.[24] However, to achieve such high peak powers, these laser facilities must operate at lower repetition rates (<1 shot/min).

TABLE E.2 provides a comparison of all 22 PW-class Ti:Sapphire lasers currently in operation, under construction, or planned. This presents a statistical overview of > 0.5 PW Ti:Sapphire-based lasers worldwide. Each laser system has been represented by the factors most pertinent to the intended applications of a PW-class Ti:Sapphire system.

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[22] J.P. Zou, C. Le Blanc, D.N. Papadopoulos, G. Chériaux, P. Georges, G. Mennerat, F. Druon, et al., 2015, Design and current progress of the Apollon 10 PW project, *High Power Laser Science and Engineering* 3: e2; F. Giambruno, C. Radier, G. Rey, and G. Chériaux, 2011, Design of a 10 PW (150 J/15 fs) peak power laser system with Ti:sapphire medium through spectral control, *Applied Optics* 50(17): 2617-2621; École Polytechnique, “Birth of Apollon, the Most Powerful Laser Worldwide,” last update September 30, 2015, https://www.polytechnique.edu/en/content/birth-apollon-most-powerful-laser-worldwide?language=en.

[23] Y. Chu. Z. Gan, X. Liang, L. Yu, X. Lu, C. Wang, X. Wang, et al, 2015, High-energy large-aperture Ti:sapphire amplifier for 5 PW laser pulses, *Optics Letters* 40(21): 5011-5014.

[24] F. Lureau, S. Laux, O. Casagrande, O. Chalus, P.A. Duvochelle, S. Herriot, C. Radier, et al., 2015, Design and initial results of 10 PW Laser for ELI-NP, presented at the 2015 European Conference on Lasers and Electro-Optics, Munich, Germany, June 21-25, Optical Society of America.

**TABLE E.2** Summary of the Operational, Under Construction, and Proposed Ti:Sapphire-Based PW-Class Lasers in the World[a]

| System Name | Operating Facility | Location | Energy (J) | Pulsewidth (fs) | Peak Power (PW) | Date Operational | Rep Rate (Hz) |
|---|---|---|---|---|---|---|---|
| **Ti:S systems** | | | | | | | |
| **Ti:Sapp 10Hz** | CLF, STFC | Oxford, UK | 30 | 30 | 1 | TBD | 10 |
| **ELI-L3/ HAPLS** | LLNL, ELI | Prague Czech Republic | 30 | 30 | 1 | 2018 | 10 |
| **VEGA-3** | CLPU | Salamanca, Spain | 30 | 30 | 1 | 2018 | 1 |
| **Atlas 3000** | CALA, MPQ | Munich, Germany | 60 | 20 | 3 | 2017 | 1 |
| **CETAL PW** | CETAL, Thales | Bucharest Romania | 25 | 25 | 1 | 2016 | 0.1 |
| **J-KAREN** | JAEA | Kyoto Japan | 30 | 30 | 1 | 2003 | Single-Shot |
| **J-KAREN-P** | JAEA | Kyoto Japan | 38.5 | 30 | 1.28 | 2014 | 0.1 |
| **DRACO** | HZDR, Amplitude | Dresden Germany | 30 | 30 | 1 | 2013 | 1 |
| **PULSER II** | APRI | Gwangju, South Korea | 44.5 | 30.2 | 1.47 | 2012 | 0.1 |
| **PULSER I** | APRI | Gwangju, South Korea | 34 | 30 | 1.13 | 2010 | 0.1 |
| **BELLA** | Berkeley Lab | Berkley USA | 42 | 30 | 1.4 | 2012 | 1 |
| **Diocles** | Extreme Light Laboratory | U. Neb. Lincoln USA | 30 | 30 | 1 | 2012 | 0.1 |
| **Laserix** | CLUPS | Paris | 40 | 50 | 0.8 | 2011 | 0.1 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | France | | | | | |
| **Gemini 2 PW** | CLF, STFC | Oxford UK | 60 | 30 | 2 | 2019 | 0.05 |
| **Gemini** | CLF, STFC | Oxford UK | 15 | 30 | 0.5 | 2008 | 0.05 |
| **ALLS** | INRS | Canada | 10 | 20 | 0.5 | 2008 | 2.5 |
| **SIOM Ti:S CPA** | SIOM, Amplitude | Shanghai, China | 138.5 | 27 | 5.13 | 2015 | 1/min |
| **XL-III** | IPhys | Beijing, China | 32.3 | 27.9 | 1.16 | 2011 | 0.05 |
| **OPCPA/ Ti:S hybrid lasers** | | | | | | | |
| **Apollon** | CILEX | Paris France | 150 | 15 | 10 | 2018 | 1/min |
| **ELI-ALPS** | ELI | Budapest, Hungary | 40 | 15 | 2.67 | 2018?? | <5 |
| **ELI-NP [1]** | ELI | Romania | 15 | 15 | 1 | 2018 | 0.1 |
| **ELI-NP [2]** | ELI | Romania | 150 | 15 | 10 | 2018 | 1/min |

[a]The summary includes PW-class lasers with a peak power > 0.5 PW and a repetition rate > 0.05 Hz.
SOURCE: J. Collier, Rutherford Central Laser Facility.

### E.2.1 Facilities Descriptions

***Europe***

Operational since 2008, **Gemini**[25] is one of the CLF's flagship lasers and has been accessible to the academic and industrial user communities for many years. It has two beamlines, each delivering 15 J of energy in 30 fs pulses, providing dual 0.5 PW beams to target at a pulse repetition rate of 0.05 Hz.

[25] C.J. Hooker, J.L. Collier, O. Chekhlov, R. Clarke, E. Divall, K. Ertel, B. Fell, et al., 2006, The Astra Gemini Project—A dual-beam petawatt Ti:Sapphire laser system, *J. Phys. IV* 133: 673-677.

**FIGURE E.7** Gemini Laser at the Central Laser Facility. SOURCE: https://www.clf.stfc.ac.uk

Additionally, a planned upgrade to the Gemini system is scheduled to be completed by 2019. **Gemini 2PW** would be capable of producing 60 J, 30 fs pulses at the same repetition rate as its predecessor.

**PULSAR** will be operational in 2019 and will operate up to 1 PW peak power in a 30 fs pulse at 10 Hz repetition rate. The proposed picosecond upgrade to the DiPOLE pump laser will be operational following PULSAR and further expand the research capabilities of this exciting new system.

**APOLLON** is a laser system under development at École Polytechnique, Paris, in partnership with Centre Nationnal de la Recherche Scientifique (CNRS) and CEA.[26] The laser, consisting of an OPCPA front end driving a Ti:Sapphire main amplifier, is predicted to become operational at 5 PW mode, providing 75 J in 15 fs, later this year. Apollon works in a single-shot mode; however, it is capable of producing one shot every minute. The laser currently produces focused intensities of $10^{22}$ W/cm$^2$. Apollon will be used, in part, for particle acceleration research, able to generate beams of protons or electrons at relativistic speeds close to the speed of light.

**ELI Beamlines L3**[27] is currently under development by LLNL, pumped by the High-Repetition-Rate Advanced Petawatt Laser System (HAPLS). It will purportedly offer 30 J pulses with a pulse length of 30 fs. Due to the diode-pumped architecture of the system, the laser will operate at a repetition rate of 10 Hz.

LLNL is providing ELI Beamlines with the uncompressed laser, and ELI Beamlines will integrate with its own pulse compressor.

**ELI- Attosecond Light Pulse Source** (ALPS),[28] ELI's attosecond facility, will house two main petawatt-class beamlines. Each is intended for production of ultra-short attosecond regime pulses. The first is a high repetition rate laser capable of producing pulses approaching 3 PW, with the pulse length confined to within 15 fs. Secondly, a 10 PW beamline will provide high energy pulses in a 30 fs pulsewidth. ELI-ALPS beamlines will be used to drive secondary sources at a variety of targets.

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[26] J.P. Zou, et al., 2015, Design and current progress of the Apollon 10 PW project; F. Giambruno, et al., 2011, Design of a 10 PW (150 J/15 fs) peak power laser system; École Polytechnique, 2015, Birth of Apollon.
[27] B. Rus, et al., 2013, ELI-Beamlines laser systems.
[28] G.A. Mourou, et al., 2011, *ELI WHITEBOOK*.

**ELI-NP**[29] will employ dual beamlines with OPCPA front ends and Ti:sapphire-power amplifiers. The beamlines, based upon the design of APOLLON, will produce 10 PW pulses at 1 shot per minute. In addition, a 1 PW mode, 15 J in 15 fs, of the lasers will operate at a 1 Hz rep rate. The beamlines will drive gamma sources for analyzing nuclear science.

The University of Munich's **Atlas-3000**[30] is a high intensity, high peak power system developed by Centre for Advanced Laser Applications (CALA). It is under construction for operation in 2017. The system, whose final amplifier is supplied by Thales, will be capable of shots at a repetition rate of 1 Hz, energy of 60 J, and a pulsewidth within 20 fs. It is intended for use in particle acceleration research as well as medical science, in particular cancer research.

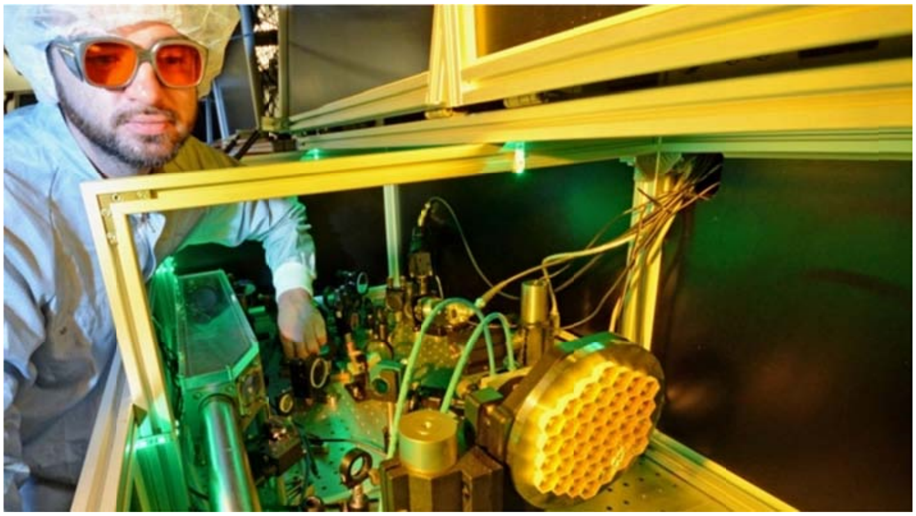

**FIGURE E.8** The CALA facility in Munich, Germany. SOURCE: http://www.cala-laser.de/

The second Thales system, under construction at the Centre for Advanced Laser Technologies National Institute for Laser, Plasma, and Radiation Physics (INFLPR), Romania, is the **CETAL** Petawatt laser(25 J in 25 fs).[31] The facility will operate at a repetition rate of 0.1 Hz and be operational later this year. CETAL will be used to investigate areas such a photonics, high field laser physics, and materials processing.

The **LASERIX** facility[32] at the University Paris Sud, France, was designed to be a high-repetition-rate multi-beam laser to pump an XUV laser. The laser was a combination of commercially supplied sub-systems primarily from Thales Laser for the front-end systems, Amplitude Technologies for the power amplification, and Quantel for the Nd:glass pump laser. The laser performance was first demonstrated in 2006, delivering 36 J of energy without full compression. The published operational capability is 40 J in a 50 fs pulse duration producing a peak power of 0.8 PW and an operational repetition rate of 0.1 Hz. The facility is in the process of being moved to Centre Interdisciplinaire Lumiere Extreme (CILEX).

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[29] F. Lureau, et al., 2015, Design and initial results of 10 PW Laser for ELI-NP.

[30] S. Karsch, 2011, "CALA and Garching Plans," presented at the European Network for Novel Accelerators Workshop, Geneva, May 3-6.

[31] Center for Advanced Laser Technologies, "CETAL-PW Laboratory," www.cetal.inflpr.ro/cetal-pw, accessed January 30, 2017.

[32] D. Ros, K. Cassou, B. Cros, S. Daboussi, J. Demailly, O. Guilbaud, G. Jamelot, et al., 2011, LASERIX: An open facility for developments of EUV and soft X-ray lasers and applications, *Nucl. Instr. Meth. Phys. Res. A* 653: 76-79.

Dresden laser acceleration source (**DRACO**)[33]at the Helmholtz-Zentrum Dresden-Rossendorf laboratory (HZDR) in Germany is a commercially sourced system from Amplitude Technologies. This is an extension to Amplitude's commercial 200 TW PULSAR system, named PULSAR PW. The facility is designed to investigate electron, ion, and proton acceleration schemes for radiation therapy as part of Electron Linac for beams with high Brilliance and low Emittance (ELBE)– Center for High Power Radiation Sources. The system currently operates at 0.75 PW, over a 30 fs pulse duration at a repetition rate of 1 Hz. Due to a recent upgrade project, DRACO is expected to deliver 1 PW pulses from Fall 2016 onwards.

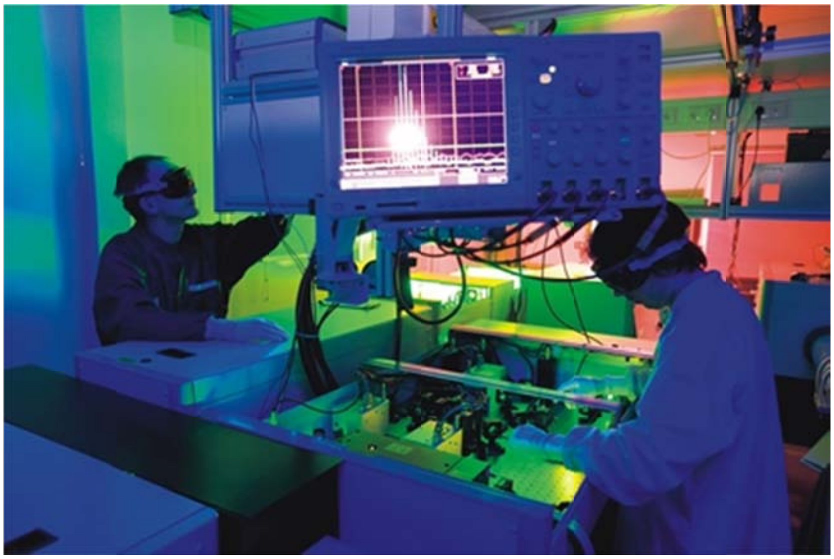

**FIGURE E.9** The DRACO facility at HZDR, Dresden, Germany. SOURCE: www.hzdr.de

**Vega-3**,[34] another Amplitude Technologies system, is under construction in Salamanca for use by the Spanish Pulsed Lasers Centre (CLPU). The system is constituted of three beamlines, the first two of which are currently operational. Each is able to deliver 10 Hz, 30 fs beams to targets at low peak powers. Vega-2 produces a 6 J pulse while the pulse from Vega-1 is in the millijoule range. Vega-3 is intended as a 30 J, 30 fs system with an operational repetition rate of 1 Hz. The estimated operational date for Vega-3 is 2018.

### *North America*

The Berkeley Lab Laser Accelerator (**BELLA**) project[35]was launched in 2009 and is funded by the U.S. Department of Energy for experiments on laser plasma acceleration at the Lawrence Berkeley National Laboratory (LBNL). BELLA was commercially built and delivered to LBNL by Thales in 2012. It can operate at peak power levels of 1.3 PW with a 42 J, and 30 fs pulse. BELLA was the first PW class system capable of operating at a repetition rate of 1 Hz.

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[33] Helmholtz-Zentrum Dresden-Rossendorf, "Petawatt Laser DRACO," hzdr.de/db/Cms?pNid=2096, last update February 2, 2016; U. Schramm and S. Bock, 2013, "Status of Draco PW," presented at the Characterisation of Ultra-Short High Energy Laser Pulses Workshop, Abingdon, UK, Sept. 23-24.

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**FIGURE E.10** The BELLA laser facility at LLBL. SOURCE: bella.lbl.gov

The **Diocles** laser[36] at the Extreme Light Laboratory, University of Nebraska–Lincoln is a flashlamp pumped system that produces 30 J in 30 fs and can provide 1 PW at 0.1 Hz to target. It was commissioned in 2012 and is used in the study of plasma physics.

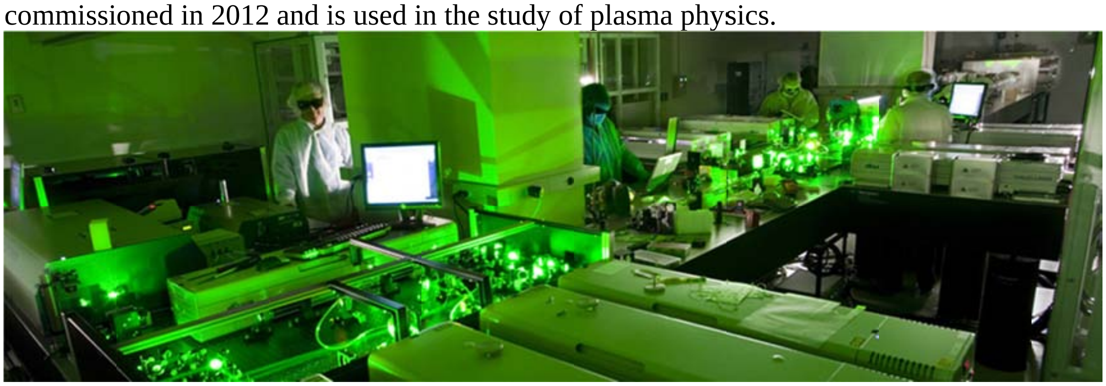

**FIGURE E.11** The Diocles facility at the Extreme Light Laboratory, University of Nebraska-Lincoln. SOURCE: www.unl.edu/diocles

The Advanced Laser Light Source (**ALLS**)[37] is based at Institut National de la Recherche Scientifique (INRS) near Montreal. The most powerful laser in Canada, the system produces ultra-short pulses at a peak power of 0.5 PW. Each pulse is 10 J, 20 fs at a repetition rate of 2.5 Hz. This laser is capable of producing pulses in a range of wavelengths, from infrared to x-ray.

***Asia***

[36] C. Liu, S. Banerjee, J. Zhang, S. Chen, K. Brown, J. Mills, N. Powers, B. Zhao, G. Golovin, I. Ghebregziabher, and D. Umstadter, 2013, Repetitive petawatt-class laser with near-diffraction-limited focal spot and transform-limited pulse duration, *Proc. SPIE* 8599: 859919.

[37] Advanced Laser Light Source, Canada, “Specialized Labs and Equipment.”

The Japan-Kansai Advanced Relativistic Engineering (**J-KAREN**)[38] laser system constructed at the Kansai Photon Science Institute, National Institutes for Quantum and Radiological Science and Technology (QST), Kyoto, Japan, was the world's first petawatt-class Ti:Sapphire facility. In 2003, the facility was generating 20 J at 33 fs, giving 0.85 PW but in single shot operation. Its upgrade, J-KAREN-P, became operational in April 2014.[39] This laser increased the pulse energy to 38.5 J, resulting in a peak power of 1.3 PW at an improved repletion rate of 0.1 Hz.

The Advanced Photonics Research Institute (APRI), Gwangju Institute of Science and Technology (GIST) in South Korea currently houses two PW-class beam lines, known as **PULSER I** and **PULSER II**.[40] PULSER I was completed in 2010 and was capable of generating a 33 J beam in 30 fs, delivering 1.1 PW at a repetition rate of 0.1 Hz and is claimed to be the very first 0.1 Hz Ti:sapphire petawatt laser in the world. Two years later, the facility was upgraded to include the PULSER II beamline which delivers 1.5 PW to target, still at a repetition rate of 0.1 Hz. The next planned upgrade for the PULSER II laser will enhance the energy to 80 J while reducing the pulse duration to 20 fs. This will allow it to operate with a peak power of 4 PW but at a much reduced repetition rate.

The **XL-III** laser facility[41] is a laser operated by the Chinese Academy of Sciences. The facility runs a number of femtosecond pulse length lasers, the foremost of these producing 1.16 PW pulses. The first experiments with the XL-III facility were carried out in 2006 with a 350 TW beamline. The facility was expanded in 2011 to include an OPCPA-Ti:Sapphire hybrid laser capable of 33 J, 28 fs pulses.

The **SIOM Ti:Sapphire CPA** laser is based at the XG-III (Qiangguang- High light) laser facility. A paper in 2013 published results of the laser working at 2 PW, 52.3 J in 26 fs.[42] There are plans to increase functionality to 5 PW, almost tripling the beam energy. The laser is used for particle acceleration experiments but is also intended to use frequency doubled light to pump an OPCPA system built at the same facility.

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[38] M. Aoyama, K. Yamakawa, Y. Akahane, J. Ma, N. Inoue, H. Ueda, and H. Kiriyama, 2003, 0.85-PW, 33-fs Ti:sapphire laser, *Opt. Lett.* 28(17): 1594-1596.

[39] H. Kiriyama, M. Mori, A. Pirozhkov, K. Ogura, M. Nishiuchi, M. Kando, H. Sakaki, et al., 2015, Recent advances on the J-KAREN laser upgrade, in *CLEO: 2015*, San Jose, Calif., May 10-15, Optical Society of America.

[40] T.M. Jeong and J. Lee, 2014, Femtosecond petawatt laser, *Annalen der Physik* 526(3-4): 157-172.

[41] Z. Wang, C. Liu, Z. Shen, Q. Zhang, H. Teng, and Z. Wei, 2011, High-contrast 1.16 PW Ti:sapphire laser system combined with a doubled chirped-pulse amplification scheme and a femtosecond optical-parametric amplifier, *Opt. Lett*. 36(16): 3194-3196.

[42] Y. Chu, et al., 2015, High-energy large-aperture Ti:sapphire amplifier.

### E.3 Optical Parametric Chirped-Pulse Amplification Petawatt-Class Lasers

Since its initial inception in 1998,[43] the OPCPA technique has undergone much development; however, at present there are a limited number of facilities around the world developing PW-class OPCPA lasers. The first such system was PEARL[44] at the Luch Facility at the Institute of Applied Physics, Russian Academy of Science, Nizhny Novgorod. This is a low repetition rate system that operates at 0.56 PW.


**FIGURE E.12** Locations of systems whose main amplifiers are based on OPCPA techniques. SOURCE: J. Collier, Rutherford Central Laser Facility.

OPCPA-based systems are considered the best route to higher peak power systems; as a result, all of the planned systems that are in excess of 10 PW are OPCPA-based. These include OPAL (United States), XCELS (Russia), Vulcan 2020 (United Kingdom), ELI 4$^{th}$ Pillar (Europe), and GEKKO EXA (Japan). A full list of the operational, under construction, and planned OPCPA-based laser systems is shown in Table E.3.

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[43] G. Cerullo, M. Nisoli, S. Stagira, and S. De Silvestri, 1998, Sub-8-fs pulses from an ultrabroadband optical parametric amplifier in the visible, *Optics Letters* 23(16): 1283-1285.

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**TABLE E.3** Summary of the Operational, Under Construction, and Proposed Worldwide PW-Class Systems Whereby the Main Amplification Technique is OPCPA

| System Name | Operating Facility | Location | Energy (J) | Pulsewidth (fs) | Peak Power (PW) | Date Operational | Rep Rate (Hz) |
|---|---|---|---|---|---|---|---|
| **OPCPA lasers** | | | | | | | |
| **PEARL** | IAP RAS | Nizhny Novgorod. Russia | 24 | 43 | 0.56 | 2007 | Single-Shot |
| **PEARL-10** | IAP RAS | Nizhny Novgorod. Russia | 150 | 30 | 5 | 2016 | Single-Shot |
| **XG-III** | SIOM | Shanghai China | 32.6 | 32 | 1.02 | 2013 | 0.05 |
| **SG-II** | SIOM | Shanghai China | 150 | 30 | 5 | 2015 | Single-Shot |
| **Petawatt field synthesiser** | LMU, MPQ | Munich Germany | 5 | 5 | 1 | 2017 | 10 |
| **Vulcan 2020** | CLF, STFC | Oxford, UK | 600 | 30 | 20 | TBD | Single-Shot |
| **ELI-Beamlines L2** | ELI | Prague Czech Republic | 20 | 20 | 1 | TBD | 10 |
| **PALS** | ELI | Prague Czech Republic | 34 | 23 | 1.48 | TBD | Single-Shot |
| **OMEGA EP OPAL** | LLE, UoRochester | U. Rochester, USA | 1600 | 20 | 75 | TBD | Single-Shot |
| **XCELS** | IAP RAS | Nizhny Novgorod. Russia | 4800 | 25 | 192 | TBD | Single-Shot |
| **Gekko EXA** | ILE | Osaka Japan | 500 | 10 | 50 | TBD | Single-Shot |
| **ELI 4th Pillar** | ELI | TBD | | | 200 | TBD | Single-Shot |

SOURCE: J. Collier, Rutherford Central Laser Facility.

### E.3.1 Facilities Descriptions

***Europe***

Plans to upgrade the **Vulcan** laser to full OPCPA have been submitted by the CLF.[45] Originally the specifications were for 10 PW; however, this was later adjusted to 20 PW; 600 J in 30 fs. **Vulcan-20PW** is anticipated to be completed around 2020. The beamlines will use the existing system as a pump source for DKDP crystals, which will amplify the beam to target.

**ELI Beamlines L2**[46] is a high repetition rate, two-stage OPCPA chain laser. The pulse from the first chain is optionally pumped by a cryogenically cooled DPSSL system supplied by the CLF before heading through to the pulse compressor. The petawatt-class output from this system is 20 J in less than 15 fs at 10 Hz.

Prague Asterix Laser System **(PALS)**[47] is a high power sub-petawatt iodine-based laser. The principle beamline of PALS is the Asterix IV system. The laser was first built at the Max-Planck-Institute (MPQ) in Garching, Germany, and completed in 1995. Asterix was subsequently moved to Prague in September 2000, becoming operational shortly thereafter. A proposed 1.4 PW upgrade has been published; however, there is not currently an estimated completion date for the project.

The **Petawatt Field Synthesizer** [48] is under construction also at MPQ, Garching. The system is designed in order to develop attosecond pulse generation capabilities. The system consists of five OPCPA amplification stages in addition to two pulse compressors. The final system output will measure 1 PW and only 5 J, however, in an ultra-short pulse of 5 fs. The laser is expected to be operational in 2017.

**ELI's 4th Pillar** is the final planned facility of the project.[49] The pillar is intended for applications in ultra-high intensity research. It will provide a cumulative power output of 200 PW. Currently there is no published design or specifications for the final pillar.

**PEARL**,[50] the first operational fully OPCPA system was developed using a pump beam derived from the Luch Facility at the Institute of Applied Physics, Russian Academy of Science, Nizhny Novgorod. The laser was upgraded to 0.56 PW in 2007. PEARL was able to reach a focussed intensity of $10^{22}$ W/cm$^2$, which is very high for a laser of its type.

PEARL has begun to be iterated to multi-petawatt functionality. **PEARL-10**,[51] designed to provide 10 times the power of PEARL, is currently approaching 5-PW functionality, i.e., 150 J pulses in 30 fs. The beam is pumped by three pump lasers, each amplified by a range of materials. The pump beams feed a two-stage amplifier. The current estimate is for the laser to come online by the end of this year.

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[45] C. Hernandez-Gomez, S.P. Blake, O. Chekhlov, R.J. Clarke, A.M. Dunne, M. Galimberti, S. Hancock, et al., 2010, The Vulcan 10PW project, *Journal of Physics: Conference Series* 244(3): 032006; Y. Tang, A. Lyachev, C. Hernandez-Gomez, I. Musgrave, I. N. Ross, O. Chekhlov, P. Matousek, and J. Collier, 2010, Novel ultra broadband front-end system for Vulcan 10 PW OPCPA Project, in *Lasers, Sources and Related Photonic Devices*, San Diego, Calif., Jan. 31-Feb. 3, Optical Society of America, paper AME1.

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[48] Z. Major, S.A. Trushin, I. Ahmad, M. Siebold, C. Wandt, S. Klingebiel, T.J. Wang, et al., 2009, Basic concepts and current status of the petawatt field synthesizer—A new approach to ultrahigh field generation, *Laser Review* 37(6): 431-436.

[49] G.A. Mourou, et al., 2011, *ELI WHITEBOOK*.

[50] V.V. Lozhkarev, et al., 2007, Compact 0.56 Petawatt laser system.

[51] Presentation: Exawatt Centre for Extreme Light Studies Project (XCELS) (2013)

A similar planned project to that of the ELI fourth pillar at the Institute of Applied Physics of the Russian Academy of Sciences in Nizhny Novgorod is the Exawatt Centre for Extreme Light Studies **(XCELS)**.[52] This megascience project in Russia is to produce an exawatt laser system for fundamental science. The system will use 12 combined 15-PW OPCPA channels, each based upon an upgraded design of the PEARL-10 PW. The combined output is specified as 200 PW.

### *North America*

Optical Parametric Amplifier Line **(OPAL)**[53] is the North American exawatt project. It is based at the LLE, University of Rochester. The laser is based upon a design using four OMEGA EP beamlines, each of which pumps a DKDP amplifier. The first stage of the project aims to establish a 75 PW output by 2022. After this, the output may be extended toward 200 PW giving focused intensities of $10^{24}$ W/cm$^2$.

### *Asia*

The **SG-II** facility,[54] based in Shanghai and managed by SIOM, is currently being redesigned to work as a fully OPCPA system. This laser utilizes two Nd:glass pumping lasers: the SG-II main system and the ninth beam from the same facility. The system is finally amplified by three OPCPA stages, two BBO crystals and one LBO. At the beginning of 2016, outputs of 30 J in 27 fs have been recorded. The laser specification indicates a goal of 150 J in 30 fs with a repetition rate of one shot every six minutes. The OPCPA upgrade is expected to become operational by 2017.

Another OPCPA system developed by **SIOM** is a **10-PW CPA-OPCPA** hybrid located in the **XG-III** facility.[55] The system uses the high contrast of a Ti:Sapphire CPA front end to produce a stable pulse for LBO OPCPA amplification. In 2013, the system produced pulses around 28.7 J in 33.8 fs. The 10 PW (300 J in 30 fs) specification is due to be delivered in 2017.

**Gekko EXA**[56] is the exawatt facility planned to be constructed at ILE, the University of Osaka, Japan. Design of the system started in 2010, though construction has yet to begin, and the given date of completion is in 2020. Gekko EXA is designed for flexible operation in three modes. Firstly, a high average power 1 PW beamline at a repetition rate of 100 Hz, corresponding to a high average power of 2 KW. Secondly, 20 PW operation aims to provide pulses of greater than 200 J in less than 10 fs, which will be achieved at 0.01 Hz operation. Lastly, the LFEX laser system is intended as a pump source for 50 PW single shot operations.

## E.4 Diode-pumped Solid-State Petawatt-Class Lasers

[52] Presentation: Exawatt Centre for Extreme Light Studies Project (XCELS) (2013); Institute of Applied Physics of the Russian Academy of Sciences, “Exawatt Center for Extreme Light Studies (XCELS): Project Summary,” http://www.xcels.iapras.ru/img/site-XCELS.pdf ; Institute of Applied Physics of the Russian Academy of Sciences, “On the way to multipetawatt power. PEARL-10,” http://www.iapras.ru/english/science/las_phys/gen_lasf2.html, accessed January 30, 2017.

[53] D.D. Meyerhofer, 2014, "OMEGA EP OPAL: A Path to a 75-PW Laser System," presented at the 56th Annual Meeting of the American Physical Society, Division of Plasma Physics, New Orleans, La., October 27–31.

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[55] L. Xu, L. Yu, X. Liang, Y. Chu, Z. Hu, L. Ma, Y. Xu, et al., 2013, High-energy noncollinear optical parametric–chirped pulse amplification in LBO at 800 nm, *Opt. Lett*. 38(22): 4837-4840.

[56] J. Kawanaka, K. Tsubakimoto, H. Yoshida, K. Fujioka, Y. Fujimoto, S. Tokita, T. Jitsuno, N. Miyanaga, and Gekko-EXA Design Team, 2016, Conceptual design of sub-exa-watt system by using optical parametric chirped pulse amplification, *Journal of Physics: Conference Series* 688: 012044.

Commercialization of diode laser technology has fueled rapid development in recent years. The majority of large-scale laser systems rely on multi-stage pump schemes, where flash-lamps or diode lasers are used to excite the gain media of a larger pump laser that can then pump the main short pulse amplifier. There are, however, schemes seeking to remove one of these stages in order to increase efficiency and reduce cost. The two petawatt-class systems seeking to achieve this are POLARIS and PEnELOPE, which are summarized in TABLE E.. These systems are large-scale direct CPA diode-pumped solid-state lasers.


**FIGURE E.13** Locations of systems based on directly diode pumping the gain material. SOURCE: J. Collier, Rutherford Central Laser Facility.

**TABLE E.4** Summary of the Operational, Under Construction, and Proposed DPSSL PW-Class Lasers in the World

| System Name | Operating Facility | Location | Energy (J) | Pulsewidth (fs) | Peak Power (PW) | Date Operational | Rep Rate (Hz) |
|---|---|---|---|---|---|---|---|
| Direct Diode pumped lasers | | | | | | | |
| **POLARIS** | HI-Jena | Jena Germany | 150 | 150 | 1 | 2016 | 0.025 |
| **PEnELOPE** | HZDR | Dresden Germany | 150 | 120 | 1.25 | 2016 | 1Hz |

Source: J. Collier, Rutherford Central Laser Facility.

Petawatt Optical Laser Amplifier for Radiation Intensive experimentS (**POLARIS**)[57] is based at the Helmholtz Institute, Jena, Germany. It is designed as a fully diode pumped Yb:Glass petawatt-class

[57] M. Hornung, H. Liebetrau, A. Seidel, S. Keppler, A. Kessler, J. Körner, M. Hellwing, et al., 2014, The all-diode-pumped laser system POLARIS—an experimentalist's tool generating ultra-high contrast pulses with high energy, *High Power Laser Science and Engineering* 2: e20; M. Hornung, H. Liebetrau, S. Keppler, A. Kessler, M.

laser. It operates at a central wavelength of 1,030 nm and a bandwidth of 10 nm. It is currently being upgraded from 4 J in 164 fs (30 TW) to 1 PW with the commissioning of the final amplifier to deliver 150 J at 150 fs in 2016. At the time of writing POLARIS has recently reached 54 J pulses.

Petawatt, Energy-Efficient Laser for Optical Plasma Experiments **(PEnELOPE)**[58] is a high repetition-rate diode-pumped laser using broadband Yb-doped glass/CaF2 under construction at the Helmholtz-Zentrum, Dresden-Rossendorf within the ELBE Centre for high power radiation source. It will be dedicated to the production of laser accelerated proton and ion beams with energies >100 MeV relevant to future cancer treatments. The facility, due to be commissioned in 2016, will deliver pulses of 150 J in 120 fs, giving >1 PW at 1 Hz.

**FIGURE E.14** The PENELOPE laser facility at HZDR in Dresden, Germany. SOURCE www.hzdr.de.

Hellwing, F. Schorcht, G.A. Becker, et al., 2016, 54 J pulses with 18 nm bandwidth from a diode-pumped chirped-pulse amplification laser system, *Optics Letters* 41(22): 5413-5416.

[58] M.Siebold, F. Roeser, M. Loeser, D. Albach, and U. Schramm, 2013, PEnELOPE: a high peak-power diode-pumped laser system for laser-plasma experiments, *PROC SPIE* 8780: 878005.

**FIGURE E.15** The PENELOPE laser facility at HZDR in Dresden, Germany. SOURCE www.hzdr.de.

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