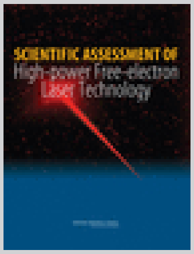

Scientific Assessment of High-Power Free-Electron Laser Technology

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SCIENTIFIC ASSESSMENT OF High-power Free-electron Laser Technology

Committee on a Scientific Assessment of
Free-Electron Laser Technology for Naval Applications

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

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[1] Dr. Patel resigned from the committee on March 14, 2008.

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Preface

The National Research Council was asked by the U.S. Navy's Office of Naval Research (ONR) to assess the current capabilities of free-electron lasers (FELs) to deliver large amounts of energy; assess the prospects for developing such devices with megawatt average power capabilities; identify the key technical problems that must be solved to achieve such performance; and evaluate the feasibility of achieving power, energy, and other technical parameters specified by the Office of Naval Research. The request did not include a charge to make a determination of the requirements for effective directed-energy weapons.

The National Research Council responded by forming the Committee on a Scientific Assessment of Free-Electron Laser Technology for Naval Applications to perform the requested study. As described below, this study will be performed in two phases. For Phase 1, covered in the present report, the committee has performed a technology assessment of the state of the art across the free-electron laser community in order to evaluate the feasibility of achieving power and other technical parameters specified by the Office of Naval Research and to identify the technical gaps that must be overcome to achieve such performance.

Directed-energy weapons have been pursued by the U.S. military for decades; these weapons use very-high-power beams to disable or destroy targets. They typically use a single optical system both to track a target and to focus the beam on the target. The Air Force has sponsored research using chemically powered lasers, the Army has researched the use of solid-state laser technologies, and the Navy has developed free-electron lasers through programs at the Office of Naval Research.

A free-electron laser is an accelerator-based device that causes stimulated emission of radiation to occur from an electron beam. It generates tunable, coherent, highly collimated, high-power radiation, currently ranging in wavelength from microwaves to x-rays. While a free-electron laser beam shares to some degree the same optical properties as optically or chemically pumped lasers (such as coherence), the operation of a free-electron laser is quite different. Unlike gas or diode lasers, which rely on transitions between bound atomic or molecular states, free-electron lasers use a relativistic electron beam as the lasing medium, hence the term "free electron." Today, a free-electron laser requires the use of an electron accelerator with its associated ionizing-radiation shielding and other support systems. The electron beam must be maintained in a vacuum, which requires the use of numerous pumps along the beam path. Free-electron lasers can achieve extremely high peak powers without damage to the laser medium.

The Navy has chosen to pursue the free-electron laser route to a directed-energy weapon, in part because free-electron lasers offer the advantage of being design-wavelength-selectable, allowing them to be designed to operate at wavelengths that are optimal for maritime environments. The free-electron laser's relatively efficient conversion of "wall-plug power" to "beam power" would make it attractive for use on a mobile platform such as a ship. However, there are still problems that need to be resolved.

Supported by the Office of Naval Research, researchers at the U.S. Department of Energy's Thomas Jefferson National Accelerator Facility (TJNAF) delivered the first light from their free-electron laser on June 17, 1998. Only 2 years after ground was broken for the free-electron laser, infrared light of more than 150 watts was delivered—15 times the power of free-electron lasers existing at that time. On July 15, 1999, the free-electron laser exceeded its design goal of 1,000 watts by producing 1,720 watts of infrared light. The current development effort at TJNAF has now achieved average beam powers of 14 kilowatts. Recent advances in accelerator science and technology using superconducting radio-frequency cavities in an energy recovery linear accelerator (linac) suggest that the necessary optical cavity could be contained within a 20-meter-long structure.

The Office of Naval Research program in free-electron-laser research is currently classified as an applied research program (budget category 6.2). The Office of Naval Research is considering an expansion of the research effort in the form of an advanced technology development program (budget category 6.3). In order to ultimately design and build a ship-based, directed-energy weapon, the next step proposed by the Navy program is to demonstrate and study a 100 kilowatt free-electron-laser system to establish the technology needed for scaling to the megawatt level in the infrared wavelength region.

To assist the Navy in planning its next steps, the committee embarked upon this study. As originally envisioned and contracted, the study included the following three tasks:

1. Review the current state of the art and anticipated advances for high-average-power free-electron lasers (FELs). Using performance characteristics defined by the Navy for directed-energy applications, analyze the capabilities, constraints, and trade-offs for free-electron lasers.
2. Evaluate the scientific and technical development path from current demonstrated capabilities toward the eventual goal of achieving megawatts of radiated power at wavelengths suited to naval applications; consider the realistic constraints of shipboard installation.
3. Identify the highest-priority scientific and technical gaps along the development path from present-day capabilities through a 100 kilowatt test facility to a megawatt demonstration project. Recommend a phased approach for this development path using staged milestones with explicit performance and success criteria at each stage.

However, the committee believed that a fourth task should be added to the study:

4. Assess the capabilities and constraints related to beam steering and atmospheric propagation at wavelengths suited to naval applications for a free-electron-laser-based system.

The committee viewed the fourth task as essential for giving the Navy appropriate advice on a free-electron-laser-based "system." The committee's intent was to address this task at a high level, touching on factors that are critical to the successful operation and feasibility of a free-electron-laser-based weapon system. The effort was not, however, intended to amount to an in-depth examination, but rather to provide a contextual summary based on information in the open literature. The addition of the fourth task was discussed with the Office of Naval Research in the initial planning phase of the study, and it was generally agreed that this was acceptable to the Office of Naval Research. Subsequently, however, the Office of Naval Research expressed its desire to not add the fourth task to the statement of task.

At the committee's first meeting (January 17-18, 2008, at the Keck Center of the National Academies in Washington, D.C.), the then Chief of Naval Research, RADM William E. Landay III, presented the charge that the Office of Naval Research wished the committee to pursue, which did not include the fourth task. The context for the Office of Naval Research's desire for this study is the Navy's view of what it will need to prevail in the anticipated conditions of future naval warfare. The Navy anticipates threats different from those it faced during the days of the Strategic Defense Initiative (SDI). To counter these new threats, the Navy wants to be able to fight at the speed of light, with all-electric systems. In accordance with this view, the Office of Naval Research is interested in exploring the potential of free-electron lasers to serve as the basis of effective weapon systems and in achieving a megawatt of power at the aperture of a free-electron laser. Its main interests in this study are how much free-electron-laser power and what size would be possible—that is, its interest is in the free-electron laser "box" rather than what happens past the free-electron-laser aperture. The Office of Naval Research's view is that the committee would help the most by identifying the "tall poles" in the free-electron-laser development "tent"—the key technical challenges that must be overcome to achieve significantly higher power output from a shipboard free-electron laser.

As the study progressed from its initial stages, it was decided that the full study would be conducted in two phases. Phase 1 (covered in this report), conducted under the auspices of the National Research Council's Board on Physics and Astronomy, addressed the first element of the statement of task. The information that was used in performing Phase 1 was limited to that obtainable in the open literature.

Phase 2 of this study will commence, at the option of the Office of Naval Research, upon completion of Phase 1. The responsibility for Phase 2 has been assigned to the National Research Council's Naval Studies Board, and the work in Phase 2 will be based on the results of Phase 1. The plan is for Phase 2 to address tasks 2-4 of the statement of task or modifications of them subject to agreement between the Office of Naval Research and the National Research Council. Based on the negotiated statement of task for Phase 2, the committee's composition will be reevaluated by the National Research Council. In addition, Phase 2 may require that the committee have access to restricted, limited-distribution information or, possibly, classified information.

The formation of this committee drew on the expertise of the Naval Studies Board in naval matters and on that of the Board on Physics and Astronomy in the relevant technical matters. Committee members were selected on the basis of demonstrated intellectual and technical leadership and familiarity with the policy aspects of the Navy's research programs. Some are expert in the science and technology of free-electron lasers and the enabling accelerator technology, and some are expert in military science and technology, especially naval architecture and seafaring performance constraints. The committee was not asked to directly address the general issue of directed-energy weapons, but a few of its members were familiar with this issue. To ensure balance, the committee included a mix of experts on military and civilian research on free-electron lasers. Most members were from the university and national laboratory communities; many were familiar with Navy research and applications needs.

The committee responded to its charge with sincere dedication and a desire to perform a valuable service to the free-electron-laser policy and science communities. It believes it has succeeded in its goal.

Thomas C. Katsouleas, *Chair*
Committee on a Scientific Assessmen of Free-Electron
Laser Technology for Naval Applications

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's (NRC's) Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for 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 wish to thank the following individuals for their review of this report:

Martin Breidenbach, Stanford Linear Accelerator Center,
David H. Dowell, Stanford Linear Accelerator Center,
Nathaniel Fisch, Princeton University,
Donald L. Hartill, Cornell University,
Jay Marx, California Institute of Technology,
Carmen S. Menoni, Colorado State University,
C. Kumar N. Patel, Pranalytica, Inc.,
Claudio Pellegrini, University of California at Los Angeles,
Triveni Rao, Brookhaven National Laboratory, and
Jonathan Wurtele, University of California at Berkeley.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Elsa Garmire, Dartmouth College. Appointed by the NRC, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

Executive Summary

This report presents a scientific assessment of free-electron laser technology for naval applications. The charge from the Office of Naval Research was to assess whether the desired performance capabilities are achievable or whether fundamental limitations will prevent them from being realized. The statement of task for the present study, Phase 1, is as follows:

> Review the current state of the art and anticipated advances for high-average-power free-electron lasers (FELs). Using performance characteristics defined by the Navy for directed-energy applications, analyze the capabilities, constraints, and trade-offs for FELs.

The Navy provided the following performance characteristics and considerations for the study:

- *Output power*. Approximately 1 megawatt class at the aperture (also address the 100 kilowatt step);
- *Wavelength*. Three atmospheric windows (reduced absorption) at 1.04, 1.62, and 2 micrometers (1-2 micrometers); and
- *Power to the free-electron laser*. Approximately 20 megawatts.

To properly understand and interpret the meaning and applicability of the results of this study, it is critical to identify the factors that it did not address. The present study did not address whether a megawatt-class free-electron laser will be an effective weapon in a naval context, nor did it address operational lethality factors, such as duration of the beam pulse on target or the repetition rate. More specifically, the study did not address the effectiveness of the device to perform Navy missions of interest or the physics associated with atmospheric propagation of the laser beam (thermal blooming, aerosols, weather effects, etc.). In addition, the study did not address the realistic constraints of shipboard operation and installation, such as sizing the beam generation system or engineering it to operate in a shipboard environment. These specific issues are not insignificant and should be addressed in a follow-on study.

The present study identifies the highest-priority scientific and technical issues that must be resolved along the development path to achieve a megawatt-class free-electron laser. In this regard, the development of a scalable 100 kilowatt device is considered an important interim step. In accordance with the charge, the committee considered (and briefly describes) trade-offs between free-electron lasers and other types of lasers and weapon systems to show the advantages free-electron lasers offer over other types of systems for naval applications as well as their drawbacks. The characteristics of different types of free-electron lasers are discussed and compared in detail throughout the report.

Following a description of the state of the art of free-electron laser technology (Chapter 2), particularly as it relates to Navy interests and applications, this report presents a detailed assessment of the scientific and technological challenges that must be addressed before the current state of the art (14 kilowatt output power) can advance to the 100 kilowatt and 1 megawatt-class output power levels (Chapter 3).

The principal findings of the present study are summarized below:

1. There have been significant engineering and technological advances in the 30 years since free-electron lasers were first considered for directed-energy applications.
2. The combination of classification and subsequent funding reductions has also led to the loss of high-average-power free-electron laser development capabilities in certain critical areas.
3. The primary advantages of free-electron lasers are associated with their energy delivery at the speed of light, selectable wavelength, and all-electric nature, while the trade-offs for free-electron lasers are their size, complexity, and relative robustness.
4. Despite the significant technical progress made in the development of high-average-power free-electron lasers, difficult technical challenges remain to be addressed in order to advance from present capability to megawatt-class power levels. In particular, in the committee's opinion, the two "tall poles" in the free-electron laser development "tent" are these:

    - An ampere-class cathode-injector combination.
    - Radiation damage to optical components of the device.

    4a. Drive-laser-switched photocathodes are the likely electron source for megawatt-class free-electron lasers. Photocathodes have been used in accelerator applications for more than 2 decades; however, they have not reached the level of performance in terms of quantum efficiency and robustness that will likely be required for a reliable megawatt-class free-electron laser.
    4b. High-performance optical resonators and coatings that operate successfully with megawatt-class lasers have existed for 2 decades. However, free-electron lasers uniquely generate harmonic radiation in the ultraviolet region, which has been shown to fatally damage many of the existing high-performance coatings.
5. There are a number of components for which the extrapolation to megawatt-class power levels represents an experience/predictive gap rather than a physics or technology gap.
6. There are other potential, difficult technical challenges ("tall poles") not addressed in the present phase of the free-electron laser study that may be important to future realization of naval applications.

The technical basis and the context for these findings are elaborated in Chapters 2 and 3 of this report.

1

Introduction and Principal Findings

INTRODUCTION

The National Academy of Sciences was asked to perform a scientific assessment of free-electron laser technology for naval applications. The specific Office of Naval Research charge was to assess whether the desired performance capabilities are achievable or whether some fundamental limitations will prevent them from being realized.

The speed-of-light delivery of energy from a high-energy laser has the potential to provide the Navy with a ship defense capability against a class of threats not available to conventional defenses. Starting in the late 1960s, the Navy embarked on significant high-energy laser development, looking first at gas dynamic CO_2 lasers and then at deuterium fluoride chemical lasers, demonstrating megawatt-level power output in the early 1980s. The Navy successfully engaged a supersonic target in a crossing pattern, but after tests against a target in a head-on engagement, it was determined that the potential utility of the deuterium fluoride chemical laser was severely limited by the propagation issue of thermal blooming. At that point, the Navy discontinued the chemical laser program but continued technology studies to look for a laser that would produce wavelengths that optimized propagation. The free-electron laser, which could produce a continuum of wavelengths and was an all-electric device (preferable to energetic chemicals like deuterium fluoride), was considered an attractive alternative but was only at the tens-of-watts level in its development when the Navy program was initiated in the mid-1990s. Since that time, through a series of scale-ups, 14 kilowatts of continuous-wave power has been demonstrated. In 2008, the Navy issued a Broad Agency Announcement to design and fabricate a 100 kilowatt free-electron laser for the purpose of developing the technologies required for a megawatt-class free-electron laser. The free-electron laser is currently seen as a potential way for the Navy to achieve megawatt-class output power levels, good optical beam quality, and wavelengths of interest from an all-electric device.

The specific statement of task for Phase 1 of the study is as follows:

> Review the current state of the art and anticipated advances for high-average-power free-electron lasers (FELs). Using performance characteristics defined by the Navy for directed-energy applications, analyze the capabilities, constraints, and trade-offs for FELs.

The Navy provided the following performance characteristics and considerations for the study:

- *Output power*. Approximately 1 megawatt class at the aperture (also address the 100 kilowatt step);
- *Wavelength*. Three atmospheric windows (reduced absorption) at 1.04, 1.62, and 2 micrometers (1-2 micrometers); and
- *Power to the free-electron laser*. Approximately 20 megawatts.

It is important to realize that although it may be possible to design and build a free-electron laser with the desired high levels of output power, that does not necessarily mean that an effective weapon system that uses the free-electron laser as a component can be built and operated in a naval environment of interest. To properly understand and interpret the meaning and applicability of the results of this study, it is critical to identify the factors it does not address. It does not address whether a megawatt-class free-electron laser will be an effective weapon in a naval context nor does it address operational lethality factors, such as duration of the beam on target or repetition rate. More specifically, the study does not address:

- The effectiveness of the device to perform Navy missions of interest or
- The physics associated with atmospheric propagation of the laser beam (thermal blooming, aerosols, weather effects, etc.).

This study and report also do not address the realistic constraints of shipboard operation and installation such as those that follow. These constraints are not insignificant and should be addressed in a follow-on study:

- Sizing the free-electron laser beam generation system and engineering it to operate in a shipboard environment, including the following associated factors:

  —Inherent ship vibration and motion;
  —Radiation safety and shielding;
  —Protection of the free-electron laser system from warfighting damage;
  —Power conditioning;
  —Support for cryosystem operation;
  —Provision of vacuum;
  —Transmission of the beam between the free-electron laser and the beam director;
  —Engineering of the beam director; and
  —Manpower, personnel, and knowledge-base issues related to the operability, maintainability, and repairability of the system by sailors.

This study identifies the highest-priority scientific and technical gaps that will need to be overcome along the development path to achieve a megawatt-class free-electron laser. The development of a 100 kilowatt device is considered an interim step to demonstrate the scalability of component technologies to the megawatt class. While a 100 kilowatt device may exhibit naval utility in its own right, component-level scalability to the megawatt class is considered essential to this study. The committee's principal findings are provided in the following section.

The information that follows this chapter is organized into two chapters. Chapter 2 describes the state of the art with free-electron lasers. It provides a history of free-electron lasers for Navy applications, gives an overview description of free-electron lasers, discusses the trade-offs between free-electron lasers and other types of high-energy lasers, and describes the relationship of free-electron lasers to scientific applications.

Chapter 3 provides a detailed assessment of free-electron laser technologies and challenges. It begins with a general discussion of how we get from the current state-of-the-art free-electron lasers to free-electron lasers in the 100 kilowatt class and 1 megawatt class. The discussion that follows is organized around the components and major operational issues of a free-electron laser and addresses the technical operation, state of the art, and challenges to progress associated with each aspect of an overall free-electron laser system.

Following Chapter 3, the appendixes include the statement of task for the study and report, agendas for the committee meetings, biographies of the committee members and staff, and a combined glossary and acronyms list.

In preparing this report, the committee was aware that the audience comprises two general groups of readers. One group is composed of decision makers and other readers who are not experts in free-electron laser technology and operation. The other group is composed of those who are deeply knowledgeable in the technical details associated with free-electron lasers. The report attempts to address the needs of both groups. The preface, executive summary, and introduction and principal findings chapters are written to be easily understandable by all readers. The state-of-the-art and technical assessment chapters of the report provide sufficient technical detail to give the free-electron laser community a good grounding in the information base and extrapolations employed by the committee in performing this study.

For easy reference, the principal findings of the present study are listed below. The technical basis and context for these findings are provided in Chapters 2 and 3 of this report.

PRINCIPAL FINDINGS

1. **There have been significant engineering and technological advances in the 30 years since free-electron lasers (FELs) were first considered for directed-energy applications.**

   The most notable technical advance is the development of energy recovery technology using a superconducting radio-frequency (RF) linac, but other advances in the understanding and management of both high-peak-power and high-average-power beams are also significant. These include the modeling and mitigation of the beam breakup instability, beam halo production and associated scraping and loss, emittance preservation in the gun and magnetic optics, the modeling and mitigation of coherent synchrotron radiation in bends, and the microbunching instability, to mention a few examples.

2. **The combination of classification and subsequent funding reductions has also led to the loss of high-average-power free-electron laser development capabilities in certain critical areas.**

   The committee notes that the unintended effect of prior stewardship of free-electron laser research has been to reduce rather than protect the nation's valuable advantage in some key areas of technology. The combination of classification and inconsistent funding of free-electron laser research and development has led to advances that were neither sustained in the laboratory nor preserved in the open literature and are for all intents and purposes lost from the national science base. This is particularly evident in the case of high-damage-threshold, free-electron-laser-unique optical coatings. In some cases, the key investigators have since left the field and the knowledge base has been lost. By providing consistent and sustained support to early-career scientists participating in free-electron laser research and development programs, the ongoing transfer of key technologies can be assured.

3. **The primary advantages of free-electron lasers are associated with their energy delivery at the speed of light, selectable wavelength, and all-electric nature, while the trade-offs for free-electron lasers are their size, complexity, and relative robustness**.

   Like other high-energy laser systems, free-electron lasers offer extremely fast tracking and response compared to ballistic devices for engaging maneuvering targets. Unlike other laser systems, they offer the freedom to choose wavelengths to match propagation windows in the region of maritime interest, and the free electrons that are their lasing medium facilitate removal of waste heat as well as electric power recovery. Since they could be powered by a ship's own fuel supply, they offer a deep magazine. They have the potential to scale to high power and the optical beam quality is high. On the other hand, free-electron lasers require high-current accelerators and cryogenic coolers of substantial size, significant mechanical isolation from vibration and shock, hard vacuum, and radiation shielding.

4. **Despite the significant technical progress made in the development of high-average-power free-electron lasers, difficult technical challenges remain to be addressed in order to advance from present capability to megawatt-class power levels. In particular, in the committee's opinion, the two "tall poles" in the free-electron laser development "tent" are these:**

   - **An ampere-class cathode-injector combination.**
   - **Radiation damage to optical components of the device.**

   In both cases, the most well-developed approach (demonstrated in a 14 kilowatt free-electron laser) does not scale in a straightforward manner to the parameters needed for megawatt-class average power levels. However, there are several options in each case that appear to be promising research directions for addressing the critical technology gaps.

   4a. **Drive-laser-switched photocathodes are the likely electron source for megawatt-class free-electron lasers. Photocathodes have been used in accelerator applications for more than 2 decades; however, they have not reached the level of performance in terms of quantum efficiency and robustness that will likely be required for a reliable megawatt-class free-electron laser.**

   Drive-laser technology appears to be approaching the level required for megawatt-class free-electron laser operation. There are some promising photocathode approaches under investigation; however, there are still considerable basic physics and engineering issues that must be resolved.

   4b. **High-performance optical resonators and coatings that operate successfully with megawatt-class lasers have existed for 2 decades. However, free-electron lasers uniquely generate harmonic radiation in the ultraviolet region, which has been shown to fatally damage many of the existing high-performance coatings.**

   There were promising approaches under development during the Strategic Defense Initiative (SDI) era, and additional research is ongoing that has been making substantial advances.

5. **There are a number of components for which the extrapolation to megawatt-class power levels represents an experience/predictive gap rather than a physics or technology gap.**

   The committee notes that in some areas there appears to be no fundamental showstopper to achieving the parameters described in Chapter 1 of this report; rather, there is a lack of experience or predictive modeling capability, which makes it difficult to quantify how challenging the technology gap will be to address. The committee refers to these as "gray poles," which include ring and high-gain oscillator configurations (lack of experience, very few technical papers), beam halo production and control (lack of benchmarked predictive models), amplifier configurations, coherent synchrotron radiation, and the development of diagnostic techniques and algorithms for measuring experimental beam distributions with sufficient accuracy to provide realistic input to modeling.

6. **There are other potential, difficult technical challenges ("tall poles") not addressed in the present phase of the free-electron laser study that may be important to future realization of naval applications.**

   These challenges include tight constraints on the allowable shipboard vibration (less than 10 nm radio-frequency accelerator cavity deformation), atmospheric propagation issues, and automated (sailor-friendly) controls and readiness challenges.

2

State of the Art

A BRIEF HISTORY OF THE FREE-ELECTRON LASER FOR NAVY APPLICATIONS

Although others had previously conceived of similar devices,[1] the history of the free-electron laser (FEL) for Navy applications begins in 1972, with the conception (and name) of the free-electron laser by John Madey. In 1976, he and a team of early-career physicists at Stanford experimentally demonstrated gain at 10.6 micrometers (μm) using a CO_2 laser probe. A short time later they succeeded in achieving oscillation at 3 μm.[2] Serious military interest in FELs began in 1978, when the Defense Advanced Research Projects Agency (DARPA) concluded that no other high-power laser could achieve the optical beam quality necessary to focus the beam on a distant (thousands of kilometers) target. The responses to the call for proposals included a conceptual design from Los Alamos for a 10 MW FEL. That design included energy recovery and a very long optical resonator to reduce the irradiance on the mirrors. Although there have been important technological advances since then, especially in superconducting accelerators and injectors, and we would now use one linear accelerator (linac) for both the acceleration and the energy recovery, the design bears a strong resemblance to the designs considered today; considerable experience has been obtained in the intervening 30 years. The Los Alamos National Laboratory (LANL) design also identified the critical problems in injectors and mirrors. These challenges remain today.

During the late 1970s and 1980s, the Navy developed the technology for high-energy laser (HEL) weapons systems based on scaling deuterium fluoride (DF) gas lasers to the megawatt class. These devices produced radiation distributed over a series of lines from 3.6 μm to 3.9 μm. At low power, these lines would transmit through the sea-level maritime environment fairly efficiently with relatively low total extinction. Unfortunately, at high power the molecular absorption component of the atmospheric extinction was determined to cause an unacceptably high level of thermal blooming to be useful for self-defense. (Thermal blooming results from a small amount of heating due to atmospheric absorption in the middle of the laser wavefront, causing beam spreading.) In the early 1990s, a search for improved (low absorption and low-to-moderate scattering) wavelengths was initiated. Using HI-TRAN modeling and experimental measurements, three wavelength regions were found that were far better than the 3.6 μm to 3.9 μm band and appeared to be adequate for megawatt propagation. These fairly narrow spectral bands were near 1.045 μm, 1.6 μm, and 2.2 μm. Unfortunately, there were no obvious lasers that held the promise of scaling to the megawatt level at those wavelengths. For this reason and the Navy's desire for electric (nonchemical) lasers, FELs were selected to explore their scalability to the megawatt level.

In 1983, the Strategic Defense Initiative (SDI) began, and tremendous progress was made in high-power FELs. In particular, the radio-frequency (RF) photoelectric injector was invented at LANL and substantial advances were made in optics, both in the FEL program and in other (especially chemical) laser programs. Unfortunately, when the SDI program ended in the early 1990s, much of the progress in optics for FELs was lost. Industrial experience with high-power coatings atrophied, and understanding of relevant optical architecture was lost. On the positive side, injector development continued for other FEL programs, and substantial progress has been made in superconducting accelerators, so that these are now the preferred technology. Thus the Navy proposal to construct a high-power FEL is based on a long history of progress. This history includes both significant successes, such as the 14 kW continuous-wave (cw) FEL at the Thomas Jefferson National Accelerator Facility, known as the Jefferson Laboratory, or JLab, and enduring challenges in injectors and optics.

Table 2.1 lists demonstrated relativistic FELs in 2008. A location or institution, followed by the FEL's name in parentheses, identifies each FEL. (In the location/name column, KAERI is the Korea Atomic Energy Research Institute, Nihon refers to Nihon University in Japan, RIKEN is a natural sciences research institute in Japan, and DESY is the German Electron-Synchrotron Research Center.) The first column following the FEL name lists the operating wavelength, λ, or the wavelength range. The longer wavelengths are listed at the top with short x-ray wavelength FELs at the bottom of the table. The large range of operating wavelengths, seven orders of magnitude, indicates the flexible design characteristics of the FEL mechanism. In the next column, σ_z is the electron pulse length divided by the speed of light, *c,* and ranges from 25 ns to short subpicosecond pulse timescales. The expected optical pulse length in an FEL oscillator can be three to five times shorter or longer than the electron pulse depending on the optical cavity Q, the FEL desynchronism, and the FEL gain. The optical pulse can be up to 10 times shorter in the high-gain FEL amplifier. Also, if the FEL is in an electron storage ring, the optical pulse is typically much shorter than the electron pulse. Most FEL oscillators produce an optical spectrum that is Fourier transform limited by the optical pulse length.

The electron beam energy, E, and peak current, I, are listed in the third and fourth columns, respectively. The next three columns list the number of undulator periods, N, the undulator wavelength, λ_0, and the root mean square (rms) undulator parameter, $K = eB\lambda_0/2\pi mc^2$ (cgs units), where e is the electron charge magnitude, B is the rms undulator field strength, and m is the electron mass. For an FEL klystron undulator, there are two undulator sections as listed in the N column; for example, 2 × 33. The FEL klystron configuration uses two undulators separated by a drift space or dispersive section in order to increase the FEL gain in weak optical fields, but at the expense of extraction in strong optical fields. Some undulators used for harmonic generation have multiple sections with varying N, λ_0, and K values as shown. Most undulators are configured to have linear polarization. Some FELs operate at a range of wavelengths by varying the undulator magnetic field, as indicated in the table by a range of values for K. The FEL resonance condition, $\lambda = \lambda_0(1 + K^2)/2\gamma^2$, provides a relationship that can be used to relate the fundamental wavelength, λ, to K, λ_0, and $E = (\gamma - 1)mc^2$, where γ is the relativistic Lorentz factor. Some FELs achieve shorter wavelengths by using harmonics. The last column in Table 2.1 lists the accelerator types and FEL types, using the abbreviations defined at the bottom of the table.

For the conventional oscillator, the peak optical power can be estimated by the fraction of the electron beam peak power that spans the undulator spectral bandwidth, 1/(2N), or $P \approx EI/(8eN)$. For the FEL using a storage ring, the optical power causing saturation is substantially less than this estimate and depends on ring properties. For the high-gain FEL amplifier, the optical power at saturation can be substantially greater than 1/(2N). The average FEL power is determined by the duty cycle, or spacing between the electron micropulses, and is typically many orders of magnitude lower than the peak power. The infrared FEL at the Jefferson Laboratory has now reached an average power of 14 kW with the recovery of the electron beam energy in superconducting accelerator cavities.

In the FEL oscillator, the optical mode that best couples to the electron beam in an undulator of length $L = N\lambda_0$ has a Rayleigh length $z_0 \approx L/12^{1/2}$ and a mode waist radius of $w_0 \approx N^{1/2}\gamma\lambda/\pi$. The FEL optical mode typically has more than 90 percent of the power in the fundamental mode described by these parameters.

In 2008, the DESY FLASH FEL reached the shortest wavelength ever for an FEL, $\lambda \approx 6.5$ nm. There was one other new lasing at Kyoto (KU-FEL) at $\lambda \approx 11\text{-}14\ \mu$m.

Countries worldwide participate in FEL development as a tool for scientific research. More than 10 countries from Europe, North America, and Asia are represented, with more than half of the FELs located in the United States and Japan.

TABLE 2.1 Relativistic Free-Electron Lasers in 2008

Location (Name)	λ (μm)	σ_z (ps)	E (MeV)	I (A)	N	λ_0 (cm)	K (rms)	Type
Frascati (FEL-CAT)	760	15-20	1.8	5	16	2.5	0.75	RF,O
UCSB (mm FEL)	340	25,000	6	2	42	7.1	0.7	EA,O
Novosibirsk (RTM)	120-230	70	12	10	2 × 33	12	0.71	ERL,O
KAERI (FIR FEL)	97-1,200	25	4.3-6.5	0.5	80	2.5	1.0-1.6	MA,O
Osaka (ISIR,SASE)	70-220	20-30	11	1,000	32	6	1.5	RF,S
Himeji (LEENA)	65-75	10	5.4	10	50	1.6	0.5	RF,O
UCSB (FIR FEL)	60	25,000	6	2	150	2	0.1	EA,O
Osaka (ILE/ILT)	47	3	8	50	50	2	0.5	RF,O
Osaka (ISIR)	32-150	20-30	13-19	50	32	6	1.5	RF,O
Tokai (JAEA-FEL)	22	2.5-5	17	200	52	3.3	0.7	RF,O
Bruyeres (ELSA)	20	30	18	100	30	3	0.8	RF,O
Dresden (U-100)	18-230	5-20	20-40	25	38	10	2.8	RF,O
Osaka (FELI4)	18-40	10	33	40	30	8	1.3-1.7	RF,O
LANL (RAFEL)	15.5	15	17	300	200	2	0.9	RF,O
Kyoto (KU-FEL)	11-14	2.0	25	17	40	4	0.99	RF,O
Darmstadt (FEL)	6-8	2	25-50	2.7	80	3.2	1	RF,O
Osaka (iFEL1)	5.5	10	33.2	42	58	3.4	1	RF,O
BNL (HGHG)	5.3	6	40	120	60	3.3	1.44	RF,A
Beijing (BFEL)	5-20	4	30	15-20	50	3	1	RF,O
Dresden (ELBE)	4-22	1-10	34-16	30	2 × 34	2.73	0.3-0.7	RF,O,Kl
Tokyo (KHI-FEL)	4-16	2	32-40	30	43	3.2	0.7-1.8	RF,O
Nieuwegein (FELIX)	3-250	1	50	50	38	6.5	1.8	RF,O
Orsay (CLIO)	3-53	0.1-3	21-50	80	38	5	1.4	RF,O
KAERI (HP FEL)	3-20	10-20	20-40	30	2 × 30	3.5	0.5-0.8	RF,O,Kl
Osaka (iFEL2)	1.88	10	68	42	78	3.8	1	RF,O
Nihon (LEBRA)	0.9-6.5	<1	58-100	10-20	50	4.8	0.7-1.4	RF,O
UCLA-BNL (VISA)	0.8	0.5	64-72	250	220	1.8	1.2	RF,S
JLab (IR upgrade)	0.7-10	0.15	120	400	30	5.5	3	ERL,O
BNL (ATF)	0.6	6	50	100	70	0.88	0.4	RF,O
Duke (OK-5)	0.45	0.1-10	270-800	35	2 × 32	12	0-4.75	SR,O,Kl
Dortmund (FELICITAI)	0.42	50	450	90	17	25	2	SR,O
Osaka (iFEL3)	0.3-0.7	5	155	60	67	4	1.4	RF,O
Orsay (Super-ACO)	0.3-0.6	15	800	0.1	2 × 10	13	4.5	SR,O,Kl
BNL (SDL FEL)	0.2-1.0	0.5-1	100-250	300-400	256	3.9	0.8	RF,A,S,H
Okazaki (UVSOR)	0.2-0.6	6	607	10	2 × 9	11	2	SR,O,Kl
Tsukuba (NIJI-IV)	0.2-0.6	14	310	10	2 × 42	7.2	2	SR,O,Kl
Trieste (ELETTRA)	0.2-0.4	28	1,000	150	2 × 19	10	4.2	SR,O,Kl
Duke (OK-4)	0.193-2.1	0.1-10	1,200	35	2 × 33	10	0-4.75	SR,O,Kl
RIKEN (SCSS Prototype)	0.03-0.06	1	250	300	600	1.5	0.3-1.5	RF,S
DESY (FLASH)	0.0065	0.025	1,000	2,000	984	2.73	0.81	RF,S

NOTE: λ, optical wavelength; σ_z, pulse length; E, beam energy; I, beam peak current; N, number of undulator periods; λ_o, undulator period; K, undulator parameter; RF, radio-frequency linac; EA, electrostatic accelerator; ERL, energy recovery linac; MA, microtron accelerator; SR, electron storage ring; A, FEL amplifier; O, FEL oscillator; Kl, FEL klystron; S, self-amplified spontaneous emission (SASE) FEL; H, high-gain harmonic generation (HGHG) FEL.

SOURCE: W.B. Colson, J. Blau, J.W. Lewellen, B. Wilder, and R. Edmonson, "Free Electron Lasers in 2008," *Proceedings of the 30th International FEL Conference, Gyeongju, Korea*, in press, Table 1. Available at www.JACoW.org.

FREE-ELECTRON LASER DESCRIPTIONS

The FEL schematic diagram in Figure 2.1 shows an energy recovery linac (ERL)-based FEL amplifier or oscillator. The electron beam path, shown in red, is in a vacuum pipe. At the beginning of the path, a cathode drive laser excites a sequence of electron pulses from the cathode surface into the electron gun and booster, acting as the injector system. The electron pulses leave the injector with energy E_i and move into the merge, where they enter the superconducting linear accelerator (linac). The electron pulses entering at RF phases suitable for acceleration reach an average energy E_0 at the end of the accelerator before entering the 180° bend. The electron pulses then are directed into one of the undulators, where a small percentage ($\Delta E/E_0$) of their energy is converted into light. In the case of the FEL oscillator, the optical pulses are bouncing between the cavity mirrors of an open optical resonator. Care must be taken to synchronize the sequence of electron pulses triggered by the cathode drive laser into the correct phase of the RF cycles and to overlap with the stored optical pulses at the entrance to an undulator. In the case of the FEL amplifier, there is no optical resonator; a seed laser sends optical pulses synchronized to overlap the electron pulses as they enter the undulator. After the undulator, the electron beam continues at reduced average energy ($E_0 - \Delta E$) around a second 180 degree bend to the merge, where the electron pulses re-enter the linac. Here they are interleaved with the accelerating electrons, but at RF phases that reduce their energy. Their kinetic energy is converted (recovered) to RF energy, substantially reducing the external drive power required by the linac RF cavities and also reducing the ionizing-radiation shielding required. After deceleration, the low-energy electron beam is separated from the path of the high-energy beam and directed into the beam dump at energy E_d. Not shown are various bending and focusing magnets along the electron beam path.

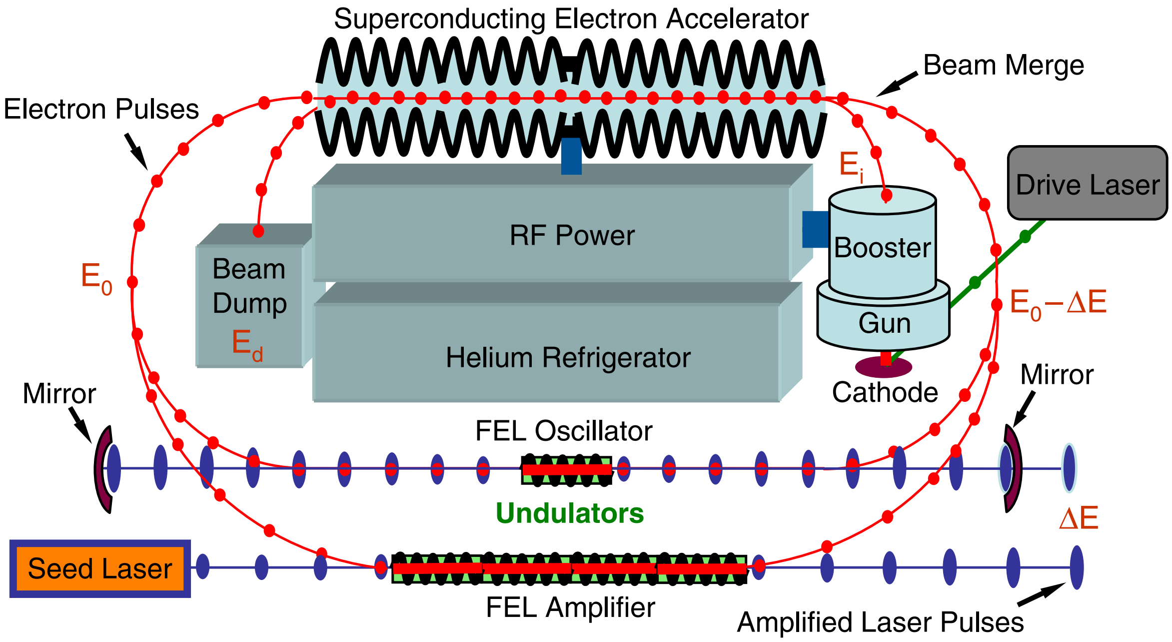

FIGURE 2.1 Representative schematic diagram of a free-electron laser (FEL) energy recovery linac (ERL) system illustrating both major genres of FELs (oscillators and amplifiers). This illustration captures the major elements of the FEL ERL and is not to scale. An FEL ERL need not operate in both genres. SOURCE: W.B. Colson, Naval Postgraduate School.

HIGH-ENERGY LASER TRADE-OFFS

Trade-offs between competing systems concepts and technologies form the basis for decision making. Ultimately, if HEL weapons are to be deployed, they must show a competitive advantage over other system concepts, such as the well-developed defense-in-depth missile and gun systems currently deployed by the Navy. A trade-off analysis with missile systems is not within the scope of this study, but it is worth mentioning the threat scenario in which a missile-based defense has limitations and HEL weapons have potential strengths. In particular, these emerging antiship threats include sea-skimming missiles with very low signatures, high supersonic maneuvering sea-skimming missiles, and antiship ballistic missiles. In each of these cases, the time lines for reaction from threat detection to ship impact are very short, and in the second two threat cases, defensive missile agility (pulling enough *g*'s) is severely stressed. The HEL speed-of-light delivery of energy and the ability to slew a beam to track a target at high rates is a potential counter to these advanced threats. In addition, the advanced optical systems in HEL devices could highly augment conventional detection and tracking systems for low-signature targets. This section discusses trade-offs between different HEL concepts (all of which share these advantages) rather than between HEL and alternative weapon systems. Trade-offs within FELs form the basis for the FEL technical assessment in Chapter 3.

The following list, based on information provided by the Navy and the knowledge base of the committee, forms the decision space for Navy HEL trade-off analysis:

- Potential to scale to megawatt power levels with multisecond continuous operation;
- Ability to provide optimized wavelength for propagation in the marine layer (modeling and experimental data point to wavelengths of 1.045 μm, 1.62 μm, and 2.2 μm);
- Beam quality to maximize energy on target;
- Size and complexity of entire HEL system,
  - —Energetic chemicals vs. electric power,
  - —Complexity of optical system,
  - —Requirements for cooling, cryogenics, and vacuum,
  - —Sensitivity to shock and vibration,
  - —Need for ionizing-radiation shielding and other safety factors; and
- Technology maturity.

Three different classes of HEL are evaluated accordingly: chemical lasers, slab and fiber solid-state lasers, and free-electron lasers.

- *Chemical lasers.* These have already been scaled to the megawatt level with adequate beam quality and operational optical trains. The DF laser operates at a wavelength over a series of lines from 3.6 μm to 3.9 μm, while the chemical oxygen iodine laser (COIL) operates at 1.315 μm. The showstopper for chemical lasers for naval applications is propagation in the marine boundary layer, where even modest absorption (principally by aerosols) leads to thermal blooming that reduces the energy on the target to subcritical levels for head-on engagements no matter how much energy is provided at the laser output aperture. No chemical laser systems have been identified to operate at the wavelengths mentioned above for optimized propagation in the marine layer.
- *Solid-state lasers (SSLs).* These are at a similar state of technical maturity as FELs in terms of scale-up but have distinct attributes and technology issues. The principal potential advantage of SSLs over FELs is in overall system size and complexity for moderately high power. While the device does require cooling (the major issue in scale-up), it does not require cryogenics or a hard vacuum; furthermore, SSLs should be relatively insensitive to shock and vibration, as well as being compact compared to FELs. The SSL devices are electrically pumped; however, there is not a significant ionizing-radiation hazard. A principal obstacle to scale-up to megawatt power levels is the removal of waste heat from the solid-state gain medium. As the gain medium heats, optical quality is lost as the medium distorts, and eventually heating will kill the gain.

Another obstacle to scale-up to very high powers for the SSL comes from the limitations in combining compensated and phased amplifier chains from multiple slabs or fibers. At power levels above ~100 kW, the projected size and complexity of SSLs begin to exceed those of the projected FEL. Solid-state (slab or fiber) lasers can approach some of the requirements for propagation at 1.045 μm, depending on the SSL gain medium, but not easily at 1.62 μm or 2.2 μm. For naval applications the SSL does not appear to be an attractive alternative for megawatt applications, but it may be an attractive alternative for requirements below 100 kW.

- *Free-electron lasers.* These have several natural advantages for high-power weapon applications. At least in an oscillator configuration, the small Fresnel number of the resonator assures that the optical beam quality will be good. Experience has proved that this is true in amplifiers as well as in oscillators. In addition, the high speed of the gain medium (the electron beam) assures that the waste heat is rapidly removed from the optical system. Called the "garbage-disposal" principle, this is the principal restriction on the power of solid-state lasers. Finally, by their nature, FELs are wavelength tunable by simply adjusting the electron energy or the undulator field strength via a gap change. Although this tunability is restricted by optical coatings, it is always true that the wavelength is at least selectable for the application (a marine atmosphere, in the Navy application) when the FEL is designed. FELs also have significant scale-up issues, which are described in detail in Chapter 3. Not described in this report but a significant hurdle for the FEL is the assumed overall system size and complexity. The system will require significant isolation from ship-induced shock and vibration, a hard vacuum, and cryogenic cooling. Moreover, the dumping of high-energy electrons will require ionizing-radiation shielding.

This trade-off discussion on laser alternatives to reach megawatt power levels at wavelengths of interest to the Navy supports the conclusion that the FEL has clear and significant advantages over other types of lasers to meet these laser device-level requirements. It does not, of course, address whether the FEL will meet system-level requirements for a weapon system or provide trade-offs with kinetic energy weapons systems.

RELATION TO SCIENTIFIC FREE-ELECTRON LASERS

The scientific opportunities presented by free-electron lasers and other advanced coherent light sources were studied in a 1994 report by the Committee on Free Electron Lasers and Other Advanced Coherent Light Sources, organized by the Board on Chemical Sciences and Technology and the Board on Physics and Astronomy of the National Research Council (NRC) with the support of the Department of Energy and the Office of Naval Research.[3] Due to cost and benefit considerations, the report was organized according to spectral regions, but it was recognized that the same physical principles govern the design of free-electron lasers in all wavelength regions. The most compelling scientific case for a free-electron laser facility was found to be in the far infrared, the region between 1,000 and 10 μm. The research advantage of the FEL in this context is its wide tunability and its flexible pulse structures, with the possibility of using chirped pulses being a capability that is unavailable with conventional lasers in this wavelength region. In addition, the report pointed out that research and development aimed at improving FELs in a specific wavelength region may be important to the improvement of FELs in all wavelength regions.

Since that NRC report in 1994, significant advances in the development of FELs have been propelled by scientific utilizations of next-generation light sources capable of producing coherent photons continuously tunable from the terahertz (THz) to the hard x-ray regimes. In particular, the committee notes the emergence of the x-ray FEL and its connection with advances made in the emittance of nanocoulomb charge beams from RF electron guns, the development of superconducting RF guns, and the development of energy recovery linacs, advanced by the synchrotron radiation community and electron cooling technology. Crucial to the realization of turnkey, high-average-power FELs in the wavelength region of interest for Navy applications is the synergy between the advances in hardware and software simulations that have occurred during the past decade.

The synchrotron radiation sources of the past and present can be defined as follows. First-generation machines are electron synchrotrons and storage rings that were built for other purposes—for example, for high-energy and nuclear physics—but their bending magnet radiation was parasitically used by synchrotron radiation users. This radiation covered many wavelength regimes due to the nature of the bending magnet emission. In addition, the machines produced rather large photon source sizes as the electron beam emittance was large and not intended for (or ideal for) synchrotron radiation applications. Second-generation machines are dedicated machines for synchrotron radiation users and employ bending magnets as the primary source of synchrotron radiation. The beam emittances were designed by the machine architects to be smaller in order to provide users with a smaller source size and greater brilliance. Third-generation machines are dedicated for synchrotron radiation users and were designed to accommodate many so-called insertion device magnets, such as undulator and wiggler magnets. Undulator magnets generate narrow spectral lines, which enhances the overall photon brilliance. Next-generation light sources involve an optical gain mechanism, with the goal of transverse and longitudinal optical coherence such as in an FEL.

NOTES

1. A.J. Balkcum, D.B. McDermott, R.M. Phillips, and N.C. Luhmann, “High-Power Coaxial Ubitron Oscillator: Theory and Design,” *IEEE Transactions on Plasma Science* 26: 548-555 (1998).
2. D.A.G. Deacon, L.R. Elias, J.M.J. Madey, G.J. Ramian, H.A. Schwettmann, and T.I. Smith, “First Operation of a Free-Electron Laser,” *Physics Review Letters* 38: 892-894 (1977).
3. National Research Council, *Free Electron Lasers and Other Advanced Sources of Light: Scientific Research Opportunities* (Washington, D.C.: National Academy Press, 1994).

3

Technical Assessment:
Scalability to One-Megawatt Power Levels

HOW TO ACHIEVE 100 KILOWATTS AND ONE MEGAWATT

The current level of FEL power in the near-infrared wavelength range (around 1 micrometer) is 14 kW, established at Jefferson Laboratory. The next step proposed by the Navy program is to demonstrate and study a 100 kW FEL system to establish the technology needed for scaling to the megawatt power level in the infrared. Assuming well-established undulator technology, the undulator period will be in the range of ~3 to ~5 cm, so that the electron beam energy needed to reach infrared wavelengths will be in the range of ~80 to ~120 MeV. The Jefferson Laboratory FEL system, with an energy recovery linac, has established that an energy extraction of a few percent (~2 percent) can be obtained, while inducing an energy spread of ~10 percent. This means that the necessary average current recirculating in the energy recovery system must be ~1 A for a megawatt-class FEL and ~0.1 A for a 100-kW-class FEL. Jefferson Laboratory now achieves its 10 kW operation by recirculating electron pulses of about 0.1 nC at a repetition rate of about 75 MHz. Therefore, the path forward in the new 100 kW FEL will need to achieve average recirculating currents of around 0.1 A, and the path forward in the megawatt-class FEL will need to achieve average recirculating currents of around 1 A.

The increase in average current can be achieved by increasing either the bunch charge or the bunch frequency, or both. To achieve a 0.1 A current for the 100 kW FEL, a bunch charge of 0.1 nC can be produced at an increased frequency of 750 MHz, or the bunch charge can be increased to 1 nC at the same frequency of 75 MHz. Some technical issues depend more on the average current, while others depend more on the peak current in the electron bunches. The lower bunch charge of ~0.1 nC and the associated problems have already been explored at Jefferson Laboratory, while the increased bunch charge of ~1 nC may well lead to new technical issues. The 100 kW FEL will require exploration of the higher average current of around 0.1 A at 750 MHz (“filling every bucket”) but can also involve exploration of the generation and transport of ~1 nC bunches at the lower repetition rate of 75 MHz. To scale the power to the MW class, it will be necessary to increase both the pulse charge to ~1 nC and the pulse repetition frequency to ~750 MHz.

Bunch charges in the nanocoulomb range have been demonstrated and have produced lasing. In the regenerative amplifier FEL demonstration at Los Alamos National Laboratory (LANL), the FEL reached an output power of 140 kW over a timescale of 10 microseconds (μs). This low-duty-factor, high-power FEL demonstration suggested that FEL amplifiers could potentially reach 100 kW continuous average power if high-power radio-frequency (RF) systems and high-duty-factor accelerators were used to provide the electron beams to drive the FEL. The low-duty-factor advanced FEL facility is still available for doing proof-of-principle experiments to test new ideas for high-gain FELs. It consists of a 20 MeV integrated photoinjector capable of 5 nC bunch charge at a repetition rate of 108 MHz, or 0.5 ampere average current over 10 µs.

At Argonne National Laboratory, the Argonne Wakefield Accelerator with an L-band high-Q injector has demonstrated the world's highest charge per bunch. In single bunch operation, the system has demonstrated a micropulse charge that is tunable between 1 nC and 100 nC, a current of 10 kA, an energy of 15 MeV (using one 30 MW klystron), and an energy of 30 MeV (by adding a second 30 MW klystron). In bunch train operation, the system has demonstrated four bunches × 50 nC and 64 bunches × 50 nC, 50 ns long (needs a cesium telluride cathode), and a beam power of 1.5 GW.

It is important to achieve the 2 to 3 percent extraction mentioned above; otherwise the recirculating beam current will have to be increased further beyond the already impressive 1 A. FEL simulation and experiments indicate that more than 2 percent is possible with sufficiently good electron beam quality. This extraction would require something around a ~20-period undulator for the oscillator design and a ~200-period undulator for the amplifier design. Both the oscillator and the amplifier undulators can be tapered to increase extraction.[1,2,3] In fact, the amplifier must be tapered to reach the 2 percent required extraction. The untapered amplifier will only achieve about 0.5 percent extraction (both simulation and experiment show this) and would therefore require substantially more average beam current to reach the same laser power levels.

The motivation for tapering to increase extraction can be seen in the resonance condition, which has already been described. As the average electron beam energy decreases, reducing the Lorentz factor in the denominator of the resonance condition, electrons go out of resonance, beginning the saturation process in strong optical fields. A "trick" to extend resonance is to increase the undulator gap, reducing the undulator magnetic field and hence the value of the undulator parameter, K, in the numerator of the resonance condition. The tapering trick has been demonstrated in a number of experiments and many simulations. Often, the tapering does not start until about halfway down the undulator, thereby allowing the FEL to reach strong optical fields near saturation in the first half.

While tapering can be used in the amplifier to increase the extraction to the 2-3 percent level, there is also an induced energy spread, as in the untapered case. This induced energy spread cannot be excessive and is considered to be limited to about 10-15 percent because of two important processes in the recirculating FEL. First, bending an electron beam around a 180-degree arc is difficult with a beam containing a large range of energies, and hence bending angles in the dipole magnetic field. The second process is the deceleration of an electron beam with a large energy spread. A fractional momentum spread of 10 percent in the 100 MeV beam becomes roughly 200 percent when the beam is decelerated to the injection energy, typically 5 MeV. Such a large momentum spread can exceed the acceptance of the downstream beam line, causing particle loss. Further, the large energy spread on the decelerating beam causes the longitudinal phase space to be curved, as the particles in the beam occupy a large range of the RF phases of the cavity fields. Beyond a certain limit of the energy spread, these nonlinear distortions of the phase space can cause some of the low-energy particles to get lost in the last RF cavities and not arrive at the exit of the linac. Experience at the Jefferson Laboratory FELs has shown that, for proper energy recovery, the nonlinear distortions must be corrected. So in the Jefferson Laboratory FEL, the optics of the recirculator are set up to impart not only a linear position-energy correlation, but also a quadratic dependence of the fractional momentum spread on the longitudinal position upstream from the linac, which compensates the RF-induced curvature. At the Jefferson Laboratory FEL, these corrections are done with sextupole magnets. The details of the process are too lengthy to include in this report, but are described in Piot et al.[4]

Optical sidebands can be generated in high-peak-power FELs. The sideband power can be significant and is a second laser line about ~1/N, or ~1 percent away from the fundamental frequency on the long-wavelength side. It is caused by the mixing of the oscillation frequency of electrons trapped in strong optical fields with the fundamental frequency of the FEL. This sideband generation has been observed in experiments and simulations and is the result of strong optical fields at saturations in each micropulse, not high average power.

Both the FEL oscillator and the amplifier may experience sideband generation for the parameters considered in this report. Their presence in the laser beam could be seriously detrimental to propagation through the atmosphere, since windows of low absorption tend to be narrow. If the fundamental FEL wavelength was in such a window, the sideband would experience significant absorption, leading to thermal blooming. Fortunately, the sideband instability can be controlled in a few ways. First, tapering the amplifier, or even the oscillator, in FEL configurations tends to reduce or remove the sidebands. Secondly, adjusting the resonator mirror separation by a small amount (1 part in 10^7) will desynchronize the bounce time of the optical pulses and the electron pulse repetition frequency so as to remove the sidebands. Also, the output coupling of the FEL oscillator resonator can be increased to remove the sidebands. Finally, the sideband power may be removed by optical means after the FEL interaction. In all, it is not considered a problem to remove the sidebands leaving only the power in the FEL fundamental wavelength. In general, removing the sidebands is accomplished by "turning down" the FEL interaction so that saturation occurs in strong optical fields, but not excessively strong fields. For narrow-band applications, the FEL would be expected to rely on the normal FEL power at saturation.

It is important to note that the final obstacle to the achievement of 14 kW at Jefferson Laboratory was thermal distortion of the mirrors. Mirror coatings (absorption and damage) and mirror cooling remain challenging issues. Of particular concern is increased absorption by the optical coatings caused by the UV harmonics of the high-power laser. These issues are more severe when the peak current (and gain) are lower and must be balanced against the injector and beam-transport problems (such as coherent synchrotron radiation) associated with higher peak current. The Jefferson Laboratory FEL is still available for experiments in the oscillator configuration. The average beam current is ~10 mA, with energy of 110 MeV, operating at a wavelength of 1.6 μm.

It is important at each level of development to establish a solid connection between experiment and simulation and modeling. Simulations should be established to have a record of predicting experimental observations as well as to explain the observed experimental results. It is only with validated simulations that scaling from the 10 kW level, achieved now, to the 100 kW level and eventually to the megawatt class can be established with adequate confidence. Many codes have been benchmarked with each other as well as to experimental results, but some areas of the system are not modeled well. A discussion of simulation and modeling capabilities and challenges is provided in a separate section, after the following detailed discussion of FEL system blocks.

END TO END BY SYSTEM BLOCKS

The following sections discuss the FEL from end to end by system blocks. These system blocks are shown in Figure 2.1 in Chapter 2. It should be noted that the path to optimization of the overall system to achieve the parameters specified in the charge to this report is not necessarily that of optimizing each block. This is because there are trade-offs between blocks that allow the requirements on one to be relaxed at the expense of another, and vice versa. For example, by increasing the injector requirements to increase gain, one may use an amplifier and relax the need for high-damage-threshold oscillator mirrors. Other trade-offs exist between the current and the voltage of the accelerator and between repetition rate and charge per pulse. Furthermore, optimization of the system for a weapon application, taking into account the constraints of shipboard operation not considered here, would be different still. Nevertheless, the committee believes this block analysis is a useful way to assess where there are gaps between the current state of the art and the needs of a megawatt FEL.

Electron Gun Systems

There are three varieties of electron guns—direct current (DC) high-voltage (HV); normal-conducting (NC) radio-frequency (RF); and superconducting RF (SRF)—employing one of three different types of cathodes (thermionic-, field-, and photoemission cathodes). A photoinjector uses a laser-switched photocathode in one of the above electron guns with a booster that accelerates the beam to an energy of several MeV, which allows optimized control of injection of the electron beam into the main accelerator in an energy recovery linac (ERL) configuration. In all cases, a high-average-current electron gun should produce a continuous train of electron pulses. The repetition rate of the electron pulses should be equal to, or a subharmonic of, the RF of the accelerator. For optimum acceleration in an RF field, each electron pulse should be much shorter than the RF period. If we assume a nominal RF for the accelerator of 700 MHz, a 1 A average current would require electron bunches that each contain 1.4 nC of charge repeated at a 700 MHz repetition rate. Lower average currents can be achieved either by reducing the repetition rate of the electron bunches, or by reducing the charge per bunch, or both.

The committee believes that the most expeditious pathway forward to the 100 kW average-power FEL, scalable to the megawatt class, is a photoinjector, because the FEL requires a very well controlled series of electron pulses matched into the accelerator capable of achieving repetition rates in the gigahertz range.[5,6] The electron gun system in block diagram is shown in Figure 2.1. A megawatt-class FEL will require a 1 A average-class electron beam. The Boeing gun of the early 1990s holds the record of 32 mA for approximately 3 hr.[7,8] The characteristics of this gun are close to those required for 100 kW FEL operation. The Boeing NC RF photocathode gun, operating with a multialkali photocathode, described below, is the state of the art for the NC RF gun. The next-ranked state of the art is the DC HV gun, with a cesiated GaAs photocathode, also described below. The SRF photocathode guns are ranked as least state of the art. It is difficult to de-couple the photocathode from the electron gun when describing the state of the art as it is truly a system of components that is required to produce the initial beam. Several state-of-the-art laser systems were already used to produce average currents in the NC RF and DC HV systems mentioned above.

Laser systems are already being improved in terms of power levels and repetition rates through investments such as in the U.S. Department of Energy Small Business Innovation Research (SBIR) program[9] to accommodate the high-repetition-rate ERL light sources of the future. The specifications they are set to deliver in 2009, based on ongoing work and improvements, are as follows:

- Repetition rate: arbitrary;
- Pulse duration: 50 picoseconds (ps) is straightforward, 10 ps is in development;
- Average power: 60-100 W green; and
- Peak power (determined by pulse duration and repetition rate): achieving high peak power becomes more challenging as one goes from 2 kW to 5 kW to 10 kW and higher.[10]

To summarize, the drive laser, the photocathode material, and the electron gun work together to ensure a high-quality beam of sufficient energy to lock in the quality. The challenging part is ensuring that the choice of these three components delivers the parameters required by the FEL—the peak and average current, the transverse and longitudinal beam emittances, and the energy spread.

Photocathodes

Photocathode materials have been researched, developed, and tested extensively over the past 20 years for many free-electron laser systems.[11] Progress from 100 kW to megawatt FELs will require short (10 ps) electron pulses from the cathode. To produce such short pulses of high beam quality sufficient for acceleration, transport, and lasing, photoemission driven by a high-quality drive laser pulse with a pulse length on the order of 10 ps, with sufficient energy, and of a certain wavelength is required to overcome the materials' work function. A suitable cathode will have a high enough quantum efficiency to produce sufficient electron current at a reasonable drive laser power and wavelength and will have a lifetime commensurate with operational requirements. The quantum efficiency is the number of electrons released compared to the number of incident photons. A key issue for the 100 kW FEL scalable to the 1 MW class is the robustness of the cathode—that is, the total charge that can be delivered over a sustained period of operation. The robustness depends on the cathode material, with the most efficient cathodes generally found to be the most fragile. Achieving the 100 kW FEL power requires approximately 100 mA of average electron current (e.g., 0.14 nC per pulse at a 700 MHz repetition rate) and the megawatt-class FEL would require 10 times the charge per bunch, yielding 1 A average current. The committee considers the Boeing photocathode (a multialkali K_2CsSb photocathode) to be the state of the art, producing an average current of 32 mA over 3 hours of operation. In addition, there are several other promising pathways to achieving the 100 mA and 1 A average currents. Currently, the Jefferson Laboratory FEL system is capable of producing an average current of 10 mA for extended periods of time using cesiated GaAs cathodes. While cathodes that meet the quantum efficiency requirement of a megawatt-class system have been developed, their robustness and lifetime are not yet at levels that would make them suitable for long-term use.

For the 100 kW and megawatt-class FELs, the cathode is one of the most challenging components of the high-average-power FEL. This is due to both knowledge and technological issues. First, it is difficult to maintain sufficient vacuum pumping in the environment of electron guns that have large electrical gradients at the cathode for acceleration. Second, this gradient leads to electrical breakdown at times that degrades the cathode. Third, it is challenging to continuously refresh or change the cathode due to the ultrahigh vacuum requirements. The knowledge of how to develop an ultrarobust cathode is still being developed.

Photocathode Drive Lasers

To achieve a 100 mA to 1 A average current beam, the per-pulse charge should be between 0.1 and 1 nC, with pulse length of around 10 ps off the cathode and at a pulse repetition rate between 100 MHz and 1 GHz. The electron beam can be compressed later in a magnetic chicane to increase the peak current per pulse. Drive lasers suitable for driving cathodes to produce 100 mA of average current have been produced; however, no attempt has been made to develop a drive laser suitable for 1 A average current. A photocathode drive laser capable of producing a 1 A average current from a cathode with a quantum efficiency of 2 percent will require approximately 100 W of green laser power to the cathode, which is approximately five times the average power of the current state-of-the-art drive laser at Jefferson Laboratory. The cathode must be adequately cooled to handle such a high incident drive laser power.

Electron Guns

As was mentioned, there are three varieties of electron guns: direct current (DC) high-voltage (HV); normal-conducting (NC) radio-frequency (RF); and superconducting radio-frequency (SRF). The ideal gun should have excellent vacuum characteristics to preserve the cathode lifetime and a high accelerating gradient to maintain the electron beam quality. DC HV systems are able to achieve excellent vacuum; however, the accelerating gradient is currently limited to less than 6 MV/m, which limits the charge per bunch capability to <1 nC. The Jefferson Laboratory DC HV gun has the highest average current (10 mA) of any operating gun. NC RF guns offer the prospect of higher accelerating gradient (close to 10 MV/m) and, consequently, a charge per bunch capability in excess of 1 nC; however, poor vacuum has the potential to limit cathode lifetime. The performance of NC RF electron guns at high duty factor is limited by ohmic heating of the structure. The Boeing NC RF gun holds the record in average power, approaching the requirements for the 100 kW device. SRF guns offer the prospect of both high accelerating gradient (>20 MV/m) and superb vacuum characteristics, with the prospect of excellent photocathode lifetime. To date, SRF guns have only been tested at very low average currents (<1 mA).[12] At present, the limiting factor in SRF gun design is the mounting of the cathode in the gun. Several high-average-current SRF guns are in design, and one is under construction.[13]

Booster

The booster is a high-current, non-energy-recovered linac section that boosts the energy of the gun for acceleration by the ERL. The booster is located between the electron gun and the beam merger of the ERL. Technically, the booster is considered a part of the injector. It may be either a distinct unit or part of the electron gun.

The parameters of the booster are an energy gain of a few MeV (between 2 and 8 MeV) at the full current of the linac, which may be up to 1 A. The booster is characterized by a very high RF power input since it is not energy recovered. The present parameters achieved by the Jefferson Laboratory FEL booster are about 10 mA at 7 MeV. The goals of the Cornell booster are 100 mA and an energy gain of 15 MeV; however, this booster is still in the commissioning phase and the parameters have not yet been demonstrated.

The objective of the booster is to accelerate the beam rapidly to the energy level at the entrance of the ERL. This is important in order to minimize the emittance growth, both longitudinal and transverse (emittance growth degrades performance). The energy at the end of the booster is determined by the minimum required to achieve efficient energy recovery in the presence of a large energy spread induced by the FEL interaction on the one hand and the energy gain required for stabilizing the emittance growth on the other. The booster design energy gain is limited by the fact that this energy is mostly dumped, thus increasing the power consumption and complicating the beam dump. This consideration places a large premium on reducing the energy of the booster. There is also a penalty for going over 9.91 MeV (the neutron generation threshold in copper). Since some electrons will be dumped at energies exceeding the injector energy, the booster energy should be below 9 MeV. Ongoing research efforts at Jefferson Laboratory and Brookhaven will help determine how low an energy level can be used in the booster.

Even though the booster requires a very high RF power input (typically the bulk of the RF power required by the FEL), it is still anticipated to be superconducting RF, primarily to increase the overall efficiency of the FEL, increase the energy rapidly, and reduce the footprint of the FEL, but also to improve the vacuum in the vicinity of the gun. While no booster has been demonstrated at the energy and current required for a high-power FEL, the committee sees and anticipates no physics or knowledge issue associated with achieving the required parameters. Given the freedom to break the booster into a number of smaller cavities (as is done in the Cornell injector), there is no technical issue associated with the coupling of RF power or the handling of higher-order-mode power. A higher-order mode is a cavity mode in the accelerator other than the desired acceleration mode. Higher-order modes are generated by the electron beam and can have undesirable electromagnetic fields that can kick the electron beam and lead to beam disruption. This makes it important to design the cavities such that higher-order-mode power is removed and dissipated quickly.

Merger Optics

The “merger” is an electron beam optical device composed of magnet beam optical elements. It is an essential element of the same-cell ERL. It serves the function of merging the low-energy beam from the injector with the high-energy beam returning from the FEL, such that both will be directed along the axis of the ERL accelerating (and decelerating) cavities. The merger is located at the entrance of the ERL and is also the last low-energy (arguably the injector) beam element.

The main concern with the merger is the minimization of emittance growth. One reason for this emittance growth is that the merger system mixes transverse and longitudinal degrees of freedom and consequently violates emittance compensation conditions. Several merger schemes are in use, such as a reverse bend (Jefferson Laboratory FEL), a “chicane” (Budker Institute of Nuclear Physics FEL), and a “dog leg” (Japan Atomic Energy Research Institute FEL). All of these mergers introduce some emittance growth. A new merger system, the “zigzag,” is under construction at the Brookhaven National Laboratory (BNL) ERL, which should introduce the least emittance growth. (More information on mergers can be found in Litvinenko et al.[14])

The merger does not present any technological or scientific issues. However, one should note that the zigzag merger, which is the only merger presenting a negligible emittance growth, has not been demonstrated experimentally.

Energy Recovery Linac

The ERL is the element that accelerates the beam from the injection energy to the FEL energy and then recovers (most of the) energy before dumping the beam. Because of this dual function—acceleration and deceleration—the ERL is continually traversed twice by the beam and thus appears in Figure 2.1 between the injection beam merger and the FEL and then again between the FEL and the beam dump. Even though the ERL provides most of the energy for the FEL, its RF power consumption is low thanks to the energy recovery feature. However, the ERL represents the largest load on the liquid helium refrigeration system, which runs continuously.

The ERL is composed of one or more cryomodules. A cryomodule is a cryostat containing accelerating cavities and ancillary equipment such as tuners, couplers, and higher-order-mode (HOM) loads. In addition, the ERL requires medium-power RF power units and a cryogenic system.

The ERL parameters are up to ~1 A of beam current and ~100 MeV of acceleration. The energy of 100 MeV has been demonstrated (in the Jefferson Laboratory FEL), but the highest current demonstrated so far is 20 mA (in the Budker Institute of Nuclear Physics FEL).

There are many technological subjects of interest associated with the ERL. These include stable operation at the design current (beam breakup instability issues), attaining the operational gradient of the superconducting cavities at a reasonable power consumption level for the refrigerator, dissipating and safely removing HOM power, and controlling vibrations (microphonics).

A number of technical issues have been adequately addressed and are not of concern. One of them is the achievement of a high gradient at low cryogenic losses. There are some issues that have not been resolved, but recent developments lead the committee to believe that these issues do not represent a gap in physics or technology. In this category is the beam breakup instability, which has reliable solutions for a beam current of up to a few amperes. Couplers (at the ERL cavity level) and tuners are also not an issue. One should, however, consider microphonics. Mechanical vibrations and helium pressure changes and noise change the resonant frequency of the cavities by up to a few hertz. Since the superconducting cavities in an ERL are narrow-band devices with a Q of about 10^8 (a bandwidth of ~7 Hz), a large mechanical disturbance can drive a cavity away from the RF to the extent that the accelerating fields will either collapse or change enough to prevent the FEL from delivering power. This is considered a solved problem for laboratory-based machines but has not been considered for naval applications.

The committee sees and anticipates no physics or technology gaps in this area, but because no ERL has operated at 100 mA (much less at 1 A), there is a certain knowledge gap.

Radio-Frequency Couplers and Power Handling

RF couplers are used to feed power to the cavities of the ERL and injector, extract higher-order modes from these cavities, and sample the field levels. The sampling (or pickup), as well as the fundamental power couplers (FPCs) of the ERL cavity (but not the injector cavities), are rather routine.

Strong, HOM damping of high powers of monopole and dipole modes is essential. The higher-order-mode power can be of significant magnitude (up to kilowatts) and extends over a broad frequency range. The challenge is to ensure adequate damping of HOMs and the extraction of HOM power with good cryogenic efficiency. Several HOM extraction schemes have been proposed for broadband HOM damping, with power dissipated at room or intermediate temperatures (for example, 80 K). For power efficiency, the HOM power should be damped at room temperature without undue increase in the complexity or length of the cryomodules. There is sufficient experience with high-power, HOM damping in high-current storage rings, and a nice adaptation of such devices has been made at Cornell University for incorporation inside a cryomodule, but there is no operational experience with high-power, cryomodule-located, HOM dampers. Ampere-class cryomodule design and fabrication efforts (with appropriate HOM damping) are ongoing at BNL and Jefferson Laboratory.

High-power fundamental power couplers for SRF elements, such as RF guns and booster cavities, have been built, but there is no operational experience at the megawatt level. (More information on RF couplers may be found in Rusnak.[15])

Based on the lack of operational experience with high-power fundamental power couplers and in-cryomodule higher-order-mode dampers, there is a knowledge gap in this area.

Energy Recovery Linac Lattice and Peripherals: Transport Challenges

The ERL lattice is a system of magnets that serves to transport the electron beam from the output of the linac cavities, through the FEL, and back to the linac for deceleration and energy recovery. The lattice also serves in other functions: matching the beam size and divergence into the wiggler and other components of the ERL; longitudinal phase space manipulations (if necessary); separating the decelerated beam from the accelerated beam to send it to the beam dump; and providing various beam diagnostic functions. The lattice is characterized by machine functions, such as the β function, phase advance, and dispersion. These functions are important for the stability of the ERL and its ability to transport the beam with minimal losses. Another challenge is to preserve the six-dimensional emittance. There are several other considerations, including the effects of coherent synchrotron radiation, halo and beam loss, and ion trapping. At the injection end, longitudinal space charge may lead to beam quality deterioration, particularly for very short bunches.

The combination of short bunch lengths and high average currents of high-power FELs presents the technical challenges of beam quality preservation and heat generation. The resistive-wall wakefields created by the electron bunches can generate a high heat deposition in various locations. The FEL wiggler, where the walls are near the bunch and the bunches are at their shortest, is one such place. Bellows or other high-impedance elements must be shielded. Short, high-charge beam bunches interacting with the lattice may cause coherent synchrotron radiation and microbunch instabilities. These lead to emittance growth and severe performance penalties. The coherent radiation from short bunches can deposit significant power on devices where such high power can lead to performance degradation.

It is important to control halo and beam loss in ERLs. Beam loss is a serious issue, since it can directly damage equipment, produce unacceptable increases in the vacuum pressure and cryogenic load, and lead to radiation hazards for equipment and personnel. Beam losses in the Jefferson Laboratory FEL have been quantified at ~10 mA operation. The total beam loss was <1 μA, <100 nA in the worst locations, and about 10 nA in some other locations. In ERLs that may operate at 10 to 100 times higher current, beam loss must be controlled to better than 1 ppm. Collimation at the injection site, a high-quality photocathode and gun, well-matched beam optics, and excellent machine protection systems will be critical for achieving this goal.

Similarly with synchrotron light sources, ERLs need to diagnose and control short bunches at high average beam power, which implies noninvasive diagnostics that allow continuous monitoring of transverse and longitudinal beam properties, synchronization systems, and protection systems.

Dipole HOMs in ERLs can pose a beam stability challenge. The beam and the RF cavities can form a positive feedback loop that closes when the beam returns to the same cavity. The feedback loop can lead to a transverse beam breakup (BBU) instability at sufficiently high currents, driven predominantly by the high quality factor of the superconducting cavities. The theoretical models for the BBU instability are mature and in excellent agreement with simulations and experiments. The BBU instability can be significantly ameliorated by specially designed RF cavities, operating at lower frequencies with strong HOM damping.

Ionization of residual gas molecules by the electron beam creates an ion column, which can lead to a distortion of the accelerator optics and coupled oscillations of the beam and the ions, both troublesome to the FEL operation. Good vacuum and possibly ion clearing electrodes may be important to minimize deleterious effects of the electron-ion two-stream instability (electron cloud instability).

As this long list of potential technical issues indicates, the ERL lattice is far from being a simple system. (Additional information may be found in Merminga.[16]) While there are no physics gaps, there are technical and knowledge gaps due to the required large increase in beam current from the known territory of 10 mA average beam current to the level of 100 mA and then 1,000 mA, envisaged for the 100-kW-class and 1-MW-class FELs, respectively.

Undulator and Associated Pinch for Amplifiers

The design and manufacturing techniques for undulators suitable for high-power FEL operation are well advanced. Most of the design features in existing FEL undulators for third- and next-generation light sources can be adapted for use in megawatt-class FELs as needed. There are no significant issues in manufacturing undulators with sufficient magnetic quality to produce lasing at the wavelengths under consideration.[17,18]

The undulators for FEL amplifiers will be much longer than those for short Rayleigh-range oscillators. Accordingly, the alignment of the amplifier undulators will require more attention than that of the oscillator undulators. The knowledge base for high-power FEL oscillator performance at ~1 μm wavelength is much greater than that for amplifiers. A particular concern for amplifier operation is the need to pinch the electron and optical beam near the exit of the undulator in order to cause the optical beam to expand sufficiently before encountering any optical elements. While this concept has been proposed, it has not been tested experimentally.[19]

Optical System Issues

Introduction

The optical gain of an FEL is strongly related to the peak current of the electron beam in the wiggler. For an oscillator, higher optical gain enables a higher optical out-coupling fraction and reduces the ratio of circulating intracavity power to out-coupled power. For example, the Jefferson Laboratory 14 kW FEL oscillator's modest optical gain only allowed an out-coupling fraction of about 10 percent. This resulted in 140 kW of power on the cavity resonator optics. For an amplifier, increased optical gain allows the use of a smaller drive laser or a shorter wiggler. However, higher gain demands higher current or smaller emittance, which places greater demands on the injector and may introduce greater problems with coherent synchrotron radiation.

In either case, the diameter of the electron beam and the optical beam in the interaction region is only a few millimeters. Diffraction over some distance is then required to allow expansion of the optical beam to the level where the oscillator's resonator optics or the amplifier's first relay optics can survive (typically an irradiance of 100 to 200 kW/cm^2).

Coatings

The development of optical coating technology for high-power laser applications in the ultraviolet to near-infrared over the past 35-40 years has been focused largely on the requirements of the national laser fusion and isotope separation (atomic vapor laser isotope separation) programs. These applications involve periodic laser pulse operation: laser-fusion lasers operating at wavelengths from 0.3 to 1 μm produce ~1 ns pulses at much less than 1/s, and the atomic vapor laser isotope separation Cu vapor laser, operating at wavelengths of 511 nm and 578 nm, produces 50 ns pulses at 4 kHz. Unfortunately, the coating materials that have been developed to survive these pulsed laser environments are not optimal for operation in either high-average-power cw lasers or in quasi-cw FELs, where the micropulse fluence (J/cm^2) is low.

From 1980 to 1990, optical system development for FEL applications was supported by the Strategic Defense Initiative (SDI) for a megawatt-class RF-linac FEL. Substantial progress was made during that time, but coating R&D ended when the SDI program was terminated in about 1991. However, a number of significant results were reported in the open literature and are discussed below. They are important for the development of megawatt-class FEL systems for naval applications.

At LANL, Sanders and colleagues (1990) identified hafnium oxide/silicon dioxide (HfO_2/SiO_2) multilayer dielectric reflectors, produced by ion-beam sputtered deposition (IBSD), as a prime candidate for meeting the requirements of megawatt-class FEL oscillators.[20] The IBSD technology was a direct adaptation from the successful methods and experience in producing ultra-low-loss (<10 ppm) mirrors for laser gyros. Collaborations with the industrial scientists who originally developed the IBSD coating technology for laser gyro optical systems resulted in production of IBSD HfO_2/SiO_2 reflectors with reflectance >0.9999 at 1 μm wavelength.[21] Sanders et al. reported that the cw damage resistance of these reflectors at 1 μm far exceeded the FEL system requirement.

Two decades later, IBSD multilayer reflectors of HfO_2/SiO_2 have been installed in the Jefferson Laboratory FEL and have survived cw intracavity average power densities well over 100 kW/cm^2 with the FEL operated at 1.6 μm wavelength with <0.4 ps (FWHM) micropulses at 18.71 MHz repetition frequency.[22] In addition, Menoni reported to the committee that output-coupler mirrors of this type were not damaged by irradiation of up to 200 kW/cm^2 with a 1.06 μm cw laser.[23]

In addition to needing a sufficiently high damage threshold, FEL oscillator optical systems must have very low absorption losses, approximately <10 ppm, to limit mirror substrate thermal loading and the resultant distortion that limits the operating power of the FEL. Currently available commercial IBSD reflectors for laser-gyro applications based on optical systems of, for example, TiO_2/SiO_2 and Ta_2O_5/SiO_2, are advertised to have absorption (and scattering losses) of <10 ppm at 633 nm.[24] In her presentation to the committee, Menoni also reported that her laboratory group at Colorado State University had employed IBSD to produce HfO_2/SiO_2 optical systems with <10 ppm loss at 1 μm for a high reflector and <14 ppm loss for an antireflection coated surface.[25] She also cited the absorption loss of 10 ppm for a 90 percent HfO_2/SiO_2 reflector (commercially produced) as measured at Jefferson Laboratory.

While attainment of sufficiently high damage resistance and low absorption in candidate reflectors is very encouraging for scaling to 0.1-1 MW-class FEL oscillators, there are other optical system degradation mechanisms particular to FELs that must be overcome. One is the terahertz radiation generated by the short electron bunches interacting with the magnet fields within the oscillator. Absorption of this radiation in the mirror substrates leads to distortion of the reflected optical wavefront, as observed in the Jefferson Laboratory FEL. Effective means to prevent the terahertz radiation from reaching the mirrors were reported.

The second and probably most serious optical system degradation mechanism is UV-harmonic-induced infrared absorption in the multilayer dielectric reflectors. FEL oscillators and amplifiers inherently generate substantial power in the optical harmonics of the fundamental lasing wavelength, and the relative strength of these harmonics has been measured in a number of operating FELs. Mirror degradation caused by absorption of the UV harmonic radiation was observed in the Orsay storage-ring FEL in 1984,[26] and more recently in the Jefferson Laboratory FEL. In both FELs, the resonator mirrors exhibited increased absorption at the lasing wavelength, which seriously limited the operating power.

Sanders et al. measured the magnitude of UV-induced infrared absorption at 1 μm for a number of candidate multilayer reflector materials using excimer radiation at 353 nm and 248 nm.[27,28] (These wavelengths corresponded to the third and fourth optical harmonics of the design wavelength.) Not surprisingly, the induced optical system absorption was more severe at 248 nm than at 353 nm. Fortunately, radiation at higher harmonics (shorter wavelengths) and radiation on even harmonics is generally somewhat weaker than radiation on lower or odd harmonics. The summary of the growth and decay of the induced absorption caused by 248 nm radiation is shown in Figure 3.1. It is noteworthy that the HfO_2/SiO_2 reflector produced by IBSD using highly pure (0.9997 percent) HfO_2 exhibited the least amount of increased absorption, 0.03 percent (300 ppm). In her April 2008 presentation to the committee,[29] Menoni cited a recent measurement in the Jefferson Laboratory FEL: <50 ppm absorption loss in the 90 percent HfO_2/SiO_2 output reflector coating induced by the optical harmonics. This was significantly less severe than had been experienced using other coating materials for the resonator mirrors.

In summary, one coating material system—IBSD HfO_2/SiO_2 using ultrapure HfO_2—has been developed that may well prove resistant to the multiple environmental hazards of FEL oscillators designed to produce output powers in the 100 kW to 1 MW class. Even with this materials system, the most serious limit on FEL circulating

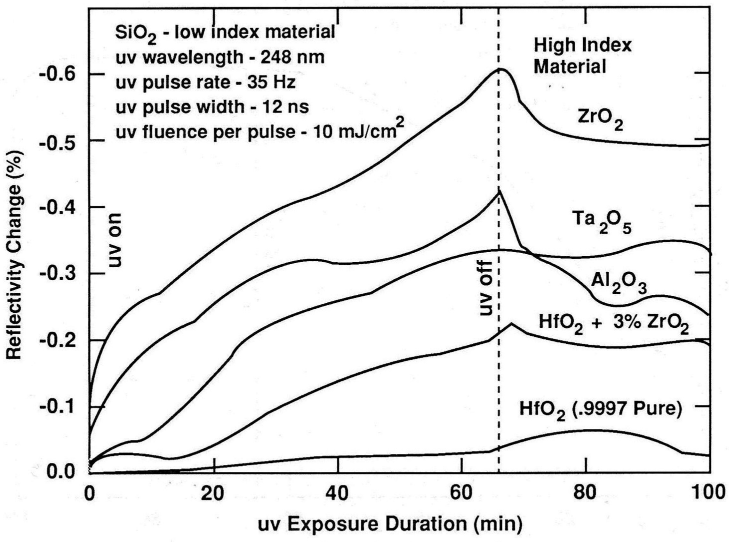

FIGURE 3.1 248 nm ultraviolet irradiation at low average intensity (0.35 W/cm^2) produced time-dependent increases in absorption (decreased reflectance) of five 1.1 μm multilayer dielectric reflectors $(X/SiO_2)^N X$. The magnitude and time dependence of the UV-induced absorption changes were strongly dependent on the high-index oxide layer. Laser irradiation was in 10 ns pulses at 35 Hz with 10 mJ/cm^2 pulse fluence. Reflectance was monitored at the design wavelength. SOURCE: V.E. Sanders, J.W. Early, and W. Leamon, "The Response of Multilayer Dielectric Coatings to Low Fluence Ultraviolet Light Exposure," *Laser Induced Damage in Optical Materials: 1989—Proceedings of the Boulder Damage Symposium, November 1-3, 1989* (Washington, D.C.: U.S. Government Printing Office, 1990), pp. 561-567.

power is UV-induced infrared absorption. Further optimization of the optical system properties should be pursued, and other candidate materials should be evaluated. Since no dielectric material will be totally immune from degradation by the FEL harmonics, ways (such as gratings) to redirect the intracavity harmonic power should be explored.

In addition, ongoing and future optical-systems work in other programs, such as the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) project, in which very low loss mirrors are being pursued for use on test masses, may also have relevance for FEL applications. The project's interferometer is expected to have cw power levels of ~1 MW at 1.064 μm, and even though UV harmonics will not be involved in this application, the parallel work on coated optics for Advanced LIGO may well reduce the gap between the current state of the art and the needs of the Navy. (Some researchers working in this area are Harry,[30] Chalkley et al.,[31] Markosyan et al.,[32] and Sun et al.[33])

There are a number of possible "work-arounds" for the optical system problem. Ways to address the threat posed by UV-harmonic-induced laser absorption (and, less likely, laser damage) of the resonator mirrors of an FEL oscillator include (1) ion-beam sputter coating R&D using very pure HfO_2 sputter targets for producing HfO_2/SiO_2 multilayer mirrors with minimized UV-induced absorption (the level possible to be determined); (2) exploration of other candidate materials for the high-index layers; (3) an FEL resonator design that has a sufficiently large diameter laser beam on the cavity mirrors (a more unstable resonator cavity); and/or (4) incorporation of a silver-coated intracavity grating at a large angle of incidence if such could be shown to survive the intracavity power. However, the most conservative and certain path for bypassing optical system degradation risks associated with an FEL oscillator will be (1) an FEL amplifier configuration driven by a synchronous seed laser or (2) a master-FEL oscillator/power amplifier (MOPA) for producing the high-power beam or (3) a regenerative FEL amplifier (large holes in the mirrors of a recirculation resonator, mirrors that would see very low FEL power, essentially only at laser start-up). The last-mentioned scheme would be the most compact of the alternatives.

Oscillators

As mentioned earlier, FEL resonators operate at a very low Fresnel number. Provided that hole output coupling is not used, such resonators discriminate strongly against higher-order modes and produce excellent output beam quality. Although the index of refraction and gain of the electron beam in the wiggler can distort the optical mode in the resonator, computer simulations and experimental measurements show that the optical beam has very good quality. Generally the resonator is long and slender, since the optical beam must be long and slender to fit through the undulator. In addition, the resonator is typically much longer than the undulator to give the optical beam the opportunity to expand before it reaches the first optical surface in order to reduce the irradiance incident on the surface. It is found that the Rayleigh range can be much smaller than the length of the undulator to make the beam expand faster.[34] This is important, since damage to the first optical surface is the most important issue for FEL resonators. In addition, increasing the gain reduces the burden on the optical system. In the first place, higher gain makes it possible to increase the output coupling, which reduces the recirculating power in the resonator. In the second place, higher gain corresponds to higher peak electron beam current, which reduces the necessary duty factor of the electron beam and, correspondingly, the duty factor of the optical beam on the optical surface.

Many options are available for the optical architecture of the resonator. Before the Navy's FEL average power scale-up program began in 1995, the highest demonstrated average power was ~10 W. The first laser in the Navy's scale-up program was a 1 kW oscillator built at Jefferson Laboratory. It successfully employed a near-concentric resonator at 6 μm, with a 100 percent reflector on one end and a ~10 percent transmitting out-coupler on the other. This same approach was used by Jefferson Laboratory for the next step (10 kW at 1.6 μm), but this encountered multiple difficulties with optical coating survivability and distortion under thermal load. It was learned that the resonator's total optical distortion needed to be $<\lambda/10$ rms. The approach that ultimately succeeded involved a back-plane-cooled high reflector (with thermal management to control the radius of curvature under thermal load) and a sapphire 10 percent out-coupler with cryogenic edge cooling for thermal and figure control.

As the average power of the FEL increases with the 100 kW Innovative Naval Prototype (INP) and follow-on megawatt upgrade, a beam-splitting out-coupler may become unusable due to the requirements to maintain optical figure (extremely low absorption in the coatings and substrate, a low-coefficient-of-thermal-expansion (CTE) substrate, and high-damage-threshold coatings on both surfaces) while edge cooling. The existence of significant UV harmonic radiation in the optical cavity (discussed above) further complicates the challenges for a beam-splitting out-coupler. Other approaches need to be examined.

An alternative approach for a resonator is one that uses a reflective annular out-coupler. This approach avoids a partially transmitting beam-splitter out-coupler and allows all resonator optics to be back-plane cooled. Every megawatt-class chemical laser that has been built by the Department of Defense since the inception of its high-energy laser program in the 1970s has successfully used this type of out-coupler. The optical resonator can be operated in a stable or unstable configuration. One characteristic of these megawatt-class chemical lasers has been their extremely high optical gain. For instance, the Navy's MIRACL laser out-coupled 85 percent of the round-trip energy. The harmonics of the fundamental lasing wavelength are a unique feature of FELs and make the transport optics and resonator optics more complex.

For FELs operating in a restricted space, such as a Navy ship, the use of a ring resonator with intracavity grazing-incidence, beam-expanding mirrors offers a way to reduce the power density on the cavity mirrors and allows for coatings with larger absorption than could be tolerated at normal incidence. Another advantage of non-normal incidence is the reduced phase error in the reflected beam.[35] For the beam-expanding mirrors, vacuum-deposited silver coatings may be feasible since the s-plane reflectance at 1 to 2 μm is very high and metallic coatings are not degraded by the UV harmonics. The ring resonator also allows for the convenient insertion of a reflective grating to redirect the harmonics. For this configuration, setting the correct cavity length and maintaining alignment of the multiple mirrors will require a more extensive set of beam diagnostics than with a concentric resonator, as was experienced in operating the Boeing/LANL grazing-incidence ring-resonator FEL experiment.[36]

At this point it is worth mentioning that the committee had difficulty identifying a knowledgeable speaker and could find scant literature on optical resonators for free-electron lasers. This was despite the fact that the experimental Boeing program on this topic mentioned above was vigorously pursued for several years in the 1980s and 1990s. Similarly, there is a dearth of literature and knowledgeable speakers on the development of optical coatings with damage tolerance to high harmonic radiation despite work on this topic at LANL. This loss of scientific capabilities seems to have been the outcome of a period of relatively high funding in the late 1980s, combined with classification of the results, and followed by a long period of significantly lower funding a decade later. (Information about the SDI budget and shutdown may be found in Marshall.[37])

Single-Pass Free-Electron Lasers

As an alternative to oscillators, single-pass FELs (often, and for simplicity in this report, referred to as "amplifiers") offer advantages and disadvantages. Amplifiers completely eliminate the resonator and out-coupler optics. The irradiance on the first optical surface depends on the divergence of the output beam. For equal divergence, the irradiance on the first optical surface can be smaller than the internal cavity power of the oscillator. At a distance from the output and out-coupler of the amplifier wiggler for the beam to expand adequately, the first optical surface may be a beam-expanding mirror at grazing incidence. The capability of reflecting the beam without significant wavefront distortion will be dependent on the irradiance of the incoming beam, the angle of incidence, polarization of the beam, and the reflectance of the coating material. Use of adaptive optical technology on these mirrors should provide substantial compensation of beam-induced thermal distortion.

On the other hand, in the early days of FELs, somewhat less experience was obtained with amplifiers than with oscillators. Historically, this follows from the fact that in the early days, when electron beam quality was poorer than it is today, FELs did not have enough gain to operate as useful amplifiers. The first significant experience with amplifiers was obtained at Livermore, using high-current (but not high-quality) e-beams from induction linacs. The Electron Laser Facility (ELF) experiments at millimeter wavelengths were quite successful, but the optical wave had to be propagated through a waveguide, and so the results are not completely relevant to the problems faced here. The follow-on Advanced Test Accelerator (ATA) experiments at shorter wavelengths were less successful and did not produce much data of use here. The most relevant experiments are those ongoing at Brookhaven National Laboratory and at Elettra in Italy. Although they are conducted at very low average power, essentially single-pulse experiments, they have produced many useful results on saturation of tapered wigglers, beam quality, bunch compression, and other issues.

In place of the resonator, the amplifier FEL requires a master oscillator, but 10 W average power (10 kW peak) should be sufficient. The optical quality of the input beam should not be an issue since the beam will be optically guided by the electron beam inside the undulator, and the output beam quality will not be dependent on the quality of the input optical beam. However, the master oscillator must operate at a wavelength determined by the atmospheric windows for propagation in a maritime environment. This increases system complexity and will require technology development, as discussed later (see the section on tunability).

To achieve the saturated gain necessary for a useful amplifier, it will be necessary to use a long undulator, on the order of 5 m or 10 m.[38,39] To propagate the optical beam this far in the narrow dimensions of the undulator, the optical beam will be gain-guided by the electron beam. In the absence of any special measures, the optical beam will arrive at the end of the undulator highly collimated, which will place a very high irradiance on the first optical surface or require it to be widely separated. Sprangle et al.[40] have proposed a potential solution, which is to pinch the electron beam near the end of the undulator by placing additional focusing magnets in this region. This will cause the optical beam also to pinch near the end of the undulator, and the smaller-diameter optical beam will expand by diffraction more rapidly when it emerges from the undulator. They calculated that the combination of beam pinching and grazing incidence at the first relay mirror (possibly curved to obtain additional expansion) could make it possible to place the first mirror within ~3 m of the undulator. Their design would require a peak current of 2 kA, which increases the demands on the injector and the degradation of the beam by coherent synchrotron radiation. Other FEL amplifier designs involving pinching the electron beams with lower peak current, e.g., 1 kA,[41] have been proposed. Experiments to test these ideas will be needed to determine their feasibility. The variety of potential solutions enhances the potential for a workable solution.

Regenerative Amplifier Alternative to the Master Oscillator Power Amplifier (MOPA)

The regenerative amplifier FEL (RAFEL) is a hybrid FEL configuration with the combined features of an oscillator and a high-gain amplifier. The key idea is to feed back a very small fraction (<10 percent) of the optical power generated in the high-gain undulator (~1,000 per pass) to enable the FEL to reach saturation in a few passes. This effectively eliminates the need for a transmissive beam splitter out-coupler/feedback cavity optic. It uses a compact ring resonator (four off-axis reflectors), thereby eliminating the need for a seed input from a master oscillator. This makes it easier to select or tune the operating wavelength. With high single-pass gain, the electron beam causes optical guiding that determines the optical mode, largely independent of the ring resonator. Since the output optical beam quality is only weakly dependent on the input beam quality, a hole in the center of the entrance mirror is used to pass the electron beam on axis. This eliminates the chicane normally used and avoids the concomitant terahertz radiation and electron beam degradation. A special feature of this optical system is that essentially all of the high-power laser radiation is coupled through a large hole in the output mirror. The optical feedback from the output annular mirror is taken from wings of the optical beam, where the intensity is much smaller, so mirror loading is not an issue. This configuration allows a separate output window to be mounted at a suitable distance from the mirror to transmit the beam to the relay optics. Beam-induced thermal distortion of the window must be adequately compensated, but it should not restrict the operation of the laser resonator.

A RAFEL operating in the infrared at 16 μm at LANL exhibited a very large, small-signal gain of ~330 per pass and an average output power of 200 kW during each 8 μs macropulse.[42] Other notable characteristics included the very large ~1 mm cavity detuning range and large ~1 mrad mirror alignment tolerance, both of which made the resonator cavity relatively insensitive to vibrations. The spectral width of the output was ~6 percent full width at half maximum, as expected for LANL's low-Q resonator.

With sufficient electron beam energy and average current, the RAFEL should be scalable to megawatt output average powers at 1 μm. As with the single-pass amplifier option, an issue for the RAFEL is determining a means to rapidly expand the intense output beam so that its intensity can be handled safely by the first downstream relay reflector. Pinching the electron beam at the exit of the wiggler and use of a grazing-incidence reflector are two approaches being considered. Also, the system will need to be designed to produce a sufficiently narrow laser spectral width for transmission through the selected atmospheric window.

Beam Dump

The beam dump's purpose is to stop the electron beam after it has been decelerated by the ERL. It is located at the end of the electron trajectory, which begins at the photocathode. The beam dump has to handle an energy that can somewhat exceed the injector energy (since some electrons are accelerated by the FEL interaction) at a current that is practically the whole injector current. In addition, the beam dump must perform its function over a large range of electron energies and maintain good vacuum conditions. An additional requirement is good ionizing-radiation shielding, given the electron's high energy and the high currents that are stopped at the beam dump.

Beam dumps of 1 to 2 MW are rather routine; for example, the beam dump of a megawatt cw klystron can handle over 1.5 MW. Some adaptation will be needed to account for the higher electron energy, which is more than enough for a 100 kW FEL. There does not appear to be a technical gap to extending beam dump technology to the necessary few megawatts of power (depending on the FEL efficiency) that will be required by a megawatt-class FEL.

Tunability

FELs are inherently tunable by varying the electron beam energy or certain parameters of the wiggler and have been built to operate from millimeter wavelengths down into the soft x-ray region. Individual FELs have been demonstrated to tune by a factor of 10 in wavelength. However, as the average power of an FEL increases, the limit on its tunability becomes the wavelength range over which the resonator optics retain their high reflectivity. For the Navy, tunability during operation is not an issue, because very precise wavelength control must be maintained to stay at the desired low-absorption spot in any one of the three possible bands. (Figure 3.2 shows typical atmospheric molecular absorption and scattering versus wavelength. The absorption curves show that the transmission widths around the desired wavelengths are up to several percent and much broader than the natural bandwidth of the FEL, though sideband production can make absorption an issue; see the discussion in the first section of this chapter.) But it may prove desirable for the Navy to be able to select among the three spectral bands during use, depending on the meteorological conditions at the moment (this remains to be seen).

Of the three candidate wavelengths of interest for naval applications (1, 1.6, and 2.2 μm), molecular scattering is somewhat worse at 1 μm than at the other two wavelengths, and the differences in aerosol scattering among them are to be determined. Molecular absorption at 1 μm is a clear winner, but aerosol absorption is to be determined. In addition, the eye damage threshold is substantially lower at 1 μm than at 1.6 or 2.2 μm. Research in propagation is under way to help with the wavelength choice.

The ability to select the desired wavelength(s) during the design phase is a fundamental FEL oscillator attribute and is quite achievable by proper design of the FEL parameters and resonator coatings. If switching among the various atmospheric windows, which range from 1 to 2.2 μm, becomes essential, the design of the resonator, coatings, and out-coupler substrate will become far more challenging. High-reflectivity dielectric coatings with multiple high-reflectivity bands have been built, but they come at the expense of additional coating layers and higher overall absorptivity. The required coating improvements to allow multiband operation fall into the area of technology issues.

For an FEL amplifier, the issues are quite different. This device requires a drive oscillator to properly seed the amplifier with the proper wavelength and pulse format. Overall gain greater than 10^6 is generally difficult to deal with owing to parasitic oscillations. If the amplifier is assumed to have a gain of $\sim 10^5$, the drive laser must supply approximately 10 W of average power in mode-locked pulses with a pulse repetition frequency (prf) of 500-700 MHz synchronized to the RF drive, a pulse width of a few picoseconds, and a peak power on the order of 10 kW. Solid-state (slab or fiber) lasers can approach some of the requirements at 1.045 μm but not easily at 1.6 or 2.2 μm. For the longer wavelengths, it probably will be necessary to shift the wavelength using nonlinear optical techniques such as parametric amplifiers. This would require technology development. In principle, a low-power FEL could be used to drive the amplifier, but this also adds to system complexity.

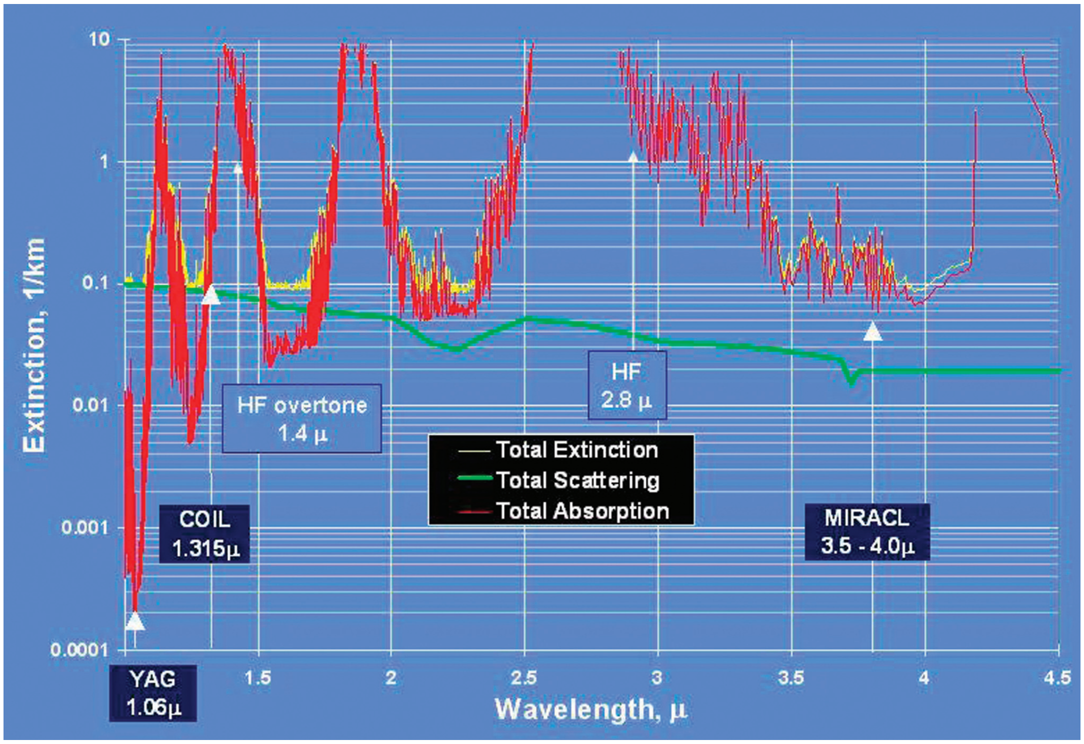

FIGURE 3.2 Typical atmospheric molecular absorption and scattering versus wavelength. SOURCE: Courtesy of Joung Cook and John Albertine.

Controls

Control of the FEL and its subsystems is important for its operational stability and for personnel and equipment safety. The control system is composed of the following:

- Operator interfaces;
- Equipment set points and readbacks;
- Data acquisition, conversion and filtering, and analysis;
- Closed-loop control;
- Access security;
- Sensors (including electron, photon, and radiation diagnostics);
- Digital signal processing;
- Timing and synchronization;
- Equipment protection;
- Alarm detection, reporting;
- Automatic sequencing; and
- Operator assistance (save, compare, restore functions of data sets).[43,44]

The complexity and control issues of a high-average-power FEL are similar to those of numerous electron-accelerator-based scientific user facilities. The immediate control needs of a 100-kW-class FEL and a 1-MW-class FEL can be met through this extensive experience base with integrated control systems. Operational needs of weapons-class FELs go beyond the experience base of the accelerator community; however, there is considerable overlap with the needs of some planned facilities, such as light sources based on energy recovery linacs.

Active alignment systems have been developed that are better than 10 times what the community thinks will be needed for stability in the ultimate FEL system, but they have not actually been tested at sea with the vibration spectrum appropriate to ships. Brief discussions with engineering companies and experts suggest that this is not a showstopper, but it needs to be seriously addressed in the future and concurrently with the development of higher-power FELs for Navy applications. Until there is a proven design, or at least one that is closer to it, it would be premature to study the vibration issue in detail and then have to alter the study if the FEL design changes. However, it is clear that the unique operational environment of an FEL on a ship will call for specialized diagnostics that are well integrated with the control system—for example, component motion and vibration sensors and beam position monitors. For high average beam current operation, minimally intercepting or nonintercepting electron beam diagnostics should be developed to monitor and control, for example, coherent synchrotron radiation and related electron microbunching; electron beam halo, transverse emittance, and energy spread; and cathode performance.

Existing accelerator facilities have made heavy use of trained operators to interface with the control system. Although there have been efforts to implement automation, the science machines still rely on operators and experts to interface between start-up, shutdown, and many automation routines. Therefore, limited effort has been put into true autonomous operation with real-time decision making and order variation steps based on failure modes. In a megawatt-class FEL, just as in some land-based accelerators, the amount of circulating electron and photon energy is substantial. This means that a fault that results in reduced operational availability or in uncontrolled beam loss could have significant adverse consequences for the safety of personnel and equipment. It will therefore be important to develop automated control systems for turnkey operation, rapid start-up and shutdown, availability on demand from a quiescent state, and recovery from fault conditions that go beyond the current state of the art.

SIMULATION AND MODELING

The committee recognizes that part of the assessment of current technology is the assessment of numerical simulation capabilities and their ability to predict performance in future experiments. The current state of the art varies from one system element to another, with very good modeling capabilities existing for some and others not being understood or quantitatively predictable. The committee observes that the limitations of particular simulations are, in many cases, a by-product of both hardware and modeling. Simulation and modeling associated with major system issues and components are discussed next.

Injectors

Because high-average-power FELs will most likely operate in a high-charge-per-bunch mode (~1 nC per bunch) and with a low accelerating gradient in the gun, the electron dynamics are likely to be much more dominated by time-dependent space-charge forces than they are in existing electron guns. This presents a greater challenge for simulation and modeling of the electron dynamics in the gun and injector. Short-pulse, space-charge-dominated beams are much more sensitive to the distribution function of the electrons than are less intense beams. In particular, the space-charge forces in a beam from a photoinjector are:

- Time-dependent and transversely nonlinear (because of nonuniform beam density)—the beam pulse length is much less than the transit time in the gun or first accelerator cells;
- Dependent on the beam distribution (transverse and temporal); and
- Dependent on the cathode emission and drive-laser profile (transverse and temporal).

Simple extrapolations from low space-charge results are useless. In order to have an accurate model of the self fields, any reasonable simulation must have realistic transverse and temporal beam distributions. Accordingly, there must be close interaction between simulation studies and experiments so that the simulations represent realistic rather than idealized conditions. The limiting factor at present is the lack of realistic data on the electron beam distribution under the gun conditions required for a megawatt-class FEL electron gun.

Coherent Synchrotron Radiation

During the last decade, a number of coherent synchrotron radiation (CSR) simulation codes were developed based on different approaches to modeling CSR and different implementations.[45,46,47]

The one-dimensional or projected approach incorporates one-dimensional CSR algorithms for the calculation of the longitudinal forces. These algorithms are based on a formula for the energy change by a line-charge distribution in a dipole magnet, with extensions to downstream drift spaces. Codes based on this model tend to be very efficient, but the approach ignores physical effects such as transverse forces and ignores transverse beam dimensions. Examples of this approach include the codes **Elegant**[48] and **CSR_calc**.[49] **Elegant**'s high longitudinal resolution, which is enabled by the use of one-dimensional models, has led to discovery of the CSR-driven microbunching instability in the Linac Coherent Light Source (LCLS),[50] and has allowed exploration of the instability involving CSR, longitudinal space charge, and longitudinal wakefields and possible cures such as strong wigglers or laser/undulator beam heaters.

The macroparticle approach self-consistently models the self-interaction of the bunch, which consists of a set of macroparticles, by storing away the complete history of the macroparticles as the bunch travels along the beamline. This approach has been used in two-dimensional[51] and three-dimensional models, and it can be time consuming. **TraFiC^4**[52] and **CSRtrack**[53] are examples of three-dimensional codes based on the macroparticle approach. **CSRtrack** incorporates the physics of **TraFiC^4** and uses new algorithms for the calculation of the CSR fields. Efficient calculation techniques have increased the speed of execution compared to the direct method for a large number of particles. CSR codes also exist that are based on a fully self-consistent Vlasov-Maxwell treatment.[54,55] This approach has less noise than the standard particle approaches, but it is computationally intensive.

Benchmarking among the various codes has been done for 1 nC Gaussian bunches at 5 GeV.[56] These investigations show agreement on the emittance growth but significant differences in the relative energy loss obtained by all one-dimensional codes compared to macroparticle codes. The Vlasov-Maxwell calculation confirms the results of the macroparticle methods. Stronger deviations are noted in the case of 500 MeV, where the interference of the compression process with self-forces is much stronger.

It is harder to validate the available CSR codes with experimental data because the experiments are difficult, and experimentally reconstructing the initial and final six-dimensional phase space in order to compare the data with simulation is challenging. Furthermore, other effects, such as space charge and wakefields, also affect the beam phase space significantly. Accordingly, the development and experimental validation of a code that models the coupled system are critical to improve the understanding of these effects and their significance to the design of a high-average-power FEL.

Beam Halo

Halo particle production in linacs is a consequence of filamentation in the six-dimensional phase space caused by nonlinear and time-dependent forces. The two-dimensional projections of the six-dimensional filaments appear as an extended beam halo. Although there is no consensus on a rigorous definition of "beam halo," the term usually refers to particles extending beyond the normal beam rms radius, from a few rms beam radii to about 10 rms beam radii or more. Because beam halo increases the risk of beam losses with their multiple deleterious effects, control of halo and beam loss is important in high-average-power ERLs. It is important to measure and reduce the halo significantly for Navy shipboard applications.

Computer simulations show that substantial halo is formed in high-current, mismatched linac beams. So far only a limited effort has been put into computer simulations of halo in high-current ERLs. Macroparticle simulations using the three-dimensional parallel PIC code **IMPACT** have been used to compare with experimental measurements of beam halo in the high-current, 67 MeV proton beam in the Low Energy Demonstrator Accelerator (LEDA) facility at LANL.[57] These simulations were successful in reproducing the core of the measured matched beam profiles and the trend of emittance growth as a function of the mismatch factor, but they underestimated the growth rate of halo and emittance for mismatched beams. The discrepancy was attributed to a lack of knowledge of the detailed input distribution in the six-dimensional phase space of the injected beam.[58]

In an ERL with nanocoulomb bunch charge, the beam is in a highly space-charge-dominated regime, and mismatches can be present because of either beam optics or alignment errors. In order to predict the fraction of the beam that may end up in halo, one needs realistic computer simulations that include machine errors and detailed knowledge of the initial particle distribution from the source. Experimental measurements of beam halo on operating high-power FELs and other electron accelerators are critical for benchmarking the simulations and identifying all of the physical mechanisms for halo generation in high-current electron linacs.

Beam Breakup

Multipass beam breakup (BBU) in recirculating linacs has been observed and studied for a long time. Many computer simulation codes have been developed in laboratories around the world. There are two main approaches to modeling beam breakup: (1) beam tracking, which calculates the beam position as a function of time and searches the threshold current by changing the beam current, and (2) the eigenvalue method, which converts the beam transport equation to an eigenvalue equation and solves the eigenvalue problem. Codes based on the first approach include **TDBBU** and **ERLBBU**, developed at Jefferson Laboratory; **BBU-R**, developed at JAERI; and **BI**, developed at Cornell. The code **MATBBU**, which was also developed at Jefferson Laboratory, is based on the eigenvalue method.[59]

Cross-benchmarks among the codes show consistent beam behavior and excellent agreement with theoretical models. In a series of comprehensive measurements at the Jefferson Laboratory FEL, the beam breakup threshold current was experimentally determined and found to agree with simulations to within ±10 percent.

Overall, beam breakup simulations are mature and have provided reliable predictions. They can confidently be used to derive specifications for the higher-order-mode damping requirements of future high-power-ERL FELs.

FEL Simulation Codes

FEL simulations have been developed over three decades and compared to many FEL experiments with successful validation. The most sophisticated simulations are now four-dimensional, including all the optical field components in x, y, and z followed in time t for an unlimited number of bounces of the optical pulse between the mirrors or in a single pass through the undulator for the amplifier. Some of these are **GENESIS**, **MEDUSA**, **WAVEV**, **GINGER**, **TDA3D**, **RON**, **FRED**, and **FELIX**. The last two, **FRED** and **FELIX**, have been inactive for a number of years, while the others have been active, simulating several different experiments and proposed FEL systems. Various types of optical resonators have been modeled. The number of electrons is sampled but can now approach ~1 percent of all the electrons in an electron pulse. All forces from the optical and undulator fields, as well as coulomb forces, can be included, as well as higher-frequency optical harmonics. The basic physics is described with the self-consistent, relativistic Lorentz force and optical wave equations, assuming a slowly varying amplitude and phase as is appropriate for a laser. Even quantum noise and shot noise have been included as well to model start-up of the x-ray FELs. Reviews of several FEL codes describe their attributes and make comparisons.[60,61]

Nearly all laboratories around the world have some form of FEL simulation. These programs have varying degrees of sophistication, some running on laptops and others running on large clusters. The FEL models have been successfully applied to a remarkably large range of FELs, from centimeter wavelengths to x-ray wavelengths, without a fundamental change other than the input parameters. The simulations are accurate in strong optical fields and with high or low growth rates.

The limitation of all FEL simulations is in determining accurate input information describing the initial electron beam and optical fields. The full description of the electron beam's six-dimensional phase space includes all initial positions and velocities. Electron spin is not included and is typically negligible. Determining the initial electron and optical parameters is often limited by experimental diagnostics.

FEL Start-to-End Simulation Codes

In the preceding sections, the committee established the importance of reliable and experimentally verified simulations for all the important physical effects that enter into the design of a high-power-ERL FEL. While these individual simulations are necessary for a credible design, they are not sufficient. Effects from one part of the machine can interfere destructively or constructively with effects from another part of the machine. In some cases, this interference may be a design choice used to cancel or partially compensate an effect. For this reason, a carefully constructed and experimentally validated start-to-end simulation code that takes into account space charge, CSR, resistive wall effects, and RF cavity and other wakefields *together* is necessary to define the performance of the entire system. This level of modeling will also provide insights into halo production and control. Two FEL system codes have been developed, **FELSIM** (Advanced Energy Systems) and **INEX** (Boeing, LANL).

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Appendixes

A

Statement of Task

Review the current state of the art and anticipated advances for high-average-power free-electron lasers (FELs). Using performance characteristics defined by the Navy for directed-energy applications, analyze the capabilities, constraints, and trade-offs for FELs.

B

Committee Meeting Agendas

FIRST MEETING
WASHINGTON, D.C.
JANUARY 17-18, 2008

Thursday, January 17

Closed Session

8:00 a.m.	Welcome, introductions, and committee discussions

Open Session

9:00	Opening remarks
	—T. Katsouleas
9:15	Naval S&T Strategic Plan—Defining the Strategic Direction for Tomorrow
	—M. Deitchman, ONR
9:30	Perspectives from ONR: Its View of Needs of This Study
	—L. Schuette, ONR
10:00	Break
10:15	General talk on technologies—ONR investments
	—L. DeSandre, ONR
10:45	General talk on technologies—Introduction to FEL technology and LANL work on high-power FELs
	—D. Nguyen, Los Alamos National Laboratory
11:30	Presentation by Jefferson Lab on its FEL program and facilities
	—G. Neil, Thomas Jefferson National Accelerator Facility
12:30 p.m.	Working lunch
1:30	Overview
	—RADM W. Landay, III, Chief of Naval Research
2:00	Atmospheric propagation/other work
	—P. Sprangle, Naval Research Laboratory

2:45 p.m.	Break

Closed Session

3:00	Committee discussions
8:00 p.m.	Adjourn for the day

Friday, January 18

Open Session

8:00 a.m.	Reconvene for committee discussions
8:30	Background talks on other previous studies of interest —L. DeSandre, ONR

Closed Session

9:00	Committee discussions
1:30 p.m.	Adjourn

SECOND MEETING
WASHINGTON, D.C.
APRIL 4-5, 2008

Friday, April 4

Closed Session

8:00 a.m.	Committee discussions

Open Session

9:00	Opening remarks —T. Katsouleas
9:15	Optics —C. Menoni, Colorado State University
10:00	Coherent Synchrotron Radiation —P. Emma, SLAC
10:45	Break
11:00	Injectors —D. Dowell, SLAC
11:45	Working lunch
12:45 p.m.	Building/manufacturing (injectors and accelerators) —A. Todd, Advanced Energy Systems
1:45	Controls —J. Carwardine, Argonne National Laboratory
2:30	Break
2:45	Halo —T. Wangler, National Superconducting Cyclotron Laboratory

Closed Session

3:30	Committee discussions
8:00 p.m.	Adjourn for the day

Saturday, April 5

Open Session

8:00 a.m.	Reconvene for committee discussions
9:00	Energy Recovery Linac Diagnostics —G. Hoffstaetter, Cornell University

Closed Session

9:45	Committee discussions
3:00 p.m.	Adjourn

C

Biographies of Committee Members and Staff

COMMITTEE MEMBERS

Thomas C. Katsouleas, *Chair*, is the dean of the Pratt School of Engineering at Duke University. Before moving to Duke in July 2007, he was the vice provost for information services and a professor of electrical engineering, University of Southern California. In 2005 and 2006, Dr. Katsouleas served as president of the Academic Senate at USC, during which time he focused on enhancing the university's academic technology infrastructure. Dr. Katsouleas also served as associate dean for research and as associate dean for student affairs in the Viterbi School of Engineering at USC. He was the first chair of the faculty advisory committee for USC's High Performance Computing and Communications (HPCC) Center. In 2005 and 2006, he co-chaired the Senate-Provost Committee to Examine Information Services, which recommended restructuring USC's information technology services into a federated model. Dr. Katsouleas's research focuses on the applications of plasma physics to particle accelerators and high-power microwave sources. He leads a large multiinstitution effort (with Stanford and UCLA) to demonstrate that a plasma can be used to miniaturize a particle accelerator from kilometer to meter scales. His group also performs large-scale supercomputing simulations to track the complex motion of the billions of particles that make up these relativistic plasmas. Dr. Katsouleas received his Ph.D. in physics from the University of California, Los Angeles, in 1984. He is a fellow of the American Physical Society and the Institute of Electrical and Electronics Engineers (IEEE). He is associate editor of *IEEE Transactions on Plasma Science*. He served on NRC's Committee on High-Energy-Density Plasma Physics Assessment.

Ricardo Alarcon is a professor of physics at Arizona State University. He did his undergraduate studies at the University of Chile and received his Ph.D. in 1985 from Ohio University. He did postdoctoral work at the University of Illinois at Urbana-Champaign until 1989, when he joined Arizona State University as an assistant professor. His research covers experiments in electromagnetic nuclear physics and, more recently, in fundamental neutron science. He held visiting professor appointments at the Massachusetts Institute of Technology in 1995-1997 and 1999-2001 and served as project manager for the Bates Large Acceptance Spectrometer project at MIT-Bates from 1999 to 2002. He was a member of the Department of Energy/National Science Foundation Nuclear Science Advisory Committee from 2001 to 2005. In 2003, he was elected a fellow of the American Physical Society. He was a member of NRC's Committee on Rare Isotope Science Assessment.

John Albertine, an independent consultant, received his B.S. and M.S. degrees in physics from Rose Polytechnic Institute and Johns Hopkins University, respectively. Before working for the Navy, Mr. Albertine was a senior staff physicist in the Space Division of the Johns Hopkins Applied Physics Laboratory. From 1976 through 1997, he worked in the Navy's High Energy Laser (HEL) Program Office, directing the Navy's technology development for the last 15 years of that assignment. During that time, he led the development and test of the first megawatt-class HEL system in the free world. He retired from the civil service in 1997 and now consults for the Office of the Secretary of Defense, the Air Force, the Office of Naval Research, the Navy HEL Program Office, and Penn State in the field of directed energy. Mr. Albertine was a member of the Air Force Science Advisory Board and served as executive vice president and was a member of the board of directors of the Directed Energy Professional Society (DEPS), where he is a fellow.

Ilan Ben-Zvi is a tenured senior scientist at Brookhaven National Laboratory (BNL). Dr. Ben-Zvi serves as the associate chair for superconducting accelerator R&D and is the group leader for the electron cooling of the Relativistic Heavy Ion Collider in the Collider-Accelerator Department. He also holds an adjunct professorship in physics at Stony Brook. His current research interests are electron cooling of hadron beams, the generation of high-brightness electron beams, superconducting RF, energy recovery linacs, and high-power free-electron lasers through superconducting accelerator techniques. Dr. Ben-Zvi received his Ph.D. in physics from the Weizmann Institute of Science, Rehovot, Israel, in 1970. He joined the National Synchrotron Light Source at Brookhaven National Laboratory in 1989 and the Collider-Accelerator Department (joint appointment) in 2000. He served as the director of the Accelerator Test Facility, a user's facility for beam physicists, from 1989 to 2004, building up the facility to serve as the premier DOE facility for advanced accelerator R&D. He is a fellow of the American Physical Society, a fellow of the American Association for the Advancement of Science, and a senior member of the Institute of Electrical and Electronics Engineers. He is the recipient of the 1999 IEEE Accelerator Science and Technology Award, the 2001 BNL Science and Technology Award, the 2007 Free-Electron Laser Prize, and the 2008 IEEE Nuclear and Plasma Sciences Society (IEEE/NPSS) Merit Award. Dr. Ben-Zvi has been active in international cooperative projects and has developed special relations with industry, including transfer of technology projects and collaborations on the development of novel accelerator components and software. He was a member of the editorial board of *Physical Review Special Topics—Accelerators and Beams* from its inauguration in 1998 until 2004. He is a member of the International Committee for Future Accelerators (ICFA) Panel on Advanced and Novel Accelerators. He has served on or chaired several advisory and program committees of beam physics conferences and workshops, including as a co-chair of the 1995 International FEL Conference, program chair of the 1999 Particle Accelerator Conference and the 2001 International FEL Conference, and chair of the 2004 Advanced Accelerator Concepts Workshop, on technical advisory panels, and reviews of accelerator and FEL projects. Since 2005, he has served as the chair of the IEEE/NPSS Particle Accelerator Science and Technology Committee.

Sandra G. Biedron serves as the director and physicist of the Department of Defense Project Office of Argonne National Laboratory and is an associate director of the Argonne Accelerator Institute. Dr. Biedron is also a consultant on the FERMI project at Elettra, at Sincrotone Trieste. She is a physicist whose main research is in beam and laser source development and use. She is cross-trained in chemistry, biology, and electrical engineering. She was one of the team members who proved the SASE FEL concept in the visible to VUV wavelengths. Dr. Biedron was also the Argonne representative and participant on the Brookhaven/Argonne high-gain harmonic generation FEL experiment. She has been involved with electron-gun design and testing for over 12 years and was the first in the world to predict and measure the nonlinear harmonic growth on two types of high-gain free-electron lasers, an important component of many new FEL projects worldwide. For more than 8 years, she has managed and led the international workgroup FEL Exotica, which examines exotic beam and photon schemes, including novel undulator designs. Dr. Biedron is an active member of several professional societies. For the SPIE, she served as chair of the Scholarships and Grants Committee for 2 years and was on the Awards and Education Committees. For 2007-2009, she is a member of the executive committee for the SPIE's Optics and Photonics Optical Engineering and Applications Conference, representing the x-ray, gamma-ray, and particle technologies track. Dr. Biedron is a senior member of the Institute of Electrical and Electronics Engineers (IEEE). She served as the secretary and treasurer of the Chicago Section, Nuclear and Plasma Sciences/Magnetics Society and served on the Program Committee of the 2003 Particle Accelerator Conference jointly sponsored by the IEEE and the American Physical Society (APS). Since 2005, she has been the particle accelerator science and technology elected representative to the Nuclear Plasma and Sciences Society of the IEEE and is a member of the organizing and program committees for the 2009 Particle Accelerator Conference. She has served on a variety of international program and organizing committees and has organized a number of conferences, workshops, and plenary sessions, including the upcoming FEL session at the 2008 Directed Energy Professional Society Meeting. Dr. Biedron has 40 archival papers in the area of FELs/coherent radiators, 14 as first author.

Charles A. Brau is a professor of physics in the Physics and Astronomy Department at Vanderbilt University. Dr. Brau received a Ph.D. in physics from Harvard in 1965. His research areas are atomic and molecular physics, lasers and light sources, and electron beams. His current research is in high-brightness electron beams, tabletop Cherenkov and Smith-Purcell FELs, and Compton backscatter x-ray sources and FELs. He was the program manager for the Free-Electron Laser program at Los Alamos National Laboratory from 1976 to 1987. Following that he was on sabbatical leave at the Quantum Institute/University of California, Santa Barbara, and then a visiting scientist in Oxford University's Department of Nuclear Physics. From 1988 to 1995, he was director of the Free-Electron Laser Center, Vanderbilt University. He is a fellow of the American Physical Society. He received the William Streifer Award for Scientific Achievement from the IEEE Lasers and Electro-Optics Society in 1995 and the Free-Electron Laser Prize of the 18th International Conference on Free-Electron Lasers in Rome in 1996.

William B. Colson is a distinguished professor of physics in the Department of Physics, U.S. Naval Postgraduate School. He received a Ph.D. from Stanford University in 1977. His research interest is primarily the theory and simulation of free-electron lasers, but he also concentrates on the physics of complex radiating systems. Dr. Colson has been a visiting scientist at LURE, University of Paris, Orsay, France; at the Center for Energy Research (ENEA), Frascati, Italy; and at the Shanghai Institute of Optics, Academia Sinica, Shanghai, Peoples Republic of China. Dr. Colson has also been a member of the Medical Free-Electron Laser Program Review by the Life Sciences Research Office of the Federation of American Societies for Experimental Biology and the Office of Naval Consortium's Free-Electron Laser Program at the Continuous Electron Beam Accelerator Facility (CEBAF), Newport News, Virginia. He is a fellow of the American Physical Society, Physics and Beam Division, and a member of Sigma Xi. Dr. Colson received the 1989 Free-Electron Laser Prize from the IEEE Laser and Electro-Optic Society. He has been guest editor for the *IEEE Journal of Quantum Electronics* and is a coeditor of the *Free-Electron Laser Handbook*. He served on the NRC's Committee on Free-Electron Lasers and Other Advanced Coherent Light Sources in 1994.

Ronald C. Davidson has been a professor of astrophysical sciences at Princeton University since 1991 and was director of the Princeton Plasma Physics Laboratory from 1991 to 1996. Dr. Davidson received a B.Sc. from McMaster University in 1963 and a Ph.D. from Princeton University in 1966. He was assistant research physicist at the University of California at Berkeley from 1966 to 1968, an assistant professor of physics at the University of Maryland from 1968 to 1971, an Alfred P. Sloan Foundation fellow for 1970-1972, an associate professor of physics for 1971-1973, a professor of physics at the University of Maryland for 1973-1978, and professor of physics at the Massachusetts Institute of Technology for 1978-1991. Dr. Davidson has made numerous fundamental theoretical contributions to several areas of pure and applied plasma physics, including nonneutral plasmas, nonlinear effects and anomalous transport, kinetic equilibrium and stability properties, intense charged-particle-beam propagation in high-energy accelerators, and coherent radiation generation by relativistic electrons. He is the author of more than 300 journal articles and books, including four advanced research monographs: "Methods in Nonlinear Plasma Theory" (Academic Press, 1972), "Theory of Nonneutral Plasmas" (W.A. Benjamin, 1974), "Physics of Nonneutral Plasmas" (Addison-Wesley, 1990), and "Physics of Intense Charged Particle Beams in High Energy Accelerators," with Hong Qin (World Scientific, 2001). From 1976 to 1978, he served as the assistant director for the Applied Plasma Physics Office of Fusion Energy Sciences in the Department of Energy. Dr. Davidson also served as director of the MIT Plasma Fusion Center for the decade 1978-1988, as the first chair of the DOE

Magnetic Fusion Advisory Committee (MFAC), 1982-1986, as chair of the American Physical Society's Division of Plasma Physics in 1983 and 1984 and its Division of Physics of Beams in 2001 and 2002, and has served on numerous national and international committees on plasma physics and fusion research. Dr. Davidson is a fellow of the American Physical Society, a fellow of the American Association for the Advancement of Science, and a member of Sigma Xi. He is also a recipient of the Department of Energy's Distinguished Associate Award and the Fusion Power Associates Leadership Award, both in 1986, and recipient of the Kaul Foundation's Award for Excellence in 1993 and the IEEE Particle Accelerator Science and Technology Award in 2005.

VADM Paul G. Gaffney II, U.S. Navy (retired), became the seventh president of Monmouth University in July 2003. From 2000 to 2003, President Gaffney was president of the National Defense University. Before that, he was the Chief of Naval Research, with responsibility for science and technology investment. He was appointed as a commissioner to the statutory U.S. Commission on Ocean Policy and served during its full tenure from 2001 to 2004. His naval career spanned more than three decades, including duty at sea, overseas, and ashore in executive and command positions. While a military officer, his career focused on oceanography, research administration, and education. President Gaffney is a 1968 graduate of the U.S. Naval Academy. Upon graduation, he was selected for immediate graduate education and received a master's degree in ocean engineering from Catholic University of America in Washington, D.C. He completed a year as a student and advanced research fellow at the Naval War College, graduating with highest distinction. He completed an M.B.A. at Jacksonville University. The University of South Carolina, Jacksonville University, and Catholic University have awarded him honorary doctorates. He also has been recognized with a number of military decorations: the Naval War College's J. William Middendorf Prize for Strategic Research, the Outstanding Public Service Award from the Virginia Research and Technology Consortium, and the Potomac Institute's Navigator Award. He is a fellow of the American Meteorological Society, has served on several boards of higher education, was a member of the Ocean Studies Board of the National Research Council during 2002-2004, and is currently vice chair of the statutory Ocean Research/Resources Advisory Panel. He chaired the Governor's Commission to Protect and Enhance New Jersey's Military Bases, is a director of Diamond Offshore Drilling, Inc., and he serves on the Meridian Health board of trustees.

Lia Merminga is head of the Accelerator Division at TRIUMF, Canada's National Laboratory for Particle and Nuclear Physics. Dr. Merminga received her B.S. in physics from the University of Athens, Greece, in 1983 and then attended the University of Michigan, where she received her Ph.D. in physics in 1989. She worked at the Stanford Linear Accelerator Center from 1989 to 1992 before joining the Accelerator Division at Jefferson Lab, first as a staff scientist and later as the director of the Center for Advanced Studies of Accelerators. Her research interests include advanced accelerator systems and nonlinear dynamics, with a recent focus on the design and development of energy recovery radio-frequency linear accelerators and their applications to high-power free-electron lasers, synchrotron radiation sources, and electron-ion colliders for nuclear and particle physics. In 2005, she co-chaired the first international workshop on energy recovery linacs. She has taught courses at the U.S. Particle Accelerator School and is currently serving on several machine advisory committees as well as on the editorial board of *Physical Review Special Topics—Accelerators and Beams*. Dr. Merminga is a fellow of the American Physical Society. She also was a member of the NRC's Committee on Plasma 2010: An Assessment of and Outlook for Plasma and Fusion Science.

Joel D. Miller is the Aegis Ballistic Missile Defense (BMD) program manager and a member of the principal professional staff of the Air Defense Systems Department at Johns Hopkins University's Applied Physics Laboratory (APL). Dr. Miller's Ph.D. from the University of Michigan is in nuclear engineering. He has been with the APL since 2000 and is currently in the Area Defense Program Office of the Air Defense Systems Department. Dr. Miller has experience in research and development, technical project leadership, and program management, including an extensive background in complex physics experiments and engineering test and evaluation (T&E). As Aegis BMD program manager, he manages all APL activities in support of Aegis BMD development and deployment, including technical direction agent (TDA) activities in support of the Standard Missile-3 development program. He planned major T&E program efforts in theater ballistic missile defense. He directed the successful Standard

Missile-2 Block IVA live fire T&E ground test lethality program. Dr. Miller was technical lead for operation of the nuclear weapons effects simulator facility. He managed laser technology for the Navy High-Energy Laser program and planned and conducted charged particle beam and directed energy weapons laboratory experiments. From 1995 to 2000, Dr. Miller worked with the Navy Standard Missile and Theater BMD Program Offices and from 1989 to 1995 with the Electronics Hardening and Directed Energy Technology Branches in the Physics and Technology Division of the Naval Surface Weapons Center's White Oak Laboratory.

Brian E. Newnam retired from Los Alamos National Laboratory (LANL) in 2002 and is currently affiliated with the LANL FEL project as a visiting scientist. Previously, Dr. Newnam served as deputy leader of LANL's Superconductivity Technology Center. He received his Ph.D. in electrical engineering from the University of Southern California in 1972, where he studied high-power, laser-induced damage and self-focusing in dielectric films, solids, and inorganic liquids. During the early years (1979-1984) of the Los Alamos FEL program for national defense (SDI), Dr. Newnam was responsible for the laser and optical aspects of the FEL amplifier and oscillator experiments. Thereafter, he led a major effort to extend FELs into the extreme ultraviolet for both research applications and industrial photolithography. He also demonstrated the ability of infrared FELs to destroy the Freon pollutants responsible for the atmospheric ozone hole and designed and tested the laser damage resistance of resonator mirrors. At LANL, Dr. Newnam has contributed to DOE external independent reviews of the OMEGA Extended Performance addition to the OMEGA Laser Facility (University of Rochester) and Linear Coherent Laser Source (SLAC) large-scale DOE projects. He has contributed to the fields of laser damage to optical materials, FEL development and experimentation, FEL applications in science and industry, thin-film and XUV reflector design, laser physics, and thermal radiation properties of spacecraft coatings with many technical publications and presentations. He holds three patents on optical components. He organized and co-chaired the 1991 International FEL Conference in Santa Fe, New Mexico. Dr. Newnam is a fellow of the Optical Society of America, and the SPIE awarded him its 1991 Rudolf Kingslake Medal and Prize for the most noteworthy paper in optical engineering.

Patrick O'Shea is professor and chairman of the Department of Electrical and Computer Engineering at the University of Maryland's A. James Clark School of Engineering, with additional appointments in the Department of Physics and the Institute for Research in Electronics and Applied Physics. He received his B.Sc. degree in physics from the University College Cork, Ireland, and M.S. and Ph.D. degrees in physics from the University of Maryland. He has worked at LANL, where he was chief accelerator physicist on the Beam Experiment Aboard Rocket (BEAR) project, which tested a linear accelerator in space, and the project leader for the APEX Free-Electron Laser Project, which was the first photoinjector and linear-accelerator-driven ultraviolet FEL. He also led the commissioning of the 300 MeV photoinjector linac at the Duke University Free-Electron Laser Laboratory. He has served as director of the Institute for Research in Electronics and Applied Physics (IREAP), at Maryland. He played a leading role in founding the Maryland Nano Center and the Maryland Center for Applied Electromagnetics. His experimental and theoretical research is concentrated in the areas of applied electromagnetics and charged particle beam physics and technology. He is a fellow of the American Association for the Advancement of Science, the American Physical Society, and the Institute of Electrical and Electronics Engineers and a member of the Washington Academy of Sciences.

Donald Prosnitz joined the RAND Corporation in September 2007 as a senior principal researcher. Dr. Prosnitz's studies at RAND concentrate on the use of technology to solve national and homeland security issues. Dr. Prosnitz was previously the deputy associate director of programs for nonproliferation, homeland and international security at Lawrence Livermore National Laboratory (LLNL) and was responsible for overseeing all of the directorate's technical programs. He received his B.S. from Yale University and his Ph.D. in physics from the Massachusetts Institute of Technology. He then spent 2 years as an assistant professor in the Engineering and Applied Science Department at Yale before joining LLNL as an experimental laser physicist. Over the next three decades, he conducted research on lasers, particle accelerators, high-power microwaves, free-electron lasers, and remote sensing and managed the design, construction, and operation of numerous research facilities. In 1990, he was awarded the U.S. Particle Accelerator Award for Achievement in Accelerator Physics and Technology. In 1999, Dr. Prosnitz was named the first Chief Science and Technology Advisor for the Department of Justice (DOJ) by Attorney General Janet Reno. In this newly created position, he was responsible for coordinating technology policy among the DOJ's component agencies and with state and local law enforcement entities on science and technology projects and programs. In 2002, he was named a fellow of the American Physical Society. He is currently a member of the National Academy of Sciences' Board on Chemical Sciences and Technology.

Elihu Zimet is a distinguished research professor of the Center for Technology and National Security Policy at the National Defense University. Dr. Zimet's background includes naval science and technology, including kinetic and nonkinetic effects, and low-observable and counter-low-observable technologies. He received his Ph.D. from Yale University in 1969. From 1969 to 1971, he was a lecturer at Yale University, where he conducted research in the field of fluid mechanics. Dr. Zimet started his government career at the Naval Ordnance Laboratory in 1971, working on gas dynamic and chemical high-energy lasers, and after the laboratory became part of the Naval Surface Warfare Center, he became branch head of the Detonation Physics Branch. From 1991 to 2002, as a member of the Senior Executive Service (SES), he headed, first, the Special Programs, and subsequently, the Expeditionary Warfare Science and Technology Departments at the Office of Naval Research. Currently, he is a member of the NRC's Naval Studies Board (NSB) and its Committee on the "1,000 Ship Navy"—A Distributed and Global Maritime Network and, formerly, a member of the NSB's Committee on the Role of Naval Forces in the Global War on Terror. He served for many years on NATO's AGAARD and RTO technology panels. He was twice awarded the Meritorious Presidential Rank Award in the SES and has also been awarded the Distinguished Civilian Civil Service Award.

NRC STAFF

Donald C. Shapero received a B.S. from the Massachusetts Institute of Technology (MIT) in 1964 and a Ph.D. from MIT in 1970. His thesis addressed the asymptotic behavior of relativistic quantum field theories. After receiving the Ph.D., Dr. Shapero became a Thomas J. Watson postdoctoral fellow at IBM. He subsequently became an assistant professor at American University, later moving to Catholic University and then joining the staff of the National Research Council in 1975. Dr. Shapero took a leave of absence from the NRC in 1978 to serve as the first executive director of the Energy Research Advisory Board at the Department of Energy. He returned to the NRC in 1979 to serve as special assistant to the president of the National Academy of Sciences. In 1982, he started the NRC's Board on Physics and Astronomy (BPA). As BPA director, he has played a key role in many NRC studies, including the two most recent surveys of physics and the two most recent surveys of astronomy and astrophysics. He is a member of the American Astronomical Society and the International Astronomical Union and a fellow of both the APS and the AAAS. He has published research articles in refereed journals in high-energy physics, condensed-matter physics, and environmental science.

Cy L. Butner is a senior program officer with the NRC's Laboratory Assessments Board. Shortly after joining the NRC in 1997, he moved from the Aeronautics and Space Engineering Board to the Army Research Laboratory Technical Assessment Board, which has since expanded to become the Laboratory Assessments Board. His primary duties have involved supporting the Army Research Laboratory and the National Institute of Standards and Technology peer assessment programs. He also has participated in a number of ad hoc studies, covering a range of scientific topics. Before joining the NRC, Mr. Butner served as an independent consultant to the Aeronautics and Space Engineering Board for 2 years, supporting a peer review process for Air Force Office of Scientific Research proposals and several reports on topics related to space and aeronautics programs. From 1985 until 1994, Mr. Butner worked with two aerospace consulting firms, where he supported space and aeronautics technology development programs at NASA Headquarters. Before that, he worked for RCA as a satellite solar array engineer, for NASA at the Goddard Space Flight Center as a science co-op student and a materials engineer, and for the New Mexico Environmental Improvement Agency as a statistician. Mr. Butner has B.S. and M.S. degrees in physics from the American University and a B.S. degree in mathematics from the University of New Mexico.

Robert L. Riemer joined the staff of the Board on Physics and Astronomy in January 1985. Dr. Riemer served as study director for the 1991 and 2000 decadal surveys of astronomy and astrophysics and with many other NRC committees, including committees on physics, aeronautics, space, mathematics, and interdisciplinary research. He received a B.S. with honors in physics and astrophysics from the University of Wisconsin-Madison and a Ph.D. with honors in physics from the University of Kansas-Lawrence for research in experimental high-energy physics.

Caryn Joy Knutsen is currently a program associate with the NRC's Board on Physics and Astronomy. She came to the BPA in 2006 as a senior program assistant after completing a B.S. in mathematics from the University of Colorado at Colorado Springs in 2006. While attending the University of Colorado at Colorado Springs she also earned two certificates in industrial mathematics (levels 1 and 2). At the BPA, she operates in various administrative and supporting roles for multiple committees, and in January 2008 she received the "Rookie" award from the NRC's Division on Engineering and Physical Sciences. She is a member of the Society of Industrial and Applied Mathematics.

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Acronyms and Glossary

amplifier	In the case of the FEL amplifier, there is no optical resonator; a seed laser sends optical pulses synchronized to overlap the electron pulses as they enter the undulator to ensure longitudinal coherence.
ANL	Argonne National Laboratory
BAA	Broad Agency Announcement
BBU	beam breakup
beam dump	located at the end of the electron trajectory, its purpose is to stop the electron beam after it has been decelerated by the energy recovery linac
BINP	Budker Institute of Nuclear Physics
BNL	Brookhaven National Laboratory
booster	high-current, non-energy-recovered linac section, which boosts the energy of the electron gun for acceleration by the ERL
cathode robustness (cathode lifetime)	A robust cathode is one that operates without degradation of quantum efficiency for an extended time in an electron gun. The quantum efficiency of the cathode can be degraded either through adsorption of foreign materials onto the surface or through desorption of cathode materials. Cathodes with higher quantum efficiency tend to degrade more quickly than those with lower quantum efficiency. The quality of the vacuum in the gun is critical to cathode robustness. Electrical breakdown (arcing) can lead to poor vacuum quality and damage the surface of the cathodes.

COIL	Chemical Oxygen Iodine Laser; operates at 1.315 μm
cryomodule	a cryostat containing accelerating cavities and ancillary equipment such as tuners, couplers, and HOM loads
CSR	coherent synchrotron radiation; coherent long-wavelength emission from the beam end that can cause emittance growth
cw	continuous wave; an electromagnetic wave of constant amplitude and frequency
DC HV gun	electron gun that relies on a direct current (DC) and high voltage (HV) applied across plates as the accelerating gradient for the electrons extracted from the cathode surface; a typical accelerating voltage is 300-500 kV over about 12-14 cm until the gun exit
DF	deuterium fluoride; these lasers operate at a wavelength over a series of lines from 3.6 μm to 3.9 μm
DOE	Department of Energy
emittance	measure of beam quality that is related to the product of beam divergence and spot size
ERL	energy recovery linac
FEL	free-electron laser
field emission	the emission of electrons from the solid-state surface caused by applying high electric fields perpendicular to the surface
FWHM	full width at half maximum
FPC	fundamental power coupler
"generation" nomenclature	The synchrotron radiation sources of the past and present can be defined as follows: • First-generation machines are electron synchrotrons and storage rings that were built for other purposes—for example, high-energy and nuclear physics—but whose bending magnet radiation was parasitically used by synchrotron radiation "users." This radiation covered many wavelength regimes due to the nature of the bending magnet emission. In addition, the machines produced rather large photon source sizes as the electron beam emittance was large and neither intended for nor ideal for synchrotron radiation applications. • Second-generation machines are machines dedicated for synchrotron radiation users that employ bending magnets as the primary source of synchrotron radiation. The beam emittances were designed by the machine architects to be smaller in order to provide users with a smaller source size and greater brilliance. • Third-generation machines are also dedicated for synchrotron radiation users and were designed to accommodate many so-called insertion device magnets, such as undulator and

wiggler magnets. Undulator magnets generate narrow spectral lines, and this enhances the overall photon brilliance.
- Next-generation light sources involve an optical gain mechanism, with the goal of transverse and longitudinal optical coherence such as in a free-electron laser.

halo	"spreading" of the beam in linacs; it is a consequence of filamentation caused by nonlinear and time-dependent forces, and it increases the risk of beam losses
HEL	high-energy laser
HGHG	high-gain harmonic generation
HOM	higher-order mode; a cavity mode in the accelerator other than the desired acceleration mode
IBSD	ion-beam sputtered deposition
JAERI	Japan Atomic Energy Research Institute
JLab	Thomas Jefferson National Accelerator Facility
LANL	Los Alamos National Laboratory
LCLS	Linac Coherent Light Source (at the Stanford Linear Accelerator Center)
LEDA	Low Energy Demonstrator Accelerator (at LANL)
linac	linear accelerator; an electrical device for the acceleration of subatomic particles such as electrons
merger	electron beam optical device composed of magnet beam optical elements; it merges the low-energy beam from the injector with the high-energy beam returning from the FEL, such that both will be directed along the axis of the energy recovery linac's accelerating and decelerating cavities
microphonics	mechanical vibrations and helium pressure changes and noise that can change the resonant frequency of FEL cavities up to a few hertz
MOPA	master oscillator power amplifier
NC RF gun	electron gun that relies on a radio-frequency (RF) resonant cavity made from a normal-conducting (NC), low-resistance material, such as copper, to form the electric field gradient necessary to accelerate the electrons extracted from the cathode surface
NRC	National Research Council

ONR	Office of Naval Research
oscillator	In the case of the FEL oscillator, the optical pulses are bouncing between the cavity mirrors of an open optical resonator. Care must be taken to synchronize the sequence of electron pulses triggered by the cathode drive laser into the correct phase of the RF cycles, and to overlap with the stored optical pulses at the entrance to an undulator.
photoemission	emission of electrons from the solid state through the absorption of incident photons
prf	pulse repetition frequency
Q	Q factor or value is a dimensionless parameter that compares the frequency at which a system oscillates to the rate at which it dissipates its energy; the higher the Q value, the lower the rate of energy dissipation relative to the oscillation frequency (i.e., the oscillations diminish more slowly).
quantum efficiency	the number of electrons released compared to the number of photons absorbed
RAFEL	regenerative amplifier FEL; a hybrid FEL configuration with the combined features of an oscillator and a high-gain amplifier
RF	radio frequency
rms	root mean square
SASE	self-amplified spontaneous emission
SDI	Strategic Defense Initiative
SLAC	Stanford Linear Accelerator Center
SRF gun	superconducting RF gun, an electron gun that relies on an RF resonant cavity made from a superconducting material such as niobium cooled to a few degrees Kelvin, for example, to form the electric field gradient necessary to accelerate the electrons extracted from the cathode surface
SSL	solid-state laser
thermal blooming	atmospheric effect encountered by high-energy laser beams, which is the result of the nonlinear interaction of laser radiation with the propagation medium (typically air), which is heated by the absorption of a fraction of the radiation. The amount of energy absorbed depends on the laser wavelength; the term is frequently used to describe any type of self-induced thermal distortion of laser radiation.

thermionic emission	charge emission process excited or induced by heating a cathode
TJNAF	Thomas Jefferson National Accelerator Facility
undulator (or wiggler)	array of magnets with alternating poles along the beam path in a laser cavity. It produces a periodic transverse magnetic field causing the electrons in the beam to follow a sinusoidal path.
UV	ultraviolet
VUV	vacuum ultraviolet
wavelength	distance between repeating units of a propagating wave of a given frequency
wiggler (or undulator)	see *undulator* above