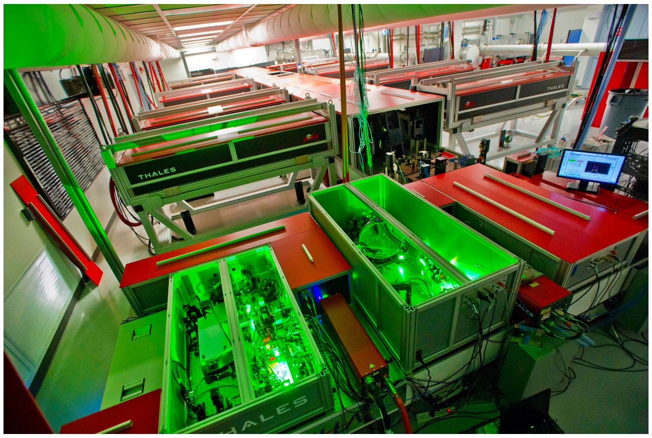
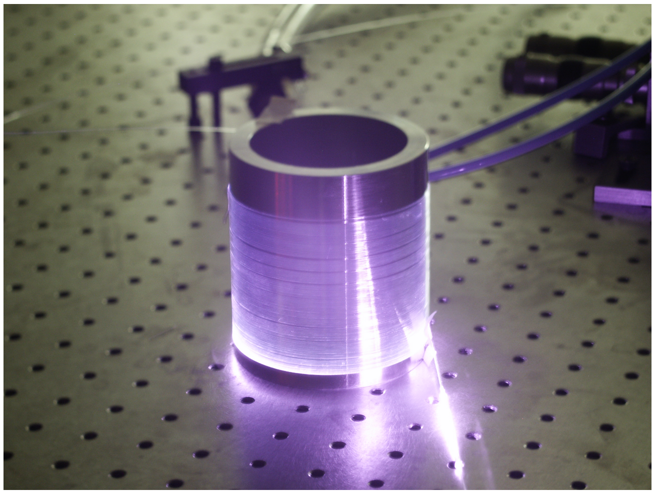
U.S. DEPARTMENT OF ENERGY





Workshop on Laser Technology for Accelerators

Summary Report

January 23–25, 2013

Table of Contents

Executive Summary

Particle accelerators and lasers have made fundamental contributions to science and society, and are poised to continue making great strides in the 21st century. Lasers are essential to modern high performance accelerator facilities that support fundamental science and applications, driving electron and ion sources, providing pump and probe beams, seeding and slicing x-ray lasers, and exciting matter into exotic non-equilibrium states. Moreover, future generations of accelerators are expected to employ lasers as power sources, enabling science to reach orders of magnitude further into the attosecond, angstrom, and teravolt regimes.

Future accelerators span a broad range of applications, from large-scale colliders for exploration of fundamental physics, to compact systems for medicine, industrial applications, and defense and security. Lasers are used as part of accelerators such as advanced light sources (e.g., in beam generation, seeding, and pump-probe experiments), covering a range of wavelengths from the terahertz regime to gamma rays produced by Compton scattering. They also play roles in particle sources via photoemission or photoionization, and they are used in femtosecond manipulation and diagnosis of beams.

Lasers are, of course, widely used in many other applications, including telecommunications, manufacturing, defense and security. However, accelerator applications have key requirements that are substantially different, and lasers being developed for those other applications are generally unsuitable. All future accelerator applications need one or more of: high peak power (high energy in a very short duration pulse), high average power (many pulses per second), and high electrical ("wall plug") efficiency. Higher peak power enables discovery science in the ultra-high field regime, increasing our fundamental understanding of matter-light interactions and opening up new directions for particle acceleration. High average power is essential for achieving high average brightness in light sources and high particle-beam luminosity in colliders. High wall plug efficiency is essential for cost-effective operation of the lasers and the facilities they support. In all cases, beam quality, tunability, stability and reliability are extremely important.

The U.S. Department of Energy (DOE) Office of High Energy Physics sponsored the Workshop on Laser Technology for Accelerators to identify R&D that can bridge the gaps between current laser system capabilities and future requirements. The workshop identified future laser developments that could be carried out under DOE's accelerator R&D stewardship effort that would contribute to the advancement of accelerator- and laser-enabled science.

Developing laser technologies for high average power (tens to hundreds of kilowatts), ultra-short pulses (picosecond and shorter), and high peak power at high efficiency will require a focused R&D effort involving national laboratories, universities, and U.S. industry.

A substantial amount of wide-ranging R&D will be required over at least the next decade to enable the development of the laser technology required for supporting future accelerator and laser driven science. Fundamental materials research must be conducted to develop new gain materials, diode lasers, non-linear materials, and high-damage-threshold optical coatings, with enhanced thermal and optical properties to allow operation with improved efficiency at average power levels that are three orders of magnitude higher than those of today's lasers. New laser geometries need to be explored and developed to enable a combination of high average power and high peak power.

Dedicated laser test bed facilities are needed to allow validation and testing of novel optical materials and laser architectures. Meeting the wide range of challenges identified at the workshop will require a similarly wide range of technologies, applications and partnerships; multiple test beds will be needed. Cooperative research among U.S. and international laser centers, academic institutions, and industry will expedite progress and cooperation between U.S. Services and Agencies working on near-identical and related technologies in lasers and peripherals. Such cooperation is essential for leveraging resources and may enhance the ability of industry to participate.

Training of the workforce (both students and professionals) is essential for maintaining and growing the accelerator and laser based science and technology areas. The need for highly skilled personnel in the photonics industry and laser based facilities is rapidly growing, and investments are needed for developing the required human resources.

The U.S. was a leader in laser technology for many decades until the late nineties. Over the last decade, very significant government and industry investments have been made overseas in the development of ultrafast-laser technology, with the result that the European laser industry dominates this market. Major investments are now being made in Europe as well as in Asia (in excess of $1B over the next five years), to further nurture and expand the technology base and available capabilities. This leads to dominance not only in scientific infrastructure for ultrafast-laser-based science, but also in innovation into photonics and laser technology, resulting in very significant industrial and economic benefits to European and Asian manufacturing.

The U.S. has made very strong investments in defense related systems and dominates this area of laser technology. It also has a very strong industrial base for optical and opto-mechanical components, high-average-power diodes and fiber systems, medical lasers, and medium peak power (few-terawatt) ultrafast lasers, which is of great benefit to the development of high peak and average power ultrafast lasers for accelerators.

A well-targeted stewardship effort in ultrafast laser technology that invests and focuses on the elements discussed in this report would result in a sustained intellectual effort that builds on current state-of-the-art know-how and U.S. competences. It will allow the invention and deployment of technologically critical systems in the U.S. and will reposition the nation for leadership in ultrafast lasers and photonics—leadership that will have substantial industrial and economic benefits.

1. Introduction

Advances in laser capabilities have such strong impact on accelerator applications in the discovery sciences that laser R&D has long been an integral part of accelerator R&D. Recognizing this, the Office of Science has for years made tactical investments in laser R&D. Advisory panel reports, prior workshops, and international societies have all underscored the importance of laser R&D as an enabling step towards advanced accelerator applications. In addition, the primary forums in which future accelerator research is discussed—the Advanced Accelerator Concepts Workshops and the Accelerator & Detector R&D Program meetings—have long included laser technology R&D as part of the broader discussion on accelerator development [1,2].

In 2008, the Office of High Energy Physics Particle Physics Project Prioritization Panel ("P5") reaffirmed the need for a broad strategic program in accelerator R&D and other enabling technologies (such as laser technology) to maintain leadership at the energy frontier. Five years after the P5 report, experiments at the energy frontier have moved to CERN, and investment in high-potential (and high-risk) technologies is seen as the only route by which the U. S. could recapture a leading role at the energy frontier [3]. Laser-driven acceleration is one such high-potential technology that HEP is pursuing in order to recapture this lead.

The Office of Basic Energy Sciences has also identified laser technology as a key enabling technology for its research. The 2009 workshop on Accelerator Physics for Future Light Sources and the 2010 Compact Light Source workshop each identified key R&D that is needed to make light sources perform at the level necessary to support basic energy science research. The need for significant laser R&D was identified in the overarching conclusions of both workshops. The primary issue is obtaining scientifically useful photon fluences from laser-driven sources, which will demand kilowatt-class IR lasers and intensity enhancement in optical storage cavities. Control of jitter, timing synchronization at the femtosecond level, and increased flexibility were also identified as key areas needing further R&D work [4,5].

The International Committee for Future Accelerators (ICFA) and the International Committee on Ultra-Intense Lasers (ICUIL) held joint meetings in 2010 and 2011 to develop white papers that survey the needs for laser systems and possible technologies (see ICFA Beam Dynamics Newsletter #56) [6] that future accelerators will demand. Machine concepts and laser specifications developed in preparation for these joint meetings served as a starting point for the specifications developed and discussed in chapter 3 of this report.

Seeking a long-term strategic approach to accelerator technology stewardship, the Department of Energy's Office of High Energy Physics sponsored a symposium and workshop in 2009 on "Accelerators for America's Future" chaired by Walter Henning and Charles Shank [7]. Its purpose was to elicit the views and opinions of a wide range of accelerator users on the challenges and opportunities for developing and deploying accelerators to meet national needs.

The report of this workshop, published in June 2010, has drawn Congressional interest in enhancing U.S. stewardship of accelerator science R&D.

With this as the context, Dr. Jim Siegrist, Associate Director of Science for the Department of Energy's High Energy Physics (HEP) Program within the Office of Science (SC), in consultation with other SC Associate Directors, asked the SLAC National Accelerator Laboratory to convene a community task force, chaired by Dr. Norbert Holtkamp, to provide updated information on accelerator stewardship from a team of experts. This ultimately led to the development and submission to Congress of the U.S. long-term accelerator R&D stewardship strategic plan. One focus of this plan was to develop laser technology for accelerators.

The Laser Technology for Accelerators Workshop was planned (see Appendices A.2 and A.3) to understand what laser capabilities are currently available, what capabilities are desired for the future, and what R&D activities are needed to bridge the gap. About 50 participants from the U.S., Germany, Italy, Japan, South Africa, and United Kingdom attended this DOE-HEP supported workshop. (see Appendix A.2 for a list of participants and observers) They participated in lively discussions with a goal of obtaining ideas for new approaches to high-peak- and average-power lasers that provide the required parameters for discovery science as well as for helping U.S. industry in the development and commercialization of such systems.

Three lectures provided the global context for laser technology discussions: a summary of the National Academy Report on Optics and Photonics; an overview of laser development in Europe; and a synopsis of high-energy, high-power laser development in the United Kingdom. There were lectures on the laser needs for a future collider, laser needs for basic energy sciences applications, and laser needs for accelerators on chips. These lectures were followed by a session that summarized the identified laser requirements for future science applications relating to accelerators and light sources. Following two lectures on new developments in fiber technology and optical materials, two panel discussions were held to discuss the challenges and potential directions for future research and investments in these two important areas. A panel session was also held on gas lasers and their technology challenges. The final session of the workshop was on the synergy between industry and government in developing new laser technologies.

The specific charges addressed at this workshop were:

Charge 1: Identify a set of key accelerator-related applications for laser technology and the scientific opportunities they create.

Charge 2: Assess the laser specifications needed to enable each of these key applications.

Charge 3: Identify technical gaps between present laser capabilities (current state-of-the-art) and the performance required for these key laser-technology applications.

Charge 4: Specify R&D activities needed to bridge these gaps; include an assessment of which R&D investments are expected to have the highest near-term performance benefits and be most cost effective.

Charge 5: Assess how the proposed U.S. R&D activities compare with global laser R&D efforts

The report that follows summarizes the discussion of the five charges by the workshop participants. A glossary of abbreviations can be found in Appendix A.3.

Coincident with the release of this focused workshop report will be the release of an industry-sector-wide National Academy report on Optics and Photonics. This report follows up on prior studies by the National Research Council (NRC) on optics and photonics in 1988 (Photonics: Maintaining Competitiveness in the Information Era) [8] and in 1998 (Harnessing Light: Optical Science and Engineering for the 21st Century) [9]. Since 1998, many other countries have developed their own strategic documents and organizations in the area of optics and photonics, and many have cited the U.S. NRC's 1998 Harnessing Light study as instrumental in influencing their thinking.

The 1998 study identified the importance of photonics and laser technology for U.S. competitiveness. This initiated very significant investments outside of the U.S. (in particular in Europe) and has resulted in a dominant role for European industrial laser manufacturers. Laser technology expertise continues to grow at a very rapid pace in Europe as well as in Asia, due to national policies in some countries that promote use of lasers and investments at the billion dollar level in state-of-the-art facilities for discovery science. In several critical areas the U.S. currently lags behind the larger international community in research and development for laser technology and laser-based applications. In 2012, after 14 years of dramatic technical advances and economic impact, another study was conducted to help guide the nation's strategic thinking in the photonics area.

This recent NAS study, "Optics and Photonics; Essential Technologies for our Nation" [10], recommended launching a National Photonics Initiative (NPI). The NPI organizing committee has identified five areas having high economic impact where photonics is essential: energy, healthcare and biomedicine, security, telecommunications and manufacturing. Basic science and the lasers used for science and discovery form the foundation for many of the devices that are critical for U.S. competitiveness in these five areas. This foundation is a major focus of the accelerator R&D stewardship strategic plan.

2 Identification of key applications

Charge 1

Identify a set of key accelerator-related applications for laser technology and the scientific opportunities they create.

2.1 Overview

We discuss here the use of lasers in the development of novel accelerator concepts for future colliders, in the generation and manipulation of electron beams, in the generation of electromagnetic radiation ranging from THz to gamma rays, and in medical applications.

High energy, short pulse lasers are now routinely able to achieve focused intensities that can access the relativistic regime, where the quiver velocity of an electron in the field of the laser approaches the speed of light. Such lasers are drivers for the following science topics:

- Acceleration of electrons, protons, and ions through laser-excited electric fields.
- Generation of coherent light in the extreme ultra-violet, x-ray and gamma-ray regimes.
- Exploration of material properties at extreme pressures and temperatures.
- Exploration of the structure of vacuum via radiation reaction forces and ultra-high intensity particle-photon interactions.
- Production of nuclear reactions.

Development of laser technology for these applications can be split into two categories. The first is the development of higher repetition rate, higher average power laser systems to create new, more-powerful tools for physics, chemistry, biology and medicine. The second is development of higher-intensity laser sources for the discovery of new physical phenomena and exploration of physical regimes not accessible by any other means.

2.2 High energy electron-positron accelerators

A key challenge in particle physics is that exploration of new physics requires continued increases of accelerator beam energies. Due to inherent limitations in achievable field gradients in radio-frequency (RF) based accelerators, new methods of accelerating particles are being studied that may have the potential to access new energy regimes at acceptable costs.

Two laser driven methods have been proposed to accelerate electron beams: (1) dielectric laser acceleration (DLA) and (2) laser plasma acceleration (LPA). DLA employs a laser beam to accelerate electrons in a manner analogous to current RF technology. Structure dimensions scale proportionately to the electromagnetic wavelength employed for the acceleration, leading to small apertures and thus requiring small electron bunches at high repetition rate. A key challenge is to phase-match the laser field to the electron beam to ensure a net positive acceleration. An initial demonstration experiment occurred in 2005 and demonstrated about 5 keV of acceleration and deceleration. Subsequent experiments in 2008 demonstrated attosecond bunch train formation, and staged laser acceleration at optical wavelengths. Since then, R&D efforts have focused on making extended dielectric accelerator structures by fiber or lithography techniques. Preliminary results suggest an accelerating gradient >200 MV/m has been observed, but further analysis is required. A key current challenge with this technology is launching the electron packets into the small structures employed for the acceleration.

Laser plasma acceleration uses a laser beam to generate density waves in a plasma that can accelerate electrons to relativistic energies with gradients in excess of 10 GV/m. LPAs have achieved the generation of percent-level energy spread beams at 100–200 MeV in 2004 using 10–30 TW laser pulses, and at the GeV level in 2006 using cm-scale capillary discharge based guiding structures and 40 TW peak power laser pulses. More recently, broadband electron beams up to 2–3 GeV have been observed and experiments are under way to achieve 10 GeV electron beams and to demonstrate staging of two consecutive LPA modules. During the past decade the LPA community has grown dramatically; many groups have entered the field since the "Dream Beam" results of 2004, and strawman designs have been put forth for a collider based on this technology. [6]

2.3 Accelerator-based light sources

Major facilities such as synchrotron and FEL sources have special laser needs that include: drivers for photocathodes for FELs, seed lasers to control longitudinal coherence in FELs, pump-probe lasers, fs-level synchronization, diagnostic uses, and control of beam instabilities (e.g., laser heaters) [4–6]. As light source repetition rate increases, the average power of the laser systems will be pushed to proportionately higher average power. Further, due to the limited access to these facilities, the lasers requirements are demanding—turn-key, reliable operation with hot-swap capability, and robust and extensive remote control. In the case of high-repetition-rate sources, high average power requires attention to efficiency and thermal management.

Photoinjectors require higher stability, reliability, and spatio-temporal control, as well as new wavelengths. Lasers are also required for precision electron beam manipulation to enhance the accelerator performance (e.g., emittance control or bunch slicing). As the accelerator repetition-rate increases towards the tens to hundreds of kHz, the required average power may increase towards the several hundred watt level for pulses with energies of a millijoule or less. This is within the realm of what is possible today.

FEL seeding will be required to achieve the ultimate control of the FEL temporal and spectral output. Options include at-wavelength seeding, which places the majority of the technical challenge on the laser, or multiplicative schemes, such as HGHG or EEHG, which seed at a longer wavelength and then frequency multiply to the required photon energy in the undulator systems. Reaching keV-photon energies will most likely require conversion of optical lasers using HHG to 50–100 eV and then HGHG or EEHG to multiply up to the keV level. [4–6] High repetition-rate pushes the average power to kW levels and requires reliable efficient UV conversion with excellent optical phase error control. Given the low efficiency of current HHG schemes, average power well into the kW range, with tens of mJ per pulse, will be required. Any increases in the state of the art for HHG conversion would reduce the average power requirements on the drive laser. Because these techniques rely on frequency multiplication in an undulator, any phase errors in the seed pulse are also multiplied, which means the phase of the seed pulse needs to be measured and controlled at a level that exceeds the current state of the art.

With the improvement in short pulse capabilities at synchrotron sources and the realization of XFELs, x-ray science is rapidly moving into much more complex time-domain studies. These studies generally require a pump-probe laser at the experimental endstation. Many of these experiments require multiple stages of wavelength conversion to UV, XUV, IR, mid-IR, or THz wavelength ranges. The efficiency of these multiple wavelength conversion stages drives average power to the kW level for high-repetition-rate machines.

In all pump-probe cases, fs level timing with respect to the x-ray beam is required. This requires new techniques for distributing timing signals, locking lasers to those signals, and measuring the arrival times of the optical pulses relative to the x-rays.

Laser based facilities are emerging that increasingly involve multiple beams, such as the Extreme Light Infrastructure facilities in the Czech Republic and Hungary [11]. These facilities use radiation and/or particles for complex experiments involving novel techniques. In many experiments, lasers with carrier envelope phase stability and/or arbitrary and complete control over dispersion, phase, amplitude, polarization, temporal & spatial mode are required.

Novel “compact light sources” have needs that include high-power, short-wavelength sources (e.g., HHG, soft x-ray plasma lasers), Compton backscattering sources, betatron sources and even compact accelerators to drive free electron lasers. [4,5]

The science needs for short pulse, high repetition rate, and high average power motivate the development of a range of novel laser architectures including diode-pumped bulk materials, thin disks, rods, slabs, coherently combined fibers and high-power parametric amplification systems.

2.4 Medical accelerators (proton and ion beams)

Radiation treatment of cancerous tumors benefits from the use of proton and ion beams primarily because of the Bragg peak in the rate of energy loss versus penetration distance. The energy of the ions is deposited in a much narrower depth range, near the end of their penetration, compared to x-rays and gamma rays. Damage to surrounding tissue can therefore be minimized.

Treatment with proton and ion beams is done at dedicated treatment centers. However, the size and cost of cyclotron- or synchrotron-based facilities is limiting the widespread availability of this technology. The main cost drivers are the mechanical construction of physically large components—cyclotrons/synchrotrons, transport magnets, and radiation shielding.

Laser-based accelerators offer the possibility of more-compact treatment facilities, since the acceleration occurs over a very short distance near the patient. [6] The ion source itself could, in principle, be compact enough to be moved around the patient with the use of an articulated laser beam transport system, along with lightweight optics and laser targets. Shielding volume may be reduced if these systems can be made small, if the ion beam quality improves substantially over present day performance, and if mechanisms are developed where ion beam tuning can be done reliably and in a controlled and stable manner. Current laser proton sources fall short of the particle energy required for therapy by approximately an order of magnitude and typically have large energy spread, which would necessitate the use of collimation and energy selector magnets in order to take advantage of the Bragg peak's treatment precision and ability to spare healthy tissue. Furthermore, current state-of-the-art experiments have not yet shown the required reliability and control.

In the last few years, the Radiation Pressure Acceleration (RPA) mechanism has been shown to produce narrower energy spread and more efficient scaling of proton energy with laser energy than previous mechanisms. Further agreement with theoretical models must be achieved before a clear path emerges for designing a therapeutically useful laser ion source. Nevertheless, the mechanism is well enough understood to enable the laser requirements to be estimated. Using solid state or fiber lasers operating in the near infrared requires both the target construction and laser contrast requirements at or beyond current capabilities. The anticipated laser requirements in the near-IR region are well beyond state-of-the-art in average power, and scaling of existing PW lasers to the required repetition rate is perhaps the largest challenge.

2.5 Other laser needs for Office of Science and related applications

Lower repetition-rate, high energy (0.1–1 kJ) lasers at the kW level would be of great benefit to the high-energy-density (HED) or warm-dense-matter (WDM) science and engineering programs, including those of the DOE/SC portfolio. For example, DOE/FES HED science pushes for very high energy (>10 J fs, >100 J ns) at high repetition rate.

Compact neutron sources capable of producing fluxes in the 10^{11} n/sr/sec range would also be enabled by 100 J, kW-class lasers.

Some users requiring high-average power, continuously tunable light (over several wavelength regimes – IR, UV, and soft/hard x-ray) are relying on FEL light as their laser, and this means that the accelerator produced electron beams are the gain medium.

3 Laser specifications

Charge 2

Assess the laser specifications needed to enable each of these key applications.

3.1 Overview

Common to every scientific application discussed above are the needs for flux, flexibility, stability, reliability, and economy. As the driver and power source for the applications discussed above, the laser system's attributes in these same performance categories strongly contribute to (and in many cases completely determine) the overall system performance. Commercially available ultrafast laser systems achieve some combination of the "middle three" of these properties, but presently lack the flux (average power) and cost-effectiveness needed for next-generation applications. Here we define representative laser performance specifications and thus highlight areas where further R&D is needed.

Representative parameters are shown next for a dielectric laser accelerator driver (Table 3.2.1) , an LPA driver (Table 3.2.2), a high harmonic generation source (Table 3.3.1), and a laser driven proton or ion accelerator for solid targets (Table 3.4.1) or gas targets (Table 3.4.2). High energy accelerators

Table 3.2.1 below illustrates the range of laser parameters that are believed to match what will be needed in the future for DLA and Table 3.2.2 illustrates the range of laser parameters that are believed be needed in the future for a 1 GeV-class, high repetition rate (1 kHz) LPA. For DLA, it is unlikely that further power scaling beyond 3 kW would be required, as additional acceleration would best be achieved by adding additional DLA stages. For LPA, the 3 kW laser specifications in Table 3.2.2 would be useful immediately for light source applications requiring GeV electron beams.

Currently, 3 J lasers are available at a 10 Hz repetition rate and have been used to demonstrate 1 GeV electron beams. Pushing the repetition rate to 1 kHz would be a major step forward towards testing high power operation of LPA. Future TeV accelerator applications are envisioned as consisting of many 10 GeV modules that would require lasers to operate at ten times higher pulse energy (30–40 J) and ten times higher repletion rate (10 kHz). The average power of the laser would hence require further scaling to the 100 kW level.

Table 3.2.1 Dielectric Laser Accelerator Drive Laser Notional Requirements. Laser pulse energy and repetition rate are assumed to scale together in such as way as to keep average power constant at 3 kW.

Laser Parameter	Units	Min	Max	Goal
Center Wavelength	nm	1000	10,000	1500–2000
Pulse Width	fs	100	1000	300
Pulse Energy	μJ	0.2	10	3
Pulse Peak Power	MW	2	9	9
Repetition Rate	MHz	300	1,000	1,000
RMS Temporal Jitter	fs		10	<1
RMS Energy Stability	%		<2	<1
Beam Quality (M^2)[1]			1.2	<1.1
Average Power	kW	0.06	10	3
Wall-plug efficiency	%	20		40
Optical Phase Noise	Degrees		15°	<5°

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[1] M^2 is the ratio of the beam parameter product for the actual beam to that of a pure Gaussian beam.

Table 3.2.2 Laser Plasma Accelerator Notional Requirements for a 1 GeV, 1 kHz linac. Laser pulse energy and repetition rate are assumed to scale together in such as way as to keep average power constant at 3 kW. The variation accounts for the range over which a laser system might potentially be useful.

Laser Parameter	Units	Min	Max	Goal
Center Wavelength	nm	400	10,000	800–2000
Pulse Width	fs	30	300	30–100
Pulse Energy	J	3	5	3
Pulse Peak Power	TW	30		100
Repetition Rate	kHz	1		1
RMS Temporal Jitter	fs	1	10	1
RMS Energy Stability	%		0.5	<0.1
Beam Quality	Strehl Ratio	0.7	1	>0.95
Average Power	kW	3		3
Wall-plug efficiency	%	5		15
Pre-Pulse Power Contrast	--	10^8		10^{10}
Time Window for Pre-Pulse		5-10ps	>1ns	

3.1.1 Discussion

DLA structures scale with the laser wavelength, making it easier to fabricate the structures, and launch the electron beam into them for longer wavelengths. The LPA method can accommodate a range of wavelengths via optimization of the laser pulse energy and plasma density. DLA systems operate at relatively low peak power and do not have stringent temporal pulse contrast requirements. LPA systems can be affected by a significant laser prepulse and require contrast levels at the 10^{-8}–10^{-10} level, which is the current state of the art.

For high energy accelerator applications, high wall-plug efficiency (>30%) is an important requirement, as it will impact the operating cost of any high average power accelerator.

Both methods (LPA and DLA) require near diffraction-limited beams with a high degree of pointing stability at the focus (<1 microradian) to ensure good coupling to the structures. For higher energy LPA systems (tens of J), the focused spot size is typically on the order of 100 μm, requiring a focusing system with large *F*-number. High damage threshold coatings are essential to minimize the required size of the transport optics.

DLA relevant laser technology has overlap with lasers used in telecommunications. LPA relevant laser technology relies on system components that are used in industry for manufacturing, such as peening, machining/cutting and welding systems. For both DLA and LPA, the unique need is for ultra-fast (sub-picosecond) pulses.

3.2 Laser needs for light sources

Radiation generation from electron beams produced by LPA is being pursued and used by many groups around the world, including coherent single cycle THz radiation, XUV radiation from an LPA powered FEL, hard x-rays from betatron emissions and gamma rays from Thomson scattering of the e^- beam against a counter-propagating laser beam. Concepts are being explored in the case of DLA to generate radiation. The laser requirements for all these applications were outlined in Section 3.2.

Future high-power high-repetition rate FELs will require high-average power seed lasers from the IR to the soft x-ray region and beyond. Other laser needs for accelerators include non-intercepting diagnostics and control of beam instabilities.

Generation of attosecond pulses from laser-generated XUV and soft x-ray radiation, based on high harmonics from gas based sources or on solid targets (coherent wake excitation and relativistic oscillating mirrors) is a very active area of research; it has had significant success and could have considerable impact on, for example, Basic Energy Sciences and materials experiments. Lasers for gas-based sources typically require lower pulse energy than those for solid-target-based sources. FEL-based or laser-based high harmonics can also provide coherent seed radiation for free electron lasers. Future high repetition rate FELs will require high average power tunable seed lasers.

Notional laser specifications for an HHG x-ray source are detailed in Table 3.3.1 below.

Table 3.3.1 High Harmonic Generation Laser Notional Requirements. The variation accounts for the range over which a laser system might potentially be useful based upon current experimental and theoretical results.

Laser Parameter	Units	Min	Max	Goal
Center Wavelength	nm	800	10,000	2000–5000
Center Wavelength Tunability	%	10		10
Pulse Width	fs	10	100	50
Pulse Energy	mJ	10 (Gas) 100 (Solid)		30 (Gas) >1,000
Pulse Peak Power	TW	0.1(Gas) 1 (solid)		0.6(Gas) 100 (solid)
Repetition Rate	kHz	100 (Gas) 0.001 (solid)	300 (Gas)	100 (Gas) 10 (solid)
RMS Temporal Jitter	fs		100	<100
RMS Energy Stability	%		<2	<1
Beam Quality	M^2		1.2	<1.1
Average Power	kW	3		3

3.2.1 Discussion

For light source applications, higher average power enables higher repetition rate experiments and hence allows pump-probe experiments, such as needed for imaging ultra-fast phenomena or ultra-fast spectroscopy, to benefit from the high average brightness in present day and future lights sources.

For high harmonic sources, longer laser wavelengths permit generation of shorter wavelengths but at the cost of conversion efficiency. Flexibility in choice of wavelength would enable optimization of the source. Fine tuning of the center wavelength of the laser is required to fine-tune the frequency comb of generated x-ray lines. Timing and synchronization will be critical for the FEL seed-laser application. Pulse contrast is not important for gas-based sources but is essential for solid-target-based sources to minimize target ablation prior to arrival of the main pulse. Accurate control of both the spatial and temporal pulse profiles is essential; aspects of control include carrier envelope phase stabilization, near diffraction limited focal spots, and temporal and spatial chirp. By controlling the chirp, single attosecond pulses of high harmonics have been generated from solid targets by relying on the so-called lighthouse effect.

3.3 Laser needs for proton and ion beams

Proton and ion beams can be generated via visible to near-infrared high energy short pulse lasers focused onto a solid foil target or via mid to long infrared high energy short pulse lasers focused into a gas jet. The latter scheme may be advantageous as the target is easily replenished. The former scheme also has advantages, as it is generally easier to fabricate high energy, short pulse lasers in the near IR and cryogenic targets are being developed to allow near-critical-density operation. Table 3.4.1 provides notional laser parameters for solid and gas target proton and ion sources.

Table 3.4.1 Proton and Ion Sources Employing Solid/Gas Targets: Notional Laser Requirements

Laser Parameter	Units	Min	Max	Goal
Center Wavelength	nm	800 (solid) 4000 (gas)	2000 (solid) 10,000 (gas)	
Pulse Width	fs	100(solid) 100 (gas)	1000	100(solid) 500 (gas)
Pulse Energy	J	100		300
Pulse Peak Power	PW	1 (solid) 0.1 (gas)		3(solid) 0.3 (gas)
Repetition Rate	Hz	10	30	100
RMS Energy Stability	%	<5		<1
Beam Quality	M2	<2		1
Average Power	kW	3	10	3
Wall-plug efficiency	%	5		15
Pre-Pulse Power Contrast	--	10^{13}(solid) 10^{3}(gas)		10^{15}(solid) 10^{5}(gas)
Time Window for Pre-Pulse		100 ps to 1 ns		<10 ps to 1 ns

3.3.1 Discussion

Solid target experiments have mainly been done with solid-state lasers, and gas-target experiments with gas lasers. Gas lasers operate at longer wavelengths, an advantage for gas-target experiments because gas jets can be operated at densities that exceed the critical density for a 10 micron driver wavelength and also are transparent for optical probes, enabling detailed characterization of the accelerating medium.[2] Both solid- and gas-target-based laser-driven ion acceleration require very energetic pulses (hundreds of J) to attain proton and ion energies relevant for medical applications at repetition rates in the tens of Hz range. Exceptional pre-pulse

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[2] Cryogenic gas jets are being developed to extend that operational regime towards shorter wavelengths, combined with the use of high harmonics for probing.

power contrast is required for the solid-state lasers, though not for the gas lasers. The former are typically operated at 4–5 orders of magnitude higher intensity than the latter, and utilize as target material thin foils, which ionize at one to two orders of magnitude lower intensity than the gas targets.

The combination of energy, repetition rate and pulse duration needed for laser-based ion therapy accelerators overlaps closely with inertial fusion laser drivers. Energy stability may be critical in that it will determine the final ion energy and thus the depth of penetration into a patient during therapy. Laser beam quality in time and space domains is important to optimize the ion acceleration physics.

4 Technical gaps

Charge 3

Identify technical gaps between present laser capabilities (current state-of-the-art) and the performance required for these key laser-technology applications.

The applications discussed in the previous section have some generic technological requirements in common:

- Ultrafast pulses (<1 ps).
- High average powers (>1 kW up to 100 kW or more).
- Diffraction limited beams.
- Good (ps) to excellent (fs) pulse timing.
- Robust and reliable operation.

Many important applications also require, or can benefit from:

- High pulse energy (>0.01 J up to 1 kJ).
- High pre-pulse power contrast ($>10^7$).
- High wall plug efficiency (>20% with a goal of 30% or higher).
- Longer laser wavelengths (>1.5 μm out to 10 μm).

4.1 Average power and wall plug efficiency

The technology challenge for ultrafast lasers of all types is scaling of average power while maintaining the other key technological requirements. For example, most current high intensity applications and ultrafast discovery science facilities use Ti:sapphire-based lasers that can support petawatt class femtosecond pulses. However these systems intrinsically have a large quantum defect and to date, the high energy systems are powered by flashlamp-pumped frequency-doubled Nd:YAG lasers with wall plug efficiency on the order of 0.1–0.5%. As a result, state-of-the-art ultrafast lasers with significant pulse energy (>0.001 J) typically operate at the 10–100 W level of average power. Improvements in average power of ultrafast lasers on the order of 10–100 times or more are needed to realize the applications and their associated benefits.

4.1.1 Diodes

Significant progress was made in the electrical-to-optical (E-O) efficiency of diode lasers in the last decade. E-O efficiencies as high as 70% have been attained in the 900–1100 nm wavelength range and >50% is easily obtainable off the shelf. Cryogenic cooling can raise these efficiencies to as high as 90%. Many longer wavelength applications would greatly benefit from longer wavelength pump diodes. However, E-O efficiency in this range is much less than 20%. To date, little materials development has been funded in this wavelength range.

Blue-green diode lasers require materials development to improve their overall efficiency. Many of the original short pulse laser gain media were pumped by inefficient visible laser systems. Development of efficient high power blue or green diodes could be a path towards better pump lasers for visible and near-IR lasers such as Ti:sapphire systems.[3]

A second technology gap identified in the diode laser area is materials for diode laser package assemblies, particularly soldering at the diode metal interface. Improved thermal management will result in improvements in overall performance and reliability.

4.1.2 Fibers

Fiber lasers are widely used in many current applications due to their high wall-plug efficiencies, multi-kW output powers with diffraction-limited beams, and compactness, robustness and reliability. Current commercially available multi-kW continuous-wave fiber lasers for industrial cutting and welding applications reach 35% wall-plug efficiency. These systems at present are exclusively Yb-doped fiber systems operating at ~1 μm, with optical-to-optical efficiencies reaching up to ~85%. Such devices are pumped with technologically mature 915 nm–980 nm diode lasers, with typical commercially available electrical-to-optical efficiencies currently at ~55%. Other commercially available fiber laser gain media are Er-doped and Er/Yb-co-doped (for operation at $\lambda \approx 1.55$ μm), Tm-doped and, recently, Ho-doped (for operation at $\lambda \approx 2$ μm).

All these fiber gain media provide significantly lower wall-plug efficiencies, compared to Yb-doped fibers. This is due to lower optical-to-optical (typically ~30–40% for Er and Er/Yb fibers, and 55–65% for Tm fibers) and substantially lower electrical-to-optical efficiency of the diode laser currently used to pump these fibers, although with resonant pumping at ~1.5 μm Er-doped fiber efficiency can reach up to ~70%. Consequently, the main contribution to the wall-plug

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[3] Applications that require very high wall plug efficiency would require gain materials that have a smaller quantum defect than Ti:sapphire. Also, Ti:sapphire has a very short upper state lifetime and is not necessarily amenable to direct diode laser pumping at repetition rates less than 1 MHz due to the large number of diodes that would be required.

efficiency comes from diode efficiency. Ongoing technological development of commercial 980 nm diodes is expected to continuously increase their electric efficiency, enabling an anticipated increase of Yb-doped fiber laser wall-plug efficiency to >50%. R&D-grade diode lasers have been demonstrated with >70% efficiencies. Investment is currently lacking for developing efficient long-wavelength pump diodes for significantly increasing Er and Tm doped fiber wall-plug efficiency. Pulsed high-energy fiber laser systems operating at ~10 kHz repetition rates have markedly lower wall-plug efficiencies of ~20%. Nevertheless, with further increases in pump diode efficiency, it is anticipated that pulsed-laser wall-plug efficiencies will also exceed ~30%.

The main technology gap in fiber laser technology is in the orders-of-magnitude difference between the pulse energies that have been achieved and the pulse energies that are required for LPA applications. State-of-the-art continuous-wave fiber lasers have reached 10 kW single mode output in commercially available systems. These lasers use relatively small core fibers (~20–25 μm core) that enabled monolithic integration of commercial lasers, but are poorly suited for high-energy ultrashort pulse lasers. State-of-the-art high-energy femtosecond fiber chirped pulse amplification systems (FCPA) use fibers with 30 μm to ~100 μm cores, necessary to control nonlinearities occurring at high peak power. The highest FCPA energies demonstrated so far have reached >1 mJ and up to ~1 kW of average powers (though not at the same time), by means of so-called photonic-crystal rod fibers, which are poorly suited for compact monolithic integration, the preferred approach for the construction of large fiber arrays. The ultrashort-pulse energies are at an approximate energy limit for a single-channel fiber amplifier, which is set by the onset of nonlinear effects. Furthermore, these large core and relatively short fibers are particularly susceptible to so-called modal instability due to thermal effects at high average power, thus constituting an additional challenge. Modal instability has been discovered recently as a general problem for large core high-power fiber lasers, and some DOD funding has already been directed to address this problem.

Given these energy and power limitations, it is difficult to expect further significant increases in pulse energy and, possibly, average power from single-channel fiber laser systems. To overcome this bottleneck, over the last 10 years DOD has invested significantly into the development of combined continuous-wave fiber laser arrays. The most relevant for LPA applications are the coherent combining efforts. Current state-of-the-art results include demonstration of coherent fiber-laser combination with up to 4 kW of average power, combination of up to 16-channel fiber amplifier arrays, and demonstration of coherent combination of up to 91 parallel-element passive-fiber array.

Concurrently with the fiber laser development, significant DOD funding have been directed to developing diffractive-optics elements for combining multiple input beams into a single near-diffraction limited beam, and withstanding average powers of >100 kW. These approaches have been recently applied to combining ultrashort-pulse fiber CPA, demonstrating combining of up to four channels, and reaching up to 3 mJ in combined pulse energy at a few hundred watts of average power. Theoretical understanding gained from these ongoing research and development efforts indicates that combining a much larger number of channels should be feasible, both in terms of coherently-phased array size and in terms of diffractive optics combiner designs for accommodating 10^3–10^4 beams. Nevertheless, current achievements are orders of magnitude lower in power, pulse energy, and number of phased and beam-combined channels than needed.

Optical fibers for fiber lasers rely almost exclusively on materials developed for the telecom industry. The technical goals of this industry are extremely low loss glass waveguides capable of robustly guiding light over long distances. While fiber lasers have made great technical progress over the last 3 decades, R&D to optimize the basic laser material from which fiber lasers are drawn has made little progress. New materials that can be formed into optical fibers may enhance progress towards the desired light sources significantly. Recent examination of fibers claimed to be of consistent high quality were analyzed at a third-generation synchrotron light source (Advanced Photon Source). Using the x-ray microprobe, experimenters were able to observe significant non-uniformity in the ytterbium distribution in the fiber core. Improvements in fiber uniformity may lead to significant increases in the maximum operating power.

4.1.3 Optical Parametric Chirped Pulse Amplification

As discussed above, optical fiber based systems have limited temporal pulse contrast, which may be a serious shortcoming for certain applications such as ion acceleration or laser-solid target interaction physics. Optical Parametric Chirped Pulse Amplification (OPCPA) has great promise to create ultrashort pulses at high energy, with good beam quality, and ultra-high contrast. Conceivably one may also consider a hybrid approach where fiber and OPCPA techniques are combined.

While the maximum theoretical optical-to-optical OPCPA efficiency is 45%, to date only 30% has been attained, indicating significant room for improvement. Pulse energies on the order of 1 J with 100 fs pulse width and 0.125 J with 8 fs pulse width have been attained with good beam quality. However, average power levels to date have only been in the few watt range. The main limitation stems not from the availability of suitable gain materials[4] but rather from the limited available average power and beam quality of current pump lasers.

4.2 Laser beam quality and wavelength

For most applications, spatial and temporal beam quality are critically important. Spatial beam quality has steadily improved and is becoming controllable with sophisticated wavefront sensors and deformable mirrors to control optical wavefronts. However, these cannot operate in a high frequency closed tuning loop for the large scale optics used on high peak power systems. Commercial systems exist for control of the temporal profile and laser pulse chirp for low energy pulses but typically have limited tuning ranges.

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[4] It worth noting that periodically poled materials that may be of use in OPCPA are currently limited by processing to less than 1 mm thickness, whereas thicknesses of the order of 10 mm are required.

High pulse contrast is one of the critical laser driver requirements for high-field applications. Pulse contrast from state-of-the-art solid-state lasers is two to three orders of magnitude below what is needed for solid target experiments at ultrahigh intensities, and high-efficiency techniques to improve the contrast are needed. Ultrashort-pulse fiber CPA systems, when operated close to extractable-energy limit, have pre-pulse power contrast on the order of 10^2, whereas many laser-plasma applications require contrast of 10^7 or higher. This critical and challenging problem remains to be solved, and there has been very little effort to address it, since none of the industrial or medical FCPA applications require high pulse contrast. Some of the ongoing research on coherently combined nanosecond-pulse systems indicates that it might be possible to increase pulse contrast in a coherently combined array, but this remains to be proven. Significant research is needed to demonstrate high-contrast operation of a single-channel FCPA, as well as to explore coherent-array based methods of increasing pulse contrast in a combined beam.

High harmonic sources, DLA based accelerators and ion acceleration would benefit from the availability of compact, high-repetition-rate, high-intensity lasers with wavelengths longer than 1.5 µm. The development of suitable optical gain materials (bulk or fiber) for optical wavelengths of ~2 µm or longer is a significant challenge. An additional challenge here is demonstrating the phase control and stability needed to stage DLA sections.

Some of the key applications identified in Section 2 require kW-class average power gas-based lasers, all of which are currently low pressure and therefore not capable of amplifying few ps pulse widths. Over the past 5 decades, development of gas (particularly CO_2) lasers has progressed more sporadically than development of solid-state and fiber lasers, since the latter field is large, whereas historically only a small number of research groups have been improving gas lasers. However, two laboratories now lead the development of short-pulse generation and applications with gas lasers, with BNL achieving 1 TW peak power, and UCLA achieving 15 TW, albeit each at very low repetition rate (<<0.1 Hz).

An ion driver application at 10 µm wavelength is anticipated to require a 1 ps, 100 J, 100 Hz class system. Presently, no laser exists with all these capabilities, although no breakthroughs are required to achieve two of the three parameters. The difficulty in providing the full parameter set arises because the large aperture (≥5x10 cm) amplifiers capable of delivering 100 J are currently operating at <0.1 Hz repetition rates, and require advanced pulsed-power designs to scale past approximately 1 Hz. Amplifiers of smaller aperture are currently commercially available at 100 Hz, and the path to direct amplification of 1-ps pulses is understood. Therefore, large aperture amplifier designs must be advanced and commercialized in order to realize the requirements for an ion driver system.

4.3 Optical elements

4.3.1 Damage threshold of optical materials and coatings

Most current ultrafast laser systems operate at fluences of <1–2 J/cm^2, making these systems inherently inefficient as well as large and costly. Commercial optical coatings have damage fluence thresholds at the few J/cm^2 level for few 100 ps pulses and at the 0.5 J/cm^2 for <100 fs pulses. To minimize fluence on the optics, large optics are needed for beam transport and focusing. Very significant laser system size and cost reductions, as well as operations at higher energies, would be enabled if damage threshold can be increased by an order of magnitude.

4.3.2 Gratings and diffractive optical elements

High efficiency (>99%) gratings are needed for compression of broadband laser pulses (>50 nm). Very significant pulse energy losses are incurred in laser compressors due to the fact that current compressor designs utilize four reflections from gratings that are typically 93–95% efficient per reflection. Development of high damage threshold coatings, as discussed above, will facilitate improved multilayer dielectric gratings. Key challenges identified with current gratings are both the damage threshold and the bandwidth of the gratings. Of particular interest to developers of short-pulse lasers are lower-groove-density gratings with broad bandwidth, high efficiency and high damage threshold. These requirements necessitate new concepts in multilayer diffraction grating design. Efforts toward meeting some of these specifications have already been put in place, and multilayer diffraction gratings with large bandwidth and high efficiency have been demonstrated in the U.S., Europe, and China. However, the laser damage performance was not great. There is concern that this technique may have issues with damage threshold due to field enhancement in the patterned top layers. Developments such as these should be monitored closely, but it is likely this problem is still outstanding and in need of additional development.

Diffractive optical elements may be a key component if the pathway to high average power is, as seems likely, via the efficient beam combination of multiple single aperture lasers. Continuous wave laser systems have demonstrated excellent efficiencies (>90%) and diffraction limited output beams from as many as 8 lasers at power levels up to 4 kW. However, it is unclear how these optics will behave for lasers with 10 THz of bandwidth; some development may be required. A key issue with these optics is that, unlike diffraction gratings, they require multiple-level or even continuous gray-scale etching. Most of the facilities to perform multi-level etching are in Germany and have very long lead times.

4.3.3 Non-linear materials

Non-linear materials are widely used for sum- or difference-frequency generation and optical rectification to produce frequencies ranging from THz to EUV. Such materials must be able to handle high average power and have high conversion efficiency without sustaining optical damage. For high fluence applications, large crystals are needed but are not readily available.

4.4 Systems engineering, design tools and testing/training facilities

Significant engineering efforts are needed to increase systems operability, reliability and stability. Start-to-end software tools built upon best engineering practices for laser design are not widely available.

A challenge with materials, coatings and diode development is testing new components under real-world conditions. Most major laser systems that could do this are focused on discovery science missions, and are generally not available for extensive lifetime testing of new optical components or subsystems. A key finding of the workshop was that progress in the development of new laser technology is hampered by the lack of facilities to develop and test new components. The availability of test bed facilities, staffed by knowledgeable laser scientists and dedicated exclusively to development and testing of new components, technologies and architectures. was quickly recognized as a significant technology gap. Combined laser/accelerator facilities are also required.

The need to train the next generation of laser scientists is acute in the field of gas lasers, as there are very few facilities and personnel available for the task, and is also becoming critical in solid state laser technology due to the large number of facilities that are planned or under construction around the world. An effort to prioritize graduate student training as part of the overall R&D program is critical to sustaining future viability of laser technology.

Furthermore, these new developments in lasers and their peripherals, as well as the test beds themselves, will provide critical early-career training where new talent can "learn by doing".

5 R&D activities needed to bridge gaps

Charge 4

Specify R&D activities needed to bridge these gaps; include an assessment of which R&D investments are expected to have the highest near-term performance benefits and be most cost effective.

A key conclusion of the workshop is that average power scaling of ultrafast lasers to the 3 kW level is an important near term (1–5 year) goal that will enable proposed applications with meaningful societal benefits. Development of technologies that will scale to even higher powers (>30 kW) beyond the 10 year time frame, and that also have pathways to high wall plug efficiencies further in the future, is of clear interest to a broad range of these applications. Developing such technologies will require a focused R&D effort involving national laboratories, universities, and US industry. Ideally, such a program would be funded in a coordinated manner by the federal and industrial stakeholders in many areas, including materials R&D; fiber lasers and fiber laser beam combining; optical coatings; diode lasers; gratings; optical parametric chirped pulse amplification; and various aspects of gas lasers. The relationships of these applications, capabilities, and technologies are shown, with commentary on their impact, in Table 5.1.

Table 5.1 Summary of R&D impact of various capabilities and technologies to applications. Capabilities (blue) are dependent upon advances in technologies.

		Mission critical science areas					
		Dielectric Laser Acceleration	Laser Plasma Wakefield Accelerators	HHG for FEL Seeding and XUV Sources	Pump-probe lasers for light sources	Proton and Ion Beams	Mid-scale facilities and individual PI labs
Capabilities	Increased average power ~kW, 1-10 micro-J, 1-0.1 GHz	1	3	2	2	3	1
	Increased average power ~kW, 1-10 mJ, 1-0.1 MHz	2	3	1	1	3	1
	~Increased Average Power kW, 1-10 J, 10-1 kHz	3	1	2	2	3	2
	~Increased average power kW, 100-1000 J, 10-1 Hz	1	2	3	3	1	2
Technologies	Coherent combination fibers	1	1	1	1	3	3
	Coherent combination bulk	1	2	1	1	2	1
	Longer wavelength gain materials 2-10 micron	1	3	1	1	1	1
	Advanced SSL gain materials	3	1	1	1	1	1
	Advanced non-linear materials	1	1	1	1	1	1
	High damage threshold materials and coatings	1	1	1	1	1	1
	Higher damage threshold and bandwidth gratings and diffractive optics	1	1	1	1	1	1
	Diode Lasers	1	1	1	1	1	1
	High power OPCPA	1	1	1	1	3	1
	High power, short pulse gas lasers	3	3	3	3	1	3

1	Very important
2	Somewhat important or transitional
3	Not so important or not applicable

We next discuss the different areas where investments are needed, from the vantage point of the system requirements: average power and wall plug efficiency; beam quality and wavelength tuning; optical elements to transport and use the laser beams; systems engineering, design tools and test bed facilities. We end this section with a list that provides a high level assessment of the performance benefits and cost effectiveness of the various R&D options.

5.1 Average power and wall plug efficiency

The development of higher average power laser systems with high wall plug efficiency will require R&D in the following areas:

- Novel laser gain and optical materials.
- Advanced pump lasers.
- Ultrafast high average power fiber lasers.
- Gas lasers.

Specific examples in these general areas that would benefit from investments are outlined below.

5.1.1 Novel laser gain and optical materials

Gain materials are critical to attaining efficient high average power with good beam quality. The ideal gain material might have properties similar to those below:

- Bandwidth >10 THz.
- Quantum defect <6 THz.
- Thermal conductivity and optical path length change equivalent to cryogenic YAG, but at room temperature.
- Saturation fluence <3 J/cm^2 and Saturation intensity <10 kW/cm^2.
- Damage threshold >10 J/cm^2 at >100 kW/cm^2
- Center wavelengths at 1 µm, 1.5 µm and/or 2 µm.
- Ideally scalable to apertures that support kJ pulse energies[5].
- Tailorable doping concentrations of active ions.
- Properties consistent with low B-integral (intensity-dependent phase shift) and low chromatic dispersion.

Optical-to-optical conversion efficiency (a key aspect of overall efficiency) requires saturation fluence and intensities to be significantly below the damage threshold of the material. Development is needed for new laser gain materials, including materials with low saturation values and high optical damage values, guided by the parameters discussed above, is important for all applications. Novel fiber materials must be developed that have 1) high purity, 2) refractive index and concentration gradients as designed and 3) low incidence of clustering of active materials, i.e., high uniformity. Ceramics hold the promise of engineered optical materials with quality far exceeding that of crystals.

Ceramic-based optics are produced by sintering powders into large-aperture optics. The R&D needed would include studies into sesquioxides that have more promise for broadband laser gain media but have not been studied very extensively. Development of periodically poled nonlinear

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[5] Although 100 J pulse energies would suffice for a majority of accelerator needs

materials that are thicker than 1 cm would be enabling for both OPCPA and frequency up-conversion of laser light into the UV wavelength range. The latter is of great importance to the development of efficient and reliable photocathode drive and H^- stripping lasers.

Modeling and simulation are essential elements of an R&D path to clearly define materials properties that would enable new levels of laser performance. A peer reviewed theoretical study that considers material properties and trade-offs to optimize a chirped pulse amplifier design for beam quality, pulse quality, and system efficiency would provide important guidance for future materials development. This area of research will also be rich in teaching and training opportunities.

5.1.2 Advanced pump lasers

Development is needed of high average power pump lasers (multi-kW) suitable for use in lasers for gas harmonic sources or high repetition rate laser plasma accelerators, as well as for use in demonstration of optical parametric chirped pulse amplification (OPCPA) at high average power.

Improvements in diode laser efficiencies both at longer and shorter wavelengths would be enabling and of benefit to all end users of high average power lasers. Improvements in materials for thermal management and packaging of laser diodes would be enabling and benefit all end users of high average power lasers.

5.1.3 Ultrafast high average power fiber lasers

Development of coherent-combining technology in the short pulse laser regime is an important and unfunded challenge. Fiber laser chirped pulse amplification approaches such as linear array-size scaling for coherent combining via direct phase control, as well as various stacking methods (e.g., temporal stacking with enhancement cavities, and temporal-interference or N^2 methods), can reduce required array sizes by orders of magnitude and potentially help offset the unit cell issues discussed above. These topics should be investigated. It is also important to establish an understanding of how coherent combining is affected by unit-cell pulse quality and if coherent combining improves these issues, as is generally believed. This area of research will also be rich in teaching and training opportunities.

For the energies required for an LPA producing a multi-GeV electron beam, one would envision requiring $>10^4$ parallel channels (assuming direct array-size scaling). It may make sense for the near-term or intermediate term to develop the intermediate pulse energies needed by high harmonic generation sources. A side benefit of this development work would be synergy with current and future commercial markets in ultrashort-pulse material processing. A key challenge with these requirements is attaining ~50 fs pulse durations. Spectral coherent combining might be used to overcome gain-narrowing limitations.

Hybrid systems with fiber laser preamps and high-energy-gain modules at the last stage may be a promising route forward that permits significant shrinking of beam combination array sizes. The fiber laser R&D proposed above, aimed at improving unit-cell quality and demonstrating beam combination technologies, should apply to this scheme in a straightforward manner. Thus, even if arrays of 10,000 fiber lasers are never practical, the ability to combine 10–100 unit cells, with a high energy bulk amplifier to attain the final required pulse energy, would still help enable the overarching goals outlined in this report.

Cost per unit block is a long term R&D need. Large scale arrays will require reduction of the unit-cell cost from few thousand dollars down to about a hundred dollars per channel. However, this is a longer-term challenge that probably need not be started until further progress is made in unit cell pulse quality and efficiency, and until beam combination has been demonstrated to work at relevant array sizes.

5.1.4 Gas lasers

Gas lasers will continue to have a unique role in the development of novel laser driven ion accelerators. Proof-of-principle experiments will require high energy systems (>100 J in <1 ps pulses) to validate their usefulness for medical applications. Subsequently this will require the development of robust, turn-key, large-aperture, high-repetition-rate amplifiers through longer-term engineering efforts on such systems.

Wider deployment of CO_2 systems will be enabled by development of 10 μm, 10 mJ-level picosecond OPCPA sources for direct high-energy amplifier injection. The main goal would be to provide dramatically more compact and robust sources built on solid state lasers, rather than the complex seed-pulse generation currently used in research settings. Efficient parametric amplification in the mid-IR would be possible with the use Er- or Ho-doped lasers pumping a nonlinear material free of two-photon absorption for both pump and signal. By allowing for generation of a chirped pulse, the fullest range of capabilities will be supported for different applications. Pump lasers in the 2–3 μm range are well developed, and scalability designs exist to achieve the required repetition rate and average power. The major impact of this effort would occur in the longer term as demand increases for robust gas lasers, and the near term benefit would be more modest. Since it would reduce overall system complexity and open more applications, as well as drive down cost, the cost effectiveness is good.

Long-term challenges include higher risk studies into new concepts. There is a need to pursue advanced methods, such as self-phase-modulation in partially ionized gases followed by recompression; Rabi flopping; chirped pulse amplification with spectral shaping; small scale molecular dynamics studies; optical pumping; and novel gas mixtures. Some of these studies could be conducted at existing or new test facilities, whereas others could occur in smaller university labs. These types of fundamental studies present less opportunity for near-term benefit, and as higher- risk activities, also have much lower cost- effectiveness than more-straightforward engineering activities.

5.2 Beam quality and wavelength

Pulse contrast and efficiency are critical to many systems requirements. For fiber lasers, a focused effort with a goal of developing single unit cell fiber lasers with high efficiency (>30% wall-plug), high pulse energy (>1 mJ) and high pre-pulse contrast (>10^7 in the >10 ps time window) is called for. Such an effort would need to address key issues in matching material dispersion across a broad bandwidth, as well as in maintaining pulse quality in the presence of the large nonlinearities that would be encountered in an efficient system. For all applications of ultra-fast lasers, focusability, pointing stability, reliability and tunability are essential for carrying out the science missions. For some experiments these attributes are critical. For all experiments they allow time- and cost-effective operation of the facility by maximizing productivity and availability of beam time.

Development of long wavelength ultrafast lasers will benefit high harmonic generation sources and ion acceleration applications.

5.3 Optical elements

5.3.1 Gratings and Diffractive Optics

Development is needed of high bandwidth (>10 THz), high efficiency (>98% over the bandwidth) diffraction gratings that have low groove density, and that are capable of operation at high average powers, spanning a broad range of wavelengths with high damage thresholds. Development is also needed of high-bandwidth, high-efficiency, high-damage- threshold diffractive optical elements for beam combining and for other applications that must handle high average power. Modeling and simulation tools that enable this effort must be further developed and benchmarked.

5.3.2 Damage threshold of optical materials and coatings

Significant R&D is needed to identify optimum materials and coating architectures that will meet the demands of lasers for accelerators. The research effort would need to address new materials and new coating architectures that are presently outside standard processes available in industry. It would be important to associate any coating development with a robust, reliable and independent U.S. based damage testing facility.

Development of low-loss, low-scatter ion-beam-sputtered coatings, in collaborative efforts among the labs, industry and academia, could have a relatively fast (2–3 year) payoff that could spin out to the broader commercial marketplace, facilitating a positive US economic impact.

5.4 Systems engineering, design tools and testing/training facilities

To enable laser and system component testing (including damage threshold of optics) establishment of 2–3 laser test beds would be needed. A key goal of these test facilities will be to explore various laser architectures and the impact of materials and component developments on overall laser system performance.

It is critical that these facilities be established in collaborative environments with open access for the high average power laser community. It will also be important to have at least one such facility located at or near an accelerator facility so that key specifications of prototype laser systems can be tested both in actual practice and in a radiation environment similar to what might be experienced in actual use.

5.5 Assessment of investment needs, performance and cost benefits

Below we provide a list of possible investment areas and provide an assessment of the performance benefits and impact of an investment. The goal of the investments is to develop laser systems that will enable the laser driven science discussed in Section 2 and to drive new technological developments in the US photonics industry.

We first present possible near term investments (1–3 years), followed by investments over medium (3–5 years) and longer term (5–10 years), and end with potential SBIR compatible investments.

5.5.1 Near term (1-3 years) investments

- *Highest impact*
    - Theoretical study and survey of existing materials for short pulse lasers. Needed to clearly define next R&D steps in materials; a 1–2 FTE scale effort.
    - Low loss, low scatter and ultra-high damage threshold broad bandwidth coatings. This would require a partnership between industry and National Labs and/or Universities (see also SBIR relevance in Section 5.5.4). The impact is very significant and broad. The initial funding level needed would be of the order of a few M$/yr.
    - Establishing the experimental basis of coherently combined FCPA array technology through theoretical, numerical and experimental studies; a 3–5 FTE scale effort, plus equipment costs.
        - System level design and analysis:
            - Experiments with 1–10 channel FCPA arrays (at relatively low power and energy).
            - Exploration of different phasing techniques and strategies.
            - New concepts of novel combining approaches to reduce array size for >1 J pulse generation.
            - New concepts of generating very short (<100 fs) pulses with FCPA arrays.
            - Design study of large arrays.
            - Exploration of the feasibility of hybrid systems.
        - Exploration of key technological elements:
            - Design study of fiber technology for monolithic integration and low cost per channel or per individual FCPA module.

      - Design study of beam combining elements (diffractive optics, spectral combining, tiling, etc.) for combining large numbers of ultrashort-pulse beams at ultra-high power and pulse energy.
      - Design study of novel fiber materials, particularly for 2–3μm wavelength operation.
    - Understanding of basic physical processes and limitations:
      - Exploration of pulse contrast from a single FCPA.
      - Pulse contrast control with coherently-combined FCPA arrays.
- *High impact*
  - Thermal management studies for optical elements and non-linear materials, a few FTE scale effort.
  - Lasers for more efficient high harmonic generation. Improvements in the efficiency, control of bandwidth and control of pulsewidth, specifically longer (50 fs) transform-limited pulses would be the primary goals. The approaches include phase and amplitude control of the drive laser, multi-color and other QPM techniques, a 3–5 FTE scale effort, plus equipment costs.
  - Establishment of U.S. damage test facility capabilities. Whereas long pulse lasers (nanosecond timescale or longer) are readily available to industry at present, several national labs and universities have at present the capability of providing laser beams with unique and relevant peak power, fluence and pulse durations (sub 100 fs) for damage testing of ultrafast laser components. Industry would greatly benefit from having access to such facilities. To provide this access, funding would be needed at the level of 1–2 FTE level (technical/laser engineering support). Testing at high average power may require the use of defense related facilities, which would need to be explored.
- Medium impact:
  - Deployment of solid state seed sources for gas lasers. Wider use of CO_2 systems will be enabled by development of 10 μm, 10 mJ-level picosecond OPCPA sources for direct high energy amplifier injection. The main goal would be to provide dramatically more compact and robust sources built on solid state lasers, rather than the complex seed pulse generation currently in research use, a 2–3 FTE effort, plus equipment costs.
  - Education and training:
    - Development of undergraduate courses and graduate courses. This could include lab courses. These courses could also be offered at the USPAS. Estimated cost $1M per year.

5.5.2 Medium term (3–5 years) investments

- *Highest Impact:*
  - Development of new laser gain materials, ceramics and novel optical fiber materials, a 1–2 FTE scale effort, structured to work closely with industry. Significant investments into ceramics are being made in Asia, led by China. U.S. facilities exist, but are not in use as they are not commercially viable due to small volume of sales and not currently funded by other agencies.

  - Development of efficient, high damage threshold, low groove density gratings, a 2–5 FTE scale effort, again structured to work closely with industry.
  - Completion of the fiber laser design studies; building and exploring scalable system demonstrators; application work using these demonstrators, a 3–5 FTE scale effort, plus equipment costs to support building laser systems (1–5M$ per system).
    - Fiber beam combination demo with 10–100 unit cells (assuming that prior work in 5–10 unit cells and unit cell contrast was successful). The main parameters of such a system would be:
      - 1–10 kW power range.
      - 20–100 mJ energy range.
      - < 100 fs pulse durations.
      - > 10^4–10^5 contrast range.
  - Development of multi-kW pump lasers such as needed for the nominal 3 kW laser for LPA and high harmonic generation applications. Such lasers would enable many applications and might be achievable in a 3–5 year timeframe at the prototype level with a sustained $2–3M/year investment.
  - Undergraduate internships and graduate-level research assistantships at the universities. Estimated funding needs are $1–5M per year.
- *High Impact:*
  - Development of long wavelength laser systems, a 2–3 FTE scale effort.
  - Development of robust, turn-key, large aperture, high-repetition-rate gas-based laser amplifiers.
  - Establishment and/or use of high average and high peak power laser test beds with parameters determined in the design studies. Funding levels would have to be determined.

5.5.3 Longer term (5 - 10 years) investments

The main objective would be to pursue power and energy scaling based on prototype system demonstrator results from the intermediate term studies. These investments will require significant funding levels and their initiation will depend on the success of prior investments into novel materials.

- *Highest impact:*
  - 1–10 kW demonstrator laser with >20% wall plug efficiency
  - Development of high average power pump laser for OPCPA
- *Medium Impact:*
  - Development of Hybrid Fiber-Bulk optic laser systems
  - Funding of high risk gas laser concepts and advanced methods, such as self-phase modulation in partially ionized gasses followed by recompression, Rabi flopping, chirped pulse amplification with spectral shaping, small scale molecular dynamics studies, optical pumping, and novel gas mixtures. Some of these studies could be conducted at existing or new test facilities, others could occur in smaller university labs. Most of these research studies could, in principle, be undertaken

    by small firms in the commercial sector. However, they may be more suited for government-funded laboratories as these types of fundamental studies present less opportunity for immediate benefit, and as higher risk activities, also have much lower cost effectiveness than more straightforward engineering activities. Scale of effort: 2–3 FTE, plus equipment cost.
  - Development of 100 J/300 fs gas laser at high repetition rate for medical applications.
  - Education and training:
    - Outreach to K-12 and universities. Specific recruitment into the established Laser for Accelerators graduate programs. Internships, assistantships, and outreach, aligned with the DEPS (www.deps.org) outreach programs. $1–2M per year.

5.5.4 SBIR Compatible Objectives

- *Highest impact:*
  - Low loss, low scatter and ultra-high damage threshold broad bandwidth coatings. This would require a partnership between industry and National Labs and/or Universities. The impact is very significant and broad and should be a very high priority. The funding needed would be of the order of a few M$/yr.
  - Thermal management of diode laser packaging for improved reliability; pursuit of improved diode laser efficiencies, particularly at longer wavelengths. These have across-the-board impact.
  - Development of ceramic-based optical materials. This would have very significant impact across the photonics industry and would probably require significant investments on the order of tens of millions over a decade.
  - Modeling and simulation tools/products for developing more efficient and higher damage threshold diffractive optics
  - Development of nonlinear materials.
- *High Impact:*
  - Cost reduction of components for high power short pulse fiber lasers. This would have very high economic impact.
- *Medium Impact:*
  - Development of periodically poled materials with >500 µm thickness.
  - Development of reliable and stable carrier envelope phase (CEP) stabilized lasers.

6 Comparison of global and U.S. laser R&D efforts

Charge 5

Assess how the proposed U.S. R&D activities compare with global laser R&D efforts.

6.1 Non-U.S. Laser R&D Efforts

Over the past decade, the global R&D efforts on high peak power laser systems as well as on non-defense related high average power lasers (e.g., machining and welding), have far outpaced the US activities.

High intensity laser research is vigorously pursued in Europe with the development of the multinational project known as the Extreme Light Infrastructure (ELI). [11] ELI intends to create 4 new laboratories focused on development of high intensity laser sources and, in Eastern Europe three major projects (each around 250 M€) are currently under construction as part of the Extreme Light Infrastructure (ELI).

ELI Attosecond Light Pulse Source (ELI-ALPS) in Hungary will focus on generation of ultra-short pulses (atto-seconds) to explore dynamic interactions in chemistry, materials science and biology. ELI Nuclear Physics (ELI-NP) in Romania will focus on generation of ultra-bright gamma-ray sources to explore the interaction of electromagnetic radiation with atomic nuclei. ELI Beamlines (ELI-BL) in the Czech Republic (Praha) will focus on high harmonic generation with high repetition rate 1–10 TW laser systems, generation of high quality electron beams for driving free electron lasers and high energy x-ray and gamma ray sources with 1–10 Hz petawatt (PW) class lasers, generation of ion beams for medical applications with multi-PW laser beams and will enable the exploration of new phenomena such as understanding the structure of vacuum using intensities as high as 10^{23} W/cm^2. Discussions are under way for a fourth ELI facility that will seek to attain >100 PW peak power in order to explore new physical phenomena.

At present there are no comparable facilities planned in the U.S. The expected number of highly skilled scientists that will be needed to staff these facilities is around 500 and world wide recruitment for these flagship European projects is underway.

In addition, there are various national efforts in France, Germany and the UK that are each funded at the 20–50M€ level. There is a well-established structure (Laserlab Europe) amongst the many European laser facilities to coordinate activities and user accessibility. High bandwidth, high efficiency gratings are under development in Jena, Germany. These devices will enable high energy, short pulse laser systems.

There is also a large effort in Europe known as ICAN (International Coherent Amplification Network) in beam combination of short pulse fiber lasers. ICAN is led by four European Union principal partners: Ecole Polytechnique in Paris, Optics Research Center in Southampton, Friedrich Shiller University and Fraunhofer Institute in Jena, and CERN, with several worldwide associated participants: University of Oxford, UK; University of Michigan, USA; Thales R&T, France; ONERA, France; KEK, Japan; MPQ, Germany; Fermilab, USA; DESY, Germany. This is an 18-month (2012 Jan – 2013 June) exploratory/preparation project funded by EU FP7 for workshops and conferences, with an objective to achieve community consensus on the current status of fiber technology, the main technological challenges and roadblocks, and on possible paths forward. The result of this project will be a detailed technical report and a EU FP8 funding proposal to build a demonstration system or systems (current acronym for that is HAPPI – High Average Power Pulsed Infrastructure) with > 10 J, >1 kHz and >20% wall-plug efficiency. This project is aiming to attract $50M in investment in the next few years. If funded and if successful, ICAN could significantly advance beam combined fiber laser technology. A U.S. funded program in fiber combining for ultra-fast lasers would allow the U.S. to remain globally competitive in this market segment that has very significant potential impact.

Significant investments are being made in Europe in the development of laser technology and laser based ion acceleration for medical applications (e.g., the >20 M€ Saphir project in France, the >50M€ CALA project in Munich, and the >50M€ Dresden-Rossendorf projects). The laser peak power requirement for production of clinically relevant energies of carbon or oxygen ions is approximately an order of magnitude greater than for protons.

Asia, particularly China, is investing heavily in the development of new materials particularly ceramic optical materials and optical gain materials. As advanced materials are key to enabling any new technology, it is critical that the U.S. keep pace in this area. Optical coatings and high damage threshold optics are also under intense development in Asia. In Korea, significant efforts have been made at APRI with the construction and operation of a PW-class system. Since 2000, Gwangju city has become Korea's premier photonics cluster, following the establishment of a phonics-related university, as well as research institutes and industrial facilities focusing on semiconductor light sources and optical communications parts and components (LEDs, etc.). There are more than 300 firms employing more than 50,000 people and they produced 944 billion Won in sales in 2007. Continued growth is expected. U.S. investment in an alternative approach such as ceramics could enable an important global counter-point and potentially yield leadership in the high energy, high average power short pulse laser field via breakthroughs in materials science.

6.2 Domestic Laser R&D

U.S. CO_2 laser facilities are dominant relative to foreign efforts. Although some limited laser expertise still exists from Soviet-era facilities in Russia, little research is taking place, and very limited manufacturing capability currently exists. Essentially no accelerator applications are being pursued. The CO_2 laser manufacturer that produces systems closest to those required for the identified accelerator applications is a subsidiary of a U.S. company located in South Africa. There are mechanisms for partnerships between universities and the commercial sector in South

Africa that are mostly funded by the national government. The National Laser Center is one such entity, tasked with taking discoveries and expertise in the research sector and making them accessible to private companies for product development in order to improve their global competitiveness. In addition to exchange of information through direct contact with university scientists, laser equipment is available for use in developing materials processing products. Such technology transfer is aimed at socio-economic growth.

The U.S. also funds development in the areas of high-energy lasers and particle beams of through several DOD Services and Agencies. Many DOD services and agencies work together, particularly with industry, on the realization of high-risk, high-payoff research and development. At the workshop, representatives from DOD funded companies and organizations were present. A brief overview of unclassified research supported by Navy was presented. Impressive results have been obtained and there is a shared interest in continued development of laser technology. No further discussion of these areas is included in this workshop report, however, due to the sensitive nature of some of the topics.

While there is some overlap in the underpinning technology, there is little overlap in the development of ultrafast lasers with performance dictated by the needs for accelerator science. Coordination with other services and agencies, such as the tri-service High-Energy Laser Joint Technology Office (HEL-JTO), DARPA, Office of Naval Research, and NAVSEA, could be beneficial, as would working with NNSA. It may be worthwhile to explore the potential establishment of joint BAAs (or other funding streams) with S&A for academic, federal participants (including DOE labs), and industrial calls. It might also be worth exploring the possibility that shared test beds, materials laboratories and joint calls may be available within the DOD investment portfolio. Joint BAAs have been made in the past between ONR and AFOSR, and may provide an efficient mechanism for jointly pursuing shared objectives.

Representatives from the U.S. commercial laser industry attended the workshop and were invited to comment on potential synergies between government and industry funded R&D. Industrial companies can be divided into small and large businesses. Small businesses have enabled commercial development of custom ultrafast laser systems and have been critical to enabling individual PIs in basic energy sciences and other fields to pursue developments in chemistry, biology and medicine without having to incur the expense of running their own laser development programs. Small businesses have also contributed to the furthering of laser technology via participation in SBIR programs. However, in general small businesses lack the extensive research staff and resources to make major breakthroughs in laser technology.

Large businesses have larger staffs and research budgets but are focused almost exclusively on high-volume product lines and quarterly earnings, an emphasis that is typically not consistent with longer-term technology goals as discussed in this report and at the associated workshop. Some of the larger laser manufacturers stated that they are interested in supplying system components (diodes, non-linear and gain materials, coatings, etc.) that can be considered commodities, and welcome investments in the technological development of these critical subsystems. As opposed to national laboratories and universities, however, as well as some overseas companies, they are currently not interested in entering the special (custom) laser business due to the complexity and demands of such systems and the challenges in providing for service, documentation and support, growing this market, and maintaining specialized staff.

The proposed areas for DOE investments would enable the US to regain international leadership in ultrafast, high peak- and average-power laser development, and photonics in general. The leverage effect of investments in photonics technologies was studied in Germany and the findings are detailed in references [12,13]. Given the size of investments that are being made overseas (ranging into the several hundreds of million dollars annually in Europe alone), significant funding levels will be crucial for the U.S. to re-establish its dominance in the high power laser technology and photonics area. The proposed areas of investment are focused on the development of critical competences and systems that will be essential for the continued success of lasers for accelerators and strategic for the growth of industrial capabilities with strong economic benefits.

7 Summary

The U.S. Department of Energy's Office of High Energy Physics sponsored the Workshop on Laser Technology for Accelerators to identify R&D that can bridge the gaps between current laser system capabilities and future requirements. The goal was to develop an understanding of future laser developments that could be carried out under DOE's accelerator R&D stewardship effort and would contribute to the advancement of accelerator and laser enabled science. All future science applications will benefit from ultrafast lasers that can operate at very high average power levels, compared to today's standards. Novel collider designs based on laser driven structures require it for high luminosity; light sources require it to enable users to benefit from high average brightness machines for many experiments such as imaging and spectroscopy; medical applications require it to minimize the time it will take for a patient to receive a cancer treatment.

Whereas much research is going on into high average power lasers for industrial or military applications, the unique requirements imposed by the science drivers on the required lasers necessitate the development of a stewardship program to target the areas of R&D towards ultrafast lasers. A substantial amount of R&D on a number of fronts will be required over several years for the U.S. to contribute in a meaningful way to efforts already under way in other countries.

The areas of investment include materials science and laser engineering (e.g., better optical and laser materials and novel laser designs that will give ultrafast lasers high average and peak power capability at high wall plug efficiency) and the development of test-bed facility and education programs. The investments will need to be coordinated with other funding agencies—including not only DOE efforts but those of DOD—to maximize overall cost-effectiveness.

A directed R&D effort in ultrafast laser technology will expand the reach of discovery science and enhance U.S. competitiveness in this vital technology arena.

References

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[4] Reports from the 2009 Basic Energy Sciences Workshop on Accelerator Physics for Future Light Sources are published in *NIM*, **637**(1), (2010).

[5] Report of the Basic Energy Sciences Workshop on Compact Light Sources, May 11-12. 2010, http://science.energy.gov/~/media/bes/pdf/reports/files/CLS.pdf .

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[13] The Leverage Effect of Photonics Technologies: the European Perspective http://www.photonikforschung.de/service/publikationen/the-leverage-effect-of-photonics-technologies-the-european-perspective/ and http://www.photonikforschung.de/fileadmin/MEDIENDATENBANK/SERVICE/Publikationen/Photonics21_Leverage-Studie.pdf

Appendices

A.1. List of participants

Table A.1-1. Invited Participants

Name	Affiliation
Enrico Allaria	Elettra – Sincrotrone Trieste
Marcus Babzien[†]	Brookhaven National Laboratory
Thomas Baer	Stanford University
John Ballato	Clemson University
Sandra Biedron[†]	Colorado State University
Jerry Britten	Livermore Lawrence National Laboratory
Jeff Bude	Livermore Lawrence National Laboratory
Robert Byer	Stanford University
John Collier	Rutherford Appleton Laboratory
Jay Dawson[†]	Livermore Lawrence National Laboratory
Mike Downer	University of Texas
Eric Esarey	Lawrence Berkeley National Laboratory
Roger Falcone	Lawrence Berkeley National Laboratory
Almantas Galvanauskas[†]	University of Michigan
Igor Jovanovic	Pennsylvania State University
Wim Leemans*	Lawrence Berkeley National Laboratory
George Neil	Jefferson Lab
Mikhail Polyanskiy	Brookhaven National Laboratory
Jonathan Price	University of Southampton
Darren Rand	Massachusetts Institute of Technology, Lincoln Laboratories
Jorge Rocca	Colorado State University
Wolfgang Sandner	ELI Germany
Sergei Tochitsky	University of California, Los Angeles
Ken-ichi Ueda	Institute for Laser Science Japan
William White[†]	SLAC National Accelerator Lab.
Russell Wilcox	Lawrence Berkeley National Laboratory
Jon Zuegel	University of Rochester

[†] Organizing committee member

*Chairperson

Table A.1-2. Other Participants

Name	Affiliation
Allan Ashmead[‡]	Coherent Inc.
Sterling Backus[‡]	KM Labs
Eric Colby	U.S. Department of Energy
Mark Curtin[‡]	Boeing
Lew DeSandre[‡]	Naval Postgraduate School
Neil Du Preez[‡]	SDI Lasers
Turan Erdogan[‡]	IDEX Optics & Photonics
Saul Gonzales	National Science Foundation
James Kafka[‡]	Newport Corporation
Manoj Kanskar[‡]	nLight
L. K. Len	U.S. Department of Energy
Eliane Lessner	U.S. Department of Energy
Martin Muendel[‡]	JDSU
Kenneth Olsen[‡]	Superconducting Particle Accelerator Forum of America (SPAFOA)
Ronald O'Rourke	Congressional Research Service of the Library of Congress
Steven Palese[‡]	Northrop Grumman Space
Steve Patterson[‡]	DILAS
Quentin Saulter	Office of Naval Research (attended by phone)
James Siegrist	U.S. Department of Energy
Prabhu Thiagarajan[‡]	Lasertel
Michael Zisman	U.S. Department of Energy

[‡] Observer

A.2. Workshop charge

DOE Workshop on Laser Technology for Accelerators
January 23–25, 2013
Napa, California

Background
Lasers play an increasingly important role in accelerator performance and are expected to provide the foundation for new techniques to make future facilities even more flexible and powerful. For example, they are currently used to produce polarized beam in an ion source, strip excess electrons from intense beams of H– ions, bunch beams to permit time slicing in light sources, perform pump-probe experiments that explore molecular dynamics at unprecedentedly short time scales, determine beam bunch parameters non-destructively, and create intense wake-fields in a plasma that can accelerate a witness beam with extraordinarily high gradients. While lasers are already essential for high-performance accelerators that support fundamental science and its applications, they are even more the key to the development of future accelerators, including compact systems for medicine, industrial applications, homeland security, and discovery science. Attributes in common to all future applications include the need for one or more of the following features: high peak power (i.e., high energy in a very short pulse); high average power (i.e., high repetition rate); and high electrical efficiency (i.e., cost-effective use of wall-plug power).

To prepare for these future laser needs, the Office of High Energy Physics of the Department of Energy's Office of Science is hosting a Community Input Workshop to gather information on possible objectives and opportunities associated with a program being considered to develop innovative accelerator-related laser technology. This workshop will identify technical challenges and opportunities specific to accelerator-based applications of laser technology and indicate R&D activities needed to achieve the desired laser performance specifications.

Attendance at the workshop will be by invitation.

Workshop Charge
This workshop is asked to:

- Identify a set of key accelerator-related applications for laser technology and the scientific opportunities they create
- Assess the laser specifications needed to enable each of these key applications
- Identify technical gaps between present laser capabilities (current state-of-the-art) and the performance required for these key laser-technology applications
- Specify R&D activities needed to bridge these gaps; include an assessment of which R&D investments are expected to have the highest near-term performance benefits and be most cost effective
- Assess how the proposed U.S. R&D activities compare with global laser R&D efforts

The workshop outcome will consist of a concise report describing what laser technology developments are needed to support future accelerator applications and accelerator-adjacent applications, along with a rough timeline indicating when R&D outcomes are needed to support the U.S. accelerator program.

A.3. Glossary of abbreviations

AFOSR – US Air Force Office of Scientific Research

BAA – Broad Area Announcement

BES – Basic Energy Science

BNL – Brookhaven National Laboratory

CPA – Chirped Pulse Amplification

DARPA – US Department of Defense Advanced Research Projects Agency

DLA – Dielectric laser acceleration – employs a laser beam to accelerate electron beams in a manner analogues to current RF acceleration but powered by lasers

DOD – US Department of Defense

DOE –US Department of Energy

DPA – Downchirped Pulse Amplification

DTRA - Defense Threat Reduction Agency

EEHG – Echo-Enabled Harmonic Generation FEL

ELI – EU Extreme Light Infrastructure Program

ELI-ALPS – ELI Attosecond Pulse Light Source

ELI-BL – ELI Beamlines

ELI-NP – ELI Nuclear Physics

E-O – Electrical-to-Optical conversion

ESASE- Enhanced Self-Amplified Spontaneous Emission FEL

FEL – free electron laser – a laser that uses a relativistic electron beam as gain medium to produce coherent radiation

FES – US Department of Energy Fusion Energy Sciences Program

FWHM – full width half maximum

HED – High Energy Density

HEL-JTO - Office of Secretary of Defense’s High-Energy Laser Joint Technology Office

HEP – High Energy Physics

HHG – high harmonic generation – a process for the generation of high harmonics of laser radiation through non-linear interaction with gases or solids

ICAN – EU International Coherent Amplification Network

ICFA – International Committee for Future Accelerators

ICUIL – International Committee for Ultra Intense Lasers

LPA – Laser Plasma Acceleration

MOPA – Master Oscillator/Power Amplifier laser architecture

NAS – US National Academy of Sciences

NAVSEA – US Naval Sea Systems Command

NRC – US National Research Council

ONR – US Department of Defense Office of Naval Research

OPCPA – optical parametric chirped pulse amplification – relies on the amplification of chirped pulses in non-linear crystals by co-propagating it with a pump laser of shorter wavelength

RF – Radiofrequency

RPA – Radiation Pressure Acceleration

SBIR – US Small Business Innovation Research program

SC – US Department of Energy Office of Science

SLAC – Stanford Linear Accelerator Center

UCLA – University of California at Los Angeles

VUV – Vacuum Ultra Violet – electromagnetic radiation with wavelengths in the range of 100-200 nm

XFEL – X-Ray Free Electron Laser

XUV – Extreme Ultraviolet – electromagnetic radiation with wavelengths in the range of 10-100 nm