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BASIC RESEARCH NEEDS WORKSHOP ON LASER TECHNOLOGY

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ON THE COVER: A pulse shaper manipulates pulses from a spectrally broadened ytterbium fiber laser to produce 6 femtosecond laser pulses. Pulses this short are just a few optical cycles in duration and encompass more than 35% spectral bandwidth, posing unique challenges to system design, optics, and materials alike. *Credit: Brian M. Kaufman, Stony Brook University.*

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Basic Research Needs Workshop on

Laser Technology

Report of the Department of Energy Office of Science Workshop

August 15-17, 2023

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Executive Summary

Laser technology research, by generating and controlling coherent light in ever more precise and powerful ways, has increased the intensity of focused light by more than ten orders of magnitude over the last seven decades. While new science regimes where matter becomes relativistic in the laser field have been enabled by these intensities, ultrafast events are unveiled by pulses reaching the attosecond range and spanning a broad range in frequency. These and other properties open new fields of science and support societal applications from health to national security, making lasers one of humankind's most valuable tools.

From sensing fundamental atomic processes at the attosecond scale to creating and probing exotic states of matter to generation and manipulation of bright particle beams used across science, laser-driven science and technology have had a strong impact. At the same time, laser technologies that have enabled the last decades of progress are in many cases approaching their limits. New approaches are needed to expand frontiers in intensity, wavelength regimes, and high average power. In many cases, these require novel laser architectures, components, and techniques.

Unless major innovations in laser technology are made, advances in science and new applications similar to those experienced over the past decades will not be possible, with profound implications for United States (U.S.) scientific leadership and for future applications in national security, industry, and medicine. With recent Nobel Prizes recognizing the science driven by ultrafast pulses in 2023, by high-intensity lasers in 2018, and by precision interferometry in 2017—with a parallel increase in the use of lasers across science and society—this need has never been clearer. Currently, advances in lasers and the science and applications they support are limited by architectures that are often inefficient, prone to optical damage, and limited in wavelength and field control. Addressing the needs of the next decade requires new laser architectures, gain materials, components, and control techniques to enable higher powers and repetition rates, the combination of peak and average power for precision operation, and regimes from the THz to X-rays with waveform control.

Laser-driven science has broad impact across the missions of the Department of Energy (DOE), the National Science Foundation (NSF), the defense agencies, and across other national needs. DOE's Office of Science (SC) utilizes more than 2,500 high-power laser systems at its ten national laboratories in a wide range of applications from medicine to semiconductor lithography. Similarly, the U.S. academic community develops and takes advantage of a large variety of laser systems ranging from the ultrafast to the ultra-intense. Lasers drive and shape the particle beams that underlie large parts of DOE's and NSF's user facilities—and provide the probes that interact with them, driving a broad range of scientific research. They provide unique sensing of the fundamental states of atoms and molecules. Lasers create states of matter otherwise only found in the cosmos, providing a unique laboratory for testing fundamental physics and our understanding of astrophysics. They are unveiling a new generation of accelerators and light sources based on plasmas with the potential for broad impact, from fundamental particle physics to new light sources.

Realizing the potential of lasers to drive new science requires fundamental research in laser technology. Because current technologies are advanced but limited in reach, such development cannot be incremental but rather requires rethinking the approach to high performance and the development of new architectures and systems in a coordinated manner.

To explore these challenges, DOE SC, NSF, and the Department of Defense (DOD) convened a Basic Research Needs (BRN) Workshop for Laser Technology in August 2023 with broad U.S. government participation. The participants were charged: 1) with identifying priority research directions (PRDs) for basic research in laser science and technology that, if developed, could support high-impact solutions for scientific research and applications and 2) with addressing how to foster a healthy domestic laser technology development ecosystem. The workshop conducted a thorough assessment of lasers and the science they drive relevant to broad agency missions; however, the topics of direct relevance to megajoule inertial confinement fusion lasers and defense lasers were outside the scope of this workshop.

The workshop participants included 86 panelists, seven observers from laser-related industry, and 23 observers from the federal government. The panelists were balanced between scientific applications of lasers, laser scientists, and technologists. Science areas included ultrafast science, high-field science, and novel radiation and particle sources. Technology areas included high peak and average power sources, extensions to new wavelength regimes and new light sources, and enabling technologies. Crosscuts considered infrastructure, workforce, international, public-private, and supply chain aspects. Academic and laboratory researchers contributed 53% and 47% of the panelists, respectively. Eight percent of the panelists were from outside the U.S.

The workshop participants identified four priority research directions (PRDs) that motivate future research in lasers. These are not ranked, and PRD 4 is foundational to all. Each PRD is highlighted below along with a summary of the underlying, decade-scale challenges:

PRD 1: Revolutionize Laser Power, Energy, and Precision Control

Key Questions: How might ultra-intense laser performance be extended to create and probe extreme conditions that represent the frontiers of science needs in the next decade? What laser architectures enable high-repetition-rate operations? How could ultrahigh-peak-power lasers also be scaled to extreme repetition rates?

PRD 2: Transform Mid-IR Sources for Science from THz to X-Rays

Key Questions: Can we create the new laser technologies needed to meet the significant demands for high average and peak power mid-infrared (mid-IR) science, and for driving secondary sources with extreme spectral coverage? How do we overcome the current limitations in mid-IR laser intensity to take full advantage of wavelength-dependent scalings? What are the ideal wavelengths, platforms, and architectures for nonlinear conversion to generate transformative sources in hard-to-access spectral ranges?

PRD 3: Revolutionize Approaches to Frequency Conversion and Field Control

Key Questions: Can we advance laser light manipulation with bandwidth efficiently extended from the deep ultraviolet to THz ranges, employing all ranges simultaneously and with exquisite control of field structure? Can we synchronize these sources to secondary radiation and particle beams? Is it possible to simultaneously greatly reduce the complexity of laser systems, making them accessible, affordable, stable, and robust?

PRD 4: Reinvent Materials and Optics for Intense Laser Science

Key Questions: What are the most significant improvements to materials and optics needed for next-generation ultrahigh intensity and high-average-power laser technologies? What can be discovered to expand the spectral range of ultrafast lasers toward the mid-IR and ultraviolet? What new concepts can be exploited to innovate materials and optics for intense laser science?

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Acknowledgement of Reviewers

This Basic Research Needs Workshop report was reviewed in draft form by individuals with broad perspectives on the subject areas in this report. Their candid remarks were instrumental to improving the final report.

The Organizing Committee gratefully acknowledges the following individuals for reviewing portions of the draft report and providing constructive comments:

- John Ballato, Clemson University
- Philip Bucksbaum, Stanford University
- Stephen Leone, University of California, Berkeley

The reviewers were asked to provide comments and suggestions to improve the report but were not asked to endorse its content. Consequently, the appearance of their names here does not necessarily imply endorsement of the contents of this report.

Introduction

Breakthroughs in a wide range of scientific disciplines have been enabled by advances in laser technologies. These include the ability to record movies of chemical reactions and trace ultrafast charge and energy transfer in materials with ultrashort light pulses on the order of femtoseconds (1 femtosecond is a millionth of a billionth of a second). On even shorter timescales, tracing the dynamics of electrons was enabled with attosecond (1 attosecond is a billionth of a billionth of a second) light pulses, recognized with the 2023 Nobel Prize in Physics. The ability to create powerful ultrashort light flashes opened science fields from compact particle acceleration to exploring unique states of matter and phenomena. The experimental verification and study of gravitational waves by the Laser Interferometer Gravitational Observatory (LIGO) Scientific Collaboration through precision laser measurements was an example that literally shook the world.

The next generation of more powerful, efficient, and precise lasers is pivotal to the next frontiers in our understanding and manipulation of the natural world. Similarly, meeting important societal challenges from the development of sustainable energy sources, to advances in microelectronics and quantum information technologies, to the search for new drugs for more efficient treatment of diseases rely on laser technologies. This Basic Research Needs (BRN) Workshop aimed to address the basic research needs in laser technology for the next leap in these and other applications.

The consequences to the nation are enormous. Lasers play an increasingly important role in physical sciences research and are expected to provide the foundation for new techniques to make future scientific research facilities even more flexible and powerful. The Department of Energy's (DOE's) Office of Science (SC) utilizes more than 2,500 high-power laser systems at its ten national laboratories in a wide range of applications [1]. Similarly, the United States (U.S.) academic community develops and takes advantage of a large variety of laser systems ranging from the ultrafast to the ultra-intense. The quality and quantity of scientific data available from experiments that rely on lasers are often directly limited by the performance of the underlying laser systems used. Finally, as the state of the art is advanced, pursuit of the research outlined in the Priority Research Directions (PRDs) will most likely experience lower costs and greatly simplified use of systems operating at the existing state of the art. This will, in turn, encourage new applications in diverse fields, spur workforce development, and facilitate growth in the private sector. We have seen this before with the development of Ti:sapphire lasers and the techniques that utilize these sources. This theme is expanded in the PRDs.

The BRN Workshop's goals were motivated by science applications spanning a) ultrafast science, b) high-field science, and c) novel radiation and particle sources. Required research has been characterized in PRDs in 1) laser power, energy, and precision control, 2) mid-infrared (mid-IR) sources, 3) frequency conversion and field control, and 4) materials and optics. Additional considerations included the required workforce, supply chain, and international and domestic context as crosscuts.

Ultrafast science of molecules and materials can be dramatically enhanced by intense, ultrashort pulses in the mid-IR spectral range. First, infrared (IR) pulses can directly drive the molecular and collective modes that play key roles in chemistry and solid-state phenomena. Second, IR pulses are ideally suited for both up-conversion to far higher frequencies in the extreme ultraviolet (XUV) and X-ray ranges through high harmonic generation (HHG) and down-conversion to much lower frequencies in the THz range through difference-frequency mixing or optical rectification. Thus, the infrared is a gateway for tabletop access to ultrashort pulses that span an extraordinary range of the spectrum. This enables ultrafast spectroscopic access to, and in some cases coherent control over, correspondingly wide-ranging molecular and collective modes. Dramatic improvements in IR pulse generation—yielding pulses with higher intensities, broader spectral bandwidths, greater tunability, and finer control over temporal and spectral profiles than currently available—will yield revolutionary advances in spectroscopy and control of gas-phase chemical dynamics, energy flow in aqueous molecular and biomolecular systems, solid-state phase transitions, and a great deal more.

Advanced measurement methods such as two-dimensional (2D) IR vibrational spectroscopy can reveal how energy flows within and between molecules, providing insights into hydrogen bonding, protein unfolding and folding dynamics, ion transport in electrolyte solutions, and molecular dynamics at interfaces including those relevant to chemical catalysis. These studies, as well as spectroscopy using IR frequency combs, will be advanced enormously by near-single-cycle mid-IR pulses with bandwidths that span the molecular vibrational "fingerprint" region. Complementary XUV and soft X-ray measurements of gas-phase and condensed-phase molecular systems, extending to the attosecond time scales of initial electronic charge redistributions, can provide a detailed view of energy flow involving electronic and nuclear dynamics by mapping transient changes in oxidation state, spin state, and bonding configuration with element-specific resolution. Attosecond tracking of radiation-induced ionization and subsequent electron collisional ionization and excitation in condensed phases with atomic and elemental specificity has important ramifications in biology, health, and environmental science.

Extending tabletop studies to more complex systems and to all-X-ray attosecond-pump/attosecond-probe experiments will require expanded XUV and X-ray frequency ranges, photon flux, and intensity, all enabled by advances in IR pulse generation. Those advances are also crucial to drive large-amplitude responses of THz-frequency collective modes such as solid-state lattice vibrations (phonons) and spin waves (magnons) through nonresonant light-matter interactions such as impulsive or multicycle-stimulated Raman scattering or through down-conversion to THz fields that will drive the modes resonantly. IR/THz switching of ferroic domain orientations and coherent control over phase transitions involving classical ferroelectric and magnetic phases as well as quantum phases (e.g., multiferroics and topological states) offer tantalizing prospects for the discovery of currently "hidden" material states and applications in ultralow-power, ultrahigh-bandwidth signal processing based on magnonic signal carriers and/or topological material conductivity properties and nonlinearities.

High-field science enables us to generate the highest electric and magnetic fields in the known universe on the laboratory scale. At such intensities, all matter is pulled apart into electrons and ions making a plasma. These strong laser fields then accelerate matter to near the speed of light. These extreme physical conditions represent a frontier of science, with applications in medicine, national security, astrophysics, and high energy density science. Understanding matter at extreme conditions of temperature and pressures, such as is the case in stellar cores and planetary interiors, will enable a better understanding of how the planets and stars formed as well as insights into how fusion energy can become a viable power source on Earth.

High-intensity laser interactions with matter can be harnessed to enable compact particle accelerators for electrons, positrons, ions, or even neutron beams. In turn, laser-driven accelerators can then produce some of the brightest and shortest beams of X-rays and gamma rays possible in the laboratory. While our understanding of underlying physics mechanisms of particle acceleration and light generation continues to be refined, these secondary sources are now being used by the scientific community. Taking the repetition rate from one to thousands of times per second will help make such lasers more robust, precisely delivering the required parameters. Such advances would enable applications of non-destructive testing, material science, additive manufacturing, medical imaging, nuclear physics, cancer treatment, and future particle colliders.

The key to a high-intensity laser is how much power is provided in a focal spot. In the next decade, achieving peak intensities beyond 10^{24} W/cm^2 will unlock entirely new areas of research. For instance, above the "Schwinger limit," matter is expected to be created out of a vacuum by a strong electric field. This theoretical idea will be explored, as will vacuum birefringence, vacuum breakdown, radiation reaction, photon-photon scattering effects, and pair plasmas. Such transformative intensities can also stimulate high energy physics (HEP) studies, including the production of relativistic proton and muon sources, testing beyond the Standard Model, and probing the existence of dark matter, as well as the investigation of gamma-gamma collider studies. On the way to such extreme intensities lies an exquisite array of astrophysical studies poised to capture a broad scientific community. Such lasers will allow the scientific community to understand, for the first time in the laboratory, events at the origin of the most energetic particles in the universe, which include relativistic magnetic reconnection and shocks.

Novel radiation and particle sources are enabled by lasers as a primary tool, through photo-activated or -controlled physical and engineered systems, including electrons, positrons, ions, and neutrons as well as secondary photons across a vast range of energies, from THz to gamma rays. The proliferation of such photoinjector-based charged-particle instruments is motivated by their incredibly versatile and powerful applicability to a myriad of forefront scientific research areas and technologies in quantum electrodynamics, HEP, ultrafast science, and medical technologies. Even though their operational requirements can differ vastly depending on their end use application (e.g., charge, phase space, energy, and spin), increased control and performance remain central challenges as these technologies are brought to new scientific and engineering frontiers.

The next generation of lasers producing (charged) particle beams and secondary radiation sources must be exceedingly precise and adaptable spatiotemporally and spectrally as well as exhibiting exquisite synchronicity and entanglement with other laser sources. With novel techniques of production and control, the longitudinal and transverse laser distributions may be used to produce unique characteristics in the particle beams, allowing new materials and states of matter to be explored. The multiplicity of all these unique features together will enable new and challenging experiments at the frontier of nonequilibrium quantum dynamics, nuclear physics, condensed matter physics, chemistry, and biology.

The laser technologies that support the scientific advances above over the next decade are described in four PRDs:

PRD 1: 'Revolutionize Laser Power, Energy, and Precision Control,' describes both ultrahigh intensity, multi-PW and multi-Hz lasers that will enable access to new fundamental physics in the strong-field regime ($I > 10^{24}$ W/cm^2) as well as lasers operating at a peak power >100 TW and kHz- to MHz-repetition rates that are drivers for laser plasma acceleration and intense photon and particle sources. It is a formidable technological challenge to achieve orders of magnitude higher average powers than currently available from high-intensity lasers. As a result, new approaches and new architectures are needed using efficient gain media that can be directly diode-pumped and effectively cooled to enable scaling to much higher average powers and peak intensities. While different approaches are currently in their early stages of development, all need substantial further research and development (R&D) efforts to reach their full performance potential. Development of precision control technologies for these next-generation lasers will at the same time transform the accuracy with which the extreme laser-matter interactions can be controlled. It is also important to lower the threshold for accessing these next-generation laser systems for basic research by reducing laser system size and cost, ensuring its reliability and providing the simplicity of "turn-key" operation.

PRD 2: 'Transform Mid-IR Sources for Science from THz to X-Rays,' will enable nonlinear IR spectroscopic studies of molecular and biomolecular interactions and dynamics as well as studies of attosecond electron dynamics in complex systems. Significant laser technology advances are needed to elevate current mid-IR sources to the peak and average power levels that are accessible in the near-IR. These sources have highly complex architectures that are difficult to operate, accrue instability through multiple nonlinear frequency conversion stages, and have a large number of individual points of failure, affecting the output stability of secondary radiation sources operating from the THz to XUV spectral range. Reaching the technological goals for mid-IR lasers will therefore require a multi-pronged effort, aimed at simultaneously up-scaling the parameter space covered by and reducing the complexity of mid-IR sources generated through both parametric and conventional chirped-pulse amplification (CPA). Such an approach will enable novel science both by reaching previously unattainable laser specifications and by allowing advanced mid-IR technology to proliferate beyond a few specialized laboratories worldwide.

PRD 3: 'Revolutionize Approaches to Frequency Conversion and Field Control,' focuses on the major advances in frequency conversion and field control technology that must be achieved to transform the science of finely controlling and probing matter in real time, while simultaneously greatly reducing the complexity of the tools, making them accessible, affordable, stable, and robust. Technologies for extending the wavelength range of lasers and controlling the properties of laser light have advanced significantly over the past decade. However, the capacity and complexity of these extended laser systems have grown tremendously, making them extremely challenging and costly in their operation, thereby limiting their accessibility and thus transformative breakthroughs in science. The next decade of achievements must address the limitations in efficiency, bandwidth, and power of the current state of the art. They must also address the demands of science to simultaneously control many degrees of freedom of material evolution, thus requiring sources covering many frequency ranges (from X-rays to THz and optical sources including UV through mid-IR, with full wavelength coverage) while also allowing field control over many dimensions (including non-separable spatiotemporal structure, orbital angular momentum, full amplitude, and phase control) and close synchronization to secondary particle and radiation sources, while providing higher energy and average power. A truly transformative advance will not only provide new capability in ultrafast laser light control but also will do so while simultaneously simplifying the source architecture. Such advancements will build a strong market for state-of-the-art ultrafast laser technologies and allow strong growth of the workforce that uses them along with it. They will also build U.S. strengths in advanced laser extension technologies that will have applications in many fields of research and industries.

PRD 4: 'Reinvent Materials and Optics for Intense Laser Science,' is critical for making future laser systems for basic research and applications in various fields such as materials science, energy, medicine, and others. Transformative advances will require optical materials and components with performance characteristics that significantly exceed current generation technologies. Specific attention is required in overcoming the limitations to produce higher gain and peak intensities and the ability to transport and control the output pulses. To expand the operational profile of future lasers, novel gain material hosts with robust thermomechanical properties that enable higher power extraction, more efficient excitation, and thermal management at application-relevant beam apertures are needed. The increased laser output must be supported with the development of higher performance optical elements for beam control and transport. Advancing nonlinear crystalline materials is also of fundamental importance to support larger bandwidths and peak intensities and to expand operation across wide spectral regions. Higher damage threshold optical components are required to realize ultrahigh intensities. Other technologies such as diode and fiber lasers as pump sources for amplifiers and optical concepts to control the electric field in time and space also need to be simultaneously advanced. Such efforts could have a tremendous impact. This may necessitate not only significant improvements in current generation technologies but also the development of novel materials and solutions. Investment in infrastructure and workforce development will ensure that the U.S. will remain in the vanguard of these developments and benefit from their economic impact.

Laser systems that represent these challenges and opportunities fall into four broad laser types described below and in Table 1:

- Type I laser systems are high-repetition-rate systems that are used to perform high-resolution and high-fidelity measurements, particularly for applications to chemical sensing and spectroscopy, excitation and probing of small-cross-section and stochastic processes, ultrafast electron dynamics, electron beam-based cooling schemes, and high-current sources of polarized electrons and positrons.
- Type II laser systems are high-average- and high-peak-power lasers used to excite plasma waves for particle trapping and high-gradient acceleration, and for the generation of X-rays through HHG and/or laser wakefield acceleration.
- Type III laser systems are ultrafast laser systems used for generating high-repetition-rate radiation pulses through nonlinear processes, particularly HHG and THz generation.
- Type IV laser systems are high-intensity lasers used for plasma-based sources of protons, light ions, and neutrons. Long-pulse kilojoule lasers with shaped pulses serve both as pump lasers and as drivers for high energy density (HED) states of matter.

While these four laser types are pulsed laser sources, narrow-line continuous wave (CW) lasers (diode, fiber, solid-state, gas etc.) and other such devices are under development and are implicitly included for other applications (pump sources for these pulsed lasers, stable and radioisotope separation/isolation, spectroscopic tools, etc.)), as are ns-duration kilojoule laser drivers for HED science.

	Type I: High-repetition-rate laser	Type II: High-average-power laser	Type III: Few-cycle laser	Type IV: Ultrahigh intensity laser
Pulse peak power	> 1 kW	10 – 300 TW	1 – 10 TW	10 – 100 PW
Wavelength	0.8 – 10 µm	0.5 – 10 µm	2 – 5 µm	0.8 – 2 µm
Pulse Energy	NC	1 – 10 J	NC	1 – 10 kJ
Pulse Length	NC	30 – 100 fs*	few-cycle	30 – 300 fs
Repetition Rate	0.1 – 1 GHz	1 – > 10 kHz	> 100 kHz	0.1 – 10 Hz
Average Power	10 – 100 W	1 – > 100 kW	50 – 500 W	NC
Energy Stability	< 1%	< 1%	< 0.5%	1%
Beam Quality	Strehl > 0.95	Strehl > 0.95	Strehl > 0.95	Strehl > 0.9
Wall-plug Efficiency	NC	> 10%	NC	NC
Pre-pulse contrast	NC	> 10^5	NC	> 10^{12} @ 10^{21} intensity
Time window for pre-pulse	NC	ns-ps	NC	ns-ps
Phase stability, if CEP locked	< 100 mrad	Optional, < 300 mrad	< 100 mrad	NC
Pointing stability	NC	< 0.1 µrad	NC	NC
Bandwidth	NC	near FTL	NC	NC

* Pulse length applies to 1–2-micron wavelengths, with scaled durations for other wavelengths.

Table 1. Target performance for the laser types discussed in the priority research directions. Common requirements for the laser systems include high beam quality, which can be achieved with wavefront shaping and pointing stability. In addition to these types, kilojoule, long-pulse (ns) lasers with pulse shaping and precision control are critical for driving high energy density science. CEP: carrier-envelope phase; FTL: Fourier transform limited; NC: not critical; Strehl: Strehl ratio.

The future of laser science depends on having a workforce capable of supporting, maintaining, and developing laser technology in novel directions. The opportunities to be involved in laser science and applications are tremendous and appeal across wide ranges of ages, demographics, regions, and interests. Capitalizing on these opportunities to grow the field through precollege engagement, technician training, exposure in undergraduate schooling, industry careers, and early academic/graduate student training is necessary to ensure that there is an available and qualified workforce for laser science. Publicizing the breadth of opportunities in lasers and the viability of multiple types of careers related to laser technology is paramount for attracting promising individuals to the field. This report offers specific suggestions and exemplar programs for bringing newcomers into the laser technology workforce.

Supply chain strategies to address challenges and promote collaboration between the public and private sectors are essential strategies to enable the BRN goals. Major challenges include limited availability and performance issues of advanced laser system components, resulting in extended lead times, production delays, and quality control problems. Challenges also involve attracting suppliers for low-volume or high-risk commodities, scarcity of specialty item suppliers, and a shortage of skilled labor. Mitigations proposed include increasing the development of critical materials, expanding domestic manufacturing capabilities through programs like Small Business Innovation Research/Small Business Technology Transfer (SBIR/STTR), investing in diverse foreign supply chains, supporting a skilled U.S. workforce, and improving supply chain knowledge and decision-making through increased collaboration and engagement in laser conferences and workshops.

Laser science and technology and applications domestically and internationally present both cooperative and competitive R&D opportunities. Joining forces to leverage efforts and facilities nationally and from around the world can advance laser technology and science applications more efficiently. International exchanges can deliver products, capabilities, and talent not available domestically but also introduce risks, limitations, and greater competition. In making decisions about whether to compete or collaborate internationally, two fundamental principles can serve as guiding factors. Firstly, open and well-supported precompetitive research creates a conducive environment for healthy cooperation and competition, allowing for the shared advancement of laser technology. Secondly, the strategy of "moving first and fast" can provide a competitive edge, emphasizing the importance of seizing opportunities promptly.

Addressing these challenges motivated the BRN Workshop on Laser Technology, which was held in Rockville, MD, August 15-17, 2023. The DOE Office of Accelerator R&D and Production (ARDAP) served as the lead organization on behalf of Office of Science (SC) programs, and the workshop was co-sponsored by the National Science Foundation (NSF) Directorate for Mathematical and Physical Sciences and the Department of Defense (DOD) Office of Naval Research. Broad U.S. government participation was a feature of this BRN to ensure related R&D activities and synergies are understood. The goal was to identify priority R&D opportunities that, if developed, could enable high-impact solutions for scientific research and applications in addition to fostering a healthy U.S. laser technology development ecosystem.

References

[1] J. King, "Welcome/EFCOG LSTT – Who we are and what we do," presentation at Department of Energy Laser Safety Officer Workshop, Lawrence Berkely National Laboratory, Berkely, CA, USA, 2022. [Online]. Available: https://drive.google.com/file/d/1K65BL8ZOSt-Izmo7A9RksCpgHcjWDadN/view

Priority Research Directions

PRD 1 Revolutionize Laser Power, Energy, and Precision Control

Key Questions: How might ultra-intense laser performance be extended to create and probe extreme conditions that represent the frontiers of science needs in the next decade? What laser architectures enable high-repetition-rate operations? How could ultrahigh-peak-power lasers also be scaled to extreme repetition rates?

INTRODUCTION

High-intensity lasers can generate electromagnetic fields many orders of magnitude larger than any other device. These fields enable extreme physical conditions that represent the frontier of science in studying matter in the universe. Significant improvements in laser power, intensity, energy, and repetition rate beyond the current state of the art would lead to transformative advances in high-field science, material science, secondary particle and radiation sources, and ultrafast science and are now realistic due to emerging opportunities resulting from new laser architectures.

The capabilities of pulsed laser technology have increased significantly over the last ten years allowing the frontier of extreme laser-matter interactions to rapidly advance. Examples include the advent of multi-Hz PW and multi-PW lasers and facilities that are operating, just coming online, or in the planning and construction stages in Europe (Apollon, three Extreme Light Infrastructure/ELI facilities, and Vulcan 20-20), in Asia (Center for Relativistic Laser Science/CoReLs, Station of Extreme Light/SEL, and Shanghai Superintense Ultrafast Laser Facility/SULF), and in the U.S. (Advanced Laser for Extreme Photonics/ALEPH, Berkeley Lab Laser Accelerator/BELLA, Colorado State University Advanced Laser for Extreme Photonics/ALEPH, EP-OPAL/OMEGA Extended Performance-coupled Optical Parametric Amplifier Lines, kBELLA, Matter in Extreme Conditions-Upgrade/MEC-Upgrade, NeXUS, OMEGA Extended Performance/OMEGA EP, Texas Petawatt Laser Facility/Texas PW, Zettawatt-Equivalent Ultrashort-pulse laser System/ZEUS), as noted in the chapter on International and Domestic Strengths.

Advancing this scientific frontier further over the next five to ten years will require developing the Type IV laser systems detailed in Table 1 with capabilities far exceeding what is achievable today. Ultrahigh intensities on-target well above 10^{24} W/cm^2 will be critical for new fundamental physics in the strong-field regime of quantum electrodynamics (QED). In the midterm, kJ-class, multi-10-PW laser systems will enable laboratory exploration of extreme astrophysical phenomena, studies in HED science, and new regimes in particle acceleration and advanced light sources (PAALS). By the mid-2030s, it will be necessary to achieve 100-PW-scale peak powers for the full range of extreme physical conditions in these experiments.

Furthermore, high repetition rates in the kHz to MHz range at moderate energies from sub-J to 10s of J with 10s-of-femtoseconds pulse durations (100-TW-scale peak powers) with Type II lasers (Table 1) will revolutionize electron acceleration and light sources, facilitate high precision manipulation of high-energy proton beams from existing linacs, and enable profound transformation in accelerator use for practical applications and as tools for discovery science. This will require overcoming formidable challenges when reaching 10-100-kW average powers simultaneously with multi-J pulse energies from ultrashort-pulse lasers.

Apart from energy and average power scaling, next-generation laser systems must significantly improve the precision and control of their operating conditions, stability, and output beam and pulse characteristics. This will enable more precise control of extreme laser-matter interactions. For example, some experiments will require very high pre-pulse contrast, improving from 10^5 now to greater than 10^{12}, which proves very challenging for these extreme energies and powers. Many of the experiments will need multiple precisely synchronized laser beams, including different types of lasers, such as kJ-class lasers with nanosecond pulse durations operating at multiple Hz for pre-conditioning laser targets.

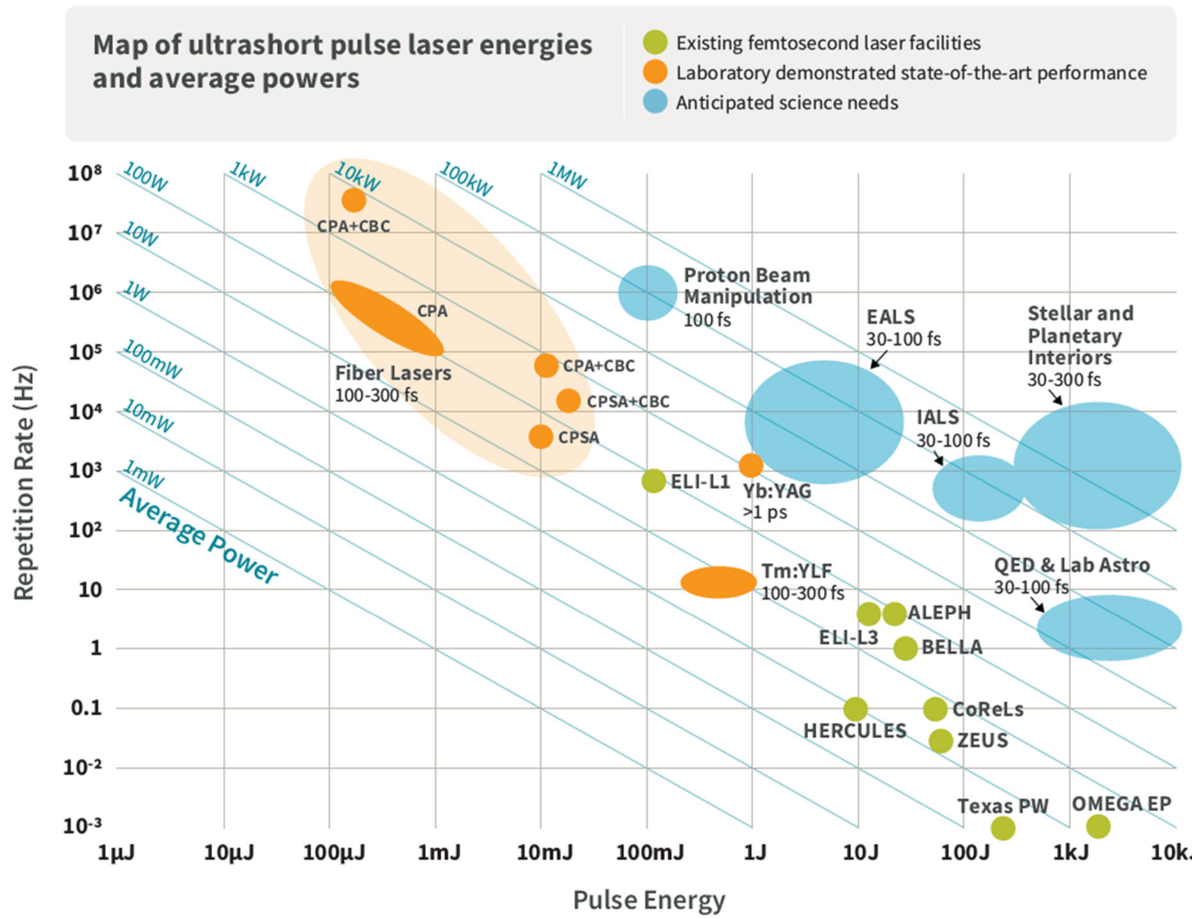

Figure 1. Map of ultrashort pulse laser energies and average powers. Existing laser facilities are marked in green. Advanced Laser for Extreme Photonics (ALEPH) Colorado State University, Berkeley Lab Laser Accelerator (BELLA), Extreme Light Infrastructure-L3 (ELI-L3); HERCULES laser, Texas Petawatt Laser (Texas PW), and Zettawatt-Equivalent Ultrashort-Pulse Laser System (ZEUS) are based on Ti:sapphire lasers and operate with 20–30-fs duration pulses. ELI-L1 operates with 100–150-fs pulses. OMEGA EP operates with sub-ps and ps pulses. Laboratory demonstrations of state-of-the-art performance of different laser technologies are marked in orange, and anticipated science needs are identified in blue, with achieved or anticipated pulse durations labeled for each. CBC: coherent beam combination; CPA: chirped-pulse amplification; CPSA: coherent pulse stacking amplification; EALS: electron acceleration laser system; IALS: ion acceleration laser system; QED: quantum electrodynamics.

SCIENTIFIC CHALLENGES

Over the last three decades, chirped-pulse amplification (CPA) in Ti:sapphire gain medium has been the main driver of rapid scientific advances in ultrafast science. This laser technology primarily enabled ultrashort pulses with TW- to PW-scale peak powers leading to the emergence of high-field science and the development of laser plasma acceleration and secondary sources of radiation and high-energy particles; however, this "workhorse" laser platform has a limited capacity to supply the extreme high-energy and average power performance required by science in the next decade. As discussed in PRD 4, this comes from the limitations associated with pumping efficiency (large quantum defect), energy storage and extraction, and thermal management at high average powers in this gain medium. Overcoming these limitations requires searching for new laser technologies.

New approaches are emerging that provide opportunities to overcome prior limitations and to substantially increase laser energies and average powers by using directly diode-pumped gain media (e.g., Yb:YAG / Yb: yttrium aluminum garnet, $Y_3Al_5O_{12}$; Tm:YLF / Tm:yttrium lithium fluoride, $YLiF_4$,; Yb- or Tm-doped fibers), new techniques (e.g., optical parametric chirped-pulse amplification/OPCPA), and new laser architectures (e.g., coherent combining). While notable variation in maturity among approaches exists, the majority are in the early stages of development, and all need substantial further research efforts to reach their full performance potential. This research should demonstrate pulse energy and average power scaling to the levels required by science needs while addressing many technological challenges and trade-offs associated with laser pumping and thermal management at extreme energies and powers, achieving high efficiency, sufficiently broad gain bandwidth, or use of other techniques for producing required ultrashort-pulse durations and reaching sufficiently high pre-pulse contrast. Furthermore, many applications require the development of new laser control techniques that enable spatial and temporal shaping of the laser output, and to achieve high levels of peak power, average power, and timing/synchronization stability. It is also important to develop such laser architectures that not only produce required extreme energies and powers but also lower the threshold for accessing these laser systems for basic research by reducing laser system size and cost, ensuring its reliability and providing simple “turn-key” operation.

There is a common underlying need to develop optics for all laser approaches (e.g., mirror coatings, laser gain media coatings, diffraction gratings for pulse compression, beam control components, laser plasma mirrors) that are capable of sustaining extreme energies and powers at the system output, as addressed in PRD 4.

RESEARCH THRUSTS

Thrust 1. 100-TW and beyond high-repetition-rate lasers

High-energy and average power lasers capable of producing ~0.1-J to >10-J pulse energies with average powers ranging from 10s to 100s of kWs and up to ~1 MW (i.e., 1 kHz–1 MHz repetition rates) and with pulse durations from 25 fs to a few ps are needed as next-generation drivers of laser wakefield accelerators and secondary radiation sources of high-field THz sources, and for pumping optical parametric amplification (OPA)-based mid-IR sources covered by PRD 2. Such pulse energies and peak powers are needed to efficiently drive these sources, while such high average powers enable high brightness of particle and radiation beams critical for the envisioned scientific studies and applications.

Specifically, laser plasma accelerators and many secondary radiation sources will need 1–10 J of energy and 25–100-fs duration pulses at multi-kHz repetition rates, with some radiation and particle sources accommodating longer pulse durations. THz generation via optical rectification (OR) will need lower energies of ~0.1 J with pulse durations <100 fs, but higher repetition rates of up to 1 MHz. Pumping OPA-based mid-IR sources addressed in PRD 2 will also need similar energies of >0.1 J, and similarly high repetition rates of up to MHz but will accommodate a variety of pulse durations within the fs to few-ps range. Many of these scientific applications are relatively insensitive to the laser operation wavelength, so many laser gain media are suitably efficient for the 1–2-µm wavelength range. Some of the envisioned applications for creating and studying extreme conditions in stellar and planetary interiors would benefit greatly from even higher pulse energies in the kJ range at multi-kHz pulse rates which, due to extreme technological challenges, fall outside of what is achievable within the next decade or so.

Producing laser pulses with 100-TW and higher peak powers at multi-kHz repetition rates is one of the most challenging tasks for ultrashort-pulse laser technology. The major difficulty is associated with the laser system thermal management under extreme thermal loading at multi-kW average powers, which is further complicated by the need to simultaneously achieve and sustain robust, stable laser operation with highly precise control of laser output characteristics. Thermal loading is directly affected by the efficiency of a laser gain medium, residual absorption in optical components and coatings, thermal conductivity of gain and optical materials in a laser system, and efficient heat removal from gain media and critical optical components. Excessive heat accumulation in a laser system is highly detrimental to the output beam and pulse quality, laser operation efficiency and stability, and can cause runaway effects leading to component and system-wide damage.

No ultrashort-pulse laser systems operating simultaneously with both multi-J pulse energy and multi-kW average power exist at the moment. State-of-the-art “workhorse” Ti:sapphire lasers currently produce 100-TW- to 1-PW-scale peak powers in ~30-fs pulses at several 10s of W of average power with potential extension to ~300 W anticipated [1,2]. State-of-the-art Yb:YAG lasers have reached ~1-J energies at ~1-kW average powers, albeit only with picosecond pulse durations [3]. Therefore, a truly revolutionary advance in femtosecond pulse laser power from one to more than two orders of magnitude will be required to meet science needs in the next decade.

This advance will require development of new gain media as well as new laser architectures that are now emerging with potential to enable more efficient laser operation and heat removal, while also providing the application-required ultrashort-pulse durations, pre-pulse contrasts, low timing-jitter, and low-amplitude noise with controllable output beam spatiotemporal characteristics. Achieving these goals will require the development of optics suitable for high-average-power and high-energy operation, especially diffraction gratings for pulse compression, as described in PRD 4. There are some new solid-state materials and new fiber laser-based architectures noted below that have favorable thermal properties with potential for scaling towards 10s or even 100s of kW average power and 10s to 100s of J pulse energies at ~1 µm and ~2 µm with further technology development.

1.1) Develop YAG- and YLF-based or other type solid-state lasers capable operating at 10s of kW and higher powers and 10s J and higher femtosecond pulse energies: This includes YAG-based solid-state lasers operating at ~1 µm, which due to the limited gain bandwidth will need the capability to achieve femtosecond pulse durations using the new energy and power scalable post-compression techniques described in Thrust 5. Tm:YLF solid-state lasers operating at ~2 µm have potential for scaling to >>10 kW and >>10 J for ~100-fs pulses [4] due to their high quantum efficiency, gain bandwidth, and favorable thermal properties. Tm:YLF possesses a saturation fluence lower than its damage fluence, which significantly limits laser efficiency at low repetition rates but can be overcome at multi-kHz rates with efficient extraction at high average powers [5].

1.2) Develop coherently combined Yb- and Tm-doped fiber lasers operating at ~1-µm and ~2-µm wavelengths, respectively. Yb-doped fused silica fiber lasers offer exceptionally high wall-plug efficiency (WPE); an ~50% WPE has been demonstrated with a 100-kW-class continuous-wave (CW) laser [6], however, their small aperture limits the energy of each individual laser. Coherent spatial beam (coherent beam combination/CBC) [7, 8] and temporal-domain pulse [9, 10] combining of multiple parallel fiber laser channels, addressed in Thrust 4, can overcome this limitation and enable the required multi-J energy and multi-kW average power scaling with an inherent advantage of a distributed heat dissipation. Coherent pulse stacking amplification (CPSA) has been demonstrated to be critical for achieving practical fiber laser arrays [10]. Coherently combined fiber lasers have demonstrated 1–10-kW average power [8], but they have not exceeded ~30 mJ so far [9, 10], so extensive further development is needed to reach the required 1–10-J energies for laser plasma acceleration and light sources. Needed developments include monolithic integration of fiber lasers; new large-core fibers capable of delivering higher pulse energies; optics and controls for coherent beam and pulse combining at high energies and powers; supporting-technologies addressed in PRD 4; and post-compression and pre-pulse contrast technologies noted in Thrust 5.

Thrust 2. Beyond-10-PW lasers

Multi-PW lasers produce the highest intensities for laser-plasma acceleration research, advanced compact light sources, and high-field science enabling opportunities to study strong-field QED. Several research institutions around the world have commissioned multi-PW laser systems (see Figures 1 and 13) with peak powers as high as 10 PW. Several newly proposed and awarded projects will add to this class of facilities. Research institutions have developed most of these demonstrated multi-PW laser systems with only a few produced by industry, mostly by European suppliers. Looking to the next decades, scientific applications will push the need for multi-PW laser capabilities well beyond 10 PW.

Multi-PW lasers present numerous technical challenges driven by the combined need for high-energy, short pulse duration (broad spectral bandwidth), large-aperture gain media and optics for generating and delivering multi-PW beams, and specialized diagnostics and controls systems to ensure reliable and repeatable performance. Multi-PW lasers require a temporal pre-pulse contrast greater than 10^{12} to avoid pre-ionization of targets, necessitating exquisite control of the spatiotemporal profile in the generation and amplification of laser pulses. Uniform excitation of targets at high focal intensity requires an accurately diagnosed and well-controlled spatial wavefront, which becomes increasingly challenging at larger beam apertures. At peak powers >10 PW, conventional CPA may not meet all these requirements. Promising alternative approaches, including OPCPA and coherently combining multiple beams, have not yet been demonstrated at the multi-PW level.

The challenges of attaining multi-PW point to the research directions listed below, with several areas of technology development overlapping with other PRDs:

2.1) OPCPA for multi-PW lasers: OPCPA systems can scale to larger apertures than existing laser systems to achieve significantly higher energies and broader gain bandwidths for shorter pulses. High-energy OPCPA systems place higher performance requirements on pump lasers than on conventional CPA amplifiers (Ti:sapphire, Nd:glass), but OPCPA methodology has advantages in reduced amplifier staging complexity, ultrahigh temporal contrast, and significantly reduced thermal challenges in the gain medium. Multi-PW OPCPA systems will require large-aperture nonlinear crystals. PRD 4, Thrust 4.1 describes development of large-aperture, highly deuterated dihydrogen potassium phosphate (DKDP) crystals for this approach.

2.2) Diffraction gratings: All multi-PW laser systems will require very large compression gratings, as described in PRD 4, Thrust 3.

2.3) Methods for achieving and measuring high temporal contrast: Research is needed to refine methods of spatiotemporal control of laser pulses including novel stretcher and compressor designs, control of ghost reflections, and methods for measuring pulse contrast with dynamic ranges exceeding 12 orders of magnitude.

In addition, development of post-compression techniques may be needed; PRD 4, Thrust 5.1 addresses the development of gas and plasma optics to understand if and how they can serve as a viable alternative to large-aperture conventional optics for these high-power pulses.

2.4) Increased shot rate: Diode pumping and new high-energy amplifier concepts with split-disk amplifiers using gas and liquid cooling show promise for increasing shot rates, as described more fully in PRD 4, Thrust 6.

2.5) Coherent beam combination: Improvements to the laser-induced damage threshold (LIDT) values for bulk materials and coatings explained in PRD 4, Thrust 2 will enable somewhat higher energies, but scaling energy significantly will generally require ever larger beams. CBC offers one approach to increase the effective size of laser beams. Maximizing the electric field at a focusing point requires coherently combining multiple laser beams to reproduce a phase-conjugated dipole radiation field [11, 12]. PRD 1, Thrust 4 describes CBC approaches. Novel plasma-based optics and amplification techniques [13] introduced in PRD 4, Thrust 5.1 might enable coherent combination of multi-PW modules while circumventing laser damage limits posed by conventional optics.

2.6) Spectral beam synthesis: Shorter pulses require broader coherent bandwidths which can be produced by synthesizing multiple broadband sources using spectral beam combination (PRD 1, Thrust 4.2). Nonlinear pulse compression (PRD 1, Thrust 5) can yield shorter pulses approaching single cycles, but this approach can introduce spatial and spectral pulse distortions that can degrade focusability and pulse compressibility/temporal contrast, respectively. Advances in adaptive laser control (PRD 1, Thrust 6) promise to limit these distortions.

Thrust 3. Nanosecond/kJ pump and HEDP lasers

High energy density physics (HEDP) is an important area of active research that studies matter at high pressure, temperature, and density with applications in astrophysics, inertial confinement fusion (ICF) and inertial fusion energy (IFE), material dynamics, and the development of intense radiation sources. A temporally- and spatially-tailored, multi-nanosecond high-energy laser pulse can drive uniform shocks at several Mbar pressure in materials via the ablation pressure from plasma formation. These lasers produce short-lived states of matter with high pressures, high temperatures, or high densities. These types of lasers can also pump ultrashort-pulse laser amplifiers.

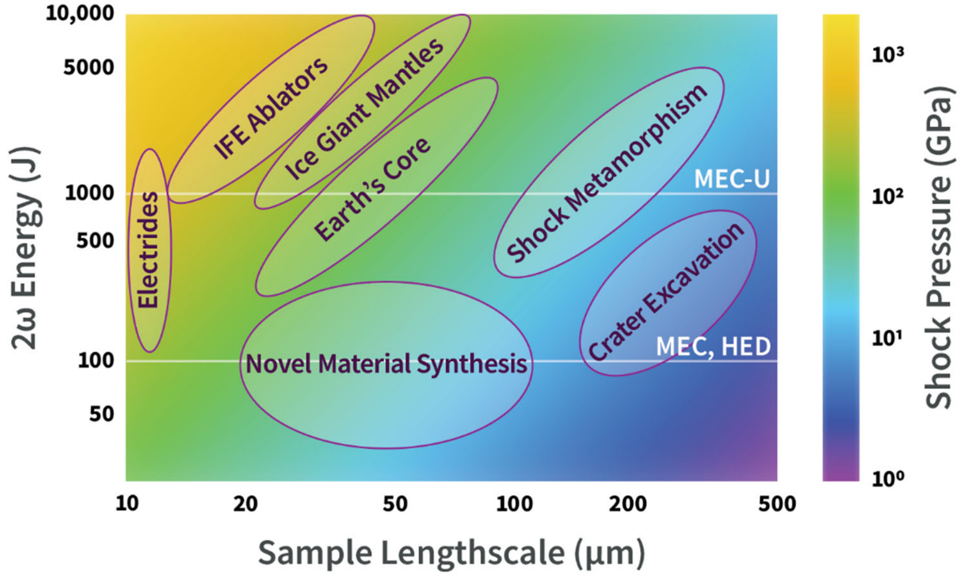

Figure 2. Sustained peak pressure capabilities (blue to yellow color scale) with length scale (in µm) of target in shock propagation direction for a range of 2ω-drive laser energies (in Joules) showing regimes of interest for the geo- and planetary science communities. Examining the kinetics effects and deformation processes requires pressure/compression sustained in thicker targets and necessitates longer (100s of nanoseconds to milliseconds) drive laser pulses with precision temporal shaping capabilities. Current capabilities are shown for instruments at current X-ray free-electron laser (XFEL) facilities: Matter in Extreme Conditions (MEC at the Linac Coherent Light Source/LCLS), High Energy Density scientific instrument (HED at the European X-ray Free-Electron Laser/EU-XFEL), and Matter in Extreme Conditions-Upgrade (MEC-U, planned for LCLS). (Image credit: A. Gleason, SLAC National Accelerator Laboratory, and R. G. Kraus, Lawrence Livermore National Laboratory.)

The characteristics of these dynamically compressed materials can be probed with pulsed X-ray sources that can interrogate the interior conditions and dynamic evolution of targets. Historically these X-ray "backlighters" have been relatively simple, broad-band, low-brightness, laser-driven plasma sources, but within the last decade, moderate-energy (100s-J) lasers have been installed at tunable, high-brightness, time-resolved X-ray sources, such as synchrotrons [14] and X-ray free-electron lasers (XFELs) [15, 16]. The precision and repeatability of the X-ray source has driven demand for improvements of target compression-driver lasers in several key performance areas including energy scaling, precision temporal shaping, spatial beam smoothing, and higher shot rates. Noteworthy efforts underway to improve these capabilities at XFELs include the Matter in Extreme Conditions-Upgrade (MEC-U) at the Linac Coherent Light Source (LCLS) [17], and the DiPOLE 100-X laser at the European X-ray Free-Electron Laser (EU-XFEL). Alternately, laser-driven X-ray and particle sources could be developed and deployed at existing dynamic compression facilities, such as the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL), the Z facility at Sandia National Laboratories (SNL), or the Omega Laser Facility at the Laboratory for Laser Energetics (LLE).

Energy demands for dynamic compression lasers scale roughly with the square of the desired pressure, the fourth power of the time scale, and the total laser energy required for achieving relevant conditions at appropriate length scales.

Dynamic compression laser systems must be optimized to create homogeneous material states with a known loading history. As has been recognized for shockless compression experiments at the Z facility, graded density impactors on a gas gun, or ICF experiments at NIF, the ability to accurately shape the pressure pulse is critical for both achieving the conditions of interest and for interpreting the results. The community has determined that the drivers must be able to achieve ±2% control over the pressure history throughout the sample volume in order to achieve sufficiently steady shocks or to ensure shockless compression of the samples [18]. For a laser driver, this equates to ±3% control over the irradiance as a function of space and time [19].

To achieve uniform shock conditions, a relatively large area (mm-scale) of the sample must be illuminated with a beam of high spatial uniformity on the order of few-percent root mean square (RMS)- variation of intensity.

Higher shot rates for dynamic compression lasers and pump lasers for ultrashort laser amplifiers would enable conducting more experiments to support parameter scans of laser and experimental conditions and more laser system performance data to improve stability and repeatability.

The principal R&D efforts required for next-generation HEDP lasers include the following topics:

3.1) Energy scaling: Energy can be increased by scaling the aperture of the gain medium (typically laser glass). Significant technical challenges with this approach include manufacturing and processing large-scale laser glass (only one qualified supplier each), managing thermally induced depolarization and thermal lens effects, and mitigating transverse amplified spontaneous emission (PRD 4, Thrust 1).

3.2) Precision temporal shaping: Achieving this performance requires development of seed sources with high shot-to-shot stability, high dynamic range, high contrast modulators, optimized feedback algorithms, and high stability amplifier chains that use laser diode or highly stabilized flash-lamp pumping.

3.3) Spatial beam smoothing: This requires precision final focusing of the laser beam with a combination of lenses and phase plates to provide the flat-top characteristics required at target. Further beam smoothing can be achieved by smoothing by spectral dispersion (SSD), a technique in which the coherence of laser beams is reduced by frequency modulation, spatially dispersing with one or more diffraction gratings, and focusing after a phase plate [20, 21]. Significant performance improvements can be achieved through development of advanced laser bandwidth formats, optimization of phase plate designs, and development of multi-dimensional SSD techniques.

3.4) Increased shot rate: Conventionally air-cooled, flash-lamp pumped lasers of 1 kJ or higher energy have shot rates of approximately 1 shot per 30 minutes or slower that are limited by the thermally induced distortions in the laser gain material. Promising approaches to increase high-energy laser shot rates include the development of diode-pumped amplifiers [2, 3] and the liquid [22, 23] and gas [2, 24] cooling of amplifiers. Early efforts are underway, but significant developments are needed to fully realize these approaches at the shot/minute scale for kJ-class amplifiers or multi-Hz repetition rates for 100-J-class amplifiers, as described in PRD 4, Thrusts 1 and 6.

Thrust 4. Coherently combine beams to expand capabilities

Combining the power and spectral width of multiple laser channels coherently offers a path to realize the very high peak and average powers motivated by the science drivers, which may exceed the capability of known, or in some cases even envisioned, individual laser channels. In the near term, these techniques are critical to achieving MHz/sub-J- to kHz/J-class lasers. CBC of many apertures may be important with bulk media to access 10 PW and beyond at high shot rates.

CBC requires highly precise laser control and stability at the level of a small fraction of an optical cycle in timing and spatial beam pointing at a small fraction of a diffraction-limited focal spot. Combination of channels spatially stacks energy from multiple channels, and combination temporally is critical for some laser technologies for fully extracting stored energy from the gain medium while combination spectrally can also expand bandwidth and reduce pulse duration. These techniques have been demonstrated at high power in CW lasers and are being developed for ultrashort-pulse lasers. Presently, coherently combined fiber arrays have produced 10-mJ-class energies at 100-fs-class durations from several fiber channels [9, 10] and have produced 40-fs pulses at low energies via spectral combining.

Scaling of these results from 0.1–10-J class energies is needed to enable a range of lasers in this report. The future ability to combine many low-energy channels and/or channels of high-energy bulk lasers offer paths to kJ energies and beyond. This motivates R&D efforts in the following topics.

4.1) Develop coherent control techniques essential for coherently phasing and combining multiple spatial, temporal, and/or spectral ultrafast laser channels. Leveraging active feedback will enable control of the envelope, phase, spectrum, pointing, and other parameters throughout the laser chain. Lasers operating at kHz repetition rates and higher may use the primary beam, while systems operating at lower rates will require secondary 'pilot' lasers.

4.2) Develop spectral combination techniques for increasing bandwidth and reducing pulse duration, as well as energy handling. This will require addressing various challenges, including off-peak gain and maintaining signal coherence.

4.3) Develop temporal stacking of pulses to fully extract stored energy and minimize channel count while addressing challenges in temporal contrast, stacking energy, and power; tailored pulse burst control; and nonlinearity.

4.4) Develop spatial combination of multiple beams by methods such as diffractive optical elements or other optical techniques that create a single filled aperture. These not only require very high energy and power handling in the combining optics but also have challenges associated with combining a large number of broad-bandwidth beams in a spatially compact arrangement.

4.5) Develop tiled-aperture (near-field) beam combining to produce a single, coherent focal spot without using beam combining components. The absence of physical combiners enables very high powers and energies but results in combining efficiencies much lower than 100%. Methods for increasing tiled aperture combining efficiency are of great interest.

Thrust 5. High-energy and high-average-power scaling of post-compression and contrast enhancement techniques

Many of the envisioned scientific applications using high-intensity laser-matter interactions require very high-energy and average power pulses with extremely short durations of 25–30 fs or even less. Another challenge for driving high-intensity laser-matter interactions with high-energy pulses is that there must be a sufficiently high pre-pulse intensity contrast, characterized as the ratio of the peak pulse intensity to the intensity anytime in the picosecond to nanosecond time window before it. High temporal contrast is required to avoid disturbing or destroying target material prior to the arrival of the main portion of the pulse. The required contrast depends on target type and laser-matter interaction, as well as on the peak intensity. For example, laser wakefield acceleration (LWFA) using gas targets requires contrasts of at least 10^5–10^6, while solid targets usually require contrasts of at least 10^{10} and higher.

The majority of the laser gain media capable of supporting multi-J energies at multi-kW average powers have bandwidth limitations that prevent achieving these short durations via direct or chirped-pulse amplification. Post-compression techniques are currently being investigated to shorten optical pulses. Longer pulses from a laser output are first spectrally broadened in a gas- or a solid-state nonlinear medium via self-phase modulation, which can be contained inside a multi-pass cell (MPC) arrangement or a hollow-core photonic crystal fiber (HC-PCF), and subsequently compressed to much shorter pulses using chirped mirrors or other devices. However, all current post-compression techniques capable of reaching sufficiently short pulse durations with a practically compact arrangement are limited in energy to less than approximately 100 mJ.

The majority of the existing nonlinear optics-based pulse cleaning techniques are compatible only with low, mJ-level pulse energies, and suffer from relatively low throughput efficiency. The only energy-scalable pre-pulse cleaning techniques that are compatible with multi-J energies are currently based on plasma mirrors [25] and second harmonic generation (SHG) and have been demonstrated to reach contrasts of >10^{10} and efficiencies of 50-80%. However, current plasma mirrors operate at very low repetition rates (~1 Hz and lower), and SHG is currently not scalable beyond a few kW. Therefore, the following R&D efforts are needed:

5.1) Research to scale post-compression techniques to higher energy and average power: The main challenge is to achieve 25–30 fs at 1–10 J or higher energies while retaining high throughput efficiency and diffraction-limited beam quality in a practical, compact system compatible with multi-kW average powers. Bridging this more than two-orders-of-magnitude pulse-energy gap will likely require exploring entirely new concepts for post-compression techniques.

5.2) Research to extend the plasma-mirror technique or develop entirely new pre-pulse cleaning techniques which must be capable of supporting multi-J (and higher) pulse energies at multi-kHz repetition rates with high throughput efficiency, producing high pre-pulse contrasts of at least 10^5 and preferably >10^{10} that maintain high beam quality.

Thrust 6. Adaptive laser control

The successful operation of the lasers envisioned in this Basic Research Needs (BRN) Workshop and their application as sources of highly useful secondary radiation require better characterization and control of the laser pulses. The level of performance required is not possible today, particularly for high-repetition-rate systems, and next-generation laser diagnostics coupled with new strategies for active feedback are required. One cannot make what one cannot measure, and stability and control require feedback.

6.1) Develop techniques for complete single-shot characterization of the laser electric field E(x,y,z,t), including polarization, in the near and far fields. The complete characterization of the electromagnetic field of a laser pulse is rarely attempted due to the difficulty of the measurement. When it is attempted, either a reference pulse or simplifying assumptions are required (i.e., Assuming there is no spatial chirp), or a scanning configuration is employed—but scanning hides important effects [26]. A capability for complete spatiotemporal characterization, including polarization, would revolutionize research, especially if it could work using only a single laser shot in a high-repetition-rate system. With this, machine learning (ML) approaches can be employed for laser and application optimization. Such laser diagnostics become effective experimental diagnostics when they are employed for the transmitted, reflected, or scattered beams from the interaction region. Measurement of the spatially averaged temporal profile, if free of aberrations such as pulse front tilt or spatial chirp, has long been available. Methods for full characterization exist, but they are difficult to employ. If a diagnostic is so difficult to employ that it becomes its own experiment or if it unduly hinders access to the interaction region, then it is no longer suitable for ML [27]. Development of this capability is nascent and one- to two-orders-of-magnitude improved speed of measurement is required.

6.2) Develop high-dynamic-range pulse contrast measurement techniques: Whereas the previous thrust focused on the main pulse, this focuses on the light before the pulse. This includes incoherent contributions, such as amplified spontaneous emission, as well as coherent contributions from isolated pre-pulses and pedestals (slow turn-on of the main pulse). Contrast requirements are given in PRD 1, Thrust 5. Current technology based on third-order cross correlation enables contrast measurements down to ~10^{-12} of the main pulse that use scanning experiments taking minutes to hours to cover a range extending to several hundred picoseconds. This may be sufficient for times >50 ps before the main pulse, however, shot-to-shot jitter in the pedestal can have a critical effect on applications and research. A high-dynamic-range diagnostic that can measure up to ~50 ps before the main pulse with better than 10^{-10} contrast using only a single laser shot is a primary need for high peak power experiments [28]. Improving the contrast sensitivity by >4 orders of magnitude and expanding the temporal range by a factor of >10 are required.

6.3) Develop techniques for arbitrary spatiotemporal and polarization pulse control: There has been substantial development of the spatiotemporal control of the laser field both to correct for aberrations introduced by the laser system and for optimization of processes, most recently using ML. For >20-fs pulses in the optical and near-IR, separate control of the temporal and spatial profiles is well demonstrated. However, this falls short of arbitrary spatiotemporal wavefront control, limiting the guiding of processes during the evolution of the pulse and discovery science. Examples where complex control of the pulse is needed or might be beneficial include wide-ranging problems such as laser acceleration of electrons, controlling ultrafast molecular dynamics, or developing advanced plasma optics. Currently, this capability has been demonstrated for lower energy, mJ pulses [26, 29]. Improvement by 3–5 orders of magnitude in pulse energy is required for the lasers envisioned here.

6.4) Develop machine learning and data handling technologies for integration with rapid feedback. This is a new and rapidly expanding area in laser technology that is vital for laser system operation and application. For example, laser-driven ion acceleration has achieved significant improvements using measurement and feedback in cases where parameter scans were insufficient [30, 31]. An ML scheme requires the ability to modify the laser pulse, measure the outcome, process the laser and experimental outputs, and then determine the next pulse to use. The likelihood of success is greatly enhanced with increased repetition rate. In addition to basic optimization, advanced approaches can explore the underlying science, for example, by measuring the number of active degrees of freedom. This information can improve the understanding of the laser system being optimized or the physical process being explored.

Long-term challenges

Combining the techniques across the research thrusts together with the enabling technologies from the other PRDs offers a path to extend high-intensity lasers to address grand challenges in science, from high-field to high energy physics colliders to pump-probe capabilities at superconducting light sources. These motivate 100s of kW average powers combined with 10s of kHz repetition rates at high WPEs in the 10-50% range. Such parameters are conceptually accessible by combining the techniques described above and motivate R&D in this decade and beyond.

SCIENCE AND TECHNOLOGY IMPACT

QED, giving a complete picture of light matter interaction, has seldom been studied in the strong-field regime due to a lack of experimental facilities enabling testing and validation of QED theories and parts of the Standard Model. Achieving the highest peak intensities (above 10^{24} W/cm^2) will unlock new areas of research. The Schwinger limit, above which matter is expected to be created out of a vacuum by a strong electric field, will be tested, as will vacuum birefringence, vacuum breakdown, radiation reaction, photon-photon scattering effects, and pair plasmas. Such transformative intensities can also stimulate high energy physics (HEP) studies, including the production of relativistic proton and muon sources, testing beyond the Standard Model, and probing the existence of dark matter, as well as the investigation of gamma-gamma collider studies. On the way to such extreme intensities, which will be produced by 100-PW-scale lasers, lies an exquisite array of astrophysical studies poised to capture a broad scientific community.

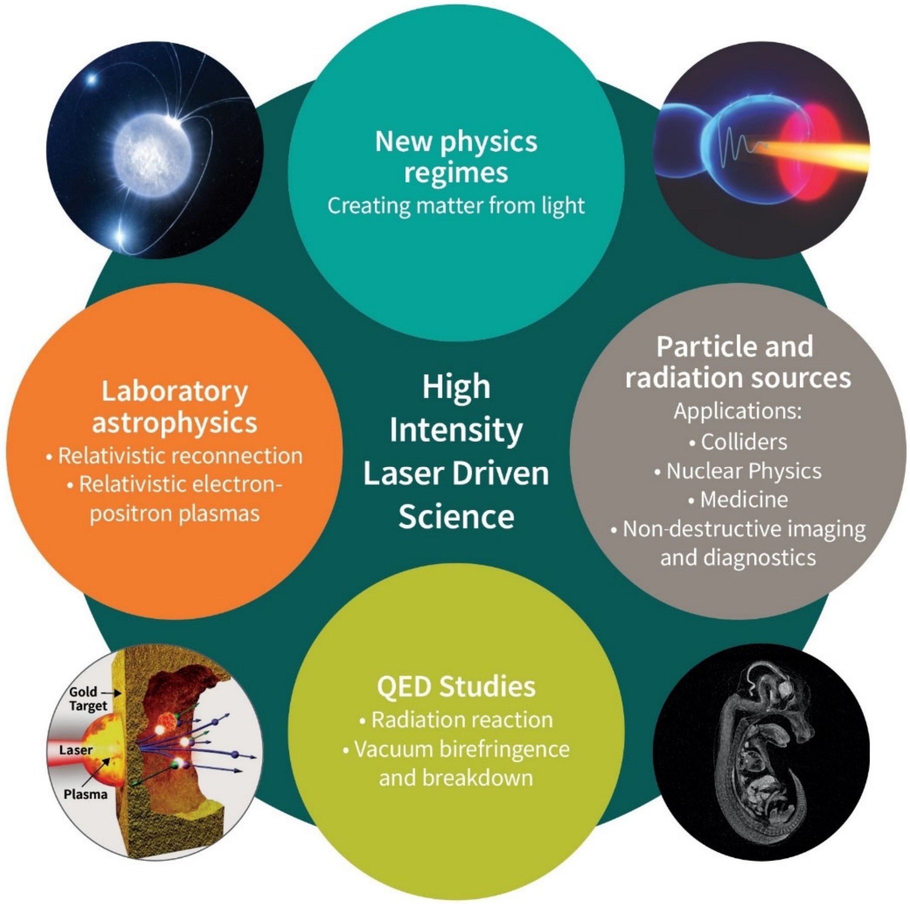

Figure 3. Science and technology impact of high-intensity laser-driven science. QED: quantum electrodynamics. (Image credits: *upper left* ESO/L.Calçada; *upper right* F Albert et al. 2014 Plasma Phys. Control. Fusion 56 084015 DOI 10.1088/0741-3335/56/8/084015; *lower left* Scott Charles Wilks, Lawrence Livermore National Laboratory; *lower right* Daniel R. Symes et al. PNAS Vol. 115 | No. 25 June 19, 2018 PubMed: 29871946.)

Large focal volumes, enabled by kJ-class 10-PW-scale laser systems, will allow the scientific community to understand, for the first time in the laboratory, events at the origin of the most energetic particles in the universe, which include relativistic magnetic reconnection and shocks. We will be able to create and control large volumes of electron-positron plasmas to understand their collective effects and instabilities and produce extreme Mtesla magnetic fields relevant to the magnetosphere of pulsars. In this regime, high conversion efficiency MeV-photon sources can also be produced via plasma rectification, enabling imaging and studies of dense materials relevant for fusion physics and HED science and pioneering nuclear spectroscopy experiments. With the addition of high contrast and mid-IR capabilities, this new class of lasers will revolutionize the production of relativistic ion sources through new physics regimes, including radiation pressure, magnetic vortex, and shock wave acceleration. The addition of precision control and repetition rate will augment our ability to manipulate the ion spectrum, source size, and phase space for utilization in medical proton therapy, heating for opacity and warm dense matter (WDM) studies, and conversion to neutrons, which is relevant for radiation damage, radiography, and fusion materials.

While high repetition rate will be enabling and transformational for high-field science in general, a kHz, 100-TW-class laser system with multiple beams, precision control, feedback and real-time ML/artificial intelligence (AI)-based optimization will revolutionize LWFA-related physics and applications to bring laser plasma acceleration on par with radiofrequency (RF) accelerator technology. One will be able to control electron injection and phase space, laser propagation for precise electron accelerator structure shaping, study the wavelength scaling of accelerator and injector structures, and produce ultrabright beam quality to match or exceed conventional accelerator capabilities. It will enable future grand challenges such as particle colliders, tabletop XFELs and medical therapy and imaging. Byproducts of LWFA with broad application are photons for material science, additive manufacturing, and non-destructive evaluation (NDE). MeV photon sources produced via inverse Compton scattering with a µm-scale source size and controllable and tunable spectra in the 1–9-MeV range will enable unique nuclear spectroscopy, material studies, and medical applications. Similarly, tunable, bright Betatron X-ray sources in the 10s-of-keV photon energy range with fs-scale temporal synchronization and µm-scale source size will transform the way we do dynamic material and condensed matter studies. A kHz 100-TW-class system also offers the opportunity to manipulate plasmas like never before to create new grating and optical components that can withstand extreme laser intensities produced by multi-PW systems. HED science, the study of matter at extreme conditions of temperature and pressures relevant to fusion plasmas, stellar cores, and planetary interiors, is in desperate need of a rep-rated, 10-Hz, ns, kJ-class laser systems to consistently generate reproducible HED and WDM plasmas, with a long-term path to higher repetition rates potentially via combination. At best, current systems can only produce a few shots per day, which is insufficient for quality physics studies on plasma turbulence and energy flows. Such a system will also take advantage of and support pump-probe measurements with secondary photon and proton sources for opacity and particle transport studies.

PRD 2 Transform Mid-IR Sources for Science from THz to X-Rays

Key Questions: Can we create the new laser technologies needed to meet the significant demands for high average and peak power mid-infrared (mid-IR) science, and for driving secondary sources with extreme spectral coverage? How do we overcome the current limitations in mid-IR laser intensity to take full advantage of ponderomotive λ^2 scaling? What are the ideal wavelengths, platforms, and architectures for nonlinear conversion to generate transformative sources in hard-to-access spectral ranges?

INTRODUCTION

Why mid-IR lasers are key enablers of ultrafast science

Ultrafast science researchers now have access to increasingly mature laser technology that can enable myriad ultrafast spectroscopy applications in the visible, near-infrared (near-IR), and near-ultraviolet (near-UV) spectral ranges. Ultrafast IR spectroscopy is also conducted routinely, but with limitations in the energy and spectral bandwidth of femtosecond-IR pulses. Ultrafast spectroscopy in all other spectral ranges, including far-IR and THz regimes at longer wavelengths and deep-UV to X-ray ranges at shorter wavelengths, remains far more challenging to access. One might expect that advances in such disparate spectral ranges would require distinct laser technology efforts in each. In this case, however, we are presented with a unique opportunity: major advances in the generation of femtosecond short-wave and mid-IR (from ~2- to >10-micron wavelength) pulses will yield dramatic advances in not only IR spectroscopy but also throughout the THz/far-IR and deep-UV/X-ray ranges accessed through frequency conversion of the mid-IR light. This will result in transformational scientific advances in wide-ranging areas spanning IR molecular spectroscopy and sensing, THz control over material structure and properties, element-specific and time-resolved nano-imaging in semiconductor devices and biological samples, and observation of molecular excited states on the time and length scales of electronic and nuclear motions.

Frequency conversion to either lower or higher photon energies is often enhanced greatly with mid-IR input fields, relative to visible and near-IR inputs, for two reasons. First, the ponderomotive energy imparted by the field scales as the inverse frequency squared. This allows IR fields to drive electronic and dipolar responses far more effectively to reach deep UV and X-ray photon energies or to down-convert to THz frequencies. Second, for THz generation using nonlinear optical crystals, multiphoton absorption that creates THz-absorbing carriers and that can cause damage through instantaneous high-intensity effects or cumulative heating is strongly suppressed. The use of IR driving fields can yield order-of-magnitude increases in outputs at lower photon energies to drive large-amplitude responses of phonons, magnons, and other collective modes and can extend HHG (high harmonic generation) of attosecond sources from extreme ultraviolet (XUV) to soft X-rays reaching through the water window and beyond to site-specific absorption edges of nearly all major elements. Access to these spectral ranges is critical to understand and control energy flow in molecules and materials on the scale of individual electrons and atoms [32-34].

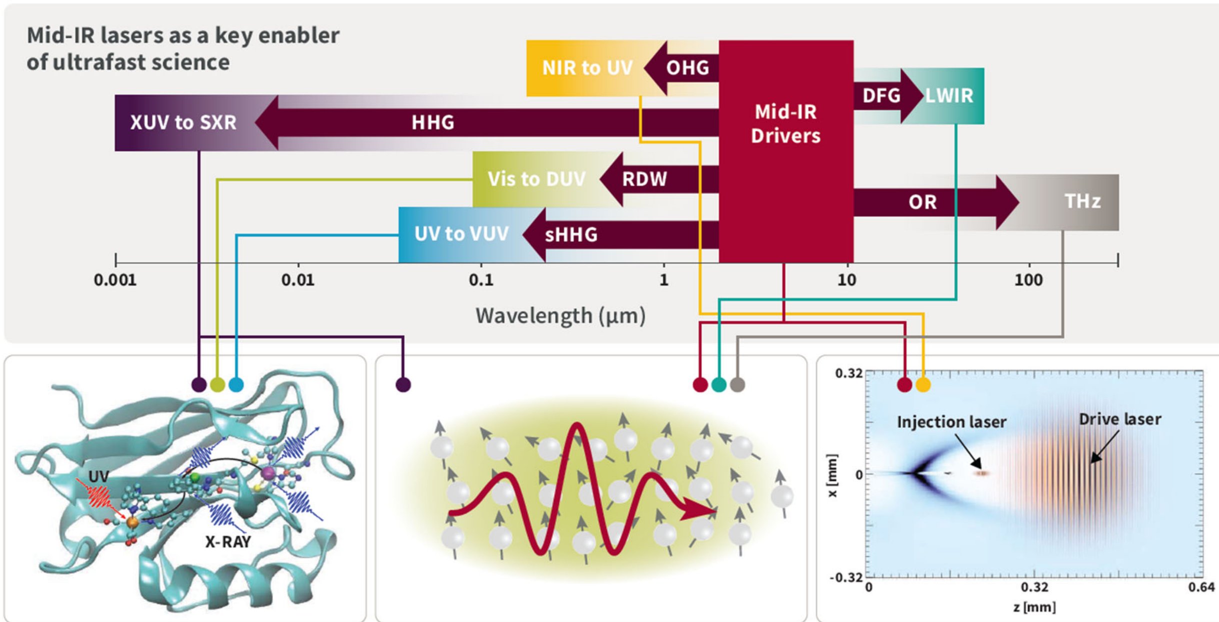

Figure 4. Mid-IR lasers as a key enabler of ultrafast science. The mid-IR is potentially an optimal starting point for frequency conversion across the electromagnetic spectrum, offering efficient conversion down to single-cycle THz pulses and up to the highest-energy high-order harmonics and attosecond pulses. Combinations of sources driven by mid-IR lasers can initiate and probe the fastest electron dynamics in complex molecules (lower left panel), collective excitation of charge, lattice, and spin degrees of freedom in solids (lower middle), and high-intensity laser plasmas (lower right). DFG: difference frequency generation; DUV: deep ultraviolet; HHG: high-harmonic generation; LWIR: long-wave infrared; NIR: near-infrared; OHG: optical harmonic generation; OR: optical rectification; RDW: resonant dispersive wave generation; sHHG: solid-state high-harmonic generation; SXR: soft X-ray; THz: terahertz; UV: ultraviolet; VUV: vacuum ultraviolet; Vis: visible; XUV: extreme ultraviolet. (Image credits: *Left* Yu Zhang et al. J. Phys. Chem. Lett. 2014, 5, 21, 3656–3661 https://doi.org/10.1021/jz501966h; *Middle* Markus Münzenberg, Universität Greifswald, from Alexey Kimel et al 2022 J. Phys. D: Appl. Phys. 55 463003 DOI 10.1088/1361-6463/ac8da0; *Right* X. L. Xu, et al. Phys. Rev. ST Accel. Beams 17, 061301 https://doi.org/10.1103/PhysRevSTAB.17.061301.)

Science applications of mid-IR sources

Ponderomotive λ^2 scaling of strong-field processes: Progress to date in the development of high peak power, ultrashort-pulse lasers in the mid-IR has largely been motivated by explorations of strong-field physics phenomena that scale favorably with longer driving laser wavelengths. These include the high-energy cutoff energies of re-scattered electrons and X-ray high-order harmonics [35, 36] demonstrated experimentally using current mid-IR sources, as well as the size of plasma bubbles generated in laser wake field acceleration, which may provide a pathway towards the generation of electron beams with small divergences and energy spreads from high peak power mid-IR drivers [37]. The development of more efficient and lower-complexity mid-IR sources with moderate peak power and high average power (at the ~1-TW and ~100-W levels, respectively) are demanded to provide reliable operation of high-order harmonic sources that can cover not only the soft X-ray water window, but also that extend to 1 keV and beyond to cover the L-edges of transition metal elements relevant to quantum materials and spintronic devices. Improving the peak and average flux of X-rays in this important spectral range would allow novel spectroscopic tools, such as attosecond transient absorption and four-wave mixing [38]. Higher driving laser peak powers and more efficient harmonic conversion schemes may provide access to X-ray attosecond pump-probe [35, 38] and X-ray second harmonic spectroscopy [39]. Development of even higher peak power mid-IR sources with few-cycle pulse duration and a 10-TW peak power level may allow better control of solid plasmas, leading to higher efficiency harmonic sources based on relativistic plasma surfaces, as well as new stand-off sensing capabilities based on laser filamentation in atmospheric transmission windows [40]. Beyond 10 TW, long-wavelength lasers (e.g., CO_2 or potentially Fe-doped solid-state amplifiers) may prove to be optimal sources for driving large, low-density plasma bubbles that can be synchronized with shorter wavelength plasma injection lasers to generate monochromatic electron beams [37]. In all these cases, the lack of widespread mid-IR laser sources has led to a wide array of unexplored frontiers and the potential for novel physics and unanticipated advances.

Dynamics in chemical, biological, and material systems: Direct, real-time observation of coupled electronic and nuclear motion is a grand challenge for the chemical, biological, and material sciences [40]. Bridging these fields, an overarching goal for the next 10 years is to develop the technology to study dynamics in complex chemical, biological, and material systems resolved at the fundamental space and time scales of electron motion [35, 38]. Toward this goal, elemental and oxidation state specificity afforded by XUV and soft X-ray pulses with attosecond durations is a key enabling technology. Such light sources would provide access to elemental edges of all atomic species contained in a molecular or material system to observe electron motion and electron-nuclear coupling on its fundamental time scale. Accordingly, these sources would enable testing of fundamental theories related to electron-driven nuclear transformations moving beyond the limitations of the Born-Oppenheimer approximation [41] or to the interactions of electrons, lattice, and spin that give rise to novel quantum material properties [42]. One promising path to realize this goal is the development of high peak and average power mid-IR sources where the mid-IR can directly probe dynamics in complex material and biological systems (e.g., multidimensional IR spectroscopies) or the mid-IR can support wavelength conversion to much higher or lower frequencies (e.g., attosecond X-rays via HHG, UV generation through optical harmonic or dispersive wave generation, or conversion to single-cycle THz pulses).

SCIENTIFIC CHALLENGES

The above demands of the ultrafast and strong-field science communities can be met through the development of femtosecond sources operating in the mid-IR, with peak and average powers that approach the current state-of-the-art for ytterbium-doped laser amplifiers (e.g., pulse energies of >1 J, average powers of >1 kW, pulse compression to few-cycle durations). Currently available mid-IR Type II and Type III laser sources not only fail to reach these lofty goals, but also, they suffer from the inherent challenges of highly complex architectures: they are difficult and expensive to build and operate, accrue instability through multiple nonlinear frequency conversion stages, and have a large number of individual points of failure. Reaching the technological goals for mid-IR lasers will therefore require a multi-pronged effort, aimed at simultaneously *up-scaling the parameter space covered* by and *reducing the complexity* of mid-IR sources generated through both parametric amplification and new gain materials for conventional laser amplification. Such an approach will enable novel science both by reaching previously unattainable laser specifications and by allowing advanced mid-IR technology to proliferate beyond a few specialized laboratories worldwide. Beyond the quest for higher power levels, novel mid-IR Type IV laser platforms, including frequency comb, fiber, and semiconductor laser sources with increased capabilities, will have transformative impact both on chemical sensing and spectroscopy and as highly stable and waveform-controllable front ends for next-generation amplifiers.

RESEARCH THRUSTS

Thrust 1. Reducing complexity and increasing efficiency of mid-IR parametric sources

The first thrust is to reduce the complexity and increase efficiency of OPA and OPCPA Type III laser sources, which will allow scaling to higher pulse energies and average powers, while providing the improved stability and robustness required for experiments using attosecond X-ray probes. Current approaches to OPCPA with 1-micron pumps often result in highly complex architectures, relying on nonlinear optical frequency conversion for pump and/or seed generation as well as multiple stages of parametric amplification to reach high energies (sequential stages) and/or high spectral bandwidth (parallel stages) [43]. This results in reduced stability, increased cost, and a large number of points of failure. The complexity also leads to significant losses: when pumped with 1-micron drivers, the conversion efficiency into the mid-IR is on the order of a few percent, well below the limit imposed by the quantum defect. While further development of 1-micron-pumped OPA and OPCPA sources may still yield improvements over the next decade, these efforts are already being pursued in the industry sector, and basic research into such platforms was not identified as a high priority.

Instead, innovative approaches aimed at both reducing the complexity and increasing the efficiency of mid-IR parametric sources, both for scaling to high peak and average power and for increasing the stability, robustness, and accessibility of these sources, should focus on the use of longer-wavelength pump sources. Recent developments in picosecond 2-micron Ho-doped solid-state lasers, which can now be straightforwardly pumped by high-power Tm:fiber, have been demonstrated as viable pump sources for mid-IR OPCPAs with higher conversion efficiencies, commensurate with the reduced quantum defect [37]. Two-micron pumps have additional benefits, such as reduced two-photon absorption, higher second-order nonlinear susceptibility, and increased phase-matching bandwidth in the mid-IR. OPCPA pump sources with 3.8-mJ pulse energy have been generated from a Ho:YAG regenerative amplifier with a repetition rate of 1 kHz, while higher-energy pulses of 260 mJ at a reduced repetition rate of 100 Hz have been generated in a two-stage Ho:YLF amplifier with cryogenic cooling. However, several issues, including the poor power stability of commercial Tm:fiber pump lasers used as pump sources, the lack of direct broadband 2-micron seed lasers, and the onset of bifurcation instability in regenerative amplifiers, have prevented the scaling of Ho-doped solid-state amplifiers to the high energies and average powers needed for pumping OPCPAs. More recently, femtosecond Cr:ZnSe amplifiers with a 2.4-micron wavelength have been identified as a promising path towards reaching even longer wavelengths.

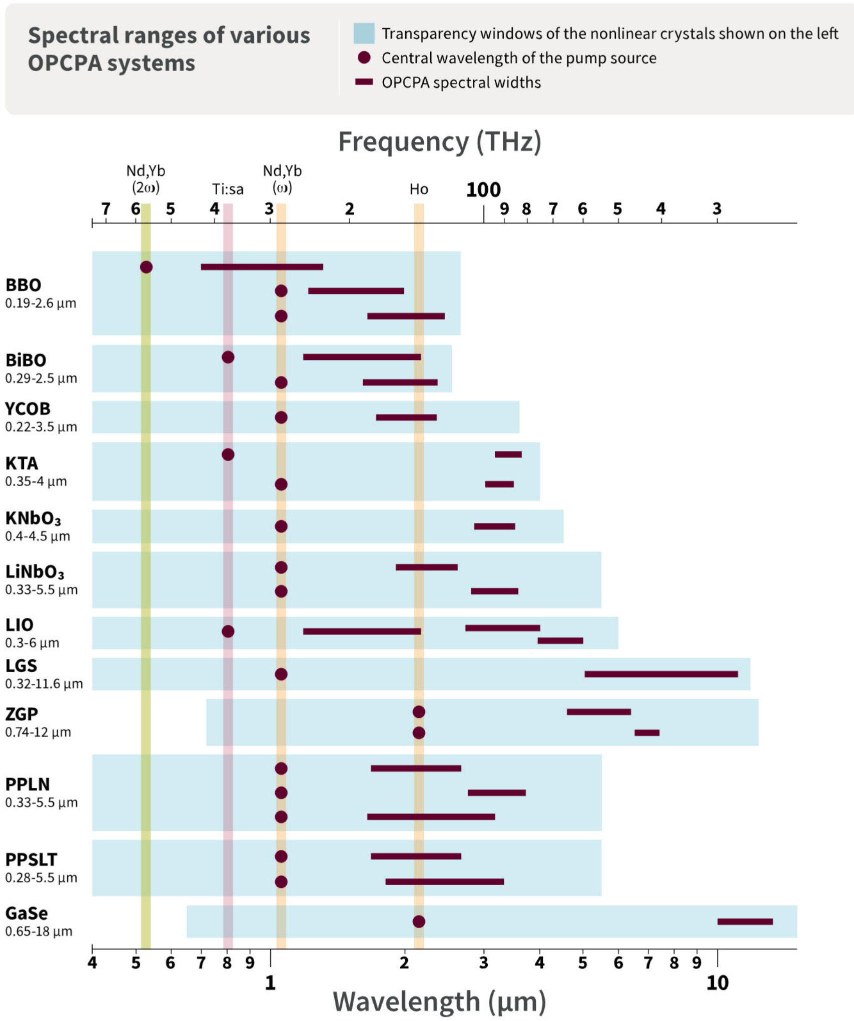

Figure 5. Spectral ranges of various OPCPA systems. The light blue areas indicate the transparency windows of the nonlinear crystals shown on the left. The black dots indicate the central wavelength of the pump source. The thick black bars indicate the spectral ranges of the OPCPAs. BBO[i]: beta barium borate, or BaB_2O_4; BiBO[ii]: bismuth triborate, or BiB_3O_6; $KnbO_3$: potassium niobate; GaSe[iii]: gallium selenide; KTA[iv]: potassium titanyle arsenate, or $KtiOAsO_4$; LIO[v]: lithium iodate, or $LiIO_3$; $LiNbO_3$[vi]: lithium niobate; LGS[vii]: lithium thiogallate or $LiGaS_2$; PPLN[viii]: periodically poled lithium niobate; PPLST[ix]: periodically poled stoichiometric lithium tantalate; YCOB[x]: yttrium calcium oxyborate, or $Yca_4O(BO_3)_3$; ZPG[xi]: zinc-germanium phosphide, or $ZnGeP_2$. Figure adapted from [37].

The combination of 2-micron and longer wavelength pump lasers with reliable broadband seed sources may enable more efficient OPCPA architectures than are currently available, allowing access to the high energies and average powers required to meet the science goals in the attosecond X-ray and high-field THz domain, and for seeding CO_2 amplifiers. When combined with novel approaches to frequency conversion (see PRD 3, Thrust 2), OPA and OPCPA gain elements capable of reaching, or potentially exceeding, the limit imposed by the quantum defect and with far higher stability and better reliability than current architectures relying on multiple stages of nonlinear conversion would be truly transformational. Several approaches have been identified to meet these goals:

1.1) Development of highly stable broadband mid-IR seed lasers that can provide both the seed pulses required for 2-micron pump lasers and the signal pulses for OPCPA: In current OPCPA systems, both the seed pulses for the pump laser and the signal pulses for the parametric amplifier are derived from a short-wavelength laser using nonlinear processes. This results in increased instability and uneven performance of the OPCPA output and motivates research into new approaches to generating broadband mid-IR seed lasers. This may include the development of fiber-based platforms with integrated periodically poled lithium niobate (PPLN) waveguides or other nonlinear elements, the development of Ho-doped or Tm, Ho co-doped CaF_2 and CaGdAlO4 seed lasers, advancements in orientation-patterned (OP) GaAs and GaP crystals, or other innovative approaches such as those discussed in PRD 4, Thrust 5.

1.2) Scaling of Tm-, Ho-, Cr-, and Fe-doped laser amplifiers to high pulse energy and average power: The development of high-energy, high-power long-wavelength pump sources with picosecond pulse durations is prerequisite to the development of high peak and average power OPCPA systems. For these applications, excellent beam quality and energy stability, as well as the ability to synchronize optically to the OPCPA signal pulse, are of paramount importance. Specific approaches to energy and average power scaling are covered more extensively in PRD 1, Thrust 1 and in PRD 2, Thrust 2, while necessary advances in gain media are discussed in PRD 4, Thrust 1.

1.3) OPCPA architectures based on longer-wavelength pumps: OPCPA systems based on Tm- or Ho-doped pump lasers have now been achieved in multiple laboratories worldwide, and it is anticipated that the parameters of these systems will eclipse those from 1-micron-pumped OPCPA with further improvements in both the pump laser parameters and the OPCPA architecture. At the same time, the parameters of current Cr:ZnSe and Fe:ZnSe amplifiers, with multi-millijoule pulse energies and ultrashort-pulse duration at 2.4- and 4.1-micron wavelengths, respectively, are now adequate for testing novel OPA and OPCPA architectures with long-wavelength pump sources. Cr:ZnSe oscillators with multi-octave spanning spectra are now available from multiple vendors. A $ZnGeP_2$ (ZGP)-based OPA with sub-two-cycle pulse duration and GW peak power at 9.5-micron central wavelength was recently demonstrated using a 4-mJ, 1-kHz Cr:ZnSe amplifier to generate both the pump and seed pulses [44]. Further investigations into OPCPA materials and architectures based on pump sources with 2-micron and longer wavelengths is therefore warranted. This involves fundamental investigations into OPCPA pump sources pumped at 2.4 and 4.1 microns—approaches that can leverage the highly effective second-order nonlinearity of materials with 2-micron pumps to realize broad-band amplification with relatively long pump pulses with lower peak power—and the investigation of dual-chirped OPCPA, subharmonic OPA and OPCPA, and other techniques.

1.4) Development of tunable few-cycle parametric sources: The articulated scientific goals demand full control over the pump- and probe-pulse wavelengths. While mid-IR driving lasers in the 2–5-micron range appear to have significant promise as driving lasers for frequency conversion into soft X-ray high-order harmonics and THz regions of the spectrum, it is not clear that there is a singular "optimal" starting wavelength that allows efficient frequency conversion across the intermediate spanning region. For this reason, the development of broadly tunable OPA and OPCPA sources with moderately high energy and repetition rate are required. Approaches to this may include novel OPA architectures such as Fourier-plane OPA, sub-harmonic OPA and OPCPA, the combination of tunable OPCPA with nonlinear spectral broadening and pulse compression, and other innovative approaches.

In addition to the above, solutions to important optical engineering challenges are also needed, such as the development of high-damage threshold, low-group velocity dispersion (GVD) mirrors, nonlinear crystals for parametric amplification, holographic gratings and/or Bragg gratings for pulse stretching and compression, and diagnostic tools specific to the mid-IR spectral range. These aspects are covered in more depth in PRD 4, Thrusts 2 and 3.

Thrust 2. Scaling peak and average power in mid-IR CPA

Mid-IR laser sources based on direct CPA offer several critical advantages over parametric amplifiers. Importantly, direct CPA architectures are inherently less complex and can be far more efficient than OPCPA platforms with similar output specifications. However, CPA lacks the tunability of parametric sources and, critically, relies on the availability of suitable gain media and pump sources. Historically, long-wavelength CPA was largely limited to CO_2 gas lasers, which operate based on transitions between molecular rotational and vibrational levels and produce output wavelengths near 10 microns and pulse durations that can reach below 1 picosecond. More recently, research in transition metal-doped II-VI chalcogenides has identified other attractive host materials and laser transitions in the mid-IR [45]. Most notably, the last decade has seen major advances in femtosecond Cr:ZnS/Se oscillators and frequency combs, and the first demonstrations of CPA in Cr:ZnSe and Fe:ZnSe reaching multi-GW peak power levels at 2.5- and 4-micron wavelengths, respectively [37]. Research over the next decade is needed to scale the pulse energy and repetition rates of Cr- and Fe-doped lasers to the levels (25 mJ at 10 kHz) required for increasing the X-ray cutoff energy and photon flux of high-order harmonic sources, and to reach the higher peak power levels from Cr:ZnSe and Fe:ZnSe amplifiers required for fundamental studies of long-wavelength-driven relativistic laser plasmas.

The U.S. currently leads the technology development of Cr:ZnSe/S gain media, carrier-envelope phase (CEP)-stable Cr:ZnS oscillators, and Cr:ZnSe CPAs providing >5 mJ and >0.1 TW, and the current state of materials fabrication technology is adequate for meeting the demands of the next decade. Scaling these systems, therefore, will mainly result from improvements to pump technology and optical components. The U.S. also leads the technology development of Fe:ZnSe gain media. However, in this case, it is likely that meeting the scientific challenges will require improvements to both the pump source and gain elements. For both Cr- and Fe-doped laser systems (including current polycrystalline ZnS/Se but potentially other host media as discussed in Thrust 3), a complementary approach to peak and average power scaling should be taken, since high repetition rates with more modest pulse energies are required for applications to HHG while higher peak powers at lower repetition rates will allow proof-of-principle studies of LWFA.

2.1) Repetition rate scaling of millijoule-class mid-IR lasers to a level >10 kHz: Current technology developments in Cr:ZnSe amplifiers point towards increasing the pulse energy of current 1-kHz sources from the <10-mJ level to the >25-mJ level within the next several years. This will largely be achieved by modest improvements to large-aperture crystals and the development of higher-energy Tm:fiber pump sources. Scaling the repetition rate to the 10-kHz level will likely require more substantial changes to both the pump and laser architecture to mitigate thermal issues. However, such parameters for Type III lasers are likely within reach, as >200 W has been demonstrated in CW mode through the use of a spinning ring cavity. In particular, novel pumping approaches (e.g., mitigating the high thermal losses in Tm:fiber pumps for Ho:YAG, mitigating losses due to in-band pumping of Ho:YAG, energy and power scaling of single-mode Er-fiber laser pumped Q-switched Er:YAG as a replacement for Ho:YAG, direct electrical pumping of n-type ZnSe or in a PIN junction) are needed, as well as the development and testing of components (e.g., gratings, isolators) that can handle the high thermal loads. For Fe:ZnSe amplifiers, the challenges are more significant, and >100-W average powers will be challenging to meet on the decadal timescale. In particular, significant efforts must be directed towards the design, energy scaling, and power scaling of diode-pumped free-running and Q-switched Er:YSGG (yttrium scandium gallium garnet) pump lasers. Furthermore, novel approaches to the suppression of amplified spontaneous emission in Fe:ZnSe gain elements, which may be achieved by spatially dependent doping or co-doping, optimization of the doping concentration and shape of the gain elements, and other approaches, will be necessary to reduce the load on isolators and increase the overall system efficiency.

2.2) Peak power scaling to the 10-TW level: Reaching the peak power levels necessary for LWFA will require mid-IR Type II lasers with J-level pulse energies. Current pump lasers and gain media are inadequate. Besides the required energy scaling of the pump lasers, high-energy amplifiers will benefit from the development of large-aperture (>5 cm) Cr:ZnSe and Fe:ZnSe crystals and/or ceramics with higher surface quality and lower surface damage threshold, the exploration of novel cavity designs (e.g., "thick disk" or spinning cavity amplifiers), and explorations of low-temperature amplification schemes for Cr:ZnSe.

2.3) Peak power scaling through nonlinear compression: Further increase of the peak power can be attained through nonlinear compression. Hollow-core fiber pulse compression has been demonstrated with multi-millijoule lasers in the mid-IR, though with higher losses and a lower compression ratio than what has been achieved at near-IR wavelengths. Approaches for efficient pulse compression, based on hollow-core fibers, MPCs, or other techniques, as well as the development of components (e.g., chirped mirrors or meta-optics for dispersion compensation described in PRD 4) could lead to 5- to 10-fold increases in the available peak power, as well as access to the ultrashort-pulse durations required for X-ray attosecond pulse generation.

Nonlinear compression techniques are discussed more generally in PRD 3; both established and novel approaches which can yield high compression factors with low losses are desired for Cr:ZnSe and Fe:ZnSe CPA.

Thrust 3. Pushing peak power for CO_2-based laser accelerators

The necessary advances in the parameters of CO_2 lasers are in some ways similar to those for Cr- and Fe-doped lasers, but the technological challenges are unique. The U.S. has been leading the development of high-peak-power 10-micron lasers in recent decades, with several systems now achieving multi-TW operation. In many ways, these systems represent one of the most promising pathways for future particle accelerators based on LWFA, since the large spatial scales of the plasma structures allow finer control over the acceleration gradients and the injection of electrons.

Meeting the scientific goals requires scaling the peak power of CO_2 Type II lasers well beyond the levels that have so far been demonstrated. However, the inherent stability, scalability, and repetition-rate limitations associated with high-pressure gas discharge pumping represent significant scientific challenges. To reach the 50-TW level and beyond in the next decade, development of novel seed architectures for high-energy amplifiers and a shift towards optical pumping are immediately necessary.

3.1) Elevating the seed energy from the 10-µJ to the 10-mJ range: The attainable peak power of current CO_2 CPA amplifiers is limited not only by the achievable pulse energies but also by gain narrowing which results in long output pulses after amplification. In solid-state CPA lasers, gain narrowing can be effectively mitigated through the use of spectral filters within the amplifier or through double-CPA architectures in which the output of a first CPA stage is spectrally broadened to provide a high-energy, broadband seed for the final stage of amplification. In the case of current CO_2 CPA lasers, broadband seed pulses are typically derived from inefficient difference frequency generation (DFG) processes, and the seed pulse energy is therefore limited to the 10-microjoule level. Increasing the seed pulse energy to the 10-mJ level would allow a reduction of the pulse duration by a factor of four, leading to a corresponding rise in peak power to the ~15-TW level. This will require the development of novel mid-IR OPAs based on long-wavelength drivers (see Thrust 1 above) and other efficient frequency conversion techniques to generate energetic seed pulses with 10-micron wavelength and appropriate bandwidth for seeding a CO_2 power amplifier.

3.2) Peak power scaling through nonlinear compression: Further increase of the peak power can be attained through nonlinear compression. Various schemes have been proposed for spectral broadening of CO_2 lasers in a solid or gas-based nonlinear medium, followed by pulse compression to the few-cycle (<100 fs) regime using grating-based pulse compressors. Even with substantial losses expected for the initial demonstrations of these effects, the substantial pulse compression factors from the <ps- to <100-fs level can provide a >2x increase in the peak power, beyond the 25-TW level required for proof-of-principle studies of LWFA. Nonlinear compression techniques are discussed more generally in PRD 3; both established and novel approaches that can yield high compression factors with low losses are desired for CO_2 CPA systems.

3.3.) Optical pumping with kJ-class pump lasers: Attaining >50-TW-class CO_2 CPAs will require more energetic amplifiers, which can likely be achieved only by a transition to optical pumping. For optical pumping of CO_2 amplifiers, it is still necessary to determine the best pump wavelength and platform (e.g., 2.8-micron, Q-switched, ~100-ns $Er:Y_3Sc_2Ga_3O_{12}$ or 4.3-micron, ~100-ns, gain-switched Fe:ZnSe), to demonstrate an optically-pumped mode-locked CO_2 laser in proof-of-principle, and to scale the pump pulse energy to the kJ level, in one or multiple beams. Significant synergies exist with the needs for CO_2 pump sources and the development of Er:YSGG pump sources for Fe:ZnSe amplifiers, and with the development of Fe:ZnSe gain elements for high-energy amplifiers discussed above.

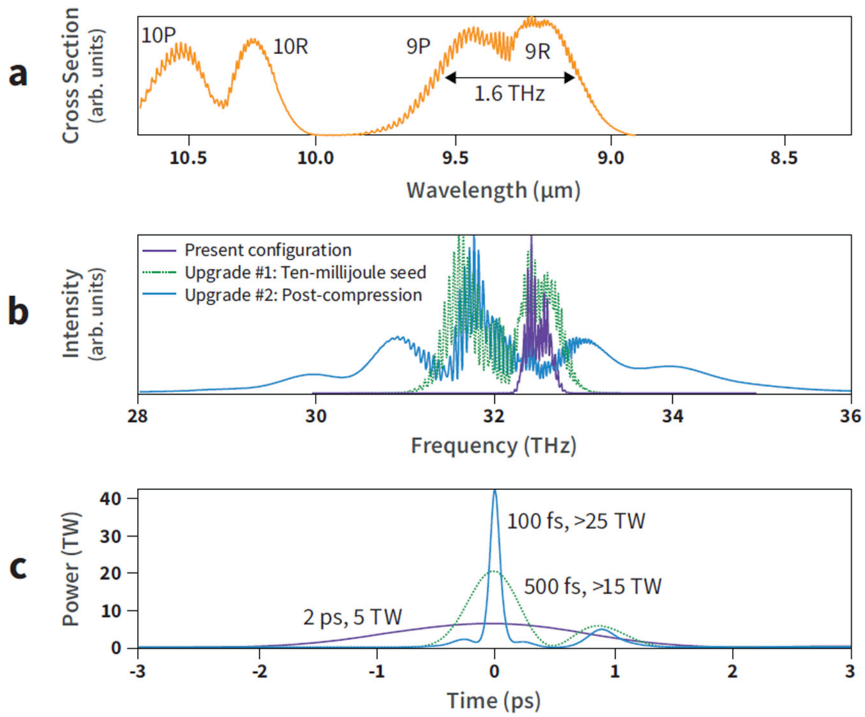

Figure 6. Peak power scaling in CO_2 lasers with high-energy seeding and nonlinear compression. (a) CO_2 gain spectrum, along with (b) spectrum and (c) temporal profile of the multi-terawatt CO_2 laser at Brookhaven National Laboratory's Accelerator Test Facility (BNL ATF) under the present configuration and with upgrades based on increasing the seed pulse energy and nonlinear pulse compression. (Image credit: Mikhail Polyanskiy, BNL, doi:10.18429/JACoW-IPAC2023-THPA177.)

Thrust 4. Stable, waveform-controlled sources spanning the mid-IR to THz

Frequency combs can enable dramatic improvements in molecular spectroscopy and chemical sensing via simultaneous enhancements in sensitivity and parallel detection. Frequency combs at mid-IR and longer wavelengths are particularly attractive due to their overlap with the "molecular fingerprint" region of the electromagnetic spectrum, where their broadband spectra would allow important applications to healthcare, energy, and defense based on trace-gas analysis in complex mixtures [46]. Recent demonstrations of mid-IR to THz frequency comb sources have begun to address some of these applications; however, significant improvements in the peak and average power of comb sources are needed to reach the sensitivity levels of comb-based spectrometers for molecular spectroscopy or to enable novel nonlinear spectroscopy techniques. The development of Type I mid-IR comb sources could have additional impacts, such as enabling sources of X-ray combs via intracavity HHG. Other applications, such as multidimensional spectroscopy, near-field imaging, and time-resolved studies of chemical dynamics, may not necessarily require the repetition rate stability of a frequency comb, but would similarly benefit from the development of high-power, high-repetition-rate Type I sources with highly stable and controllable waveform in the mid-IR.

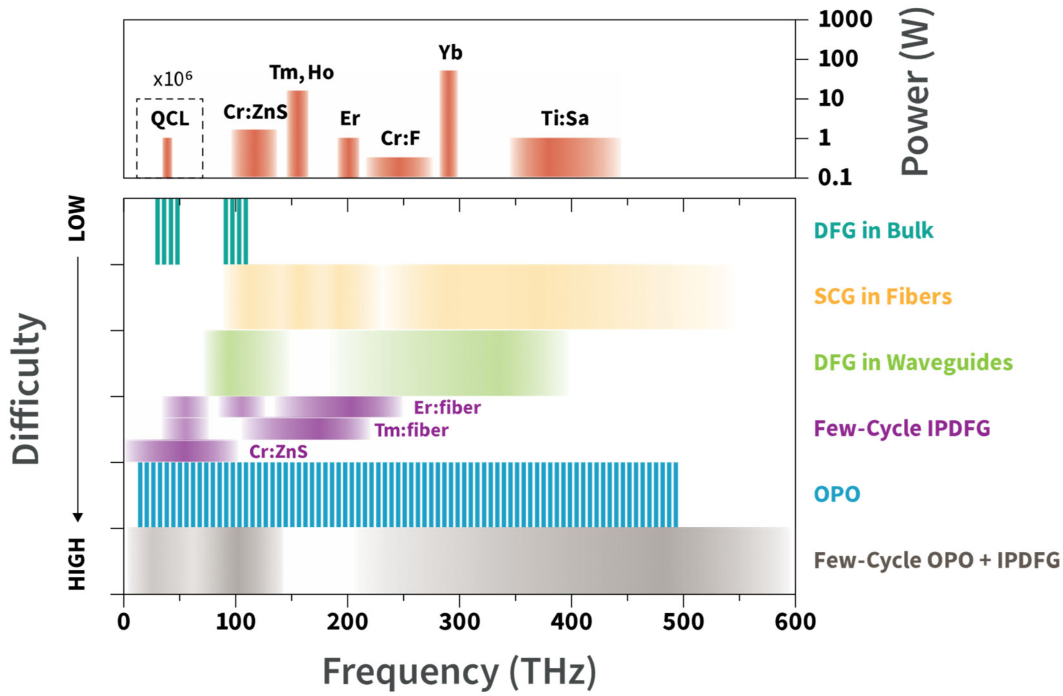

Figure 7. The development of frequency comb sources spanning the mid-infrared to THz spectral region demands high-power frequency comb sources (top) and nonlinear frequency conversion platforms (bottom). DFG: difference frequency generation; IPDFG: intra-pulse difference frequency generation; OPO: optical parametric oscillator; QCL: quantum cascade laser; SCG: supercontinuum generation. Figure adapted from Ref. [47].

The parameter space encompassed by frequency combs is in some ways less extreme than other source development advocated in this PRD. However, "brute force" approaches to power scaling are likely to be incompatible with the demands for stable comb sources with low phase noise. Specific needs are outlined below:

4.1) Full coverage of the fingerprint region: Producing combs that cover in one device the entire fingerprint range of 1–100 THz (3–300 µm) with low phase noise and with an instantaneous comb bandwidth of at least an octave remains a major challenge. Further work is needed to explore the limits that can be reached using low-noise erbium-doped fiber amplifiers seeded by frequency combs at 1.5 micron, followed by nonlinear pulse compression and frequency conversion. Advanced front-end femtosecond mid-IR solid-state lasers (e.g., Cr- and Fe-doped frequency combs) may supplant Er-doped fiber amplifiers (EDFAs) on the decadal timescale, but work is needed to approach the frequency stability allowed by fiber-based sources. For each of these laser platforms, novel approaches to frequency conversion (see PRD 3) may enable dramatic improvements in our ability to cover broad spectral bandwidths.

4.2) Power scaling for sensitivity and nonlinear spectroscopy: Despite significant recent advances in mid-IR to THz frequency comb sources, scientific challenges remain to scale these sources to the levels needed for applications. Even for linear spectroscopy, the sensitivity of comb-based spectrometers is still not competitive with those based on CW lasers. Increasing the power per comb tooth can help a lot, as can further development of mid-IR/long-wave infrared (LWIR) coatings for enhancement cavities. On a decadal timescale, frequency comb sources that can meet the stringent needs for trace-gas sensing using rotationally- and vibrationally resolved 2D-IR spectroscopy, which can allow precision measurements even in the very congested spectral regions that occur in complex mixtures or in the C-H stretch region, would be transformative. Sensitivity estimates indicate the need for power spectral density levels of 100 mW/cm (or about 300 microwatts per comb tooth at a repetition rate of 100 MHz). Considering the bandwidth requirements detailed above, this requires broadband mid-IR combs with an average power of at least 10 W.

In the near term, the development of watt-scale mid-IR combs, combined with enhancement cavities, could bridge the gap.

Several innovative approaches, including subharmonic optical parametric oscillators (OPOs) and amplifiers and efficient OR driven by Cr:ZnS frequency combs, have been proposed and in some cases demonstrated in proof-of-principle. However, moving beyond the demonstration phase to applications will require power scaling of the front-end comb to the kilowatt-level at 1 micron or the 100-W level at a 2.5-micron wavelength, along with the improvements in nonlinear crystal platforms discussed in PRD 4.

SCIENCE AND TECHNOLOGY IMPACT

Advances in mid-IR source technology can provide important platforms for transformational science both through direct spectroscopy and through efficient frequency conversion into shorter- and longer-wavelength regions of the spectrum. Consequently, mid-IR sources are a key enabling technology to address societal challenges related to renewable energy and sustainable chemical synthesis, efficient electronic materials for information storage and processing, and radiolytic applications to nuclear waste remediation and medicine.

Renewable energy, efficient chemical synthesis, and catalysis: The last decade has seen major advances in studies of attosecond dynamics in small, gas phase molecules. Special attention has been paid to investigating wavepacket dynamics at conical intersections, which are critical to understanding and controlling the outcomes of chemical reactions. On a decadal level it would be transformative to extend these studies from simple model systems to biological molecules operating in their native solvation environments and/or catalytic processes occurring at surfaces. However, this requires attosecond XUV sources spanning the soft X-ray region to access a much wider range of elemental absorption edges, particularly those in the water window. Such experiments promise to provide a clear picture of the coupled electronic and nuclear degrees of freedom responsible for guiding chemical reactions along highly selective pathways on complex free energy surfaces. Complementary information is needed from ultrabroadband nonlinear IR measurements including 2D IR and 2D IR-visible spectroscopies. This understanding is required to address pressing societal challenges related to solar energy conversion and sustainable chemical synthesis because fundamentally these processes require designing systems that can direct energy from light into the strongly coupled electron and nuclear motion required for energy conversion and storage via selective chemical synthesis.

Radiation-induced processes on the physicochemical timescale

Imaging the radiation-induced origin of reactive species and their subsequent reactions is a research opportunity enabled by ultrafast X-ray pump-probe methods. Attosecond X-ray pulses of sufficient flux, as currently provided by XFELs, are a requirement to initiate the radiolytic process and synchronized probes over a wide spectral range are required to capture the ultrafast local and subsequent spatially distributed response. Synchronizing the ionizing pump pulses (XUV, soft and hard X-rays) to a variety of probe pulses is necessary to dissect the radiolysis process. Research into mid-IR lasers that can simultaneously produce inherently synchronized ultrafast-ionizing XUV and fingerprint IR probe pulses could be transformative for these studies. Such studies will provide vital information on the earliest stages of material transformation in radiation environments associated with next-generation nuclear energy, legacy waste environmental remediation, space travel, and medical applications [48].

Ultralow-power, ultrahigh-bandwidth information processing

The proliferation of quantum materials with low barriers between multiple metastable states in complex free-energy landscapes invites applications in switching and modulation at extremely high (THz) frequencies and bandwidths and with extremely low energy consumption. Magnonic and magnon-polaritonic signal propagation, rectification and nonlinear mixing, and a host of other linear and nonlinear signal processing capabilities have already been demonstrated at THz frequencies. Advances in these areas made possible by more effective THz field generation for resonant excitation and by stronger IR sources for nonresonant excitation will guide the achievement of drastic reductions in the energy consumption of computational resources, already a significant component of worldwide energy use and projected to increase dramatically in the absence of transformational improvements [49].

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[i] Jan Rothhardt, Stefan Demmler, Steffen Hädrich, Jens Limpert, and Andreas Tünnermann, "Octave-spanning OPCPA system delivering CEP-stable few-cycle pulses and 22 W of average power at 1 MHz repetition rate," Opt. Express 20, 10870-10878 (2012). Rossi, Giulio Maria, et al. "Sub-cycle millijoule-level parametric waveform synthesizer for attosecond science." Nature photonics 14.10 (2020): 629-635. Kyung-Han Hong, Chien-Jen Lai, Jonathas P. Siqueira, Peter Krogen, Jeffrey Moses, Chun-Lin Chang, Gregory J. Stein, Luis E. Zapata, and Franz X. Kärtner, "Multi-mJ, kHz, 2.1 µm optical parametric chirped-pulse amplifier and high-flux soft x-ray high-harmonic generation," Opt. Lett. 39, 3145-3148 (2014).

[ii] N. Ishii, K. Kaneshima, K. Kitano, T. Kanai, S. Watanabe, and J. Itatani, "Sub-two-cycle, carrier-envelope phase-stable, intense optical pulses at 1.6 µm from a BiB3O6optical parametric chirped-pulse amplifier," Opt. Lett. 37, 4182-4184 (2012). M. Neuhaus, H. Fuest, M. Seeger, J. Schötz, M. Trubetskov, P. Russbueldt, H.D. Hoffmann, E. Riedle, Zs. Major, V. Pervak, M. F. Kling, and P. Wnuk, "10 W CEP-stable few-cycle source at 2 µm with 100 kHz repetition rate," Opt. Express 26, 16074-16085 (2018). Tianli Feng, Anke Heilmann, Martin Bock, Lutz Ehrentraut, Tobias Witting, Haohai Yu, Holger Stiel, Stefan Eisebitt, and Matthias Schnürer, "27 W 2.1 µm OPCPA system for coherent soft X-ray generation operating at 10 kHz," Opt. Express 28, 8724-8733 (2020).

[iii] Pia Fuertjes, et al., "Few-cycle 65-µJ pulses at 11.4 µm for ultrafast nonlinear longwave-infrared spectroscopy," Optica 9, 1303-1306 (2022).

[iv] Faming Lu, Peiyu Xia, Yoshiyuki Matsumoto, Teruto Kanai, Nobuhisa Ishii, and Jiro Itatani, "Generation of sub-two-cycle CEP-stable optical pulses at 3.5 µm from a KTA-based optical parametric amplifier with multiple-plate compression," Opt. Lett. 43, 2720-2723 (2018). M. Baudisch, M. Hemmer, H. Pires, and J. Biegert, "Performance of MgO:PPLN, KTA, and KNbO3 for mid-wave infrared broadband parametric amplification at high average power," Opt. Lett. 39, 5802-5805 (2014).

[v] D. Brida, C. Manzoni, G. Cirmi, M. Marangoni, S. De Silvestri, and G. Cerullo, "Generation of broadband mid-infrared pulses from an optical parametric amplifier," Opt. Express 15, 15035-15040 (2007).

[vi] Xun Gu, Gilad Marcus, Yunpei Deng, Thomas Metzger, Catherine Teisset, Nobuhisa Ishii, Takao Fuji, Andrius Baltuska, Rytis Butkus, Volodymyr Pervak, Hideki Ishizuki, Takunori Taira, Takayoshi Kobayashi, Reinhard Kienberger, and Ferenc Krausz, "Generation of carrier-envelope-phase-stable 2-cycle 740-µJ pulses at 2.1-µm carrier wavelength," Opt. Express 17, 62-69 (2009). Nicolas Thiré, Raman Maksimenka, Bálint Kiss, Clément Ferchaud, Grégory Gitzinger, Thomas Pinoteau, Hervé Jousselin, Sebastian Jarosch, Pierre Bizouard, Vittorio Di Pietro, Eric Cormier, Károly Osvay, and Nicolas Forget, "Highly stable, 15 W, few-cycle, 65 mrad CEP-noise mid-IR OPCPA for statistical physics," Opt. Express 26, 26907-26915 (2018).

[vii] Bo-Han Chen, Emanuel Wittmann, Yuya Morimoto, Peter Baum, and Eberhard Riedle, "Octave-spanning single-cycle middle-infrared generation through optical parametric amplification in LiGaS2," Opt. Express 27, 21306-21318 (2019).

[viii] T. Fuji, N. Ishii, C. Y. Teisset, X. Gu, Th. Metzger, A. Baltuska, N. Forget, D. Kaplan, A. Galvanauskas, and F. Krausz, "Parametric amplification of few-cycle carrier-envelope phase-stable pulses at 2.1 µm," Opt. Lett. 31, 1103-1105 (2006). Nicolas Thiré, Raman Maksimenka, Bálint Kiss, Clément Ferchaud, Pierre Bizouard, Eric Cormier, Károly Osvay, and

Nicolas Forget, "4-W, 100-kHz, few-cycle mid-infrared source with sub-100-mrad carrier-envelope phase noise," Opt. Express 25, 1505-1514 (2017). N. Bigler, J. Pupeikis, S. Hrisafov, L. Gallmann, C. R. Phillips, and U. Keller, "High-power OPCPA generating 1.7 cycle pulses at 2.5 µm," Opt. Express 26, 26750-26757 (2018).

[ix] T. Fuji, N. Ishii, C. Y. Teisset, X. Gu, Th. Metzger, A. Baltuska, N. Forget, D. Kaplan, A. Galvanauskas, and F. Krausz, "Parametric amplification of few-cycle carrier-envelope phase-stable pulses at 2.1 µm," Opt. Lett. 31, 1103-1105 (2006). X. Zou, W. Li, H. Liang, K. Liu, S. Qu, Q. J. Wang, and Y. Zhang, "300 µJ, 3 W, few-cycle, 3 µm OPCPA based on periodically poled stoichiometric lithium tantalate crystals," Optics Letters 44, 2791-2794 (2019).

[x] Tianli Feng, Anke Heilmann, Martin Bock, Lutz Ehrentraut, Tobias Witting, Haohai Yu, Holger Stiel, Stefan Eisebitt, and Matthias Schnürer, "27 W 2.1 µm OPCPA system for coherent soft X-ray generation operating at 10 kHz," Opt. Express 28, 8724-8733 (2020).

[xi] Tsuneto Kanai, Pavel Malevich, Sarayoo Sasidharan Kangaparambil, Kakuta Ishida, Makoto Mizui, Kaoru Yamanouchi, Heinar Hoogland, Ronald Holzwarth, Audrius Pugzlys, and Andrius Baltuska, "Parametric amplification of 100 fs mid-infrared pulses in ZnGeP2 driven by a Ho:YAG chirped-pulse amplifier," Opt. Lett. 42, 683-686 (2017). U. Elu, et al, "Table-top high-energy 7 µm OPCPA and 260 mJ Ho:YLF pump laser," Opt. Lett. 44, 3194-3197 (2019).

PRD 3 Revolutionize Approaches to Frequency Conversion and Field Control

Key Questions: Can we advance laser light manipulation with bandwidth efficiently extended from deep ultraviolet to THz ranges, employing all ranges simultaneously and with exquisite control of field structure? Can we synchronize these sources to secondary radiation and particle beams? Is it possible to simultaneously greatly reduce the complexity of laser systems, making them accessible, affordable, stable, and robust?

INTRODUCTION

Over the past several decades, science based on ultrafast optical pulsed sources has made great strides through the development of concepts that extend the boundaries of optical field complexity and spectral coverage and allow synchronization with X-ray and particle beams. Today, experiments demand the incorporation of multi-octave bandwidth or multi-color pulse sequences in greatly disparate spectral ranges, with increasingly complex spatiotemporal and polarization structure and with radiation spanning XUV through THz frequencies. Pulsed and continuous wave (CW) lasers operating at a wide range of wavelengths in disparate spectral ranges with high-efficiency could enable atomic manipulation applications including those for national security (pump sources for pulsed lasers, stable and radioisotope separation/isolation, spectroscopic tools, etc.). The component technologies addressed in this PRD are the nonlinear and linear optical methods that extend the reach of lasers to achieve this. These include wavelength extension devices; devices for nonlinear post-compression techniques, CEP control, passive and active pulse and beam shaping, orbital angular momentum (OAM) generation, and complex polarization structuring, which are applied both to laser sources and to waveform-extended sources; dispersion management devices; optical to secondary source synchronization devices; and the technologies needed for waveform synthesis.

Over the next decade, emergent fields of science—such as investigating the dynamic aspects of condensed phase physics, achieving multimodal control of molecular and material systems far from equilibrium, and creating brighter and full phase-space programmable electron beams for visualizing dynamic states of matter—will depend heavily on achieving even greater spectral coverage and field control [49-53]. This PRD addresses these challenges. We believe success will happen not only by transcending the current state of the art, but by simultaneously reducing complexity of the systems used. Such complexity limits access to these advanced technologies to the technical specialist. A truly revolutionary approach will not only make technology more effective but also will significantly simplify it, making it more robust, affordable, and stable, and thus more accessible.

Technologies for frequency conversion and field control

Today, the scientist who employs advanced lasers also relies on a great number of technologies developed to extend their reach. Historically important areas of development have included the hollow capillary fiber compressor [54], which allowed the gain-narrowed spectra of millijoule-class Ti:sapphire chirped-pulse amplifiers to be re-broadened, providing amplified pulses of only a few cycles in duration. This opened the university laser lab to gas-phase ionization and electron recollision physics as well as relativistic laser-plasma physics on few-cycle timescales. The further invention of active CEP stabilization allowed fine control of field-driven electron acceleration within the optical cycle, making isolated attosecond pulse generation feasible and opening the door to sub-cycle timescale metrologies [55-57] that are otherwise only routinely possible at far lower (THz) frequencies. OPCPA [58] and other nonlinear optical techniques, including optical parametric oscillation, up- and down-conversion, OR, and four-wave mixing, allowed the extension of Ti:sapphire technology to few-cycle sources with wavelength ranging from the deep ultraviolet (DUV) to THz. These technologies, in tandem with acousto-optic-based pulse shaping at up to 10-kHz speeds, enabled new optical pump-probe and multi-dimensional spectroscopies that drove a wealth of discovery in femtosecond-scale evolution dynamics of electronic and vibrational structure in materials and molecules. Meanwhile, laser-driven photoinjectors have allowed ultrafast time-resolved experiments involving the synchronization of optical pulses with X-ray or electron pulses, which have revealed insights into gas-phase chemistry, condensed matter phase transitions, and structural biology. These tools provide guidance toward driving transformations selectively and efficiently by accessing matter far from equilibrium. Recently, multi-color experiments, often linking a near-IR primary source with an extended wavelength to cover an octave or more of bandwidth in contiguous or disparate spectral ranges, have allowed probing of more complex phenomena, including the coupling of excitonic phenomena with vibrational degrees of freedom, the evolution of excited state wavepacket dynamics in nonadiabatic transitions, and the effects of THz/far-IR excitation of quantum materials on electronic band structure and optical properties. The further extension of multi-color pulses to synthesized field transients at single- to sub-cycle duration based on coherent wavelength multiplexing has offered a new glimpse into the possibilities of 'lightwave electronics' and has been used to steer electrons in gas-phase and condensed-phase systems with sub-femtosecond precision [59].

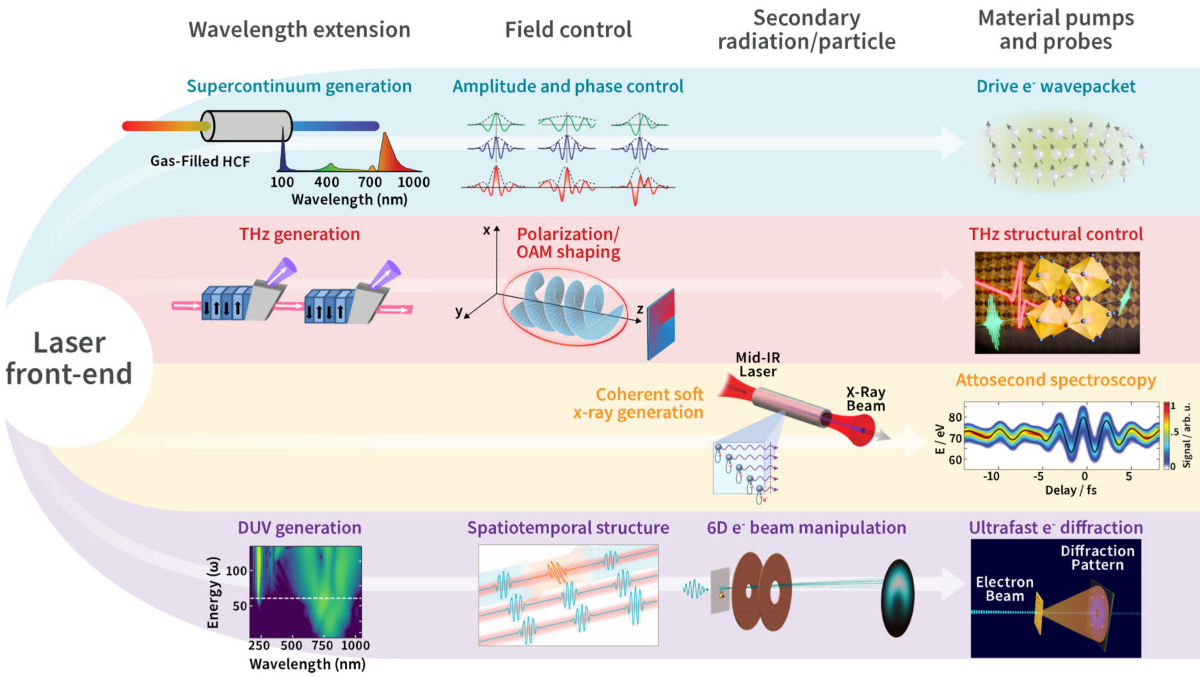

Figure 8. Enabling a transformative study of material physics through wavelength extension, field control, and secondary radiation and particle generation. A precisely shaped ultraviolet/visible continuum selectively controls an electron wavepacket in a condensed matter sample while polarization-shaped bright THz controls its structure; synchronized coherent soft X-rays allow attosecond transient absorption to probe changing electronic structure, while six-dimensional (6D)- electron beam control with spatiotemporally structured deep ultraviolet (DUV) light enables a simultaneous advanced ultrafast electron diffraction probe. While some of these capabilities are already possible, achieving all of them simultaneously represents a decadal challenge requiring new standards in efficiency, technological simplicity, synchronization, and precision. Success will enable transformative science and progress in the control of matter. OAM: orbital angular momentum. (Image credits from left to right: *top row* Alexandra Feinberg, SLAC National Accelerator Laboratory; C. Manzoni et al (2015), Laser & Photonics Reviews, 9: 129-171. https://doi.org/10.1002/lpor.201400181; Markus Münzenberg, Universität Greifswald; *second row* Lu Wang et al. Optics Express Vol. 26, Issue 23, pp. 29744-29768 (2018); Sergio Carbajo; Maximilian Frenzel, FHI; *third row* T. Popmintchev et al. PNAS Vol. 106 No. 26 June 30, 2009 PubMed: 19541611; Matthias Kling; *bottom row* Christian Brahms and John C. Travers, Journal of Physics: Photonics, DOI 10.1088/2515-7647/ac6345; R. Lemons et al. Integrated structured light architectures. Sci Rep 11, 796 (2021) https://doi.org/10.1038/s41598-020-80502-y; J. Pettine et al. Nature Communications 11, 1367 (2020). https://doi.org/10.1038/s41467-020-15115-0; Greg Stewart, SLAC National Accelerator Laboratory.)

Scientific drivers for the next decade and beyond

Revolutionary advances in the laser extension technology described above will drive transformative scientific advances in the coming decade.

Understanding and controlling the dynamical aspects of condensed phase physics with UV and long-wavelength light and enabling light-wave electronics:ith revolutionary advances to ultrafast sources of light from UV to THz, there will be transformational opportunities for the probing and control of condensed phase dynamics.

Sub-femtosecond UV pulses tuned to the electronic band gap of wide-gap semiconductors are the prime tool to excite the fastest electronic wavepackets in the condensed phase. These can be used to boost our understanding of the dynamical aspects of condensed phase physics [59, 60]. At the same time, such wavepackets are the shortest electronic signals and serve as a platform for ultrafast integrated optoelectronics. Moving beyond the ro-vibrational spectroscopic characterization of materials, single-cycle waveforms as impulsive excitations will lead to the inclusion of electronic degrees of freedom as fingerprint signatures in spectroscopic techniques, providing a new degree of specificity including the electronic state and its transients.

Intense single-cycle or tunable multi-cycle mid-IR and THz fields will also present opportunities for revolutionary control of materials by driving them along specified pathways toward far-from-equilibrium and metastable configurations. With increased ponderomotive energy as well as the strongly reduced probabilities for unwanted nonlinear responses or damage induced by multiphoton absorption, stimulated Raman scattering and higher-order excitation processes using long-wavelength pulses may provide the basis for collective multimodal control over key coupled degrees of freedom, where early efforts using visible pulses could not. Currently, most nonlinear spectroscopy involving resonant phonon, magnon, and low-frequency electronic modes is conducted in the low-order perturbative regime. In some favorable cases, higher-order responses including structural, electronic, and magnetic phase transitions or domain switching have been achieved [61,62]. These responses have been driven in each case by nonlinear THz field interactions with individual modes. With intense, single-cycle and multi-color long-wavelength sources, we anticipate collective coherent control, in some cases guided by AI-driven searches across multidimensional parameter spaces, enabling guided transformations across multiphase landscapes in quantum materials of intense current interest and ultrafast domain switching and phase transitions in conventional ferroelectrics and other materials as well. This will yield applications in ultrahigh-bandwidth reversible switching and modulation of electrical, magnetic, and optical properties; generation of metastable phases and domain orientations that can serve as control or memory elements; and discovery of new phases that have not been reached through conventional temperature or pressure variations.

Understanding the first steps of photochemical transformations with ultrashort UV pulses: Elementary events that determine photochemical outcomes and molecular functionalities occur on femtosecond and sub-femtosecond timescales. Real-time imaging of such light-induced processes are being accelerated by recent developments in ultrafast molecular imaging techniques, such as soft X-ray transient absorption [63], ultrafast X-ray [64] and electron [65] diffraction, time-resolved photoelectron spectroscopy [66] and Coulomb explosion imaging (CEI) [67]. However, right now, such breakthrough experiments are severely limited by the lack of reliable and accessible lasers in the UV domain that match this critically important part of the sunlight spectrum and that have pulse durations short enough to monitor the first, decisive steps of chemical transformations. Typical instrumental time resolution for pump-probe experimental observations of light-induced chemistry [63-66] have been ~100 fs, of which a large fraction derives from the UV-pump laser pulse duration itself. Reliable, tunable UV pulses (<10 fs), synchronized to X-ray probing tools can be transformational for this research field.

Probing and control of molecular systems via strong-field and attosecond domain techniques: The availability of a broad spectrum of intense, ultrafast radiation by frequency conversion methods proposed in this PRD will enable new time domain techniques for selectively exciting and probing electrons, vibrations, phonons, and spins. With these tools, we can deduce how the coupling of the various degrees of freedom is responsible for an evolution of physical properties and address challenges in quantum materials, light-spin interactions, and complex heterogeneous environments. For attosecond transient absorption, where XUV and soft X-ray probe pulses provide element specificity, extension of tabletop pump sources to frequencies beyond the UV through the near-IR will expand science to cover new functionalities. For solid-state HHG, where electrons can be driven to different momenta in k-space to provide sensitivity to electronic band structure on ultrafast timescales, present pump-probe experiments have been limited to simple above-bandgap excitations. The incorporation of mid-IR and THz pump wavelengths at higher repetition rates with stable CEP will vastly expand the impact of the technique for the study of quantum materials. For XUV SHG spectroscopy, experiments at XFELs have demonstrated surface sensitivity, elemental specificity, and the ability to probe buried interfaces. The ability to perform these experiments on tabletop laser systems, as opposed to large scale facilities, is contingent upon the development of short-wavelength sources with GW peak powers.

6D-phase-space programmable electron beams: The proliferation of photoinjector-based electron instruments is driven by their applicability to QED, high energy physics, ultrafast science, and medical radiation technologies. From large-scale facilities and advanced accelerator beamlines, electron-based colliders, and XFELs, to laboratory-scale instrumentation such as ultrafast electron diffraction or transmission electron microscopy, free electron generation in a photoinjector is the first and foremost significant predictor of instrument performance either as a stand-alone electron beam source or for accelerator-based light and novel particle sources. A foundational strategy for tailoring the electron bunch phase space for greater performance and brightness is to control the shape of the optical pulses used in photoemission. Coherent multi-momenta-state and electron wavepackets longitudinally modulated at optical and sub-optical frequencies will enable novel superradiance or parametric secondary radiation processes as well as technologies for driving and reading quantum states in condensed matter. Single-cycle waveforms will equip electron and tunneling microscopy with transformative temporal resolution.

SCIENTIFIC CHALLENGES

The capacity and complexity of laser systems underpinning such a broad breadth of scientific and technological progress has grown tremendously over the last decades. Many of the examples given above are 'hero' experiments that have unveiled new frontiers of scientific inquiry, but are extremely challenging and costly, limiting accessibility and thereby also limiting transformative breakthroughs in science. As the needs of the ultrafast science community for the next ten years' time are even more demanding, this problem will only grow if research is not prioritized to address it. We note, however, that historically some of the most revolutionary discoveries in ultrafast science managed, paradoxically, to simplify the technology while simultaneously extending the complexity and control of the light field structures. For example, the discovery of the Kerr-lens mode-locked (KLM) Ti:sapphire laser and its subsequent commercialization in the 1990s made few-cycle duration laser pulses commonplace in laboratories, replacing active mode-locking and dye-laser systems that required great expertise to use and maintain. The emergence of noncollinear optical parametric amplification (NOPA) allowed Ti:sapphire-like ultrabroad gain bandwidth to be extended to new frequency ranges, averting the need to develop laser materials to cover all parts of the spectrum.

A decadal challenge of the field is to achieve the needed major advances in frequency conversion and field control technology while simultaneously greatly reducing the complexity of the tools, making them accessible, affordable, stable, and robust. Such advancements will build a strong market for state-of-the-art ultrafast laser technologies while allowing strong growth of the workforce that use them along with it. They will also build U.S. strengths in component technologies that will have applications in many fields of research and industries. And as is always the case, the scope of the science that is imaginable significantly grows when new, advanced technology is made commonly accessible.

To achieve these advancements, basic research is needed to establish new concepts. Some specific challenges addressed in the thrusts below include stretching the territory that exists for optical techniques to probe and control matter on ultrashort timescales to include all ranges from XUV to THz simultaneously with exquisite control of field properties. Applications also demand greater average power, requiring use of newer diode-pumped high average power lasers as the front end for wavelength extension. Linking many of the challenges of the thrusts described below are opportunities to make use of the current mature state of

1-micron wavelength solid-state diode-pumped laser technology, which provides both high peak and average power (see PRD 1 for the decadal challenges involved in pushing this technology even further) and the emerging technologies at a 2-micron wavelength and beyond (see PRD 2). More efficient, flexible, multi-faceted, and simple approaches for extending these sources to meet the future needs of science are required. To surpass the current and projected momentum space limitations of photoinjected charged-particle beams, tunable, spectrally- and spatio-temporally tailored laser pulses from picosecond durations down to single-cycle duration in the UV-to-visible range will be needed. This exemplifies the great challenge of requiring field control along many degrees of freedom simultaneously, one of the main challenges facing technology development over the next decade for the advancement of science.

RESEARCH THRUSTS

Thrust 1. Frequency extension in fibers and gasses

Frequency extension, by conversion to new wavelengths or through spectral broadening, is the method by which ultrafast and high-power laser systems are extended to wavelengths that do not fall within the gain spectrum of established lasers. Relevant lasers are well developed in the near-IR (PRD 1) and are emerging in the mid-IR (PRD 2). Nonlinear optics allows extension of these sources to frequencies from DUV through THz and to greater than octave-spanning bandwidths (as needed, e.g., for 36evelop36e electronics and the coherent control of wavepackets in solids and molecules). Gas-core fibers and guided-wave (or quasi-guided-wave, e.g., Herriot cell cavities) structures offer key advantages for solving present-day and decadal challenges. They greatly simplify alignment and delivery of light and thus constitute an important platform for reducing complexity and improving robustness. Gas-core fibers and gas-filled cavities can accommodate high peak and average powers, can possess an extended transmission window allowing conversion between disparate frequency ranges or generation of ultrawide bandwidths. Structured air-core fiber, such as anti-resonant hollow-core fiber (AR-HCF) can possess tailored high transmission bands and dispersion. This thrust addresses needed R&D of techniques for frequency up- and down-conversion and spectral broadening for the direct extension of the frequency range of laser sources. Concepts that can transform such technology include:

1.1) Up- and down-conversion based on four-wave mixing (FWM): Unlike many nonlinear optical approaches, FWM allows the creation of a copy of an optical wave, preserving properties such as spectral amplitude and phase, while translating it to a new frequency range, potentially simplifying the design of multi-color laser systems with near-IR front ends. The development of up- (to visible/UV) and down-conversion (to mid-IR) methods based on FWM in noble gas-filled hollow-core fibers (HCF) provide an opportunity to extend this method to the 100-W level and higher average powers while mitigating beam-quality distortion and material damage [68, 69]. The wide transparency window of gasses (avoiding the low-energy electronic resonances in the UV and convoluted multi-phonon resonances in the mid-IR of solids) combined with the ability to tailor waveguide dispersion through design of fiber dimensions and structure (for example, by using AR-HCF) present an opportunity to provide ultrawide phase-matching bandwidth. The tapering of fibers allows longitudinal control of dispersion and intensity, which can be used to further control nonlinear wave-mixing evolution and widen phase-matching bandwidth. FWM in mixed gasses may provide dynamic control of the nonlinear interaction to tailor the spectral and temporal shape of the generated pulses.

1.2) Up-conversion based on dispersive wave generation: DUV generation in solids is severely handicapped by above-bandgap absorption. Resonant dispersive wave (RDW) generation in gas-filled fibers offers a route to reach ~1–10-fs pulses in the DUV. A challenge to reaching the sub-femtosecond duration needed for applications is the complexity of needing to cascade several fibers when the input is a 10-fs near-IR wave. To date, RDW generation has been done with only a few laser platforms (800 nm, 1030 nm). Mid-IR drivers (as targeted in PRD 2) would allow the RDW to be tuned into the visible (currently confined to the UV/DUV).

1.3) Spectral broadening in fibers and Herriot cells: Post-compression techniques in capillary fibers has been a workhorse for the field, allowing efficient mJ-scale energy compression down to few-cycle duration at 800 nm and 1.8 microns at up to 100-W average power. However, Yb- and Ho-doped solid-state lasers, with sub-ps to ps duration, require greater compression ratio, and have pulse energy and/or average power that can greatly surpass this current state of the art. It remains an important challenge to scale peak powers beyond 1 TW and eventually surpass 10 TW at kW-scale average power, delivering few-cycle duration with preserved CEP stability. Herriot cells are already commercially available for Yb solid-state laser post-compression techniques, delivering 200-mJ, 40-fs pulses at up to kW average power. Importantly, can these be extended to few-cycle duration? Moreover, can they be extended to cover the extreme energy and power specifications of emergent lasers (PRDs 1 & 2), all while maintaining high efficiency, CEP stability, and pristine beam quality? These challenges will require a combined basic research and engineering approach and will rely on the development of high fluence and intensity optical components (PRD 4). Serrodyne approaches and deep-learning algorithms may offer solutions. Extending these post-compression technologies to short (UV/Vis) and long wavelengths (mid-IR) stands as an additional challenge.

1.4) Raman generation and amplification: Raman-enhanced spectral broadening can provide very broad bandwidths, allowing single-stage compression of 100s of fs to few ps lasers. A negative chirped output allows compression with normal dispersive materials, allowing a simple architecture. Important challenges include the investigation of long-wavelength generation (both in the middle-wavelength infrared/MWIR and LWIR), where high vibrational frequency gasses such as hydrogen and methane may be beneficial, and scaling to average powers above 10 W. The latter issue may be solved through the engineering of novel nonturbulent gas delivery approaches to rapidly remove heat, but fundamental modeling of thermal processes will be key [70]. Raman amplifiers are also important to support national security applications including next generation laser isotope separation applications with high electrical-to-optical efficiency.

In order for these methods to become impactful, emphasis must be placed on robustness, stability, ease of alignment, efficiency (see Thrust 2), flexibility to incorporate shaping and structuring methods (spectral phase, spatiotemporal, OAM, and polarization) (see Thrust 3), and simplicity in integration with laser architectures (see Thrusts 4 and 5).

Thrust 2. Efficient nonlinear optics (NLO) methods surpassing quantum defect

This thrust addresses the often severe inefficiency of nonlinear optical conversion methods, which leads to great complexity of extended wavelength sources, requiring higher-power pump sources and complex chains of amplifiers that deteriorate robustness and significantly increase the dollar per photon cost. Most importantly, this inefficiency handicaps long-wavelength science—preventing a clear roadmap for applications such as LWPA and other high-field science applications that can benefit from increased ponderomotive energy and particle current capacity at long wavelengths but must make up for order-of-magnitude scale power losses during frequency conversion.

Inefficiency may stem from incomplete conversion of a pump source or due to a quantum defect, i.e., the energy lost per photon to an unwanted idler. The former issue, a result of non-saturating conversion, can be mitigated through shaping of a beam to remove inhomogeneity in both space and time, an approach that is, however, impractically lossy for sub-ns pump sources, or partially through waveguiding, though this approach is limited to lower energy pulses. Non-saturating conversion also results in efficiency that scales unfavorably with gain, which necessitates pre-amplifier/power-amplifier architectures that add to complexity. The latter issue, the quantum defect, plagues long-wavelength applications. For example, quantum defect-limited efficiency for conversion from Yb-doped solid-state lasers to 1-THz frequency is only 0.33%. Transformative solutions for the next decade will include:

2.1) Nonlinear conversion methods that provide saturating evolution dynamics: The cyclic nature of nonlinear wave-mixing evolution dynamics is at the root of inefficiency as well as limitations to conversion bandwidth. The length of a conversion medium must be chosen to coincide with the peak of the conversion cycle. Beyond this length, nonlinear conversion reverses. However, laser beams and pulse profiles are naturally bell-shaped, and the optimal length for conversion varies along the spatiotemporal dimensions, preventing uniform conversion. This problem can be solved through concepts that prohibit back-conversion, providing monotonic or quasi-monotonic (i.e., saturating) conversion evolution dynamics. Already, techniques that alter the normal wave-conversion physics of OPA/OPCPA, such as idler elimination and coherent subharmonic generation [71–74], show the promise of achieving high conversion of the pump (quantum efficiency). In the next 1–5 years, these and other yet undiscovered techniques must be developed and investigated in order to allow solutions that can reach the full wavelength tunability, few- to single-cycle bandwidth, energy, and average power specifications demanded for applications.

2.2) Surpassing the limitation of the quantum defect: An OPA that amplifies 10-micron pulses with an Yb solid-state laser driver only delivers one tenth of the pump energy per converted photon. Conversion of the same laser to a 1-THz frequency via OR delivers only 0.33% of the energy per photon. Pushing into the 5–10-year timeframe, methods must be established that can efficiently recover energy lost to the quantum defect, providing a route to surpassing quantum-defect limited efficiency with an ultimate goal of near-100% energy conversion from a pump source to a longer wavelength. New techniques such as cascaded OR have surpassed the quantum defect for THz generation but still produce efficiencies of only ~1% [75]. To improve OPA/OPCPA efficiency beyond the quantum-defect imposed limit, idler elimination methods mentioned above that can efficiently re-use idler energy can be developed. These cascaded techniques, however, can increase complexity by necessitating many stages of conversion or incident pulse shaping. Methods that can allow multiple cascades of idler reuse in a monolithic device will be key to architectures that are simultaneously efficient and robust.

Thrust 3. Field-control across the spectrum

This thrust addresses shaping of the spatiotemporal properties and polarization of light across the spectrum, ranging from the DUV to the THz domain, including techniques that can transfer shaping from the optical into the XUV and X-ray ranges. Spatial waveform shaping can be performed using bulk optics, custom phase plates, optical fibers and other waveguides, and plasmonic nanostructures. Active shaping can be enabled by spatial light modulators, acousto-optic modulators, or deformable mirrors. Spatiotemporal shaping can be performed with line-by-line shaping and time-to-spatial domain transforms (e.g., time lens). The thrust also includes multi-spectral sources for coherent spectroscopy and arbitrary waveform synthesis of super-octave spectra obtained after spectral broadening or coherent combination of beams at different central frequencies, to enable the control of light's interaction with matter down to sub-cycle time scales and enable material control and probing schemes covering many degrees of freedom simultaneously. Multi-spectral sources and multi-octave continuous spectrum sources as generated by waveform synthesis pose significant difficulty in the design of optics for dispersion control, such as multilayer optics. Active techniques, such as 4f pulse shaping and acousto-optic programmable dispersive filtering are limited in bandwidth, efficiency, and power handling, making them techniques that must be integrated early in an amplification system, increasing complexity and introducing post-shaping distortion. Waveform synthesis also addresses challenges in achieving a highly stable synthesized waveform, with controlled intensity noise, absolute CEP, and timing of constituent components. Finally, achieving spatiotemporal and polarization structural control of such ultrawideband sources is a challenge not yet addressed.

Several key challenges prompt new R&D to reach the capabilities demanded for transformative science:

3.1) Ultrawide shaping methods at up to extreme powers: The active devices listed above are limited in one or more of efficiency, frequency range, bandwidth, repetition rate, and degree of control. For high power and high intensities, only a subset of these technologies, both active and passive, are suitable. Basic research in the development of new coatings and materials for ultrawide shaping devices to accommodate high average powers and intensities at each of the constituent wavelength ranges desired is needed (see related thrusts in PRD 4). Such R&D applies to, e.g., cutting-edge fiber and waveguide technology, and gratings/prisms/high-power metasurfaces/unique dispersion compensation devices. An additional challenge for multi-octave waveform synthesis will be to enable smoother and wider spectra while also scaling up in repetition rate and average power, which will enable much new science.

3.2) Transformative solutions for waveform shaping in the UV and mid-IR: Wideband temporal shaping methodologies are well established in the near-IR spectral range. However, relative bandwidth is greatly reduced in most up-conversion processes. This dramatically limits the range of spectral shaping in the visible and UV. In the case of DUV and shorter wavelengths, even in the absence of bandwidth limitations, the photon energy range lies right on most materials' electronic transition energies. This makes UV absorption and UV-induced permanent or catastrophic materials damage nearly unavoidable at moderately low power and peak fluence levels, of the order of sub-W and few-W/cm^2, respectively, which further reduces not only the capacity to shape but also to deliver laser pulses to the application. Solutions are needed to tackle these challenges. For both down- and up-converted sources, dispersion management can be prohibitively complex for robust operation, especially when frequency ranges are combined for multi-spectral and multi-octave architectures. This can be solved potentially by frequency conversion methods that can incorporate shaping intrinsically, such as FWM in structured fibers with custom-designed dispersion profile and aperiodically poled quasi-phase matching devices that can impress a custom dispersion profile.

3.3) Generating OAM and other complex field structure: Spatial wavefront shaping can be performed with spatial light modulators, deformable mirrors, bulk optics, custom phase plates, and fibers, waveguides and plasmonic nanostructures. However, for high power and high intensities, only a subset of these technologies is suitable. One workhorse, spatial light modulators, struggles in this space. Fibers, in particular hollow-core fibers [76], are especially promising for OAM generation [77, 78] and other wavefronts, as they provide both a phase and amplitude filter. Nanostructured devices (e.g., metasurfaces) may provide an alternative if they can be developed to withstand high powers and intensities. Temporal wavefront shaping can be performed with line-by-line shaping, and by time-to-spatial domain transforms (e.g., time lens). Spatiotemporal vortices have recently been demonstrated from several groups, for example from 4f shapers [79, 80]. Efficient shaping solutions are required not only for scaling to high powers and intensities, but also for covering the full DUV-THz spectrum.

3.4) Non-separable control across all degrees of waveform structure: While many techniques exist for controlling field structure along a single axis (temporal, spatial, OAM, polarization structure), a decadal challenge is to create concepts for full, non-separable control over all dimensionalities and degrees of waveform structure, and over ultrawide bandwidth, at up to the intensities needed for strong-field and relativistic light-matter interactions. This will also include the development of single-shot diagnostics that can capture non-separable aspects of complex structure (PRD 1).

3.5) Solutions for shaping X-ray beams via optical methods: X-ray free electron laser technology has transformed X-ray light sources but has yet to approach the degree of phase space control achievable in the optical domain because of the stochastic nature of self-amplification of spontaneous emission (SASE). Pioneering work has highlighted the role high-power laser manipulation of relativistic electron beams can have on the SASE and the resultant X-ray laser pulses [81]. The ability to manipulate the spatiotemporal properties of the X-ray laser through the light generation process is critical because of the limited capabilities and tremendous cost of X-ray optics. Significant improvements in temporal control would enable optics-free multidimensional X-ray spectroscopies and spatial control would provide a new pathway to solving the phase problem in coherent diffractive imaging (CDI). A compelling goal for time-spectral pulse shaping of X-rays is to create multiple pulses where the relative phase of the pulses is controlled at a platform for nonlinear X-ray spectroscopy [81, 82].

Thrust 4. Understanding integration and driving technology democratization

To a significant degree, the challenge of making accessible sources that are advanced in electromagnetic field control and/or wavelength extension is the many-parameter complexity of the system architecture. Advanced optical modeling and new optimization approaches are needed to explore laser sub-system integration that escapes human intuition. Integrating complex laser systems with multiple sub-components and functionalities requires highly skilled expertise, careful planning, and often inaccessible testing to ensure design performance. The associated costs and complexities can also impose significant barriers to practical development and research timelines. In particular, varying mode-locking mechanisms, amplification and gain conditions, spectro-temporal shaping, nonlinear conversion stages, and feedback systems can be challenging to modularize and integrate as it is not always straightforward to model and measure which configurations may yield optimal results.

Fully integrated and physically accurate modeling and data-driven approaches are needed to tackle the optimization of system architecture involving wavelength extension and field control (see PRD 1, Thrust 6.4, for ML and data handling for integration with rapid feedback that specifically tackles laser performance) to reduce complexity while increasing stability and electromagnetic field control capabilities across the spectrum. Success in this area will help to democratize complex technology, making it accessible to the non-expert. In particular, technical areas of specific interest include the integration of hybrid high-speed feedback for electromagnetic field control (e.g., waveform synthesis, spatio-temporal shaping, or wavefront), ML-assisted data handling for rapid feedback integration, and physics-informed (recurrent) neural networks for the design or prediction of transformative laser architectures with wavelength extension and field control.

One example of where such an approach is needed is to address the complexity of current mid-IR sources (see PRD 2 and Thrust 2 above), which limits achievable stability. Accurately and efficiently modeling modularized laser pulse shaping and frequency extension architectures is challenging because of the multitude of coupled linear and nonlinear processes and high variability in simulation frameworks. Another example is spectro-temporal shaping, which requires precise manipulation of laser pulses in both time and frequency domains, which may involve the use of specialized optics and pulse shaping techniques. These techniques are often optical damage limited and thus limit their use prior to pre-amplification and pre-nonlinear conversion stages, which further curtails their shaping capacity. Nonlinear conversion stages introduce additional complexities, such as the amplification of noise. Fully integrated and physically accurate modeling and data-driven approaches are key to enabling emerging (self-)optimization, inverse design approaches, or data-driven ML methods. Examples of advanced ML techniques for augmenting nonlinear optical simulations include long short-term memory (LSTM) models [83, 84], physics-informed neural networks (PINN) [85], hybrid approaches [86], and Fourier neural operators (FNO) [87].

Thrust 5. Novel approaches to sub-femtosecond synchronization to XFELs and particle sources

Together, the wavelength-extended sources addressed in this PRD and in PRD 2 are projected to produce light spanning the THz to soft X-ray ranges but will fall short of the intense Angstrom-wavelength, attosecond pulses provided by existing XFEL sources [88]. To utilize the full potential of XFELs in concert with the extended-wavelength, laser-based pump sources for the study of light-induced processes on atomic length and timescales, a precise synchronization between the independently generated laser and X-ray pulses is required. This has been a persistent issue since the dawn of the XFEL era. Current state-of-the-art arrival-time measurement of an external pump pulse with an X-ray pulse is ~10 fs [89]—a value that is far short of the potential time-resolution afforded by a perfectly synchronized laser pump with the recently available attosecond X-ray probe.

To date, methods used for optical/X-ray arrival-time measurement have been based upon either X-ray-induced changes in optical properties of a material (index of refraction) that are spatially or spectrally encoded, or, via photoelectron angular streaking from a gas phase target, i.e., the "attoclock" method. Both allow a shot-by-shot measurement of optical/X-ray arrival time; however, the large global jitter (~100 fs) of the accelerator-generated X-rays limits the absolute precision attainable. The streaking method with a circularly polarized laser has the potential to achieve an absolute precision of ~1/12 of a laser period (laser period = 4.3 fs for a 1.3-µm streaking laser). The large global jitter has prevented that achievement so far at LCLS-I, but the high-repetition-rate LCLS-II brings new challenges and opportunities. Alternatively, field sampling methods, demonstrated with optical pulses [90], could be translated to the X-ray regime for sub-femtosecond, sub-optical-cycle arrival-time monitoring, but must be adapted as a one-shot diagnostic tool. Such capabilities would be transformative—e.g., enabling probing of attosecond timescale, field-sensitive phenomena such as site-specific tunneling as well as other ultrafast light-induced processes. Precise synchronization of particle sources derived from a femtosecond laser pump pulse, such as MeV ultrafast electron diffraction, might be accomplished in an analogous manner—thus, opening new fields of inquiry. Specific approaches to achieving such synchronization include the following:

5.1) Combining angular streaking with spectral encoding for attosecond timing: The high-repetition-rate LCLS-II is expected to have improved synchronization with respect to external pump lasers relative to that of LCLS-I. Thus, the combination of a spectrally encoded arrival time monitor (ATM) with angular streaking could give sub-femtosecond absolute timing if the ATM is performed within a single optical cycle of the streaking laser. Tradeoffs between the streaking laser period and ATM performance will need to be investigated. Clearly, the materials associated with the ATM become a topic for research. X-ray fluence levels for 10% changes in reflectivity are of order 50–100 mJ/cm^2, a level that is near the material damage threshold and that produces discoloration and damage at 120-Hz operation at LCLS-I. A more dose-tolerant material with sufficient thermal transport is needed for LCLS-II where there is much higher average power. In addition, the much lower pulse energies at LCLS-II will require higher-sensitivity ATMs for single-shot measurements of transient X-ray-induced refractive index change—which may be achieved using polarization-based interference methods.

5.2) Field sampling for attosecond optical/X-ray synchronization: Optical pump-probe measurements have reached time resolutions in the attosecond regime through the use of field-resolved spectroscopy, where the transient refractive index changes are imprinted directly on the electric field of the optical pulse and measured directly in the time domain. The key to such measurements is the generation of a sub-cycle temporal "gate" capable of sampling the electric field to be measured. In the optical domain, tunneling or multiphoton absorption can be used as the sub-cycle gate to generate free carriers in the conduction band of a dielectric solid or in the vacuum. Imprinting both the reference and perturbed optical waveforms on a 2D detector [91] may allow unambiguous determination of the arrival time of a perturbing pulse [90]. An analogous implementation may be envisioned for optical/X-ray timing, where an overlapped attosecond X-ray pulse is used as the sub-cycle gate. Clearly research into material and detector response at low X-ray fluence, the timescale of the X-ray induced cascade of electrons into the material and its subsequent recovery for high-repetition-rate applications, and the X-ray dose tolerance prior to damage, is needed.

SCIENCE AND TECHNOLOGY IMPACT

Harvesting photon energy

Extending ultrafast, high-intensity sources to spectral regions spanning THz to X-rays coupled with the ability to synchronize these sources for pump-probe spectroscopy promises to address longstanding questions related to charge and energy flow in molecules and materials. Solar energy harvesting relies on the ability to control electron dynamics in complex molecules and at material interfaces on the shortest scales of time and involves strongly coupled electron charge, spin, and nuclear degrees of freedom. Precise control over the frequency, bandwidth, waveform, and pulse duration of tunable pump pulses synchronized with attosecond or femtosecond X-ray and electron probe pulses will provide a detailed view of coherent electronic and nuclear motion in molecular and material systems and promises to have a transformative impact on fields such as photochemistry, photocatalysis, and photovoltaics.

Materials control and characterization for efficient electronics

We are already seeing examples of THz-/IR-induced phase transitions, domain switching, and other collective transformations, including generation of metastable phases, especially in quantum materials that have multiphase landscapes in which the key transformational degrees of freedom involve excursions along low-frequency phonon, magnon, and other coordinates. When stronger THz/IR fields with tailored temporal, spectral, and polarization profiles become available at kHz or higher repetition rates, we are likely to see dramatic advances in collective coherent control. These will be further enabled by the use of mid-IR pulses to drive coherent low-frequency responses through stimulated scattering. Within the next decade, we can anticipate AI- and ML-guided assessment of experimental observables, real-time iteration of field parameters, and optimization of the excitation fields to achieve a wide range of material transformations including discovery of "hidden" metastable or stable phases. This fundamental study will support ultrahigh-bandwidth, ultralow-power memory and signal processing applications as well as exploitation of novel material properties.

Wavelength-extended sources for industry, defense, and civilian applications

High-average-power lasers have found use already in many sectors beyond science. However, laser applications are often limited by photon per dollar cost and by poor accessibility due to system complexity. Adding wavelength extension and field control to laser systems only worsens these limitations. The transformative advances in efficiency, wavelength coverage, synchronization, and field control outlined above, in tandem with simplification and improved robustness, will open the door for extended sources to find new applications and markets. These include industrial applications such as machining, nanofabrication, and three-dimensional (3D) printing; defense applications including directed energy, infrared countermeasures, and remote chemical detection; and civilian applications, such as medical imaging and laser surgery.

PRD 4 Reinvent Materials and Optics for Intense Laser Science

Key questions: What are the most significant improvements to materials and optics needed for next-generation ultrahigh intensity and high-average-power laser technologies? What can be discovered to expand the spectral range of ultrafast lasers toward the mid-IR and ultraviolet? What new concepts can be exploited to innovate materials and optics for intense laser science?

INTRODUCTION

The rapid development of laser technologies in the past 40 years was enabled by advances in a wide array of optical materials and components along with fundamental understanding of the underlying physical mechanisms, from laser action to CPA and nonlinear wave mixing. The laser output characteristics are constrained by the performance of individual components while the output power is often limited by the LIDT of the "weakest link" in the optical system. Efficient extraction of more energy at higher repetition rates requires diode laser pumping and effective thermal management methods that are currently at various stages of development, such as suppressing nonradiative relaxation or extracting heat via active cooling or "optical refrigeration" methods. This must be accompanied by substantial advancements in the performance of optical materials and/or components, such as gain media capable of withstanding much higher thermal loads and new gratings and coatings exhibiting significantly higher laser damage thresholds and average power performance. Figure 9 identifies the enabling technologies in which advances and innovation are critical to demonstrate several important ultrafast laser types required for discovery science.

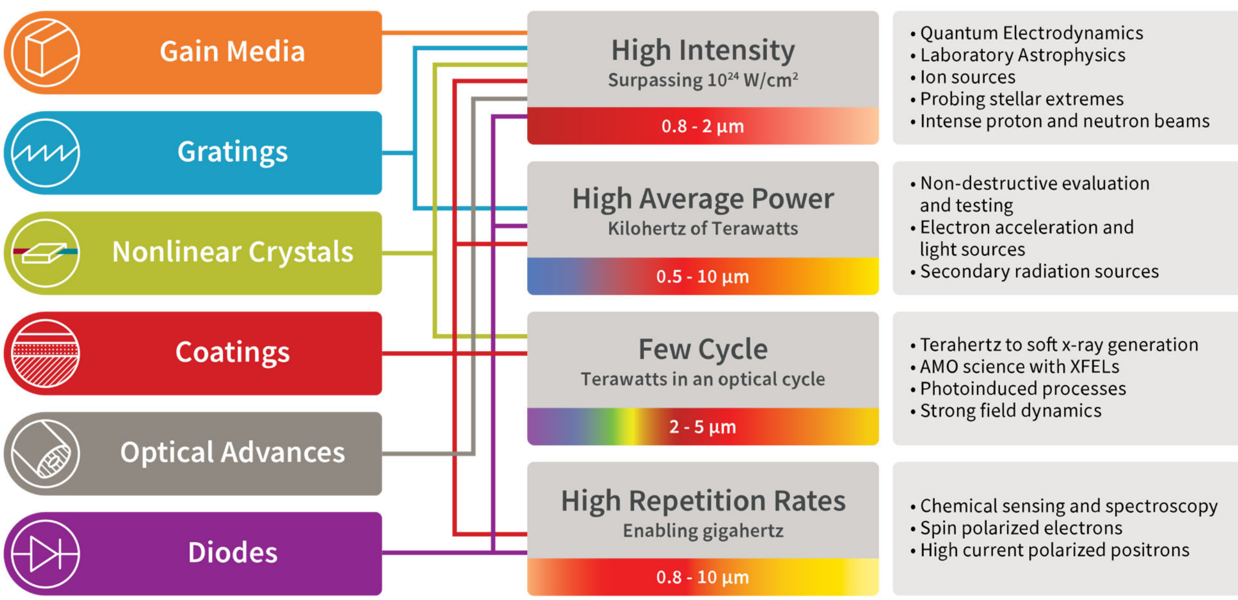

Figure 9. Fundamental technological advances in materials and optics can enable new laser platforms and lead to a host of scientific opportunities not possible with current technology. Table 1 provides the parameters for these different laser systems. AMO: atomic, molecular, optical; XFEL: X-ray Free-Electron Laser.

Science applications of materials and optics

Opportunities at the highest intensities: For the past few decades, on-target laser intensities focused to micron spot sizes have enabled access to the so-called relativistic regime where electrons can be accelerated to relativistic energies. New laser technologies will vastly broaden the areas of accessible science. Higher energy pulses allow the intensity to increase such that protons can become relativistic and get closer to the field strengths needed to study QED experimentally. They also enable new regimes of ion acceleration and neutron generation, with medical applications in radioisotope production, radiography, and nuclear spectroscopy. Simultaneously, multiple beams of higher energies enable relativistic intensities to exist across space on much larger length scales. Electron-positron plasmas can be generated, and collective motion can be measured for the first time. New regimes of laboratory astrophysics become accessible, including magnetic reconnection and relativistic jets, that exist in active galactic nuclei. A host of experiments related to QED, including pair creation from the vacuum and vacuum birefringence, are among the most exciting new physics enabled by such lasers.

Science enabled by improved experimental statistics: Poor statistics arising from shot-to-shot variations and a low number of shots dramatically limit scientific exploration. Increasing laser repetition rates combined with improving laser performance with passive and active feedback have the potential to greatly impact science applications. For example, the study of materials at conditions far from equilibrium—the ultrafast dynamics of materials responding to stress and radiation damage—become accessible. High repetition rate and high pulse energy are required for the implementation of laser-driven particle accelerators operating with better stability and improved statistics that will make it possible to explore electron injection processes, shock acceleration, and phase space control. Similarly, lower pulse energies and much higher repetition rates are critical to develop fully coherent THz radiation to study molecular structure changes for chemical and biophysical processes. Higher repetition rate and control is also required for integration with accelerators and light sources to enable science such as generation and detection of transient electronic and structural states in materials.

The fastest timescales: Even the shortest pulse durations produced by high-power ultrafast systems typically are on the order of a dozen cycles or longer. New laser technology enabling single-cycle or few-cycle optical pulses not only increases the intensity for a given power but also enables new scientific regimes that rely on the impulse nature of the pulse. Isolated attosecond pulses with tunable energies could enable dynamic studies of how matter responds to perturbations and how chemical reactions and inner core electron dynamics occur on their natural timescales.

SCIENTIFIC CHALLENGES

Advancing the laser technologies described in PRDs 1-3 (Table 2) relies to a great extent on overcoming the limitations of the constituent optical materials and components (including laser gain materials for energy scaling, nonlinear crystals to reach spectral regions from the UV to mid-IR, and optical components—coatings and gratings—to achieve the ultrahigh intensity) and advancement of supporting technologies (such as diode lasers, fiber lasers, and optoelectronic devices to control the spatiotemporal profile of the electric field). The foundations for the engineering of laser gain materials—crystal, glass, fiber, and ceramic—are well established. Hosts doped with lanthanides and transition metals are used in laser architectures producing pulses from nanosecond to femtosecond duration at near-IR (0.8–1.1 um) and mid-IR (2–5 um) wavelengths. The more recent development of higher power laser diodes for pumping has established a viable path to increase the peak and average power of ultrashort-pulse lasers. However, to expand the operational profile of future lasers, novel gain material hosts with robust thermomechanical properties that enable higher power extraction, more efficient excitation, and thermal management at application-relevant beam apertures are needed.

The increased laser output profile and operational wavelength ranges must be accompanied by the development of optical elements for beam control and transport that can support the expanded energy, intensity and/or spectral range operational profiles. These include interference coatings for different beam/pulse characteristics that will require new coating materials and coating architectures. Nonlinear crystals are also critical materials in future laser systems enabling generation of new wavelengths via multiple physical mechanisms including their use in OPCPA. For nonlinear materials to meet future needs, especially for large-aperture laser systems, investment in R&D is required. Arguably, progress depends on concentrated efforts to advance key enabling material technologies along with emphasis on workforce development. Advanced modeling, ML, and AI could be investigated to identify new crystals and speed up discovery [92-94]. Insufficient investment and the lack of academic activity in the U.S. in this field, compared with more rapidly developing domains in optics and photonics, impacts the existence of commercial sources as well as trained workforce.

RESEARCH THRUSTS

Thrust 1. Next-generation laser gain media

The lasers required to meet the experimental needs for high-field and ultrafast sciences require expansion of their operational envelope towards higher pulse energy, high repetition rate and extended tunability. Laser gain host materials with rare earth-doped impurities (Ce, Pr, Nd, Ho, Er, Tm, Yb) and transition metal ions (Ti, Cr, Fe) have been extensively developed (Table 2) and support the current generation of laser systems in the near-IR, 0.8–2µm.

The challenges that lie ahead depend on the ability to expand the power profile to include higher repetition rates while simultaneously increasing the pulse peak intensities and/or pulse energy. To achieve this goal will require the development of suitable new materials including host media that can abide active cooling and support large-aperture (when needed) and high-quality beam profile. Computational tools may help develop new crystalline laser gain materials. In addition, new manufacturing methods, such as additive manufacturing, can help fabricate gain media (glass or ceramic) with advantageous optical characteristics such as spatially tailored doping distributions, possibly with mixed ion doping or mixed host materials, to improve beam quality, extend the bandwidth, and/or achieve higher energy efficiency. A short list of the most important parameters is discussed next.

	Yb doping							Nd doping					Other		
	Yb:YAG 300-K	Yb:YAG CRYO	Yb:YLF 300-K	Yb:YLF CRYO	Yb:YLF CRYO	Yb:LuAG 300-K	$Yb:CaF_2$ 300-K	Nd:YLF 300-K	Nd:YLF 300-K	Nd:YLF CRYO	Nd:APG1 300-K	$Nd:X:CaF_2$ 300-K	Ti:Sapphire 300-K	Tm:YLF 300-K	Ho:LuLF 300-K
Emission wavelength (nm)	1030	1029	1020	1020	995	1028	1036	1047	1053	1053	1054	1048-1054	~800	1900	2066
Bandwidth (nm)	Δλ = 10	Δλ = 1.1	Δλ = 30	Δλ = 15	Δλ = 5	Δλ = 1.3	Δλ = 30	Δλ < 1	Δλ ~ 1	Δλ ~ 1	Δλ ~ 5	Δλ = 1.5-5.0	Δλ = 28	Δλ= 28	Δλ=75
Storage lifetime (ms)	1	1	2	2	2	1	2.4	0.52	0.52	???	0.36	~325	0.0032	16	15
Pump wavelength (nm)	940	940	940	960	960	940	976	863	863	863	~860	~860	~500	792	1937
Bandwidth (nm)	Δλ = 17	Δλ = 12	Δλ = 10	Δλ = 3	Δλ = 3	Δλ = 15	Δλ = 5	Δλ ~ 2	Δλ ~ 2	Δλ ~ 2	Δλ = ???	Δλ = ???	Δλ=100	Δλ=16	Δλ=30
Quantum defect (%)	9.5	9.5	9.5	6.5	3.5	9.5	5.8	17.6	18.3	18.3	~18	~18	~40	~16	6.1
Saturation fluence (J/cm^2)	12	2.2	90	11	6	7.4	76	1.2	1.6	???	5.5	~5	~0.8	???	80
Non linear index (10^{-16} cm^2/GW)	6.9	6.9	1.3	1.3	1.3	6.9	1.3	1.3	1.3	1.3	1.13	1.3	~3	1.3	1.3
Birefringence	none	none	uniaxial	uniaxial	uniaxial	none	none	uniaxial	uniaxial	uniaxial	none	none	uniaxial	uniaxial	None
Thermal cond. W/m*K	8	40	4	30	30	8	5.2	~6	~6	30	0.8	~5	33	6	5
Stress fracture (W/cm)	88	88	1	50	50	88	1 ?	~1	~1	~50	???	~1	~790	???	1
Useful size (cm)	10	10	10	10	10	10	10-20+	10	10	10	40	20+	20	10	10+
Type	ceramic	ceramic	crystal	crystal	crystal	ceramic	crystal	crystal	crystal	crystal	glass	crystal	crystal	crystal	crystal
Max Doping (%)	10	10	60	60	60	50 ?	5~2	~2	~2	~2	~2	~1	0.2	???	5%

Table 2. List of some of commonly used laser gain materials for the near-infrared and key properties for laser performance. APG1: Advanced Phosphate Glass-1; LuAG: lutetium aluminum garnet, $Lu_3Al_5O_{12}$; LuLF: $LuLiF_4$; YAG: yttrium aluminum garnet, $Y_3Al_5O_{12}$; YLF: yttrium lithium fluoride, $YliF_4$.

1.1) Develop new laser host materials for high repetition rates under laser diode pumping: Material failure (thermal shock) due to excessive inhomogeneous thermal gradients (that become increasingly detrimental for larger component dimensions) driven by increasing power volume density is a key concern in expanding the power output profile of lasers. The selection and optimization of the material performance involves two sets of parameters. The first one consists of the thermoelastic material properties and is quantified by the figure of merit (FOM) [95]. The second parameter set relates to the surface quality and preexisting mechanical damage, such as the depth of any subsurface crack-like features, which compromise the surface strength when the surface is exposed to thermal stresses. Properties such as thermal expansion coefficient, modulus of elasticity, and strength can be well modeled [96] from first principles, such as molecular dynamics, under static or shock conditions, including generation of crystalline defects such as dislocations.

1.2) Develop laser materials that suppress parasitic processes: Efficient extraction of energy stored in laser gain media is limited by energy loss mechanisms that can also increase thermal loading. These processes include transverse amplified spontaneous emission (TASE), excited-state, and multi-photon absorption. These processes largely depend on the active ion but also on the host material. TASE proves particularly vexing for large gain apertures and high population inversion densities. It limits stored energy in laser elements and can create parasitic losses that both reduce efficiency and distort spatial gain profiles. Mitigating these limitations requires developing new concepts that frustrate or even suppress TASE. Laser host materials with energy band gaps deep in the UV region can suppress the engagement of color centers interacting with pump and laser radiation. Ideally, the energy bandgap of the host material should be larger than three photons of the excitation energy to minimize multi-photon absorption. High-quality laser materials require very low scattering that can produce many diverging waves that divert energy from the main beam and interfere to create hotspots that can damage the material itself and downstream optics. Parasitic energy transfer can also occur via nonlinear processes, such as stimulated Brillouin or Raman scattering, that can divert energy into unwanted wavelengths, directions, and/or polarizations. These processes can significantly reduce laser performance or even cause damage when threshold conditions defined by gain-length products are exceeded, such as by a long propagation length in fibers or large Brillouin/Raman scattering cross sections in large-aperture potassium dihydrogen phosphate (KPD)/DKDP crystals used in ICF-class lasers. Such issues can be addressed by proper selection of material, crystal orientation, and laser excitation conditions [97]. New and sustained laser materials R&D efforts need to address all these parasitic processes to advance laser performance.

1.3) Host materials that support high beam profile quality: The quality of the output beam profile is a key parameter of the performance of a laser system giving rise to beam modulations and affecting the ability to focus the laser beam. An array of material properties affects the output beam characteristics, and modification of the index of refraction can be a primary cause of such issues. The value of the nonlinear index of refraction and the dependence of the index of refraction on the temperature is extremely important. Another advantageous optical property is optical anisotropy to support naturally polarized emission which helps compensate for the thermally induced depolarization effects under strong pumping. Such uniaxial and biaxial host laser crystals are currently available. High thermal conductivity is also essential for the laser material to be able to dissipate the heat rapidly under diode pumping and high repetition rate to suppress the buildup of thermally induced refractive index gradients.

1.4) Novel gain materials with spatial control of gain and losses: Optimal amplification performance in bulk laser systems is limited by several fundamental mechanisms that affect WPE, beam quality, and thermal loading. TASE occurs when spontaneously emitted photons propagate along unwanted paths in a laser gain element, which depletes the stored energy. Mismatch between the laser beam mode and the pumped volume of gain material poses practical challenges to achieving efficient and high-quality amplification of laser beams. Realizing anisotropic gain and/or propagation losses represents no simple feat. Laser glass and ceramic materials provide the ability to engineer gain media using additive manufacturing processes that can spatially tailor dopant species and their concentrations. Such materials engineering approaches would enable spatially controlling stored energy (gain) in both transverse and longitudinal directions. Transverse control would prove beneficial to beam quality and efficiency, while longitudinal control could deliver more uniform stored energy density to compensate for decreasing pump light flux as it passes through the gain medium and lead to better distribution of thermal loads. New concepts that employ beam shaping schemes for laser diode pumping could pattern stored energy to provide similar benefits.

1.5) Large-aperture laser gain materials: Laser power scaling depends directly on beam aperture. Current state-of-the-art, large-aperture ultrashort-pulse to fusion-class lasers use Nd-doped phosphate laser glass owing to several properties that future gain media must also possess: high rare-earth ion solubility, suitable emission cross section, relatively small phonon energy to minimize nonradiative losses, low nonlinear refractive index, and mature technology to produce large laser gain elements with excellent optical quality. Glass laser materials generally support broader gain bandwidths than most crystalline materials, and they can provide control of important optical and thermomechanical properties via adjusting the glass composition.

A major limitation in using phosphate laser glass in future lasers is its very small thermal fracture FOM (~0.3 W/√m) [98-100] and thus, an inability to handle high average power. Overcoming this limitation requires new laser glass compositions to be investigated. New fabrication methods (such as additive manufacturing) can expedite R&D and possibly simplify production constraints by offering better control of glass stoichiometry, such as eliminating incorporation of Pt particles originating from the manufacturing process. Basic research in the past that supported the development of existing laser glass materials can serve as a guide for future research [101]. For instance, previously developed experimental glasses, including aluminate (FOM ~1 W/√m) and fused silica (FOM ~23.5 W/√m), may deserve further investigation.

Crystalline host materials must be carefully selected to support large-aperture systems and highly homogenous doping based on two main criteria. Congruent melting behavior looks promising for the growth of large-aperture, high-quality crystals. Matching the dopant ion to the host material also plays an important role since the ionic radii of dopant ions should closely match that of the substituted ion. This is a rather complex problem, and for the case of lanthanide materials, it arises from the steady decrease in the size of the ions with increasing atomic number.

1.6) Laser gain material with large bandwidth for short-pulse seeding and direct CPA (glass, ceramic, crystals): Disordered laser host materials, such as glassy materials, can support large gain bandwidths due to inhomogeneous broadening of the laser-active dopant ions. Co-doping crystalline laser materials with optically inert buffer ions (e.g., Nd^{3+}-Lu^{3+}-doped CaF_2 [102]) has demonstrated broadband laser operation around 1 µm and looks promising for future research where new technologies, such as additive manufacturing, may be applied to generate large bandwidth laser gain media that may include complex multi-element materials.

Basic research into laser materials and lasing transitions is needed to discover new mid-IR platforms and support transformative research in ultrashort-pulse, high-power lasers at mid-IR wavelengths. The mid-IR region presents significant challenges due to a lack of transparent hosts and rare-earth transitions. Additionally, many materials in this region have poor thermo-mechanical properties, such as low thermal conductivity. Addressing these challenges requires investments in basic research with an approach starting from first-principles theory followed by materials growth and characterization. Currently, Fe- and Cr-doped ZnSe/S crystals provide the bandwidth necessary to support a few tens-of-femtosecond pulses for oscillators and low-power amplifiers [103] but scaling these systems in energy and repetition rate will require significant advances in the production of large-aperture crystals. This requires investments into university research labs in the short term and industry and/or national laboratory facilities in the medium to long term.

Revisiting less investigated laser transitions in rare-earth ions, transition-metal ions, and color centers could broaden the range of useful ultrafast laser gain media. For example, magnetic dipole-allowed, rare-earth transitions might help increase gain bandwidth. About thirty percent of the emission of Er^{3+} at 1550 nm comes from magnetic dipole transitions. These transitions need to be studied in a variety of hosts to optimize performance with iterations between first-principles theory and experimental characterization to accelerate progress.

1.7) Materials for high efficiency pump lasers for OPCPA systems: Suitable pump materials for OPCPA systems must support active cooling (high thermal fracture FOM) with high WPE and excellent optical properties with suitable gain cross section (saturation fluence). The different doping ions possessing favorable electronic structure for laser operation have been extensively studied. Among those, Nd^{3+}offers high cross-section transitions (influenced by the host material symmetry) in a low threshold four-level laser system. Its large ion size, however, can give rise to low segregation coefficients. Yb^{3+}provides a quasi-three-level laser with a particularly small quantum defect that enables very efficient operation but high laser thresholds at room temperature. For mid-IR and IR OPCPA systems, Tm-, Ho-, Cr-, and Fe-doped materials can support novel laser architectures, as described in PRD 2, Thrust 1.

1.8) Fiber lasers: Rapid development in fiber lasers leveraged investments in the telecom industry to achieve low background losses. CW fiber lasers find many high-average-power applications owing to their high beam quality from single-mode operation and excellent thermal properties. On the other hand, their very small apertures limit the peak power achievable from individual fibers. CBC of multiple (100s to 1,000s) fiber amplifiers (PRD 1, Thrust 4) promises a path to overcome this limitation to produce high-energy pulses at high repetition rates. Further development of fiber technologies to reliably achieve 10s-of-mJ pulse energy per fiber amplifier is required to achieve the multi-joule (PW) laser needs in PRD 1 and perhaps further expand to the 10s of joules scale. Fiber lasers may also be useful as pumps for lasers described in PRD 1, as they may be needed at disparate wavelengths with narrow bandwidths. Such narrow linewidth CW lasers will also be important for isotope separation applications. In contrast with Thrust 1.2 which seeks to suppress nonlinear effects such as Raman and Brillouin scattering, here we desire such nonlinear effects as a gateway to otherwise difficult to access spectral regions. This effort will require development of novel waveguide designs to increase the single aperture energy, leveraging new fiber fabrication techniques (e.g., high-volume and preform fabrication processes that allow for unique compositions or stack-and-draw) that allow achieving precisely controlled index profiles over large cores, as well as new types of fiber waveguide structures, both index-guiding and microstructured. This could also allow for new dopants and host materials to be developed to support research in new wavelength regimes.

Research to investigate other rare-earth transitions, possibly in novel host materials, that can support direct CPA in the UV and mid-IR will be important for enabling PRD 2 and PRD 3 lasers. Development of fiber-integrated optical components is also needed to support monolithic integration of many-channel systems.

Thrust 2. Next-generation coating materials, designs, and techniques

Amorphous metal oxides are now widely used for the engineering of thin-film, multilayer dielectric (MLD) coatings for critical optics, including mirrors and gratings, in ultrashort-pulse laser systems operating in the 0.4-µm to 2-µm wavelength range. MLD coatings, however, are prone to laser damage at fluences well below those of their bulk counterparts when operating at high intensities and high repetition rate. In near-IR CPA laser systems, it is the damage fluence to the coatings that dictates the size of the laser aperture and thus, the pulse compression gratings. At shorter UV wavelengths, coatings are less developed, and damage occurs at even lower fluence than in the near-IR. Interference coatings for ultrafast laser systems in the mid-IR also require significant development, especially if they are to handle femtosecond pulses of high energy at high repetition rate.

Addressing the limitations imposed by MLD coatings is paramount to enable ultrashort-pulse, high-intensity, and high-repetition-rate laser technologies to reach the operational level demanded by the science applications. Innovations are needed to realize MLD coatings with predictable optical, structural, and mechanical properties and with repeatable short-pulse laser damage response at wavelengths from the UV to the mid-IR. The advances in MLD coatings that will be needed in the next 5–10 years to meet the output performance of the ultrafast laser systems of PRDs 1, 2 and 3 include the following:

2.1) Improved synthesis methods to create dielectric thin films with controlled and reproducible optical and structural properties: Amorphous oxide thin films are primarily synthesized by physical vapor deposition (PVD) methods. While the optical properties can be routinely reproduced and are similar among the different deposition techniques, the structural properties are not. PVD methods create thin-film materials that are nano-ceramics and, although macroscopically amorphous, they differ significantly from glasses. Motivated by the need to understand the network organization of PVD thin films, the gravitational wave detector community is leading experimental and modeling efforts to identify the organization at medium range in amorphous oxides. These works have shown that doping, deposition at elevated substrate temperature, and post-deposition annealing are important to create a glass-like network with important consequences for reducing internal friction [104-107]. Reinventing the synthesis of amorphous oxide thin films to create glass-like materials is critical to achieve the level of control required for reproducible coating performance. Atomistic models could help advance our understanding of the mechanisms of thin-film growth (material deposition) and predict the most favorable configurations in the amorphous network that occur with alloying or depositing at elevated temperatures [105, 106]. A concentrated effort to consistently synthesize amorphous thin-film materials with reproducible optical, thermal, and mechanical properties and that incorporates the ability to synthesize new materials such as multicomponent oxides [104] or nanolaminate coatings [108] is paramount to demonstrate next-generation interference coatings with LIDTs that approach bulk transparent materials.

2.2) MLD coatings with significantly improved laser damage resistance: Figure 10 shows the trend in the LIDT of MLD coatings with wavelength and pulse duration. LIDT studies at nanosecond pulse duration have shown: i) the importance of using materials with large optical bandgaps (i.e., SiO_2 and HfO_2); ii) the dependence of the LIDT on laser wavelength, with significant reduction of the damage threshold at UV wavelengths compared to 1064 nm; and iii) the importance of fluence rather than intensity in the damage initiation process. MLD coatings for picosecond pulse duration designed with similar strategies have typically an order of magnitude lower LIDT. At femtosecond pulse duration, the LIDT of broad bandwidth MLD coatings is at best ~1 J/cm^2. First-principle and phenomenological models of the near-IR laser damage of transparent amorphous oxides have explained the trend observed in the experiments [109, 110]. Further, these models have allowed the coating community to devise strategies in the design of coatings to improve LIDT. Interference coatings in the UV and mid-IR spectral regions are less developed. Significant experimental and modeling efforts are needed to demonstrate coatings for ultrashort-pulse lasers that will provide the bandwidth and LIDT requirements necessary to scale ultrafast lasers in peak and average power at near-IR, visible, UV, and mid-IR wavelengths.

There are also unaccounted variables that affect the LIDT of MLD coatings. Variations in the synthesis process from run to run when using the same instrumentation and nominally identical processes can yield coatings with a wide spread in their LIDT. These are challenges that originate, in part, from the lack of control and reproducibility in the synthesis and the inability to identify and mitigate damage precursors in the MLD-coated optics. Improvement of the LIDT of MLD coatings within the next five–ten years will require advances in the following areas:

1. Control the synthesis process to realize thin-film materials with reproducible properties, including control of the density and distribution of inclusions and other defects that can be precursors to damage;

2. Determine the role of coating interfaces on the LIDT and how to mitigate adverse effects;

3. Quantify the influence of the substrate on the LIDT; devise ways to minimize mechanical and thermal stress and ways to increase heat removal for high-repetition-rate operation;

4. Understand the influence of the coating design on the stability of the coating after a microscale damage site is formed. This is particularly important in large-aperture optical components where initiation of damage may not be impactful, but the failure of the optic is governed by subsequent expansion of the damage sites (damage growth). To achieve this, more advanced coating design models that include 3D modeling of the electric field distribution and damage growth testing protocols are required; and

5. Control and reduce contamination in the operational environment. Transparent and metallic particulates, hydrocarbons, water, and other residues on the surface of the coatings are potential damage initiation precursors.

Improvements in the LIDT of MLD coatings will translate into higher performance MLD gratings and other optical components such as pulse compression cells. Overall, the gains in increasing LIDT will directly impact laser output, stability, and long-term operation.

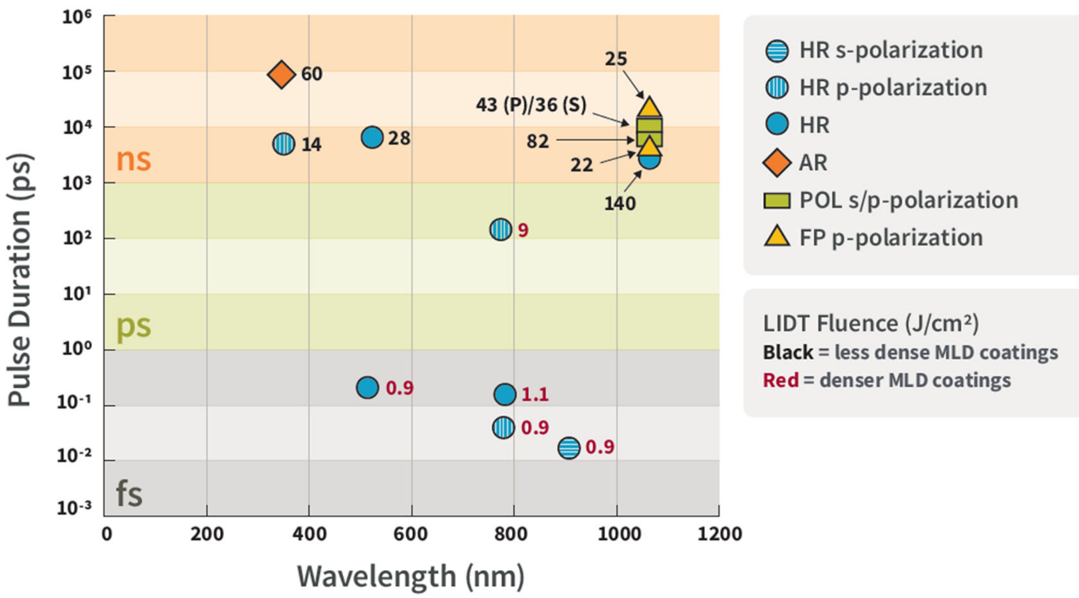

Figure 10. Compilation of small-beam laser-induced damage threshold (LIDT) testing results for multilayer dielectric (MLD) coatings at different wavelengths and pulse durations from the competition carried out yearly as part of the SPIE Laser Damage Symposium. Most results are from [111]. The data points represent the best LIDT values for physical vapor deposition (PVD) MLD coatings, which include high-reflection (HR), anti-reflection (AR), polarizers (POL), and Fabry-Perot (FP) coating structures. Their LIDT fluence is listed in black for less dense coatings and in red for denser coatings.

Thrust 3. Compression gratings

The capability to produce large-aperture gratings proves essential to achieving higher performance since the final compression grating in standard CPA laser systems faces the highest damage threat, thus limiting the maximum output energy. Operating compression gratings at high incidence angles and large beam size lowers damage risk, but drives grating sizes ever larger. Meter-scale gratings (<1-m linear dimension) exist commercially from a small number of suppliers (Plymouth Grating Laboratory and Horiba Jobin-Yvon) and research institutions (LLNL, Fraunhofer) that enable the highest energy systems now; next-generation systems will require even larger diffraction gratings. Tiled-grating architectures offer one approach, but they exist only in research systems, and they severely limit the quality of pulse compression and focusing, especially for sub-picosecond pulses. High-average-power systems will require the development of active cooling [112, 113] and the use of new substrate and coating materials with higher thermal conductivity, higher efficiency, and/or lower absorption (e.g., MLD coatings), to mitigate heating that deforms gratings and degrades their performance.

Improving grating technology has been slow, in part, due to the vast number of variables involved in the manufacturing process. To support leadership in compression, improved grating manufacturing methods need to be tested and developed for realistic beam sizes. In the long-term, realizing improved diffraction grating performance requires better understanding of how manufacturing-induced imperfections relate to laser damage performance and the interplay between many of the process variables. A well-known limitation in current gratings is related to the incorporation of absorbing defects arising from coating and etching processes. Micron-scale, nonstoichiometric defects, as well as atomic-level defects, in coatings are known to be damage precursors in gratings that govern the LIDT at different pulse duration ranges [114]. Organic contamination resulting from the grating fabrication process, including remnant fluoropolymers and subsurface contamination from the reactive ion etching [115], further degrade the material quality of the top layer(s) subjected to high electric fields. In order to make scientific breakthroughs in developing high-LIDT gratings, all the basic research and advances in low-loss coatings detailed in PRD 4, Thrust 2 will need to be leveraged in addition to the development of new grating fabrication methods. As the LIDT of the exit grating in the compressor is the limiting factor in the design of any high peak power CPA system, the R&D in this thrust has far-reaching impact in high-field and ultrafast science.

3.1) R&D to enable near-term ultrafast and high-field science research goals:

3.1.1) Improve the LIDT and background losses of MLD gratings and increase bandwidth to support 5–200-fs operation: Hybrid MLD/gold gratings show promise for high LIDT with sufficient bandwidth for the 5–200-fs range, but this concept requires significant R&D to advance from its currently immature state. Ultrabroadband polarization-insensitive MLD grating designs represent additional opportunities.

3.1.2) Scale grating apertures to a 1.5–2-m range: Extra-large gratings (2 m on side) that would enable multi-10-petawatt lasers for basic research, and could become commercially available within five years by scaling existing grating production technologies. U.S. laser technology R&D in this area leads the world currently, but it depends on episodic funding that does not support the long-term advances that would enable entirely new classes of lasers.

3.1.3) Extend current grating technology to new wavelength regimes: Emerging mid-IR CPA laser technologies, like those based on Tm:YLF [116], require high-performance diffraction gratings comparable to those available for current near-IR lasers.

3.1.4) Identify damage initiation mechanisms: It will be important to identify precursors responsible for damage initiation at different pulse duration regimes (ns, ps, fs) and in different spectral regions, as well as to investigate and mitigate laser-induced damage for very high-repetition-rate systems (>1 MHz). Vacuum compressor contamination and its effects on long-term damage and implementation of mitigation strategies are also an impactful research direction.

3.2) Develop new fabrication methods: There is a need to explore new fabrication methods that can reproduce surface patterning with higher fidelity and reduced contamination. This includes developing a better understanding of reactive ion etching-induced defects and contamination [117] and a renewed investigation into more recent etching technologies (inductively coupled plasma reactive ion etching, DUV lithography, e-beam lithography, etc.) to provide higher fidelity and improved grating material quality [118]. Development of improved coating materials and methods will certainly play an important role in limiting defects. The incorporation of dielectric alloys and defect-passivating impurity ions in the manufacturing process show promise. The application of modern nanofabrication processes, notably the use of hard masks, shows potential for improving etch selectivity.

Thrust 4. Innovations in nonlinear crystals

4.1) Large-aperture nonlinear crystals: Large-aperture nonlinear crystals allowing for phase-matched three-wave nonlinear mixing are necessary for sum- or DFG, parametric amplification, and OR to produce outputs across the spectrum ranging from THz to XUV. Ti:sapphire and near-IR OPCPA rely on the SHG of near-IR pulses. SHG can also be used to significantly increase the temporal pre-pulse contrast of short optical pulses before focusing onto a target.

The crystals in these systems must be able to handle high average power and have high conversion efficiency without sustaining optical damage. Over the last 10 years, there have been efforts to increase the size of available nonlinear materials. KDP and DKDP crystals are already produced in sizes that yield 400×400-mm^2

crystals for frequency conversion, Pockels cells, and polarization control. Large KDP/DKDP crystals required for lasers with peak powers beyond 10 PW are only available from one commercial supplier in the U.S., but significant developments have been identified in China. LBO (lithium triborate) has a higher nonlinear coefficient and larger angular acceptance, but its growth is much slower and more expensive. LBO crystals are actively being scaled to 120-mm and up to 150–200-mm square sizes in the next 2–3 years. Further scaling to greater than 200 mm may be possible with investments in larger platinum crucibles and furnaces, as well as investigation of novel manufacturing approaches such as seamless bonding. BBO (beta barium borate, BaB_2O_4beta) is another excellent nonlinear material, especially for frequency conversion up to the 5th harmonic of laser pulses at about 1 µm, but it can only be grown in small sizes. Even with development efforts over the last ten years, it is still only available in up to 30–40-mm sizes, depending on the cut and application. A clear path to scaling BBO to larger sizes is not evident. Rapidly growing nonlinear crystals with larger apertures by optimizing the growth parameters is possible [119], but other approaches to reduce the cost and time must be investigated. Composite crystals composed of smaller bonded crystals, a technique already used for laser crystals [120, 121], requires investigation. The growth of nonlinear crystals in a preferential orientation more consistent with their phase-matching requirements could speed up the production and lower the cost.

Local variations in crystal properties, such as orientation of the crystalline axes in all crystals and deuteration level in DKDP, can detrimentally impact the phase-matching properties and on-target performance. The development of large-aperture crystals will benefit from novel characterization techniques that more explicitly target the performance characterization of the nonlinear crystals, e.g., phase-matching properties and damage threshold [122, 123].

4.2) Crystals for wavelength extension to the UV and mid-IR: Frequency conversion toward the UV and mid-IR ranges, demanded by a large range of wavelength-specific applications, requires nonlinear crystals with adequate transparency range and phase-matching properties. UV generation via harmonic generation of sources in the near-IR is limited to a few crystals such as LBO, CLBO (cesium lithium borate, $CsLiB_6O_{10}$), BBO, and ADP (ammonium dihydrogen phosphate, $NH_4H_2PO_4$). Reaching the mid-IR via difference-frequency of two beams or via intra-pulse DFG is made possible by crystals such as BGSe (barium gallium selenide, $BaGa_4Se_7$), ZGP (zinc-germanium phosphide, $ZnGeP_2$), CSP (cadmium silicon phosphide, $CdSiP_2$), and OP-GaAs and OP-GaP. These crystals are not widely commercially available, and in some cases, only a single source exists that is linked to very specific capabilities and expertise. Dramatic improvements in the quality and size of OP-GaP and OP-GaAs could allow robust conversion of broadband near- and short-wave IR lasers into the mid-IR. Discovering and/or developing robust and low-loss host materials will be important.

4.3) Crystals for quasi-phase matching: Quasi-phase matching (QPM) allows for efficient nonlinear interactions that take advantage of the highest nonlinear coefficients in nonlinear materials. QPM devices, such as PPLN, where periodic polling is induced by large electric fields in the ferroelectric material and orientation-patterned materials, such as OP-GaAs and OP-GaP that employ layers of material with different orientation that are sequentially grown, typically have a small aperture that limit their use to low-energy applications. Increasing the aperture via novel fabrication processes (such as crystal bonding) would increase their range of applications. In some cases, the commercial availability of these materials is limited, which hinders the progress in the development and deployment of the associated sources.

Thrust 5. Emerging innovations in optical components

A number of by emerging technologies may be able to address important technical issues to future laser systems. While most of these concepts are still at the proof-of-principle stage, they illustrate the transformative potential of these new approaches for the design and applications of high-power lasers. To eliminate the laser damage threshold “bottleneck” in the performance of optical systems one possible path is to develop optical materials with “self-healing” properties that may be based on liquid-metal, plasma, or gas optics. Nanostructured materials designed to incorporate optical quantum confinement effects to modulate their optical properties (such as optical bandgap) can support development of an array of new synthetic materials that exhibit higher damage threshold and/or expand performance parameters over a wider spectral range. Advanced concepts could be particularly impactful for the final focusing optics in PW-scale lasers described in PRD 1 and in the far future could be impactful throughout future laser systems.

5.1) Gas and plasma optics: The opportunity to overcome current damage threshold limitations with plasma optics depends on the capability to imprint refractive index modulations in a plasma or a gas using auxiliary lasers. Gas- or plasma-based optical elements can sustain fluences that are several orders of magnitude beyond the damage threshold of solids, and are transient elements, making them well-suited for high-power lasers designs and applications (with a new optical element dynamically created at every shot, even at high repetition rate). Many new concepts of gas or plasma optics have been proposed, such as gratings, waveplates, polarizers, diffractive lenses, and beam combiners [124], and further development is needed to understand the potential impact of this emerging field.

5.2) Metasurface technologies: These are 2D-patterned transparent glass structures, similar to diffraction gratings, in which the pattern imparts modifications to the wavefront and/or polarization of the laser beam. The structuring process is scalable to meter-scale aperture optics with fabrication technologies similar to those used in diffraction gratings. Metasurface (MS) technology has been developed to enable retardation waveplates in all-glass MS optics, although glass is not a natively birefringent material but has high laser-damage durability. Such thin optical elements will help reduce accumulated nonlinearities (e.g., filamentation damage) and condense a few optical elements into one, thus reducing the size/weight of these systems. MSs could also play an enabling role in the propagation of ultrashort, femtosecond or attosecond pulses carrying complex spatiotemporal shape and for the generation of pulses that are propagation invariant or carry complex topological structures [125]. Generation and control of such complex space-time wavepackets, or structured light beams, require versatile and simultaneous control over the phase, amplitude, polarization, and spatial wavefront versus time [126]. Making MS methods and techniques mainstream for optics in ultrafast laser systems will require overcoming a number of outstanding or unforeseen challenges including realizing large-area nanopatterning and high-damage-threshold optics, or fundamentally understanding space-time coupling effects.

5.3) Nanophotonics: Emergent nanophotonic phenomena have radically advanced mid-IR photodetector performance in recent years, which suggests these novel approaches could be leveraged in innovative ways to improve mid-IR semiconductor laser efficiency. Similarly, advances in laser gain media possessing greatly reduced two-photon absorption enable novel approaches (e.g., Mamyshev regeneration [127]) to surmount the instantaneous power and pulse duration limits of current mode-locked semiconductor lasers. Further research on mid-IR diode active regions is critical for success, due to the low inhomogeneous broadening of intersubband transitions used in the dominant quantum cascade laser (QCL) technology.

Thrust 6. Laser diode pumping for high-repetition-rate ultrafast laser systems

Realizing the laser systems addressed in PRD 1 depends strongly on high-power diode-pumping lasers. The report of the 2022 Basic Research Needs Workshop on Inertial Fusion Energy sponsored by the Department of Energy Office of Fusion Energy Sciences (DOE FES) [128] identified "an urgent need for strategic development of diode lasers with the goal of providing robust, high-power sources at economically feasible price points".

High-power laser diodes and diode arrays for pumping near-IR high-energy and high-repetition-rate ultrashort-pulse lasers are commercially available from U.S. suppliers. In the 780–1100-nm wavelength range, diode bars and arrays producing many 100s of watts and even kWs of power are available. The unit price of high-power CW diode arrays has declined to the approximately one-dollar-per-watt range, but the costs remain too high for widespread adoption. A principal bottleneck is the lack of integration and automation of production methods, as diode stacks are assembled one by one. The semiconductor laser diode industry requires investment to increase production, reduce costs, and shorten lead times. This will be paramount to scale the peak and average power of next-generation pulsed, high-energy laser systems for HED applications.

High-power laser diode technology development at longer wavelengths, needed to pump laser gain material for mid-IR ultrafast sources, has lagged behind near-IR counterparts. At wavelengths in the telecom region, 1.3–1.6 µm, laser diodes based on InGaAsP are available, but efficiencies are generally lower by a factor of two, mainly due to Auger effects. The power output per bar is also generally lower, limited to a few tens of watts. Fundamental limitations due to heating have impacted array power scaling. Improvements in the electro-optic efficiency at high brightness and advancing the diode reliability and lifetime have been identified as major improvements that will be needed to support high-energy laser development for high-density science [125]. Alternatively, for direct CPA in the mid-IR, OPCPA or other laser architectures, diode pumping could capitalize on the availability of QCLs with considerable output power. QCLs provide for wavelength selectivity between 4–12 µm by design. Their gain profile is broad but can be significantly narrowed with the use of an external cavity or by providing monochromatic feedback. QCLs operating at room temperature with output power of a few watts have been demonstrated [129] and are commercially available. Future research opportunities in ultrashort-pulse lasers may also capitalize on high-bandgap GaN laser diodes that have achieved significant power output, of the order of multiple 100s of watts. With wavelengths in the 375- to 521-nm range and watt-level outputs, these commercially available diodes could be used for direct pumping of laser gain material, as has been previously demonstrated at moderate average power [130].

Fiber lasers will benefit from progress made in the laser diode development research described above. The fabrication methods for coupling light from high-power laser diodes into optical fibers are mature. However, the component technology for pump-signal combiners for specialty optical fibers will need to be further developed to make the available pump diodes useful in cutting-edge fiber laser systems. Pump-signal combiner development will need to progress in tandem with the active research efforts in novel high-power fiber lasers because co-development ensures that high coupling efficiencies are achieved early in the development process.

SCIENCE AND TECHNOLOGY IMPACT

The research actions recommended in this PRD are required to make substantial advances in the specific capabilities of ultrashort-pulse and ultrahigh intensity near-IR and mid-IR lasers needed to explore scientific frontiers. Laser systems are restricted by the available materials, coatings, and gain material diameters and the successful advancement of the associated research thrusts would enable rapid advances in laser capabilities. The maximum energy that a given laser pulse can have is currently constrained by the diameter of the gain media and the laser damage threshold of the constituent optical components. Similarly, the energy available in OPCPA systems is limited by the aperture of the nonlinear crystals. Repetition rates are limited by the ability of laser diodes for pumping to deliver high average power at a reasonable cost per watt. Advancements in gain media and nonlinear crystals could enable entirely new laser architectures. A new generation of optics, including re-invented MLD coatings, metamaterials and “self-healing” optics, can lead to much broader customizability of the wavefront and polarization, or to circumvent the need for traditional optics. Figure 11 illustrates the relative impact each PRD 4 research thrust can have on achieving the performance demanded by the scientific community for laser technologies outlined in each of the PRD 1, PRD 2, and PRD 3 thrusts.

Laser power in the near-IR is currently limited to around 10 petawatts of peak power due to limitations in the size of gain media and gratings. With advancements in material and optical design and fabrication technologies outlined above, multiple beams that can be focused to intensities surpassing 10^{24} W/cm^2 will become possible. This benchmark will enable QED to be experimentally investigated. Beyond QED, the highest intensities enable new regimes of hadron acceleration to be explored. Relativistic proton acceleration driven by lasers has unique properties that make it suitable for secondary beam generation for hadrons such as neutrons. The interaction of intense lasers with solid-density plasmas produces matter at the most extreme conditions, and with sufficiently high intensities high-energy positron and muon beams can be accelerated to relativistic energies. Such extreme conditions, which in nature can only be observed in rare or extreme events such as active galactic nuclei, will be made possible in the lab by intense lasers. New laser technologies enable relativistic shock acceleration, and the ability to study magnetic reconnection of magnetic field lines with strengths only observed on stellar scales. At higher magnetic field strengths, many more astrophysical bodies can be experimentally modeled, including pulsars and magnetars. High-brightness gamma ray sources also become available.

Advances in gain material, nonlinear crystals and optical components for the mid-IR could impact in the demonstration of high-intensity ultrafast mid-IR lasers for direct pumping of nonlinear components to generate secondary radiation in the far-IR and THz at longer wavelengths and DUV to soft X-ray at shorter wavelengths. These novel radiation sources will enable ultrafast molecular and element-specific spectroscopies and other scientific applications that will advance the understanding of the chemistry and physics of atomic, molecular, and condensed phase systems on time scales of electronic and nuclear motions.

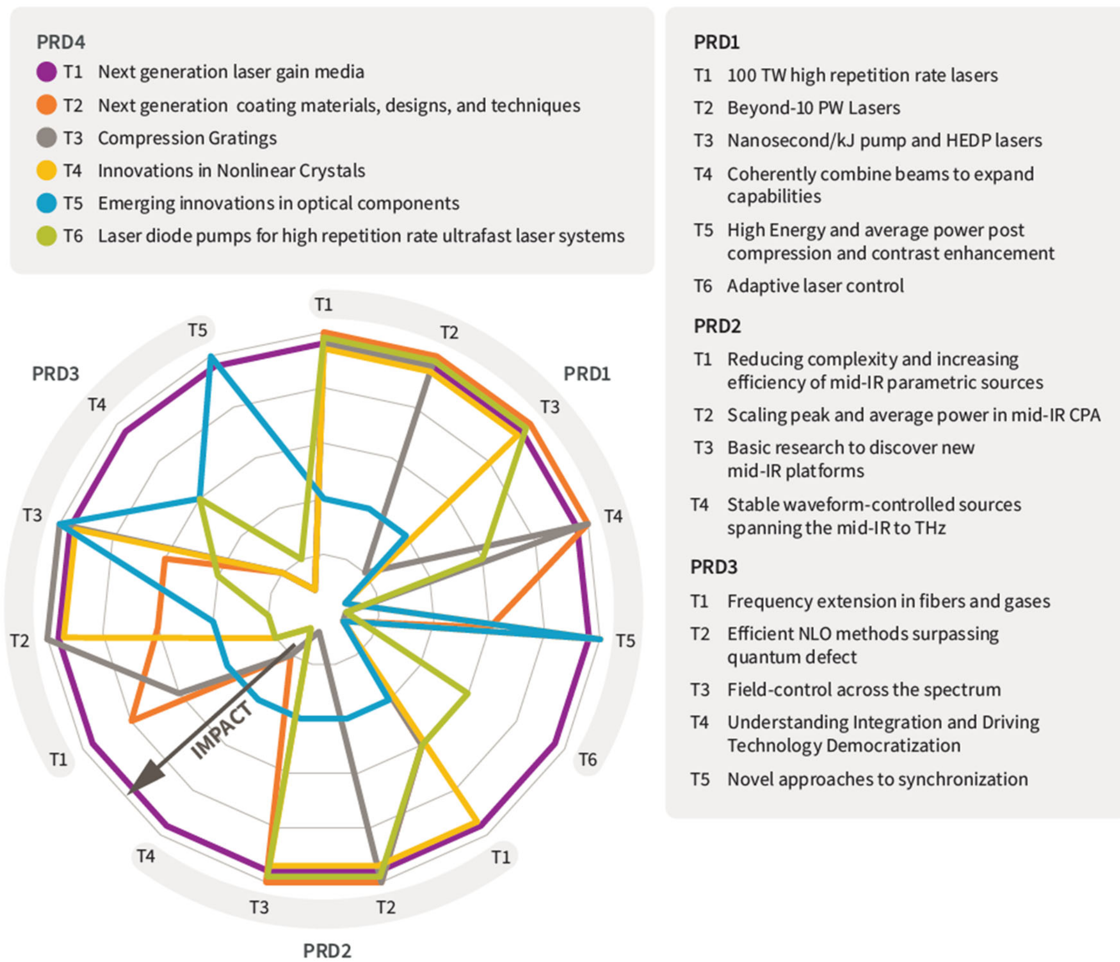

Figure 11. Relative impact of PRD 4 thrusts on those of PRDs 1–3. This graphic shows the relative impact of each thrust area of PRD 4 on the PRD thrust areas described previously in this report illustrating that advancements on the enabling technologies of PRD4 will be critical to support the development of the lasers described in PRDs 1, 2, and 3.

References

[1] C. N. Danson *et al.*, "Petawatt and exawatt class lasers worldwide," *High Power Laser Sci. Eng.*, vol. 7, pp. e54, Aug. 2019, doi: 10.1017/hpl.2019.36.

[2] ELI ERIC, "The Extreme Light Infrastructure ERIC annual report 2022-2023," pp. 39, Aug. 2023. [Online]. Available: https://eli-laser.eu/media/2790/eli_eric_annual_report_2022_2023.pdf

[3] Y. Wang *et al.*, "1.1 J Yb:YAG picosecond laser at 1 kHz repetition rate," *Opt. Lett.*, vol. 45, no. 24, pp. 6615-6618, 2020, doi: 10.1364/ol.413129.

[4] I. Tamer *et al.*, "1 GW peak power and 100 J pulsed operation of a diode-pumped Tm:YLF laser," *Opt. Express*, vol. 30, no. 26, pp. 46336-46343, Dec. 2022, doi: 10.1364/oe.475914.

[5] E. Sistrunk *et al.*, "Laser technology development for high peak power lasers achieving kilowatt average power and beyond," in *Proc. SPIE*, vol. 11034, Art. No. 1103407, Apr. 2019, doi: 10.1117/12.2525380.

[6] E. A. Shcherbakov, V. V. Fomin, A. A. Abramov, A. A. Ferin, D. V. Mochalov, and V. P. Gapontsev, "Industrial grade 100 kW power CW fiber laser," in *Advanced Solid-State Lasers Congress*, G. Huber and P. Moulton, Eds., OSA Technical Digest, Optica Publishing Group, paper Ath4A.2, 2013, doi: 10.1364/ASSL.2013.Ath4A.2.

[7] I. Fsaifes *et al.*, "Coherent beam combining of 61 femtosecond fiber amplifiers," *Opt. Express,*, vol. 28, no. 14, pp. 20152-20161, 2020, 10.1364/OE.394031.

[8] M. Müller *et al.*, "10.4 kW coherently combined ultrafast fiber laser," *Opt. Lett.*, vol. 45, no. 11, pp. 3083-3086, 2020, doi: 10.1364/OL.392843.

[9] H. Stark, M. Benner, J. Buldt, A. Klenke, and J. Limpert, "Pulses of 32 mJ and 158 fs at 20-kHz repetition rate from a spatiotemporally combined fiber laser system," *Opt. Lett.*, vol. 48, no. 11, pp. 3007-3010, 2023, doi: 10.1364/OL.488617.

[10] A. Rainville, M. Whittlesey, C. Pasquale, Y. Jing, Q. Du, and A. Galvanauskas, "Stable and efficient Coherent Pulse Stacking Amplification of 81 pulses with Four Channel Coherent Spatial Combining at 7mJ/fiber," in *CLEO 2023*, Technical Digest Series, Optica Publishing Group, paper SF3H.6, 2023, doi: 10.1364/CLEO_SI.2023.SF3H.6.

[11] A. V. Korzhimanov, A. A. Gonoskov, E. A. Khazanov, and A. M. Sergeev, "Horizons of petawatt laser technology," *Physics-Uspekhi*, vol. 54, no. 9, Jan. 2011, doi: 10.3367/UFNe.0181.201101c.0009.

[12] E. S. Efimenko *et al.,* "Extreme plasma states in laser governed vacuum breakdown," *Sci. Rep.*, vol. 8, Art. No. 2393, Feb. 2018, doi: 10.1038/s41598-018-20745-y.

[13] C. Riconda and S. Weber, "Plasma amplification for high-power lasers," Multi-Petawatt Physics Prioritization (MP3) Workshop Report, White Paper no. 35.

[14] D. Broege *et al.*, "The Dynamic Compression Sector laser: A 100-J UV laser for dynamic compression research," *Rev. Sci. Instrum.*, vol. 90, no. 5, Art. No. 053001, May 2019, doi: 10.1063/1.5088049.

[15] B. Nagler *et al.*, "The Matter in Extreme Conditions instrument at the Linac Coherent Light Source," *J. Synchrotron Rad.*, vol. 22, no. 3, pp. 520-525, Apr. 2015, doi: 10.1107/s1600577515004865.

[16] U. Zastrau *et al.*, "The High Energy Density scientific instrument at the European XFEL," *J. Synchrotron Rad.*, vol. 28, no. 5, pp. 1393-1416, Aug. 2021, doi: 10.1107/S1600577521007335.

[17] G. Dyer and A. Fry, "Matter in Extreme Conditions Upgrade (Conceptual Design Report)" SLAC National Accelerator Laboratory, Oct. 2021. [Online]. Available: https://www.osti.gov/servlets/purl/1866100, doi: 10.2172/1866100.

[18] R.G. Kraus *et al.*, "Kinetics of Materials at Extreme Conditions: Understanding the Time Dependent Approach to Equilibrium at MaRIE," Lawrence Livermore National Laboratory, Apr. 2017. [Online]. Available: https://www.osti.gov/servlets/purl/1357387, doi: 10.2172/1357387.

[19] D. E. Fratanduono *et al.*, "The direct measurement of ablation pressure driven by 351-nm laser radiation," *J. Appl. Phys.*, vol. 110, no. 7, Art. No. 073110, Oct. 2011, doi: 10.1063/1.3646554.

[20] S. Skupsky, R. W. Short, T. Kessler, R. S. Craxton, S. Letzring, and J. M. Soures, "Improved laser-beam uniformity using the angular dispersion of frequency-modulated light," *J. Appl. Phys.*, vol. 66, no. 8, pp. 3456–3462, Oct. 1989, doi: 10.1063/1.344101.

[21] S. P. Regan *et al.*, "Performance of 1-THz-bandwidth, two-dimensional smoothing by spectral dispersion and polarization smoothing of high-power, solid-state laser beams," *J. Opt. Soc. Am., B.*, vol. 22, no. 5, pp. 998-1002, 2005, doi: 10.1364/JOSAB.22.000998.
[22] N. Jourdain *et al.*, "The L4n laser beamline of the P3-installation: Towards high-repetition rate high-energy density physics at ELI-Beamlines," *Matter Radiat. At Extremes*, vol. 6, no. 1. Art. No. 015401, Jan. 2021, doi: 10.1063/5.0022120.
[23] R. Chonion, J. M. Sajer, E. Bordenave, F. Le Palud, P. M. Dalbies, and J. Neauport, "Multiphysics model of liquid-cooled Nd:phosphate split-slabs in large aperture optical amplifiers," *Opt. Express.*, vol. 28, no. 14, pp. 20162-20176, 2020, doi: 10.1364/OE.394271.
[24] P. Mason *et al.*, "Development of a 100 J, 10 Hz laser for compression experiments at the High Energy Density instrument at the European XFEL," *High Power Laser Sci. Eng.*, vol. 6, pp. e65, Dec. 2018, doi: 10.1017/hpl.2018.56.
[25] I. W. Choi *et al.*, "Highly efficient double plasma mirror producing ultrahigh-contrast multi-petawatt laser pulses," *Opt. Lett.*, vol. 45, no. 23, pp. 6342-6345, 2020, doi: 10.1364/OL.409749.
[26] L. Chen *et al.*, "Synthesizing ultrafast optical pulses with arbitrary spatiotemporal control," *Sciences Advances*, vol. 8, no. 43, Oct. 2022, doi: 10.1126/sciadv.abq8314.
[27] G. Genty *et al.*, "Machine learning and applications in ultrafast photonics," *Nat. Photonics*, vol. 15, no. 2, pp. 91-101, 2021, doi: 10.1038/s41566-020-00716-4.
[28] Y. Wang *et al.*, "Single-shot measurement of >1010 pulse contrast for ultra-high peak-power lasers," *Sci. Rep.*, vol. 4, Art. No. 3828, Jan. 2014, doi: 10.1038/srep03818.
[29] E. Franco, Ó. Martinez-Matos, and J. A. Rodrigo, "Curve-shaped ultrashort laser pulses with programmable spatiotemporal behavior," *Optica*, vol. 10, no. 3, pp.379-392, 2023, doi: 10.1364/OPTICA.478086.
[30] B. Loughran *et al.*, "Automated control and optimization of laser-driven ion acceleration," *High Power Laser Sci. Eng.*, vol. 11, pp. e35, Mar. 2023, doi: 10.1017/hpl.2023.23.
[31] B. Z. Djordjević *et al.*, "Modeling laser-driven ion acceleration with deep learning," *Phys. Plasmas*, vol. 28, no. 4, Art. No. 043105, Apr. 2021, doi: 10.1063/5.0045449.
[32] U.S. Department of Energy, "Basic Research Needs for Catalysis Science to Transform Energy Technologies," *Report of the Basic Research Needs Workshop for Catalysis Science*, Gaithersburg, Maryland, USA, May 8-10, 2017. [Online]. Available: https://science.osti.gov/-/media/bes/pdf/reports/2017/BRN_CatalysisScience_rpt.pdf
[33] J. Hemminger, G. Fleming, and M. Ratner, "Directing matter and energy: Five challenges for science and the imagination," U.S. Department of Energy Office of Science, Dec. 2007. [Online]. Available: https://www.osti.gov/servlets/purl/935427/, doi: 10.2172/935427.
[34] U.S. National Science Foundation, "NSF's 10 Big Ideas," n.d. Available: https://www.nsf.gov/news/special_reports/big_ideas/
[35] L. Young *et al.*, "Roadmap of ultrafast X-ray atomic and molecular physics," *J. Phys. B: At. Mol. Opt. Phys., vol.* 51, no. 3Art. No. 032003, Jan. 2018, doi: 10.1088/1361-6455/aa9735.
[36] T. Popmintchev *et al.*, "Bright coherent ultrahigh harmonics in the keV X-ray Regime from mid-infrared femtosecond lasers," *Science*, vol. 336, no. 6086, pp. 1287-1291, Jun. 2012, doi: 10.1126/science.1218497.
[37] Z. Chang *et al.*, "Intense infrared lasers for strong-field science," *Adv. Opt. Photon.*, vol. 14, no. 4, pp. 652-782, 2022, doi: 10.1364/AOP.454797.
[38] S. R. Leone and D. M. Neumark, "Probing matter with nonlinear spectroscopy." *Science*, vol. 379, no. 6632, pp. 536-537, Feb. 2023, doi: 10.1126/science.add4509.
[39] A. Zong, B. R. Nebgen, S.-C. Lin, J. A. Spies, and M. Zuerch, "Emerging ultrafast techniques for studying quantum materials." *Nat. Rev. Mater.*, vol. 8, pp. 224–240, Feb. 2023, doi: 10.1038/s41578-022-00530-0.
[40] A. M. Zheltikov, "Laser-induced filaments in the mid-infrared," *J. Phys. B: At. Mol. Opt. Phys*, vol. 50, no. 9, Art. No. 092001, Apr. 2017, doi: 10.1088/1361-6455/aa6109.
[41] S. R. Leone *et al.* "What will it take to observe processes in 'real time'?" *Nature Photon.*, vol. 8, pp. 162–166, Feb. 2014, doi: 10.1038/nphoton.2014.48.
[42] D. N. Basov, R. D. Averitt, and D. Hsieh, "Towards properties on demand in quantum materials," *Nature Mater.*, vol. 16, pp. 1077–1088, Oct. 2017, doi: 10.1038/nmat5017.

[43] H. Fattahi *et al.*, "Third-generation femtosecond technology," *Optica*, vol. 1, no. 1, pp. 45-63, 2014, doi: https://doi.org/10.1364/OPTICA.1.000045.

[44] V. Leshchenko, S. Li, P. Agostini, and L. F. DiMauro, "Sub-two-cycle gigawatt-peak-power LWIR OPA for ultrafast nonlinear spectroscopy of condensed state materials," *Opt. Lett.*, vol. 48, no. 19, pp. 4949-4952, 2023, doi: 10.1364/OL.500550.

[45] S. B. Mirov, V. V. Fedorov, D. Martyshkin, I. S. Moskalev, M. Mirov and S. Vasilyev, "Progress in Mid-IR Lasers based on Cr and Fe-Doped II–VI Chalcogenides," *IEEE J Sel Top Quantum Electronics*, vol. 21, no. 1, pp. 292-310, Jan.-Feb. 2015, Art no. 1601719, doi: 10.1109/JSTQE.2014.2346512.

[46] A. V. Muraviev, V. O. Smolski, Z. E. Loparo, and K. L. Vodopyanov, "Massively parallel sensing of trace molecules and their isotopologues with broadband subharmonic mid-infrared frequency combs," *Nature Photon.*, vol. 12, pp. 209–214, Mar. 2018, doi: 10.1038/s41566-018-0135-2.

[47] D. M. B. Lesko, "High Power Few-Cycle Erbium Fiber Frequency Combs." PhD Thesis, Dept. Chem., University of Colorado Boulder, Boulder, Colorado, USA, 2023.

[48] K. Beierschmitt *et al.*, "Basic research needs workshop for future nuclear energy," *Report of the Basic Energy Sciences Workshop for Future Nuclear Energy*, Aug. 9-11, 2017. [Online]. Available: https://www.osti.gov/servlets/purl/1616270, doi: 10.2172/1616270.

[49] Semiconductor Industry Association and Semiconductor Research Corporation, "Rebooting the IT Revolution: A Call to Action," Sep. 2015. [Online]. Available: https://www.src.org/newsroom/rebooting-the-it-revolution.pdf

[50] J. Hemminger, G. Fleming, and M. Ratner, "Directing matter and energy: Five challenges for dcience and the imagination," U.S. Department of Energy Office of Science, Dec. 2007. [Online]. Available: https://www.osti.gov/servlets/purl/935427/, doi: 10.2172/935427.

[51] P. Musumeci *et al.*, "Advances in bright electron sources", *Nucl. Instrum. Methods. Phys. Res., A*, vol. 907, pp. 209–220, Nov. 2018, doi: 10.1016/j.nima.2018.03.019.

[52] D. Filippetto *et al.*, "Ultrafast electron diffraction: Visualizing dynamic states of matter," *Rev. Mod. Phys.*, vol. 94, no. 4, Art. No. 045004, Dec. 2022, doi: 10.1103/RevModPhys.94.045004.

[53] M. Maiuri, M. Garavelli, and G. Cerullo, "Ultrafast spectroscopy: State of the art and open challenges," *J. Am. Chem. Soc.*, vol. 142, no. 1, pp. 3-15, 2020, doi: 10.1021/jacs.9b10533.

[54] M. Nisoli, S. De Silvestri, and O. Svelto, "Generation of high energy 10 fs pulses by a new pulse compression technique," *Appl. Phys. Lett.*, vol. 68, no. 20, pp. 2793–2795, May 1996, doi: 10.1063/1.116609.

[55] D. J. Jones *et al.*, "Carrier-envelope phase control of Femtosecond mode-locked lasers and direct optical frequency synthesis." *Science*, vol. 288, no. 5466, pp. 635-639, Apr. 2000, doi: 10.1126/science.288.5466.635.

[56] S. Okubo, A. Onae, K. Nakamura, T. Udem, and H. Inaba, "Offset-free optical frequency comb self-referencing with an f-2f interferometer," *Optica*, vol. 5, no. 2, pp. 188-192, 2018, doi: 10.1364/OPTICA.5.000188.

[57] R. Lemons *et al.*, "Carrier-envelope phase stabilization of an Er:Yb:glass laser via a feed-forward technique," *Opt Lett.*, vol. 44, no. 22, pp. 5610-5613, Nov. 2019, doi: 10.1364/OL.44.005610.

[58] A. Dubietis and A. Matijošius, "Table-top optical parametric chirped pulse amplifiers: past and present," *Opto-Electron Adv.*, vol. 6, no. 3, Art no. 220046, 2023 doi: 10.29026/oea.2023.220046.

[59] E. Goulielmakis *et al.*, "Attosecond control and measurement: Lightwave electronics," *Science*, vol. 317, no. 5839, pp. 769-775, Aug. 2007, doi: 10.1126/science.1142855.

[60] M. Borsch, M. Meierhofer, R. Huber, and M. Kira, "Lightwave electronics in condensed matter," *Nat. Rev. Mater.*, vol. 8, pp. 668–687, Sep. 2023, doi: 10.1038/s41578-023-00592-8.

[61] X. Li *et al.*, "Terahertz field–induced ferroelectricity in quantum paraelectric SrTiO3," *Science*, vol. 364, no. 6445, pp. 1079-1082, Jun. 2019, doi: 10.1126/science.aaw4913.

[62] S. Schlauderer *et al.*, "Temporal and spectral fingerprints of ultrafast all-coherent spin switching," *Nature*, vol. 569, pp. 383–387, May 2019, doi: 10.1038/s41586-019-1174-7.

[63] A.R. Attar *et al.*, "Femtosecond X-ray spectroscopy of an electrocyclic ring-opening reaction," *Science*, vol. 356, no. 6333, pp. 54–59, Apr. 2017, doi: 10.1126/science.aaj2198.

[64] B. Stankus *et al.*, "Ultrafast X-ray scattering reveals vibrational coherence following Rydberg excitation," *Nat. Chem*, vol. 11, pp. 716–721, 2019, doi: 10.1038/s41557-019-0291-0.

[65] E.G. Champenois *et al.*, "Conformer-specific photochemistry imaged in real space and time," *Science*, vol. 374, no. 6564, pp. 178-182, Oct. 2021, doi: 10.1126/science.abk3132.

[66] S. Pathak *et al.*, "Tracking the ultraviolet-induced photochemistry of thiophenone during and after ultrafast ring opening," *Nat. Chem*, vol. 12, pp. 795-800, 2020, doi: 10.1038/s41557-020-0507-3.

[67] R. Boll *et al.*, "X-ray multiphoton-induced Coulomb explosion images complex single molecules," *Nat. Phys.*, vol. 18, pp. 423-428, 2022, doi: 10.1038/s41567-022-01507-0.

[68] F. Belli, A. Abdolvand, W. Chang, J. C. Travers, and P. St.J. Russell, "Vacuum-ultraviolet to infrared supercontinuum in hydrogen-filled photonic crystal fiber," *Optica*, vol. 2, no. 4, pp. 292-300, 2015, doi: 10.1364/OPTICA.2.000292.

[69] J. C. Travers, T. F. Grigorova, C. Brahms, and F. Belli, "High-energy pulse self-compression and ultraviolet generation through soliton dynamics in hollow capillary fibres," *Nat. Photonics*, vol. 13, pp. 547–554, Apr. 2019, 10.1038/s41566-019-0416-4.

[70] J. E. Beetar, M. Nrisimhamurty, T.-C. Truong, Y. Liu, and M. Chini, "Thermal effects in molecular gas-filled hollow-core fibers," *Opt. Lett.*, vol. 46, no. 10, pp. 2437-2440, 2021, doi: 10.1364/OL.422983.

[71] J. Ma *et al.*, "Quasi-parametric amplification of chirped pulses based on a Sm3+-doped yttrium calcium oxyborate crystal," *Optica*, vol. 2, no. 11, pp. 1006-1009, 2015, doi: 10.1364/OPTICA.2.001006.

[72] N. Flemens, N. Swenson, and J. Moses, "Efficient parametric amplification via simultaneous second harmonic generation," *Opt. Express,* vol. 29, no. 19, pp. 30590-30609, 2021, doi: 10.1364/OE.437864.

[73] G. Jansonas, R. Budriūnas, G. Valiulis and A. Varanavičius, "Polarization-Based Idler Elimination: Enhancing the Efficiency of Optical Parametric Amplification," *2023 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC)*, Munich, Germany, 2023, pp. 1-1, doi: 10.1109/CLEO/Europe-EQEC57999.2023.10231989.

[74] K.L. Vodopyanov, "Ultra-broadband mid-infrared frequency combs produced by optical subharmonic generation," *Quantum Electron.*, vol. 52, no. 4, pp. 307, doi: 10.1070/QEL18012.

[75] L. Wang, A. Fallahi, K. Ravi, and F. Kärtner, "High efficiency terahertz generation in a multi-stage system," *Opt. Express,* vol. 26, no. 23, pp. 29744-29768, 2018, doi: 10.1364/OE.26.029744.

[76] M. Michieletto, J. K. Lyngsø, C. Jakobsen, J. Lægsgaard, O. Bang, and T. T. Alkeskjold, "Hollow-core fibers for high power pulse delivery," *Opt. Express,* vol. 24, no. 7, pp. 7103-7119, 2016, doi: 10.1364/OE.24.007103.

[77] R. D. Niederriter, M. E. Siemens, and J. T. Gopinath, "Simultaneous control of orbital angular momentum and beam profile in two-mode polarization-maintaining fiber," *Opt. Lett.*, vol. 41, no. 24, pp. 5736-5739, 2016, 10.1364/OL.41.005736.

[78] B. M. Heffernan, R. D. Niederriter, M. E. Siemens, and J. T. Gopinath, "Tunable higher-order orbital angular momentum using polarization-maintaining fiber," *Opt. Lett.*, vol. 42, no. 14, pp. 2683-2686, 2017, doi: 10.1364/OL.42.002683.

[79] N. Jhajj, I. Larkin, E. W. Rosenthal, S. Zahedpour, J. K. Wahlstrand, and H. M. Milchberg, "Spatiotemporal Optical Vortices," *Phys. Rev. X*, vol. 6, Art. No. 031037, Sep. 2016, doi: 10.1103/PhysRevX.6.031037.

[80] L. Rego *et al.*, "Generation of extreme-ultraviolet beams with time-varying orbital angular momentum," *Science*, vol. 364, no. 6447, Jun. 2019, 10.1126/science.aaw9486.

[81] E. Hemsing, G. Stupakov, D. Xiang, and A. Zholents, "Beam by design: Laser manipulation of electrons in modern accelerators," *Rev. Mod. Phys.*, vol. 86, no. 3, pp. 897-941, Jul. 2014, doi: 10.1103/RevModPhys.86.897.

[82] J. P. Duris *et al.*, "Controllable X-ray pulse trains from enhanced self-amplified spontaneous emission," *Phys.Rev.Lett.*, vol. 126, no. 10, Art. No. 104802, Mar. 2021, doi: 10.1103/PhysRevLett.126.104802.

[83] L. Salmela, N. Tsipinakis, A. Foi, C. Billet, J. M. Dudley, and G. Genty, "Predicting ultrafast nonlinear dynamics in fibre optics with a recurrent neural network. *Nat. Mach. Intell.*, vol. 3, pp. 344-354, 2021, doi: 10.1038/s42256-021-00297-z.

[84] J. Hirschman, M. Wangand S. Carbajo, "LSTM Nonlinear Dynamics Predictor for Accelerating Data Generation in Ultrafast Optics and Laser System Design," *Optica Open*, Jun. 2023, doi: 10.1364/opticaopen.23605839.v2.

[85] X. Jiang, D. Wang, Q. Fan, M. Zhang, C. Lu, and A. P. T. Lau, "Physics-Informed Neural Network for Nonlinear Dynamics in Fiber Optics," *Laser Photonics Rev.*, vol. 16, no. 9, Art. No. 2100483, Sep. 2022, doi: 10.1002/lpor.202100483.

[86] G. Cho, D. Zhu, J. J. Campbell and M. Wang, "An LSTM-PINN Hybrid Method to Estimate Lithium-Ion Battery Pack Temperature," in *IEEE Access*, vol. 10, pp. 100594-100604, 2022, doi: 10.1109/ACCESS.2022.3208103.

[87] Z. Li, N. Kovachki, K. Azizzadenesheli, B. Liu, K. Bhattacharya, A. Stuart, and A. Anandkumar, "Fourier neural operator for parametric partial differential equations," 2020, arXiv:2010.08895, doi: 10.48550/arXiv.2010.08895.

[88] J. Duris *et al.*, "Tunable isolated attosecond X-ray pulses with gigawatt peak power from a free-electron laser" *Nat. Photon.*, vol. 14, pp. 30–36, 2020, doi: 10.1038/s41566-019-0549-5.

[89] R. N. Coffee, J. P. Cryan, J. Duris, W. Helml, S. Li, and A. Marinelli, "Development of ultrafast capabilities for X-ray free-electron lasers at the linac coherent light source," *Phil. Trans. R. Soc. A.*, vol. 377, Art. No. 20180386, Apr. 2019, doi: 10.1098/rsta.2018.0386.

[90] M. Neuhaus *et al.*, "Transient field-resolved reflectometry at 50–100 THz," *Optica*, vol. 9, no. 1, pp. 42-49, 2022, doi: 10.1364/OPTICA.440533.

[91] Y. Liu, J. E. Beetar, J. Nesper, S. Gholam-Mirzaei, and M. Chini, "Single-shot measurement of few-cycle optical waveforms on a chip," *Nat. Photon.*, vol. 16, pp. 109–112, 2022 10.1038/s41566-021-00924-6

[92] K. Wu and S. Pan, "A review on structure-performance relationship toward the optimal design of infrared nonlinear optical materials with balanced performances," *Coord. Chem. Rev.*, vol. 377, pp. 191-208, Dec. 2018, doi: 10.1016/j.ccr.2018.09.002.

[93] S. Schimmel, W. Sun, and N. Dropka, "Artificial Intelligence for Crystal Growth and Characterization," *Crystals*, vol. 12, no. 9, Art. No. 1232, Sep. 2022, doi: 10.3390/cryst12091232.

[94] Y. Dang *et al.*, "Adaptive process control for crystal growth using machine learning for high-speed prediction: application to SiC solution growth," *Cryst. Eng. Comm.*, vol. 23, no. 9, pp. 1982-1990, 2021, doi: 10.1039/D0CE01824D.

[95] J. E. Marion, "Fracture of solid state laser slabs," *J. Appl. Physics*, vol. 60, no. 1, pp. 69-77, Jul. 1986, doi: 10.1063/1.337630.

[96] A. Neogi, L. He, and N. Abdolrahim, "Atomistic simulations of shock compression of single crystal and core-shell Cu@Ni nanoporous metals," *J. Appl. Phys.*, vol. 126, no. 1, Art. No. 015901, Jul. 2019, doi: 10.1063/1.5100261.

[97] H. Huang, T. Z. Kosc, T. J. Kessler, S. G. Demos "Modeling of Transverse Stimulated Raman Scattering in KDP/DKDP large aperture plates suitable for polarization control," *High Power Laser Sci. Eng.*, vol. 11, pp. e54, 2023, 10.1017/hpl.2023.43.

[98] D. C. Brown, S. D. Jacobs, J. A. Abate, O. Lewis, and J. Rinefierd, "Figures of merit and correlations of physical and optical properties in laser glasses," in *Laser Induced Damage in Optical Materials: 1977*, vol. 655, pp. 416-433, Dec. 1977.

[99] J. L. Emmett, W. F. Krupke, and J. B. Trenholme, "Future development of high-power solid-state laser systems," Sov. J. Quantum Electron., vol. 13, no. 1, pp. 1–23, Jan. 1983, doi: 10.1070/QE1983v013n01ABEH004004.

[100] J. E. Marion, "Appropriate use of the strength parameter in solid state laser design," *J. Appl. Phys.*, vol. 62, pp. 1595–1604, Sep. 1987, doi: 10.1063/1.339607.

[101] S. E. Stokowski, R. A. Saroyan, and M. J. Weber, "Nd-doped Laser Glass Spectroscopic and Physical Properties," Lawrence Livermore National Laboratory, University of California, Livermore, CA. Vols. 1 and 2, 1981

[102] S. Normani *et al.*, "Site selective analysis of Nd3+-Lu3+ codoped CaF2 laser crystals," *Cryst. Eng. Comm*, vol. 18, no. 47, pp. 9016-9025, 2016, doi: 10.1039/C6CE01966H.

[103] S. Qu *et al.*, "Directly diode-pumped femtosecond Cr:ZnS amplifier with ultra-low intensity noise," *Opt. Lett.*, vol. 47, no. 23, pp. 6217-6220, 2022, doi: 10.1364/OL.475438.

[104] L. Yang *et al.*, "Enhanced Medium Range Order in Vapor Deposited Germania Glasses at Elevated Temperatures," *Sci. Adv.*, vol. 7, no. 37, Sep. 2021, doi: 10.1126/sciadv.abh1117.

[105] K. Prasai, R. Bassiri, H.-P. Cheng, M. M. Fejer, "Annealing-Induced Changes in the Atomic Structure of Amorphous Silica, Germania, and Tantala Using Accelerated Molecular Dynamics," *Physica Status Solidi, B*, vol. 258, no. 9, Art. No. 2000519, 2021, doi: 10.1002/pssb.202000519.

[106] J. Jiang *et al.*, "Amorphous Zirconia-doped Tantala modeling and simulations using explicit multi-element spectral neighbor analysis machine learning potentials (EME-SNAP)," *Phys. Rev. Mater.*, vol. 7, no. 4, Art. No. 045602, Apr. 2023, doi: 10.1103/PhysRevMaterials.7.045602.

[107] M. A. Fazio, G. Vajente, L. Yang, A. Ananyeva, and C. S. Menoni, "Comprehensive study of amorphous metal oxide and Ta2O5-based mixed oxide coatings for gravitational-wave detectors," *Phys. Rev. D*, vol. 105, no. 10, Art. No. 102008, May 2022, doi: [10.1103/PhysRevD.105.102008](https://doi.org/10.1103/PhysRevD.105.102008).

[108] S. S. Thöny *et al.*, "Magnetron sputter deposition of Ta2O5-SiO2 quantized nanolaminates," *Opt. Express,* vol. 31, no. 10, pp. 15825-15835, 2023, doi: [10.1364/OE.487892](https://doi.org/10.1364/OE.487892).

[109] S. Zhang, C. Menoni, V. Gruzdev, E. Chowdhury, "Ultrafast laser material damage simulation—A new look at an old problem," *Nanomaterials*, vol. 12, no. 8, Art. No. 1250, 2022, doi: [10.3390/nano12081259](https://doi.org/10.3390/nano12081259).

[110] B. C. Stuart, M. D. Feit, A. M. Rubenchik, B. W. Shore, and M. D. Perry, "Laser-induced damage in dielectrics with nanosecond to subpicosecond pulses," *Phys. Rev. Lett.*, vol. 74, no. 12, Art. No. 2248, Mar. 1995, doi: [10.1103/PhysRevLett.74.2248](https://doi.org/10.1103/PhysRevLett.74.2248).

[111] C. J. Stolz and R. A. Negres, "Ten-year summary of the Boulder Damage Symposium annual thin film laser damage competition," *Opt. Eng.*, vol. 57, no. 12, Art. No. 121910, Dec. 2018, doi: [10.1117/1.OE.57.12.121910](https://doi.org/10.1117/1.OE.57.12.121910).

[112] D. A. Alessi, P. A. Rosso, H. T. Nguyen, M. D. Aasen, J. A. Britten, and C. Haefner. "Active cooling of pulse compression diffraction gratings for high energy, high average power ultrafast lasers," *Opt. Express*, vol. 24, no. 26, pp.30015-30023, 2016, doi: [10.1364/OE.24.030015](https://doi.org/10.1364/OE.24.030015).

[113] E. P. Power, S. Bucht, K. R. P. Kafka, J. Bromage, and J. D. Zuegel, "Design and characterization of "flow-cell" integrated-flow active cooling for high-average-power ceramic optics," *Opt. Express,* vol. 30, no. 23, pp. 42525-42540, 2022, doi: [10.1364/OE.473479](https://doi.org/10.1364/OE.473479).

[114] B. N. Hoffman *et al.*, "Mechanisms of picosecond laser-induced damage in common multilayer dielectric gratings," *Opt. Express,* vol. 28, no. 17, pp. 24928-24936, 2020, doi: [10.1364/OE.395197](https://doi.org/10.1364/OE.395197).

[115] N. Liu *et al.*, "Manufacturing-induced contamination in common multilayer dielectric gratings," *Opt. Express,* vol. 31, no. 1, pp. 714-726, 2023, doi: [10.1364/OE.478701](https://doi.org/10.1364/OE.478701).

[116] S. Zhang *et al.*, "Femtosecond damage experiments and modeling of broadband mid-infrared dielectric diffraction gratings," *Opt. Express,* vol. 29, no. 24, pp. 39983-39999, 2021, doi: https://doi.org/10.1364/OE.439895.

[117] Y. Kondo *et al.*, "Silicon nitride etching performance of CH2F2 plasma diluted with argon or krypton," *Jpn. J. Appl. Phys.*, vol. 54, no. 4, Art. No. 040303, Mar. 2015, doi: [10.7567/JJAP.54.040303](https://doi.org/10.7567/JJAP.54.040303).

[118] L. Sun *et al.*, "Effects of combined process of reactive ion etching and dynamic chemical etching on UV laser damage resistance and surface quality of fused silica optics," *Opt. Express*, vol. 26, no. 14, pp. 18006-18018, 2018, doi: [10.1364/OE.26.018006](https://doi.org/10.1364/OE.26.018006).

[119] N. P. Zaitseva *et al.*, "Rapid growth of large-scale (40–55 cm) KH2PO4 crystals," *J. Cryst. Growth*, vol. 180, no. 2, pp. 255-262, Sep. 1997, doi: [10.1016/S0022-0248(97)00223-6](https://doi.org/10.1016/S0022-0248(97)00223-6).

[120] A. Sugiyama, H. Fukuyama, T. Sasuga, T. Arisawa, and H. Takuma, "Direct bonding of Ti:sapphire laser crystals," *Appl. Opt.*, vol. 37, no. 12, pp. 2407-2410, 1998, doi: [10.1364/AO.37.002407](https://doi.org/10.1364/AO.37.002407).

[121] M. De Vido *et al.*, "High energy, high pulse rate laser operation using crystalline adhesive-free bonded Yb:YAG slabs," *Opt. Express*, vol. 31, no. 17, pp. 28101-28111, 2023, doi: [10.1364/OE.497948](https://doi.org/10.1364/OE.497948).

[122] C. Dorrer, I. A. Begishev, S.-W. Bahk, and J. Bromage, "High-resolution mapping of phase-matching conditions in second-order nonlinear crystals," *Opt. Mater. Express*, vol. 12, no. 9, pp. 3679–3695, 2022, doi: [10.1364/OME.468127](https://doi.org/10.1364/OME.468127).

[123] R. A. Negres, N. P. Zaitseva, P. DeMange, and S. G. Demos, "Expedited laser damage profiling of KDxH2−xPO4 with respect to crystal growth parameters," *Opt. Lett.*, vol. 31, no. 21, pp. 3110–3112, 2006, doi: [10.1364/OL.31.003110](https://doi.org/10.1364/OL.31.003110).

[124] P. Michel, "Plasma photonics: Manipulating light using plasmas (Full technical final report)" Lawrence Livermore National Laboratory, 2021. [Online]. Available: https://www.osti.gov/servlets/purl/1756740, doi: [10.2172/1756740](https://doi.org/10.2172/1756740).

[125] Y. Shen *et al.*, "Roadmap on spatiotemporal light fields," *J. Opt.*, vol. 25, no. 9, Art. No. 093001, Aug. 2023, doi: [10.1088/2040-8986/ace4dc](https://doi.org/10.1088/2040-8986/ace4dc).

[126] L. Chen *et al.*, "Synthesizing ultrafast optical pulses with arbitrary spatiotemporal control," *Sci. Adv.*, vol. 8, no. 43, doi: [10.1126/sciadv.abq8314](https://doi.org/10.1126/sciadv.abq8314).

[127] P. V. Mamyshev, "All-optical data regeneration based on self-phase modulation effect," *24th European Conference on Optical Communication. ECOC '98 (IEEE Cat. No.98TH8398)*, Madrid, Spain, 1998, pp. 475-476 vol.1, doi: [10.1109/ECOC.1998.732666](https://doi.org/10.1109/ECOC.1998.732666).

[128] U. S. Department of Energy Office of Science, "Inertial Fusion Energy: Report of 2022 Office of Fusion Energy Science the Basic Research Needs Workshop," 2022. Available: https://www.dropbox.com/s/go3doegms6pjgc8/IFE%20BRN_full%20report_v20230111.pdf?dl=0

[129] F. Wang, S. Slivken, D. H. Wu, and M. Razeghi, "Room temperature quantum cascade lasers with 22% wall plug efficiency in continuous-wave operation," *Opt. Express,* vol. 28, no. 12, pp. 17532-17538, 2020, doi: 10.1364/OE.394916.

[130] S. Backus, M. Kirchner, C. Durfee, M. Murnane, and H. Kapteyn, "Direct diode-pumped Kerr Lens 13 fs Ti:sapphire ultrafast oscillator using a single blue laser diode," *Opt. Express,* vol. 25, no. 11, pp. 12469-12477, 2017, doi: 10.1364/OE.25.012469.

Crosscutting Themes

Workforce Development (WFD)

This section identifies the main workforce development issues impacting laser science and technology research and development (R&D) and proposes opportunities with priorities to mitigate these issues. A pre-survey was distributed in advance of the Basic Research Needs (BRN) Workshop asking panelists to provide answers to a wide variety of questions related to the field of laser technology to get a better understanding of the current state of the field, areas for improvement, and areas of existing strengths. During the workshop, the workforce development crosscut members attended all science and technology panels, and then met in the evenings to summarize and synthesize findings.

Overall, five distinct workforce development opportunities are identified at different junctures of career paths in laser technology: pre-college, technician pathways, undergraduate training for industry, undergraduate training for research/academia, and early career/graduate student training. In addition to describing each of these opportunity areas, exemplar programs and resources are provided in Appendix G. By establishing the laser technology community as inclusive, supportive of marginalized populations, and welcoming and impactful, newcomers may be recruited from all backgrounds and regions to expose them to meaningful career opportunities in the field.

INTRODUCTION

Underrepresentation of historically marginalized populations in Science, Technology, Engineering, and Mathematics (STEM) fields limits those who are available to participate in the field of laser technology. While workforce development is commonly thought of as a pipeline issue, this discussion is reframed specifically to consider the broader ecosystem that supports and scaffolds individuals' participation in STEM and laser technology. This ecosystem includes pre-college educational systems, higher education institutions, national labs, government organizations, private industry, and the individuals, resources, and infrastructures therein. Mapping the ecosystem enables focused attention on specific opportunity areas for the improvement and understanding of how to shift cultural norms to indicate receptivity and a welcoming environment for new participants in the field of laser technology.

The necessity of expanding the laser workforce to include broader representation of diverse individuals and backgrounds is compounded by the need to grow the laser workforce. Growth at all education levels—specifically the five opportunity areas described in this section—as well as growing next-generation leadership in the field are critical to facilitate development of laser technologies for the next several decades. The future will include not only basic science research but also applications with transformative societal impact such as laser fusion, directed energy for national security and civilian applications, communications and computing, and even laser-powered propulsion for space applications in addition to new technologies that cannot be envisioned at this point. Leveraging the existing workforce and resources more efficiently through enhanced coordination across academic, industrial, and governmental entities should lead to improved utilization, supporting high-quality and impactful research in lasers, the technologies they encompass, and the impactful science they enable.

The following five sections expand on workforce development opportunities by career phase and type. Exemplars and details of specific programs from each segment are offered in Appendix G.

1. Pre-college workforce development

Workforce development opportunities begin in elementary and middle school, as it is critical to begin building a STEM and laser technology workforce before students make definitive career choices or choose majors in college. For the most impact, students must be exposed to scientific (laser) futures from kindergarten through eighth grade (K-8), before their beliefs in their own math abilities become fixed and socialized gender roles begin to affect individual motivations to study STEM subjects [1-3]. Reaching younger students also offers the opportunity to break down common myths and stereotypes of what a laser scientist looks like or who belongs in the field of laser technology [4,5].

In high school, students begin to choose science courses based on interest level and exposure, which presents another opportunity for setting the tone for positive experiences in physics and with laser technologies in pre-college education [6, 7]. One means of exposing students to the field of laser technology is to offer community open houses and tours of laser labs in academic and industry environments. This invites the public to engage with laser technology and become aware of career paths in the laser field. Emphasizing that laser technology careers are stable, are in high demand, and have significant earning potential and impact on the world is important to communicate to students, parents, and families who may have limited exposure to careers in STEM. Providing informational materials not just in English but also other languages (e.g., Spanish) broadens the potential reach of community engagement and signals to underserved and underrepresented populations that they are welcome and can realistically access a future career path in laser technology.

Another opportunity to engage pre-college audiences is through targeted curricula developed in partnership with K-12 educators, subject matter experts, and professional societies. For example, the American Physical Society (APS) sponsors the PhysicsQuest program with a new theme each year, including teacher's guides, implementation notes, fillable PDFs, student guides, and lesson plans [8]. A specific "laser kit" that can be disseminated easily to schools and educators would enable another access pathway for students to learn about laser technology.

APS already offers a variety of programs, resources, and best practices to support teachers in middle and high schools. For example, the APS Career Mentoring Fellows provide career awareness, connections to research and industry, and exposure to living, diverse role models in physics [9]. APS and AIP (American Institute of Physics) also have strong training resources for scientists and engineers to learn how to engage with non-scientist audiences in ways that are culturally responsive, build STEM identity, and cultivate mutually beneficial relationships: APS Supporting Teachers to Encourage the Pursuit of Undergraduate Physics (STEP UP) and AIP Task Force to Elevate the Representation of African Americans in Undergraduate Physics & Astronomy (TEAM-UP) [10,11]. Focusing on *engagement* with communities rather than *outreach* ensures that scientists and engineers do not position themselves as experts bestowing knowledge upon a deficient or lacking population. Instead, engagement activities start from a position of mutual respect and acknowledgement of lived experiences and community cultural wealth. The Impact Toolkit from the University College Dublin is another excellent resource to help researchers appropriately capture, communicate, and monitor their impact from a community engagement perspective [12]. Other organizations including Optica, the Laser Institute of America (LIA), and the American Society for Laser Medicine and Surgery also have community engagement resources and programs in place to reach underserved populations through education [13-15]. When engaging with the community, considering who should be prioritized for access and opportunities is important. Reaching beyond communities and regions which already have plenty of access to scientists may result in greater impact than focusing on areas that already have exposure to STEM or STEM programs in place in public schools already.

Focusing on engagement with communities rather than outreach ensures that scientists and engineers do not position themselves as experts bestowing knowledge upon a deficient or lacking population.

See Appendix G for exemplar programs which engage pre-college students with academic and industry professionals.

2. Technician training/pathways for technicians

A 2021 workforce study from the American Institute for Manufacturing Integrated Photonics (AIM Photonics) [16] predicted that the number of jobs for laser technicians, optical engineering technicians, and precision optics technicians in the U.S. would grow by 47%, from 58,000 currently to nearly 85,000 by the end of the decade. In the meantime, the number of existing laser technician training programs falls short of the demand by 90%. Closely related disciplines, from target fabrication to crystal growth, are also demanding skilled technicians. Without enough technical support, growth and innovation of science discoveries will be hindered.

Technicians enable faster progress and results, as they hold institutional memory of the lab equipment and have potentially longer-term engagement with specific laser technologies than undergraduate, graduate, or postdoctoral researchers. Developing and publicizing a career advancement pathway for laser technicians is one means to make this an attractive career for graduates from two-year degree programs (e.g., community colleges, trade schools). Emphasizing existing opportunities and successful technician training programs with proven placements into laser technology academic and industry labs is one means to further publicize the viability and efficacy of this pathway. Sharing stories from laser technicians to illustrate their enabling impact on scientific and technological breakthroughs in the field may also help drive interest and enrollment in technician training programs.

> *A 2021 workforce study from AIM Photonics predicted that the number of jobs for laser technicians, optical engineering technicians, and precision optics technicians in the U.S. would grow by 47%, from 58,000 currently to nearly 85,000 by the end of the decade.*

Funding opportunities exist to support advanced technological education (e.g., technician training) but community college faculty and administrations benefit from partnering with industry, national labs, and academic institutions to write winning proposals and administer grants.

See Appendix G for exemplar programs demonstrating effective partnerships between two-year colleges, high schools, universities, national laboratories, industry partners, and professional societies to aid in the development of laser technicians.

Laser technology industry and government coalitions such as the American Center for Optics Manufacturing (AmeriCOM) and SPIE (an international society for optics and photonics) also recognize the critical importance of training and developing optics technicians and facilitating advocacy and awareness campaigns to broadcast the career opportunities and growth potential in the field [17, 18]. These organizations also provide access to existing laser technicians, with potential to tell their stories and humanize their experiences for a broad audience. For example, a published interview with technician Philip Adderley illustrates his longevity in the field and involvement in many different cutting-edge laser vacuum projects [19].

However, the technician job category is itself a broad term that has different meanings and connotations across different contexts. For true career advancement potential along a technician pathway, opportunities for meaningful career development and training must be identified and made clear. Creating explicit criteria and incentives for becoming an advanced technician or super technician is one possible means to entice candidates into these pathways, to indicate that this is a viable career track with growth potential and increasing earning potential. Additional specialized training in the areas of target fabrication and crystal growth, for example, may be key differentiators to grow from a general optics technician to a specialized super technician role. Publicizing the availability and necessity of these roles featuring specialized skills and additional training may appeal to individuals with STEM bachelor's degrees or master's degrees who wish to contribute to laser technology in national labs, industry applications, or academic organizations in a technician rather than science or engineering role.

Crafting a culture in laser technology which recognizes and respects different preparation for different roles rather than looking down on individuals without advanced degrees is also critical for sustaining technicians in the field. In addition to technical expertise, some technicians may be interested in aspects of project management or personnel management—developing these career trajectories in the context of technician jobs and careers is another means of signaling that technicians' roles are indeed critical, truly valued, and respected within the field. Furthermore, some programs eschew a path that ends in a terminal degree that is not a doctorate and will not admit students with associates, bachelors, or masters degrees as a career goal. Addressing these assumptive career expectations and admissions criteria could be part of rethinking the culture of laser technology.

3. Undergraduate training for industry careers

Making students aware of career paths in laser technology and the scope of laser technology in supporting scientific and engineering advancements from their first or second year of undergraduate education rather than waiting to introduce lasers to upper division students enables the broadest possible reach and greatest access to potential futures in laser technology. The ubiquity of laser technology in supporting extensive science and engineering applications (high energy physics, particle physics, plasma physics, astrophysics, additive manufacturing, diagnostics for various fields, imaging, biology, chemistry, Bose-Einstein condensates, etc.) provides numerous opportunities for introducing and mentioning lasers across a variety of undergraduate courses. Emphasizing how lasers are a powerful tool which make cutting-edge science and engineering possible can capture students' imaginations and motivate career interests, improving their retention in STEM degree programs.

Introducing first- and second-year undergraduate students to a vision of the laser technology field that is highly collaborative is also a means to influence young students to view science and technology as a team sport, combatting the image of the lone genius making scientific discoveries in isolation. This image of science is likely to be more welcoming to newcomers, particularly for marginalized populations who do not see people like them represented in traditional textbooks and stories of scientific discovery. Leveraging opportunities for exposure to laser technology at professional conferences and diversity-focused STEM conferences is another means to cast a wide net in publicizing careers in laser technology. Emphasizing the perks of the field in terms of growth and earning potential, not to mention possible contributions to scientific discoveries and new technologies, helps to convey the message that young people will be welcomed and can find career and growth opportunities within laser technology. Specific opportunities to publicize career paths in the laser field include physics and optics-focused academic, professional, and industrial conferences (APS, Institute of Electrical and Electronics Engineers/IEEE, SPIE, Optica, etc.) as well as annual meetings of identity-focused STEM organizations (Society for the Advancement of Chicanos/Hispanics and Native Americans in Science/SACNAS, Society of Women Engineers/SWE, National Society of Black Engineers/NSBE, Society of Hispanic Professional Engineers/SHPE, National Society of Black Physicists/NSBP, National Society of Hispanic Physicists/NSHP, etc.).

Introducing first- and second-year undergraduate students to a vision of the laser technology field that is highly collaborative is also a means to influence young students to view science and technology as a team sport, combatting the image of the lone genius making scientific discoveries in isolation.

Many of these organizations also provide grants and scholarships for further engagement with laser technology. Publicizing these opportunities and building awareness of their existence may bring even more new people to the field. SPIE, for example, includes scholarships for students studying optics and photonics as well as outreach grants for individuals wanting to do optics or light-focused community engagement activities [20, 21].

Encouraging undergraduate students to pursue internship opportunities related to laser technology with laser companies is another way of broadening the image of laser applications beyond academic research. While engineering students are often encouraged to do internships throughout their undergraduate education, making sure science students (physics, astrophysics, chemistry, materials science, etc.) are also aware and exposed to career opportunities in laser technology industries during their undergraduate studies can help normalize the idea of proceeding directly to rewarding careers in industry positions rather than graduate school. Continuing to publicize the growth in the job market for photonics, quantum, and optical engineers may enhance the accessibility of this career path for students who are interested in working rather than more schooling.

Expanding public and private partnerships between academic institutions and private industry, connecting to industry to develop meaningful laser-focused curriculum/training programs, and building connections with community colleges are all avenues to explore to continue strengthening the laser technology workforce. Adding an entrepreneurial angle, exploring untapped markets related to laser applications, and demonstrating the breadth of opportunity in the field may also appeal to a broader demographic of students and generations who want to leave an impact on the world.

See Appendix G for exemplar programs preparing undergraduates for careers in the laser industry.

4. Undergraduate training for academic careers

Providing access to research opportunities during undergraduate studies is crucial for demonstrating to students that going to graduate school and continuing in academic research is a viable and rewarding career path. While numerous undergraduate research programs and funding opportunities exist (e.g., National Science Foundation-Research Experiences for Undergraduates/NSF-REU, Department of Energy-Science Undergraduate Laboratory Internships/DOE-SULI, National Nuclear Security Administration-Minority Serving Institution Partnership Program/NNSA-MSIPP), the current scale is still insufficient to support the size of the workforce needed, particularly in the field of laser technology. Growing and expanding access to laser-specific research opportunities is one proven method of bringing promising undergraduates into the laser field and engaging them in interesting and impactful research early on. For undergraduate research programs to be successful, however, dedicated and passionate research mentors are also needed to sponsor these novice researchers. Expanding the number of mentors as well as offering more incentives and recognition for serving as a mentor to undergraduate researchers is a necessary concomitant of growing undergraduate research programs at all levels.

> *Beyond simply providing access to undergraduate research opportunities, to truly welcome newcomers to the field careful attention must be paid to provide a welcoming, supportive, and hospitable environment for undergraduates to engage in laser science.*

Access to undergraduate research opportunities must reach beyond traditional R1 universities to include liberal arts colleges, predominantly undergraduate institutions (PUIs), and minority serving institutions (MSIs) to ensure that exposure to a future in laser research is not constrained by choice of undergraduate institution. Targeted advertising and recruiting from these institutions are means of illustrating through action that newcomers to the field are welcome, and that there are multiple ways into academic research and graduate schools besides attending a prestigious institution for undergraduate schooling. Partnering diverse institutions with community colleges and national labs is another innovative method to build more routes into academic careers in laser technology, but these opportunities may not be uniform throughout the nation as access is often determined by geographic region and proximity.

Overall, beyond simply providing access to undergraduate research opportunities, to truly welcome newcomers to the field careful attention must be paid to provide a welcoming, supportive, and hospitable environment for undergraduates to engage in laser science. Successful examples of collaborative programs that target specific groups for careers in physics and astronomy (e.g., AIP TEAM-UP [11]) can continue to be expanded, in line with growing workforce development needs.

See Appendix G for exemplar programs that focus on providing undergraduate training for academic research and careers in laser science.

5. Early career (pre-tenured) workforce development and graduate student training

One more critical point for establishing the laser technology community as inclusive, supportive of marginalized populations, welcoming, and impactful is with early career, pre-tenured scientists and engineers in national labs and universities. These individuals are at a point in their careers where they can set the tone for how they want to engage people in the field, including graduate students, undergraduate researchers, postdocs, technicians, and other laser technologists. By normalizing family leave, postdoc coverage, childcare support, and overall transparency in project/proposal budgets, these early career professionals may start moving the needle on what becomes standard in the field of laser technology. Universities across the U.S. have begun to offer these types of benefits to support the development of early career scientists, though childcare is rarely covered. Encouraging structural support through vulnerable career transition stages, including the tenure process and changing family needs (e.g., parental leave, medical leave) can illustrate the value and necessity of work-life balance and how to build indicators of humane treatment into the culture of a lab or academic environment. Recognizing, amplifying, and publicizing early career individuals who demonstrate outstanding mentorship skills, community engagement, and/or activities related to advancing diversity, equity, inclusion, and accessibility (DEIA) are additional means for the laser community to show that these efforts are valued and critically important for sustaining the field.

Early career scientists and engineers can have an outsized impact on how newcomers perceive the field and opportunities within it. It is important to establish professional behavior and inclusive norms from the start, including training and mentoring graduate students.

To be successful, early-career individuals may need additional support in the areas of developing professional skills, including leadership, mentoring, and DEIA programming. Establishing mentoring relationships and "buddy systems" within laser technology is one method to help with professional skills development specific to the field and ensure that early career individuals are aware of the numerous additional professional development opportunities available to them. Since the laser technology field is relatively small, leveraging personal connections to weave tightly knit support networks and develop collaborations is commonplace. Using these networks to discuss issues of culture and climate in laser technology is an opportunity to be intentional in establishing an inclusive and welcoming environment for all. Forging new connections beyond regional affiliations and existing partnerships is also critical to broaden participation in the field, as reaching past coastal R1 institutions to recruit from diverse communities in regions underserved or underrepresented in the laser technology field is another promising strategy to bring new people into the laser workforce. Similarly, being creative in generating opportunities for advancement and re-entry into the field in addition to the traditional principal investigator (PI)/professor track is one method to broaden access to careers in laser technology. Early career scientists and engineers can have an outsized impact on how newcomers perceive the field and opportunities within it. It is important to establish professional behavior and inclusive norms from the start, including training and mentoring graduate students.

See Appendix G for a listing of exemplar programs to aid in early career and graduate student training for laser careers.

6. Laser facility networks as enablers for workforce development

National and international networks of laser facilities can provide a range of opportunities for career development for scientists, engineers, technical staff, postdocs, and students alike. The sharing of experience and resources across a network of laser facilities brings several distinct advantages that positively impact workforce development. These potential advantages include:

- Better matching between investigator's research needs and facility capabilities, resulting in better research efficiency;

- Broad awareness of available facilities, tool, and methods;
- A facilitated proposal process, simplifying and broadening access;
- A wide network of experts and potential mentors to connect with;
- A broader training experience, made possible through cross-training opportunities on tools and methods at multiple facilities.

See Appendix G for a listing of exemplar laser facility networks.

SUMMARY OF WFD THEMES AND STRATEGIES

Growing the laser workforce across all education levels to include broader representation of diverse individuals and larger numbers overall is necessary for facilitating development of laser technology for the next several decades. The five opportunity areas described here—pre-college, technician pathways, undergraduate training for industry, undergraduate training for research/academia, and early career/graduate student training—are specific targets for growing next-generation leadership in the field. The future of laser technology includes applications with transformative society impact, including laser fusion, directed energy for military and industry use, communications and computing, and even laser-powered propulsion for space and certainly new technologies that are yet to be invented. Making sure this future is welcoming to individuals from all backgrounds and career trajectories is one means of fostering the largest possible pool of talent available to continue to develop laser science and technology.

Supply Chain Issues and Public-Private Partnerships (SCIPPP)

INTRODUCTION

The SCIPPP crosscut subpanel was directed to "Identify areas of strong mutual interest with industry, including supply chain concerns, and ways to foster public-private partnerships (PPPs) to address them." Significant overlap exists between SCIPPP issues and the issues addressed by the two other crosscutting panels, International and Domestic (U.S.) Strengths and WFD, as detailed below.

SUMMARY OF SCIPPP THEMES

Across the workshop, every area of significant scientific priority that is enabled or driven by the development of advanced laser systems requires components, materials, and processes that are at or beyond the state of the art with correspondingly limited availability and performance challenges. Many scientific laser systems are built to unique requirements and operated in unique environments; as a result, they are often designed and constructed by the scientific research community. Procurement and supply chain challenges and limited opportunities for PPP are common in these specialized environments.

In 2021, the DOE Office of Science (SC) convened a roundtable on *Supply Chain Risk Mitigation for Scientific Facilities and Tools* [22] to gather information about current supply chain risks in key technology areas unique to DOE-SC or critical to its mission. The findings of this report are broadly applicable to the specific challenges in scientific laser R&D, with a short section specifically on laser technology identifying numerous findings that were echoed in the BRN workshop.

The workshop revealed wide-spread challenges in laser-enabled research for both public institutions and private suppliers. These challenges encompass extended lead times, production delays, and quality control issues for critical laser-specific components.

The workshop revealed wide-spread challenges in laser-enabled research for both public institutions and private suppliers. These challenges encompass extended lead times, production delays, and quality control issues for critical laser-specific components. Attracting suppliers for low-volume or high-risk commodities is challenging, as is obtaining other essential materials for laser system development. These limitations extend to international vendors, leading to long lead times, scarcity of specialty item suppliers, and a shortage of skilled labor to meet the demands of suppliers. These challenges result in high-risk procurements, lengthy development cycles, and knowledge loss between major projects. Additionally, material supply chains passing through high-risk countries intensify associated risks.

Universities and laboratories collaborating with the laser industry face challenges in specialized, low-volume technologies. Issues include limited suppliers, extended lead times, high costs, and technical performance gaps. Components like specialty fibers, optical coatings, and diode lasers are often sourced from international suppliers. Challenges include identifying partners for high-risk R&D and a lack of funding programs for research-to-technology transitions. On the industry side, engagement with the public sector presents hurdles such as limited growth opportunities, long lead times, high startup costs, and a focus on proprietary developments. Intellectual property protection, limited access to public research resources, and complexities in technology transfer add further challenges. Dependence on high-risk countries for specialized materials contributes to high-risk procurements and extended development cycles. All of these conditions reduce or undermine the willingness of and incentives for U.S. laser companies to pursue the development of new scientific lasers identified in this report. Reversing this situation requires developing a coherent strategy through a collaborative industry-academia-government forum, such as the National

Photonics Initiative [23], to stabilize and grow the market for scientific lasers in the U.S. and abroad as a matter of national interest.

SUMMARY OF SCIPPP STRATEGIES

The workshop identified potential mitigations for the challenges of supply chain issues and strategies to encourage increased PPP. A related and useful framework for categorizing supply chain strategies is described in the 2022 DOE report *America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition* [24] which describes the government approach to build up an energy sector industrial base. The following strategies, specific to the findings of the BRN workshop, are adapted from strategic opportunities described in this report.

1. Increase development of critical materials

"New materials" were identified in all areas of supply chain issues and opportunities for improvement in performance of laser technologies, and the development of materials and optics was identified as one of the priority research directions (PRD 4) in this report which identifies the priority materials that will enable advances in capabilities in a broad range of scientific laser technologies. In general materials development demands significant R&D efforts, including access to rare earth elements, the need for specialty manufacturing and metrology equipment, and a skilled workforce with advanced education and skills in the field. This R&D is best addressed by public research institutions, with subsequent transfer to the private sector. Programs such as Small Business Innovation Research/Small Business Technology Transfer (SBIR/STTR) can address some of the needs for critical laser materials; however, more expansive and longer-duration programs may be needed to address the more challenging material needs. Noteworthy examples of more expansive programs (with significant commercial applications) include AIM Photonics, a Manufacturing Innovation Institute (MII) in the field of integrated photonic circuits, and SEMATECH (from Semiconductor Manufacturing Technology), a not-for-profit consortium that performed R&D to advance chip manufacturing. Similar programs for critical laser materials, manufacturing technologies, and applications would likely have similar impact.

2. Expand domestic manufacturing capabilities

The needs of the scientific laser market are often best met by small, specialized businesses with expertise in the technology and application of scientific lasers. Programs such as SBIR/STTR can encourage the establishment and growth of these businesses, and programs such as the NSF Regional Innovation Engines [25] hold great promise to stimulate small businesses, partnership with public research institutions, and workforce development. Significant PPPs, such as a laser-related analog of AIM Photonics [26] could have a dramatic impact on the development of scientific laser technology.

3. Invest and support formation of diverse and reliable foreign supply chains

Scientific laser research and technology development is highly globalized, with a significant fraction of the leading research and manufacturing occurring outside the U.S. In some cases, the supply laser technology is protected by foreign intellectual property (IP) law or otherwise centralized in established foreign public and private institutions with limited opportunities for domestic competition. In these cases, embracing the reality of the international marketplace is the sensible strategy. Specific recommendations to encourage international collaboration and technology transfer are described in the International and Domestic Strengths section of this report. Another specific enabling strategy is to reduce friction in the procurement processes for unique foreign suppliers, particularly for government-funded entities, such as national laboratories.

4. Attract and support a skilled U.S. workforce for laser technology

A robust workforce is essential for a healthy laser technology supply chain, and a workforce that can move between the public and private sectors will enable opportunities for collaboration and partnership. General recommendations are detailed in the Workforce Development section of this report and could be integrated into more expansive programs noted above to support critical laser materials, manufacturing technologies, and applications.

5. Augment supply chain knowledge and decision-making

The overall optics market is very large with numerous U.S. manufacturers; however, advanced scientific research represents a small subset of this overall market, which can lead to it being overlooked or deemphasized by suppliers who have significant non-scientific commercial markets for their products. Efforts within the public sector to aggregate requirements among different research groups can encourage greater market engagement. Typically, this would be the role of a sales specialist or product line manager, but the connection can be driven bidirectionally. Drawing attention to supply chain issues at laser conferences, workshops, and trade shows could encourage more coordination on both the demand and supply sides. The relatively small size of the scientific research community would make active engagements between the research and industrial members of the community relatively simpler to collaborate and connect through non-transactional interactions, such as specialty conferences (e.g., Conference on Lasers and Electro-Optics/CLEO [27], Photonics West [28], SPIE Photonics Industry Summit [29], SPIE Global Business Forum [30], Optica Laser Congress [31], Ultrafast Optics [32], International Committee on Ultra-High Intensity Lasers/ICUIL [33], LaserNetUS meetings [34]), career events at universities, laboratory open-houses, and public lectures. Specific professional networks (Optica [35], SPIE [36], IEEE [37], APS [38], LIA [39]) and advocacy groups (National Photonics Institutes) can play a role in ensuring a high degree of communication between researchers and the private sector. In addition to aggregating requirements from commercial suppliers, an inventory of domestic universities and national laboratories with unique, specialized capabilities that align with the priorities of this report would be valuable both to engage in possible collaborations as well as technology transfer opportunities.

Figure 12 illustrates preliminary results from a study undertaken by SPIE of the photonics industry. It shows how photonics products and services underpin more than 15% of global gross domestic product (GDP). Scientific lasers and associated technologies comprise a fraction of this total, but two important questions need to be answered. First, how much of this market activity does scientific lasers constitute and where does it exist? Second, can one estimate future growth from current and envisioned scientific and technological R&D based on historical trends for comparable technologies? Supporting background research to answer these types of questions could bolster the case for significant investments.

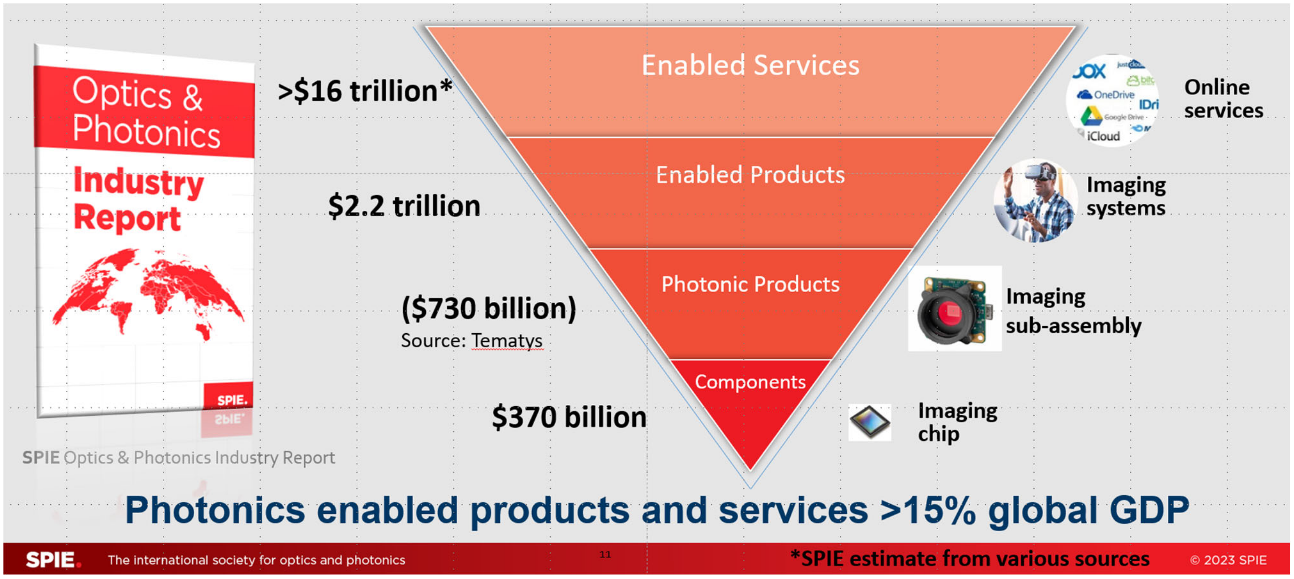

Figure 12. Photonics-enabled products and services. The global photonics industry underpins a $16-trillion market. Focusing on the contribution of lasers and laser applications to the U.S. and global economies could lead to a better understanding of related supply chain issues and developing public-private partnerships to address them. From spie.org/industryreport [40]. Provided for use by SPIE.

International and Domestic Strengths (I&DS)

The I&DS crosscut subpanel assessed how the proposed U.S. R&D activities compare with global laser R&D efforts. It specifically looked for ways that R&D in science applications and laser technology might benefit from international collaborations and other programs and policies, as well as where the U.S. might play unique and/or complementary roles with international efforts. This crosscut overlaps in important ways with both the WFD and the SCIPPP crosscut subpanels.

INTRODUCTION

International laser science and technology (LS&T) players show strengths in notable areas where the U.S. can learn from and adopt demonstrated best practices. Some important examples include approaches to organizing research, as well as encouraging business ventures, supporting PPPs, and emphasizing career development. Europe and Asia have led the U.S. in important areas, such as the formation and sustainment of laser system companies, broad laser user networks and facilities (e.g., LaserLab Europe [41], Extreme Light Infrastructure/ELI [42]), and integrated research programs and road map planning (e.g., Horizon Europe [43], European Strategy Forum on Research Infrastructures/ESFRI roadmap [44], Photonics21 [45]).

Figure 13 shows an illustrative example; the growth rate in the number of ultrahigh intensity lasers from 2009 to 2020 in Europe (11 to 49), Asia (10 to 24), and Russia (2 to 7) far outpaced that in the U.S. (17 to 23). The same trend holds for multi-petawatt (MPW) laser facilities where Europe took the lead with the three ELI pillars in Czechia, Hungary, and Romania, plus the Apollon [46] laser in France and the newly funded Vulcan [47] 20-20 facility project underway in the United Kingdom. It should be noted, however, that the U.S. delivered two of the ELI petawatt lasers (L3 and L4 at ELI-Beamlines). Korea and China also have multiple MPW lasers operating in Gwangju (Center for Relativistic Laser Science/CoReLS [48]) and Shanghai (Shanghai Superintense Ultrafast Laser Facility/SULF [49]), respectively. Plus, a 100-PW laser (Station of Extreme Light/SEL) is planned for Shanghai. The U.S. has just started pursuing this scale of laser with the NSF Zettawatt-Equivalent Ultrashort-pulse laser System (ZEUS [50]) facility at the University of Michigan now coming online and the design of the NSF OMEGA Extended Performance-coupled Optical Parametric Amplifier Line (EP-OPAL [51]) facility awarded recently to the University of Rochester. DOE FES has provided initial funding for high-repetition-rate (multi-Hz) petawatt lasers, the MEC-Upgrade (MEC-U [52]) at SLAC National Accelerator Facility and Advanced Laser for Extreme Photonics-2 (ALEPH-2 [53]) at Colorado State University. NSF has funded high repetition rate ultrafast systems at NeXUS [54] while DOE High Energy Physics, Accelerator R&D and Production, and other agencies are developing technology towards future kHz rep-rate systems at Joule energies such as kBELLA [55].

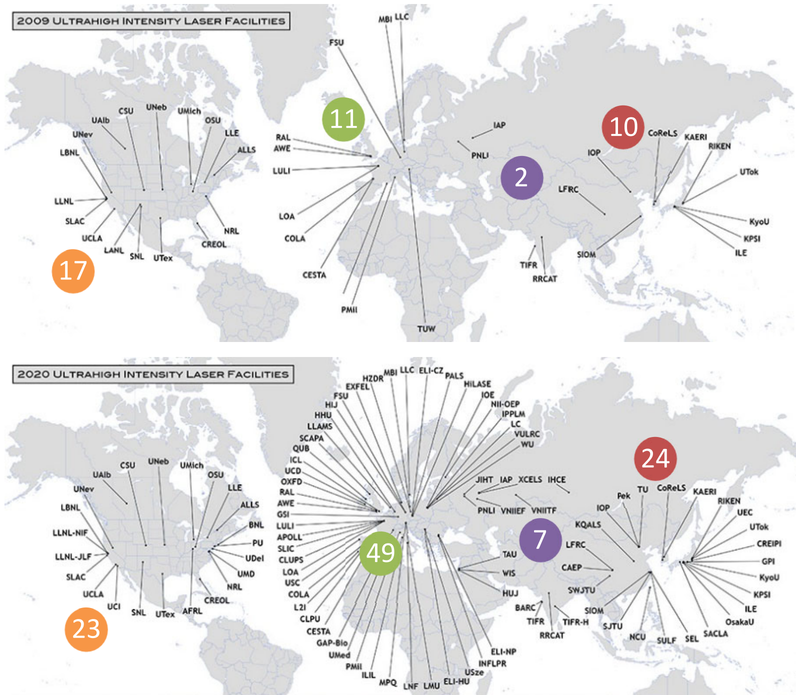

Figure 13. Global maps of ultrahigh intensity laser facilities in 2009 and 2020. High-peak-power laser research, development, and applications have expanded rapidly in the last decade (or so) with many new PW-class facilities across the world. Multi-petawatt lasers now represent an important scientific frontier; multiple study and workshop reports have identified the need for increased MPW capabilities. Apollon: Apollon Laser Facility; ELI pillars: Extreme Light Infrastructure pillars; CoReLS: Center for Relativistic Laser Science; EP-OPAL: OMEGA Extended Performance-coupled Optical Parametric Amplifier Line; NSF: National Science Foundation; SEL: Station of Extreme Light; SULF: Shanghai Superintense Ultrafast Laser Facility; Vulcan 20-20: an upgrade project to the Vulcan laser; XCELS: Exawatt Center for Extreme Light Studies; ZEUS: Zettawatt-Equivalent Ultrashort-pulse laser System. (Image credit: Prof. C Barty on behalf of the International Committee on Ultra-High Intensity Lasers [56].)

Supporting laser science, technology, and applications R&D in the context of building an overall ecosystem in the U.S. through programs could lead to recapturing the original leadership that created the field of extreme light and realizing the PRDs identified in this report. The DOE LaserNetUS network provides a recent example of a good domestic program responsive to the second recommendation of the 2018 National Academies of Sciences, Engineering, and Medicine (NASEM) Report: *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light*. Since its inception. LaserNetUS has advanced the frontiers of laser-based scientific research by providing a network structure with broad access to user facilities with capabilities not commonly available to researchers elsewhere. The 2018 NASEM report also recommended creating "a broad national network … as the cornerstone of a national strategy to support science, applications, and technology of intense and ultrafast lasers," developing "a comprehensive interagency national strategy for high-intensity lasers," as well as creating "programs for U.S. scientists and engineers." Fully realizing these additional recommendations would involve:

- establishing a coherent, interagency mechanism to develop U.S. roadmaps for laser technologies identified here in the PRDs and funding stable programs to realize them with technology transfer among universities, U.S. industry, and national laboratories;
- creating integrated programs for both developing *and* operating large-scale and midscale projects, such as those hosted at national laboratories and universities; and
- supporting engagement in international R&D activities at international facilities.

The European Union and a number of national programs abroad directly support industry-academia collaborations. Long-term support mechanisms provide psychological and political incentives to take chances on high-risk/high-reward technologies. For instance, exploring the market potential for new technologies is supported financially in Europe for up to two years. MITACS (Mathematics of Information Technology and Complex Systems) in Canada [57] is a program in which universities partner with industries specifically for student funding and training. Industrial Ph.D. and masters programs in Europe provide a career development path for employees at companies and national laboratories, which proves effective for recruitment and retainment.

A strong case can be made that Europe seems better suited than the U.S. for sustaining so-called “life-style” companies, where a business set up and run by its founders primarily with the aim of maintaining a certain lifestyle can produce cutting-edge products needed for advanced laser systems, while others observed that “craftsmanship culture” seems more prevalent in other nations (e.g., Japan, China, and Germany), where the “pursuit of perfection” is seen as cutting-edge, exciting, and necessary for technology development and innovation. Another observed that “small companies in the U.S. get bought too early” by larger companies, which prevents them from realizing these modes of operation. Precision timing represents a good example: Deutsches Elektronen-Synchrotron (DESY) and its spin-off company, Cycle GmbH, have established a *de facto* standard for sub-femtosecond timing synchronization systems based on technology that was originally developed in the U.S. under an SBIR award [58]. Lastly, international trade restrictions have driven technological developments in China for critical materials and components, like nonlinear optical materials, laser glass, and large diffraction gratings.

The U.S. boasts deep and strong leadership in notable areas of laser science and technology. NNSA-funded and DOD-funded research facilities have led the development of high-energy and high-peak-power lasers and laser-based high energy density (HED) science and technology. Similarly, academia and national laboratories lead or compete at the highest levels in the development of laser-based light and particle sources. For example, American institutions pioneered high-power, CW coherent laser-beam combination for directed-energy applications, but European researchers currently outpace the U.S. in technology for coherently combining ultrashort-pulse lasers (e.g., fiber laser systems).

The U.S. boasts significant industrial capacity to produce laser diodes, diffraction gratings, precision optics, and optical finishing, and some specific laser and nonlinear optical materials (e.g., laser glass, large-aperture potassium dihydrogen phosphate/deuterated dihydrogen potassium phosphate or KDP/DKDP crystals, and transition-metal-doped chalcogenide crystals). Sustaining and encouraging growth in these technological areas of strength, as well as fostering new ones, would go a long way towards establishing the desired domestic laser ecosystem. International examples, such as strong collaborations in Germany among the Helmholtz Association, Max Planck Foundation, Fraunhofer Society, academia, and industry, offer proven models to emulate in the U.S. or even join as international partners. Actively reducing barriers between similar entities in the U.S., including various federal agencies, would go a long way towards improving progress.

Sustaining and encouraging growth in these technological areas of strength, as well as fostering new ones, would go a long way towards establishing the desired domestic laser ecosystem. International examples, such as strong collaborations in Germany among the Helmholtz Association, Max Planck Foundation, Fraunhofer Society, academia, and industry, offer proven models to emulate in the U.S. or even join as international partners.

SUMMARY OF I&DS THEMES AND STRATEGIES:

Science and technology can advance internationally in a friendly and cooperative while also competitive manner through international “co-opetition,” but articulating principles and criteria to inform compete/collaborate decisions proves challenging since multiple factors play against each other.

- Research activities and facilities around the world offer opportunities to join forces to leverage existing efforts and facilities with the goal of advancing science applications and laser technology more efficiently and collaboratively.
- In some cases, reliance on international sources is the best or only option; for example, for products protected by foreign IP or where unique capabilities are concentrated outside the U.S. In general, however, the U.S. should reconsider the wisdom of generalized outsourcing and off-shoring the development and production of critical laser and optical components, systems, processes, and technologies to ensure sufficient supplies and workforce that meet the needs of "national interest" related to securing economic development, improved opportunities for a diverse and modern workforce, and not just "national security" concerns.
- International technology exchanges can deliver products and capabilities not available domestically, but they can also introduce risks and limitations due to a limited number of critical suppliers and supply chains that can be disrupted due to various causes like those experienced recently from pandemic and geopolitical restrictions, natural disaster, and other emerging events or policies. Likewise, the growing international nature of scientific and technological R&D represents both a larger community of talent, but also greater competition for that talent pool.

Balancing these factors rarely proves simple and always requires reassessment of current and future conditions, but a few fundamental principles can guide compete/collaborate decisions:

- Open and well-supported precompetitive research that addresses early-stage, multi-sector efforts by teams with broad capabilities that develop knowledge, expectations, and standards can create space and capacity for healthy cooperation ***and*** competition; and
- "Moving first and fast" provides a competitive advantage for advancing R&D innovation and ultimately translating these advances to product development, especially when compared with exercising defensive and protective policies that tend to stifle progress.

References

[1] D. E. Betz and D. Sekaquaptewa, "My Fair Physicist? Feminine Math and Science Role Models Demotivate Young Girls," Social Psychological and Personality Science, Mar. 2012, doi: 10.1177/1948550612440735.

[2] M. Burkley, J. Parker, S. Paul Stermer, and E. Burkley, "Trait beliefs that make women vulnerable to math disengagement," Personality and Individual Differences, vol. 48, no. 2, pp. 234–238, Jan. 2010, doi: 10.1016/j.paid.2009.09.002.

[3] L. S. Blackwell, K. H. Trzesniewski, and C. S. Dweck, "Implicit Theories of Intelligence Predict Achievement Across an Adolescent Transition: A Longitudinal Study and an Intervention," Child Development, vol. 78, no. 1, pp. 246–263, 2007, doi: 10.1111/j.1467-8624.2007.00995.x.

[4] C. M. Steele, "A threat in the air: How stereotypes shape intellectual identity and performance," American Psychologist, vol. 52, no. 6, pp. 613–629, 1997, doi: 10.1037/0003-066X.52.6.613.

[5] M. W. McLaughlin, You Can't Be What You Can't See: The Power of Opportunity to Change Young Lives. Harvard Education Press, 2018.

[6] Z. Hazari, G. Sonnert, P. M. Sadler, and M.-C. Shanahan, "Connecting high school physics experiences, outcome expectations, physics identity, and physics career choice: A gender study," *J. Res. Sci. Teach.*, vol. 47, no. 8, pp. 978–1003, Feb. 2010, doi: 10.1002/tea.20363.

[7] A. Sithole, E. T. Chiyaka, P. McCarthy, D. M. Mupinga, B. K. Bucklein, and J. Kibirige, "Student attraction, persistence and retention in STEM Programs: Successes and continuing challenges," *High. Educ. Stud.*, vol. 7, no. 1, Jan. 2017, doi: 10.5539/hes.v7n1p46.

[8] American Physical Society, "PhysicsQuest." Available: http://www.aps.org/programs/outreach/physicsquest/index.cfm

[9] American Physical Society, "Career Mentoring Fellows Program." Available: https://www.aps.org/careers/guidance/mentoring.cfm

[10] American Physical Society, "STEP UP." Available: https://engage.aps.org/stepup/home

[11] American Institute of Physics, "TEAM-UP Project | American Institute of Physics." Available: https://www.aip.org/diversity-initiatives/team-up-task-force

[12] University College Dublin, "Impact Toolkit." Available: https://www.ucd.ie/impacttoolkit/

[13] Optica, "Engagement Opportunities | Optica." Available: https://www.optica.org/get_involved/diversity_inclusion/engagement_opportunities

[14] The Laser Institute, "Resources." Available: https://www.lia.org/resources/industry-resources

[15] American Society for Laser Medicine and Surgery, Inc., "For the Public." Available: https://www.aslms.org/for-the-public

[16] R. Kirchain, E. Moore, F. R. Field, S. Saini, and G. Westerman, "Advanced manufacturing workforce: A study of occupation and skills demand in the photonics industry," Feb. 2021. [Online]. Available: https://dspace.mit.edu/bitstream/handle/1721.1/143765/Photonics%20Workforce%20070521.pdf?sequence=1andisAllowed=y

[17] American Center for Optics Manufacturing, "The future is optics." Available: https://thefutureisoptics.com/

[18] SPIE, "Optical technician resources." Available: https://spie.org/education/technician-resources

[19] Kurt J. Lesker Company, "What Black History Month means to me – an interview with Philip Adderley," Feb. 2021. Available: https://www.lesker.com/blog/black-history-month-interview-philip-adderley

[20] SPIE, "SPIE scholarships." Available: https://spie.org/membership/student-hub/scholarships/optics-and-photonics-education-scholarships

[21] SPIE, "SPIE Education Outreach Grants Program." Available: https://spie.org/education/education-outreach-resources/outreach-grants

[22] E. Johnson *et al.*, "Supply chain risk mitigation for scientific facilities and tools," U.S. Department of Energy Office of Science, May 2022. [Online]. Available: https://www.osti.gov/servlets/purl/1863553, doi: 10.2172/1863553.

[23] National Photonics Initiative, "About NPI." Available: https://www.lightourfuture.org/home/about-npi

[24] U.S. Department of Energy, "America's strategy to secure the supply chain for a robust clean energy transition," Feb. 2022. [Online]. Available: https://www.energy.gov/policy/articles/americas-strategy-secure-supply-chain-robust-clean-energy-transition
[25] U.S. National Science Foundation, "Regional innovation engines." Available: https://new.nsf.gov/funding/initiatives/regional-innovation-engines
[26] AIM Photonics, "About AIM Photonics," 2023. Available: https://www.aimphotonics.com/about-us
[27] Conference on Lasers and Electro-Optics (CLEO). Available: https://www.cleoconference.org/home/
[28] SPIE, "SPIE Photonics West." Available: https://spie.org/conferences-and-exhibitions/photonics-west
[29] SPIE, "Photonics Industry Summit." Available: https://spie.org/conferences-and-exhibitions/photonics-industry-summit?SSO=1
[30] SPIE,. "Global Business Forum." Available: https://spie.org/conferences-and-exhibitions/global-business-forum
[31] Optica, "Optica Laser Congress and Exhibition." Available: https://www.optica.org/events/congress/laser_congress/
[32] Ultrafast Optics, "Ultrafast Optics XIII." Available: https://www.ultrafastoptics2023.org/
[33] International Committee on Ultra-High Intensity Lasers, "Events." Available: https://www.icuil.org/activities/events.html
[34] LaserNetUS, "2023 LaserNetUS Users' Meeting," 2023. Available: https://lasernetus.org/resources/upcoming-events/2023-lasernetus-users-meeting
[35] Optica, Available: https://www.optica.org/
[36] SPIE, Available: https://spie.org/
[37] IEEE Photonics Society, Available: https://ieeephotonics.org/
[38] American Physical Society, Available: https://www.aps.org/
[39] Laser Institute of America, LIA, Available: https://www.lia.org/
[40] SPIE, "Optics & Photonics Industry Report" [Online]. Available: https://spie.org/industry-resources/information/industry-report#_=_
[41] LaserLab Europe, Available: https://www.laserlab-europe.eu/
[42] Extreme Light Infrastructure, ELI-ERIC, Available: https://eli-laser.eu/
[43] European Commission, "Horizon Europe." Available: https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en
[44] European Strategy Forum on Research Infrastructures, "ESFRI Roadmap." Available: https://www.esfri.eu/esfri-roadmap
[45] Photonics21, "Photonics 21 – A key enabling technology for Europe." Available: https://www.photonics21.org/
[46] Apollon Laser Facility, France, Available: https://apollonlaserfacility.cnrs.fr/en/home/
[47] Vulcan laser Facility, United Kingdom, Available: https://www.clf.stfc.ac.uk/Pages/Vulcan-laser.aspx
[48] Center for Relativistic Laser Science, CoReLS, South Korea, https://corels.ibs.re.kr/html/corels_en/
[49] Shanghai Superintense Ultrafast Laser Facility (SULF), China, Available: http://english.sari.cas.cn/Research/facilities/202106/t20210629_273225.html
[50] ZEUS, University of Michigan, United States, Available: https://zeus.engin.umich.edu/
[51] EP-OPAL, Midscale Facility, Laboratory for Laser Energetics, University of Rochester, Available: https://www.lle.rochester.edu/ep-opal/
[52] Matter at Extreme Conditions Upgrade (MEC-U), LCLS-SLAC, United States, Available: https://lcls.slac.stanford.edu/instruments/mec
[53] ALEPH, Advanced Laser for Extreme Photonics, Colorado State University, United States, Available: https://lasers.colostate.edu/
[54] NeXUS, Available: https://nsf-nexus.osu.edu/
[55] kBELLA, Available: https://bella.lbl.gov/kbella/
[56] International Committee on Ultra-High Intensity Lasers, "Laser Labs." Available: https://www.icuil.org/activities/laser-labs.html
[57] Mitacs, "Elevate Innovation with Mitacs." Available: https://www.mitacs.ca/
[58] Cycle, "Company – Cyclelasers," 2023. Available: https://www.cyclelasers.com/company/

Appendix A. Science-Technology Relationships Table

		100 TW and beyond high repetition rate lasers	Beyond-10 PW Lasers	Nanosecond/kJ pump and HEDP lasers	Coherently combine beams to expand capabilities	High energy and high average-power scaling of post compression and contrast enhancement techniques	Adaptive laser control	Reducing complexity and increasing efficiency of mid-IR parametric sources	Scaling peak and average power in mid-IR CPA	Pushing peak power for CO2-based laser accelerators	Stable waveform-controlled sources spanning the mid-IR to THz	Frequency extension in fibers and gases	Efficient NLO methods surpassing quantum defect	Field-control across the spectrum	Understanding Integration and Driving Technology Democratization	Novel approaches to sub-femtosecond synchronization to XFELs and particle sources	Next generation laser gain media	Next generation coating materials, designs, and techniques	Compression Gratings	Innovations in Nonlinear Crystals	Emerging innovations in optical components	Laser diode pumps for high repetition rate ultrafast laser system
		1.1	1.2	1.3	1.4	1.5	1.6	2.1	2.2	2.3	2.4	3.1	3.2	3.3	3.4	3.5	4.1	4.2	4.3	4.4	4.5	4.6
		1. Revolutionize Laser Power, Energy, and Precision Control						2. Transform Mid-IR Sources for Science from THz to X-Rays				3. Revolutionize Approaches to Frequency Conversion and Field Control					4. Reinvent materials and optics for intense laser science					
Laser Systems and science applications transformed by their development																						
Type I: High Repetition rate Lasers	Chemical sensing and spectroscopy	0	0	0	0	0	0	1	1	0	1	2	2	2	1	0	0	1	0	2	0	1
	Small cross-section process studies	1	0	0	0	0	2	1	1	0	2	2	0	2	2	2	0	2	0	0	0	1
	Inner core electron dynamics	1	0	0	2	0	2	2	2	1	1	2	0	2	2	2	0	2	0	1	0	1
	Ultrafast electron dynamics	1	0	0	2	0	2	2	2	0	2	2	1	2	2	2	0	2	0	0	0	1
	Electron beam based cooling schemes	0	0	0	0	0	2	0	0	0	0	1	0	1	1	0	0	1	0	1	0	1
	High-current polarized electron/positron source	2	0	0	0	0	2	2	2	0	2	0	1	2	1	2	0	1	0	0	0	1
Type II: High Average Power Laser	Soft x-ray generation	2	0	0	2	2	2	1	2	1	1	0	1	1	2	0	2	2	2	1	0	2
	Laser driven electron accelerators	2	1	0	2	1	2	1	2	1	1	0	1	1	2	0	2	2	2	1	0	2
	X-ray imaging and non-destructive evaluation	2	0	0	0	2	2	1	1	1	0	0	1	1	2	0	2	2	2	1	2	2
	Probing exotic states	2	0	0	2	0	2	2	2	1	2	2	2	2	2	2	0	2	0	2	0	2
	Probing transients in quantum computing	2	0	0	2	0	2	0	0	0	0	0	1	2	2	0	0	2	0	0	0	2
	Proton beam nonintrusive probing and extraction	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	2
	High brightness proton phase space engineering	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	2
	Charge exchange with intense proton pulses	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	2
Type III: Few-cycle	Molecular & material dynamics	2	0	0	0	1	2	2	2	1	2	2	2	1	1	2	2	1	1	2	0	0
	Photochemistry	0	0	0	0	0	2	1	1	0	1	2	1	2	1	2	0	2	0	2	0	0
	Molecular & material control	0	0	0	0	0	2	2	2	1	2	2	2	2	2	2	0	2	0	1	1	0
Type IV: High Intensity Laser	Consistent generation of HED and WDM plasmas	0	1	2	0	2	2	0	0	0	0	0	0	0	1	0	2	2	2	1	2	1
	Pump-probe measurements	2	1	1	0	1	2	1	1	0	1	1	0	0	1	1	2	2	0	1	1	1
	Plasma turbulence and energy flows	1	1	2	0	1	2	0	0	0	0	0	0	1	1	0	2	2	0	1	1	1
	Quantum Electrodynamics	0	2	1	0	2	2	0	0	0	0	0	0	0	2	0	2	2	2	2	2	1
	Laboratory Astrophysics	0	2	2	0	2	2	0	0	0	0	0	0	0	2	0	2	2	2	1	2	1
	New regimes in ion acceleration & light sources	1	2	1	0	1	2	2	2	2	1	0	1	1	2	1	2	2	2	2	2	1
	Astrophysical Phenomena	2	2	2	2	2	2	2	2	0	0	0	0	0	2	0	2	2	2	2	2	2
	Neutron, ion, gamma, muon radiography sources	2	2	2	2	2	2	1	1	0	0	0	0	0	2	0	2	2	2	2	2	2
Science applications enabled through research that improves existing laser systems																						
	High-Contrast Drive Lasers for Nuclear Physics	0	0	0	0	1	1	1	0	0	0	1	0	0	1	0	1	1	0	1	0	0
	Parity violating nuclear physics experiments	0	0	0	0	1	1	1	0	0	0	1	0	0	1	0	0	2	0	1	0	0

2	R&D advances are critical to making this application possible
1	R&D advances will substantially impact this application
0	R&D is not needed for this application

Table A-1: This table shows the relative impacts of the individual Priority Research Direction (PRD) research thrusts on scientific applications. Research that is critical to the scientific application is marked as a 2, research that substantially impacts the scientific application is marked as a 1, and research that has minimal impact on the science application is marked as a 0. The new laser types enabled as an end-result of the research are also listed mapped to the science applications that are enabled or transferred by them. PRDs 2 (mid-infrared sources) and 3 (Frequency conversion and field control) strongly align with developing ultrafast and high-repetition-rate laser systems and PRDs 1 (power, energy, and precision control) and 4 (materials and optics) strongly align with developing high-intensity lasers. For high-average-power lasers, all four PRDs play a significant role. The science applications are further defined as needed in the supporting list† below.

†Supporting definitions of labels used in Table A-1.

Science Application Title as used in Table A-1	Detailed definition as needed
Molecular and material dynamics	Learning how molecules and materials behave using ultrashort pulses in THz, infrared (IR), visible, ultraviolet (UV), extreme ultraviolet (XUV) and X-ray ranges to do spectroscopic measurements.
Photochemistry	
Molecular and material control	Coherent control and spectroscopy of molecules and materials by using ultrashort pulses.
Chemical sensing and spectroscopy	
Small cross-section process studies	Enabling small cross-section process studies limited by statistics/noise via high-repetition-rate light and electron sources (large and chip scale).
Inner core electron dynamics	Inner core electron dynamics (harder X-rays) in photon-hungry spectroscopies.
Ultrafast electron dynamics	Ultrafast electron dynamics at nanoscale (emittance) and at attosecond scale (temporal).
Electron beam-based cooling schemes	Increasing Electron-Ion Collider (EIC) luminosity via electron beam-based cooling schemes
High-current polarized electron/positron sources	High-current electron and positron sources required for energy-recovery linac (ERL)-type polarized accelerators.
Soft X-ray generation	Through high harmonic generation (HHG) and/or laser wakefield acceleration (LWFA).
Laser-driven electron accelerators	Electron injection and phase space control (best control with two to three beams). Laser plasma propagation control for precise e- accelerator structure. Wavelength scaling of accelerator and injector structure. Ultrabright beam quality to match or exceed conventional accelerators. Enabling future grand challenges—particle colliders, free-electron lasers, medical therapy, and imaging.
X-ray imaging and non-destructive evaluation (NDE)	MeV photon sources with controllable spectrum. Ability to go from 1 to 9 MeV monoenergetic spectrum, source size—nuclear spectroscopy, materials. Tunable bright sources for applications in material, up to 10s keV (tunable), temporal synchronization, brightness, source size.
Probing exotic states	Characterizing conductivity and materials and measuring phonon spectrum via high-average-power, high-repetition-rate THz and X-ray sources.
Probing transients in quantum computing	Probing transient effects, quantum entanglement and quantum computing schemes via intense particle sources with shortest pulses
Proton beam nonintrusive probing and extraction	Nonintrusive probing and extraction of high-energy proton beam from existing linacs; muon generation with optimized temporal structure for Ultra-low energy Storage Ring (USR) applications
High-brightness proton phase space	Achieving a high-brightness proton beam by engineering the

engineering	phase space using lasers.
Charge exchange with intense proton pulses	Accumulating intense proton pulses using laser-assisted charge exchange injection.
Consistent generation of high energy density (HED) and warm dense matter (WDM) plasmas	Generating plasmas with HED or which are in the strongly coupled regime, with densities and temperatures which are consistent shot to shot. Such plasmas are ideal for measuring proton stopping powers and opacities.
Pump-probe measurements	Laser-driven particle acceleration and light sources are generally ultrafast. With synchronized or split beams, matter can be placed in an excited or extreme state, while the other beams can measure or image a snapshot of the dynamics.
Plasma turbulence and energy flows	
Quantum electrodynamics	Next-generation lasers will allow us to test quantum electrodynamics (QED) in strong-field regime: ● Boiling vacuum/ Pair production ● Photon-photon scattering ● Vacuum birefringence ● Transformative laser facility will enable high energy physics (HEP) studies ● Muon and proton acceleration to relativistic energies ● Beyond Standard Model studies (e.g., axions) ● Development of gamma-gamma colliders ● Interaction-point physics and beam delivery systems
Laboratory astrophysics	Events producing the highest energy particles in the universe ● Relativistic magnetic reconnection ● Relativistic shocks ● Laser-driven gamma ray sources via plasma rectification ● Large-volume electron-positron plasma creation, control, collective effects, and instabilities ● Astrophysically-relevant B Fields (relevant to pulsars)
New regimes in ion acceleration and light sources	Radiation pressure, magnetic vortex and related mechanisms Strongly relativistic laser field Relativistic transparency Laser propagation, reflection, and target acceleration physics Shock wave acceleration in gas with mid-IR lasers Control of ion spectrum, source size and phase space Protons: medical therapy, heating for opacity and warm dense matter studies Conversion to neutrons for radiation damage, radiography, fusion materials Similar laser regime suited for light sources New gamma ray sources and spectroscopy Relativistic HHG
Astrophysical phenomena	Equation of state of super-Earth cores, white-brown dwarfs and supernova nucleosynthesis
Neutron, ion, gamma, muon radiography sources	
High-contrast drive lasers for nuclear physics	Testing beyond the Standard Model predictions in nuclear physics experiments
Parity violating nuclear physics experiments	

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** Denotes Technical POC

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Appendix D. Workshop Charge

Basic Research Needs Workshop on Laser Technology

BACKGROUND

Lasers play an increasingly important role in physical sciences research and are expected to provide the foundation for new techniques to make future scientific research facilities even more flexible and powerful. Department of Energy's (DOE's) Office of Science (SC) utilizes more than 2,500 high power laser systems [1] at its 10 national laboratories in a wide range of applications. Similarly, the U.S. academic community develops and takes advantage of a large variety of laser systems ranging from ultrafast to ultra-intense. The areas of research application of such laser systems include:

- Producing bright beams of X-rays, electrons, ions, and neutrons
- Producing unique polarized or magnetized particle beams
- Driving pump-probe experiments at unprecedentedly short time scales
- Providing fast manipulation of beams by optical bunching, time slicing, and bunch selection
- Determining beam bunch parameters (e.g., profile, polarization) non-destructively
- Generating plasmas and driving intense wake-fields for particle acceleration
- Generating, in a compact footprint, secondary beams to probe ultrafast dynamics in high energy density, biological, chemical, and materials systems
- Creating and probing extraordinary states of matter
- Driving polarized He-3 targets
- Separating isotopes

The quality and quantity of scientific data available from experiments that rely on lasers is often directly limited by the performance of the underlying laser systems used. Future applications of lasers are pushing performance in multiple ways: towards higher pulse repetition rates (i.e., higher average power), towards higher peak power (i.e., higher energy in shorter pulses); and towards higher reliability, stability, and electrical efficiency.

The DOE Office of Accelerator R&D and Production (ARDAP) is leading organization of a Basic Research Needs (BRN) workshop to assess R&D needed to enable high-impact scientific applications of laser technology to address current and future research needs. The workshop is being co-sponsored by the National Science Foundation (NSF) and Department of Defense (DOD). Broad USG participation will be a feature of this BRN to ensure related R&D activities and synergies are understood. The resultant report will update and expand the framework developed by the 2013 DOE Workshop on Laser Technology for Accelerators [2] and subsequent community-driven reports that have informed laser R&D investments for the last ten years.

The goal is to identify priority R&D opportunities that, if developed, could enable high-impact solutions for scientific research and applications in addition to fostering a healthy U.S. laser technology development ecosystem.

Attendance at the workshop will be by invitation only.

WORKSHOP CHARGE

This workshop is charged with:

- Identifying a set of key scientific challenges that can be addressed with laser technology and the application opportunities they create

- Assessing the critical needs in laser technology needed to address the challenges and enable the applications
- Identifying technical gaps between present laser capabilities (current state-of-the-art) and the performance required in each case
- Identifying areas of strong mutual interest across participating federal agencies
- Identifying areas of strong mutual interest with industry, including supply chain concerns, and ways to foster PPPs to address them
- Assessing which R&D investments are expected to have the highest impact
- Identifying present and anticipated workforce development concerns and potential mitigation strategies
- Assessing 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 scientific research and applications, along with a rough timeline indicating when R&D outcomes are needed to support the U.S. research program. The report should provide an update on the current state-of-the-art and near-term development potential in laser performance.

REFERENCES

[1] J. King, "Welcome/EFCOG LSTT – Who we are and what we do," presentation at Department of Energy Laser Safety Officer Workshop, Lawrence Berkely National Laboratory, Berkely, CA, USA, 2022. [Online]. Available: https://drive.google.com/file/d/1K65BL8ZOSt-Izmo7A9RksCpgHcjWDadN/view

[2] U.S. Department of Energy, "Workshop on Laser Technology for Accelerators: Summary Report," Jan. 23-25, 2013. [Online]. Available: https://science.osti.gov/-/media/hep/pdf/accelerator-rd-stewardship/Lasers_for_Accelerators_Report_Final.pdf

Appendix E. Definitions for Wavelength Ranges

Abbreviated name	Full name	Wavelength (µm)
SXR to XUV	Soft X-ray to Extreme Ultraviolet	0.001 – 0.05 µm
VUV to UV	Vacuum Ultraviolet to Ultraviolet	0.05 – 0.3 µm
DUV to Vis	Deep Ultraviolet to Visible	0.1 – 0.7 µm
Near-IR (or NIR or SWIR)	Near-Infrared (a.k.a. short-wave IR)	0.7 – 2 µm
Mid-IR (or MWIR)	Mid-Infrared	2 – 10 µm
LWIR	Long-Wave Infrared	10 – 40 µm
THz	Terahertz	50 µm and beyond

Table E-1: Consistent definitions for wavelength ranges used throughout this report (may vary slightly from other conventions).

Appendix F. Abbreviations and Acronyms

Abbreviation	Definition
AAS	Associate of Applied Science degree
ADP	Ammonium Dihydrogen Phosphate, $NH_4H_2PO_4$
AI	Artificial Intelligence
AIM Photonics	American Institute for Manufacturing Integrated Photonics
AIP	American Institute of Physics
ALEPH	Advanced Laser for Extreme Photonics
ALLS	Advanced Laser Light Source
AmeriCOM	American Center for Optics Manufacturing
AMO	Atomic, Molecular, Optical
APG1	Advanced Phosphate Glass-1
APS	American Physical Society
AR	Anti-Reflection coating
ARDAP	Office of Accelerator R&D and Production (in DOE SC)
AR-HCF	Anti-Resonant Hollow-Core Fiber
ATE	Advanced Technological Education Program (supported by NSF)
ATF	Accelerator Test Facility at Brookhaven National Laboratory
ATM	Arrival Time Monitor
BBO	Beta Barium Borate, BaB_2O_4
BELLA	Berkeley Lab Laser Accelerator
BGSe	Barium Gallium Selenide, $BaGa_4Se_7$
BiBO	Bismuth Triborate, BiB_3O_6
BNL	Brookhaven National Laboratory
BRN	Basic Research Needs
CBC	Coherent Beam Combination

CDI	Coherent Diffractive Imaging
CEI	Coulomb Explosion Imaging
CEP	Carrier-Envelope Phase
CityTech	New York City College of Technology
CLBO	Cesium Lithium Borate, $CsLiB_6O_{10}$
CLEO	Conference on Lasers and Electro-Optics
CORD	Center for Occupational Research and Development
CoReLs	Center for Relativistic Laser Science
CPA	Chirped-Pulse Amplification
CPIA	Colorado Photonics Industry Association
CPSA	Coherent Pulse Stacking Amplification
CSP	Cadmium Silicon Phosphide, $CdSiP_2$
CSU	Colorado State University
CSUN	California State University Northridge
CW	Continuous Wave
DEIA	Diversity, Equity, Inclusion, and Accessibility
DEPS	Directed Energy Professional Society
DESY	Deutsches Elektronen-Synchrotron
DFG	Difference Frequency Generation
DKDP	Deuterated Dihydrogen Potassium Phosphate
DOD	Department of Defense
DOE	Department of Energy
DUV	Deep Ultraviolet
EALS	Electron Acceleration Laser System
EDFA	Er-Doped Fiber Amplifiers
EIC	Electron-Ion Collider
ELI	Extreme Light Infrastructure

EP-OPAL	OMEGA Extended Performance-coupled Optical Parametric Amplifier Line
ERL	Energy-Recovery Linac
ESFRI	European Strategy Forum on Research Infrastructures
EU-XFEL	European X-ray Free-Electron Laser
FAMU	Florida A&M University
FES	Office of Fusion Energy Sciences (in DOE SC)
FNO	Fourier Neural Operators
FOM	Figure of Merit
FP	Fabry-Perot coating
FRCC	Front Range Community College
FTL	Fourier Transform Limited
FWM	Four-Wave Mixing
GaSe	Gallium Selenide
GDP	Gross Domestic Product
GRSI	Graduate Research Student Internship Program
GVD	Group Velocity Dispersion
HBCUs	Historically Black Colleges and Universities
HC-PCF	Hollow-Core Photonic Crystal Fiber
HED	High Energy Density
HEP	High Energy Physics
HEDP	High Energy Density Physics
HHG	High Harmonic Generation
HR	High-Reflection coating
IALS	Ion Acceleration Laser System
ICF	Inertial Confinement Fusion
ICUIL	International Committee on Ultra-High Intensity Lasers
I&DS	International and Domestic Strengths (a crosscut panel for this BRN)

IEEE	Institute of Electrical and Electronics Engineers
iFAST	Institute for the Frontier of Attosecond Science and Technology
IFE	Inertial Fusion Energy
ILMI	Intense Laser Matter Interactions, University of Maryland
INRS	National Institute of Scientific Research, Canada
IP	Intellectual Property
IPDFG	Intra-Pulse Difference Frequency Generation
IR	Infrared
JILA	Joint Institute for Laboratory Astrophysics
JLF	Jupiter Laser Facility
K	Kindergarten
KDP	Potassium Dihydrogen Phosphate
KLM	Kerr-lens mode-locked
KTA	Potassium Titanyle Arsenate, $KTiOAsO_4$
LBNL	Lawrence Berkeley National Laboratory
LBO	Lithium Triborate, LiB_3O_5
LCLS	Linac Coherent Light Source
LGS	Lithium thiogallate, $LiGaS_2$
LIA	Laser Institute of America
LIDT	Laser-Induced Damage Threshold
LIGO	Laser Interferometer Gravitational Observatory
LIO	Lithium iodate, $LiIO_3$
LLE	Laboratory for Laser Energetics
LLNL	Lawrence Livermore National Laboratory
LST	Laser Science and Technology (an LCLS division)
LS&T	Laser Science and Technology
LSTM	Long Short-Term Memory

LuAG	Lutetium Aluminum Garnet, $Lu_3Al_5O_{12}$
LuLF	Lutetium Lithium Fluoride, $LuLiF_4$
LWFA	Laser Wakefield Acceleration
LWIR	Long-wave Infrared
MEC	Matter in Extreme Conditions
MEC-U	Matter in Extreme Conditions-Upgrade
Mid-IR	Mid-Infrared
MII	Manufacturing Innovation Institute
MITACS	Mathematics of Information Technology and Complex Systems
ML	Machine Learning
MLD	Multilayer Dielectric
MOU	Memorandum of Understanding
MPC	Multi-Pass Cell
MPW	Multi-Pettawatt
MS	Metasurface
MSI	Minority Serving Institution
MSIPP	Minority Serving Institution Partnership Program (supported by NNSA)
MWIR	Middle-Wavelength Infrared
NASEM	National Academies of Sciences, Engineering, and Medicine
NDE	Non-Destructive Evaluation
Near-IR	Near-Infrared
Near-UV	Near-Ultraviolet
NIF	National Ignition Facility
NLO	Nonlinear Optics
NNSA	National Nuclear Security Administration
NOPA	Noncollinear Optical Parametric Amplification
NSBE	National Society of Black Engineers

NSBP	National Society of Black Physicists
NSF	National Science Foundation
NSHP	National Society of Hispanic Physicists
OAM	Orbital Angular Momentum light beams
OHG	Optical Harmonic Generation
OP	Orientation-Patterned
OPA	Optical Parametric Amplification
OPCPA	Optical Parametric Chirped-Pulse Amplification
OPO	Optical Parametric Oscillator
OP-TEC	National Center for Optics and Photonics Education
OR	Optical Rectification
ORNL	Oak Ridge National Laboratory
OSU	Ohio State University
PAALS	Particle Acceleration and Advanced Light Sources
PI	Principal Investigator
PINN	Physics-Informed Neural Networks
POL	Polarizer coating
PPLN	Periodically Poled Lithium Niobate
PPLST	Periodically Poled Stoichiometric Lithium Tantalate
PPP	Public-Private Partnership
PRD	Priority Research Direction
PREM	Partnerships for Research and Education in Materials (supported by NSF)
PUI	Predominantly Undergraduate Institutions
PVD	Physical Vapor Deposition
QCL	Quantum Cascade Laser
QED	Quantum Electrodynamics
QPM	Quasi-Phase Matching

R&D	Research and Development
RDW	Resonant Dispersive Wave Generation
RENEW	Reaching a New Energy Sciences Workforce (supported by DOE)
REU	Research Experiences for Undergraduates (supported by NSF)
RF	Radiofrequency
RMS	Root Mean Square
SACNAS	Society for the Advancement of Chicanos/Hispanics and Native Americans in Science
SASE	Self-Amplification of Spontaneous Emission
SBIR/STTR	Small Business Innovation Research/Small Business Technology Transfer
SC	Office of Science (in DOE)
SCG	Supercontinuum Generation
SCIPPP	Supply Chain Issues and Public-Private Partnerships (a crosscut subpanel for this BRN)
SEL	Station of Extreme Light
SEMATECH	an acronym derived from Semiconductor Manufacturing Technology
SHG	Second Harmonic Generation
sHHG	Solid-State High-Order Harmonic Generation
SHPE	Society of Hispanic Professional Engineers
SLAC	SLAC National Accelerator Laboratory
SNL	Sandia National Laboratories
SPIE	An international society for optics and photonics (formerly the Society for Photographic Instrumentation Engineers)
SSD	Smoothing by spectral dispersion
STEM	Science, Technology, Engineering, and Mathematics
STEP UP	Supporting Teachers to Encourage the Pursuit of Undergraduate Physics (stewarded by APS)
Strehl	Strehl Ratio
SULF	Shanghai Superintense Ultrafast Laser Facility

SULI	Science Undergraduate Laboratory Internships (supported by DOE)
SWE	Society of Women Engineers
SXR	Soft X-ray
TASE	Transverse Amplified Spontaneous Emission
TEAM UP	Task Force to Elevate the Representation of African Americans in Undergraduate Physics & Astronomy (stewarded by APS)
Texas PW/TPW	Texas Petawatt Laser Facility
UCF	University of Central Florida
UCLA	University of California, Los Angeles
UMD	University of Maryland
UMich	University of Michigan
UNL	University of Nebraska-Lincoln
UR	University of Rochester
U.S.	United States
USR	Ultra-low energy Storage Ring
UT	University of Texas
UV	Ultraviolet
Vis	Visible
Vulcan 20-20	An upgrade project to the Vulcan laser
VUV	Vacuum Ultraviolet
WDM	Warm Dense Matter
WFD	Workforce Development (a crosscut subpanel for this BRN)
WPE	Wall-Plug Efficiency
XCELS	Exawatt Center for Extreme Light Studies
XFEL	X-ray Free-Electron Laser
XUV	Extreme Ultraviolet
YAG	Yttrium Aluminum Garnet, $Y_3Al_5O_{12}$
YCOB	Yttrium Calcium Oxyborate, $YCa_4O(BO_3)_3$

YLF	Yttrium Lithium Fluoride, $YLiF_4$
YSGG	Yttrium Scandium Gallium Garnet
ZEUS	Zettawatt-Equivalent Ultrashort-Pulse Laser System
ZPG	Zinc-Germanium Diphosphide, $ZnGeP_2$
2D	Two-Dimensional
3D	Three-Dimensional
6D	Six-Dimensional

Appendix G. Exemplar Workforce Development Programs

1) Pre-college workforce development exemplar programs which engage pre-college students with academic and industry professionals:

- “Outreach” program by Shim’s group at Binghamton for underrepresented groups in Science, Technology, Engineering and Mathematics (STEM, Contact Bonggu Shim [1]): Funded by NSF, this program is a collaboration at Binghamton with a school of social work and school of education targeting grandparent-headed families and rural families living in poverty in Broome County (Binghamton), NY. There are many grandparent caregivers who are solely responsible for the care of their grandchildren, but they often face multiple challenges including family crisis, physical and mental health issues, and difficulties navigating the K-12 education system. Their grandchildren have multiple risk factors such as anxiety, depression, and insecurity which can significantly impede school success. Dr. Shim has been hosting and coordinating science camps for grandparent-headed families and also rural families living in poverty since January 2014. Largely focused on middle school age, these science camps include laser lab tours.
- Based on Photonic programs initiated by partnerships between Thorlabs, Monroe Community College (Rochester, NY), and Sussex County Community College (Newton, NY), Thorlabs sponsors a program that reaches underserved "at-risk" high school students at Boulder Prep High School [2] and partners with the laser optics program at Front Range Community College (FRCC) [3] (Contact Sterling Backus [4]). Thorlabs has committed funding for the school for science-based needs at $2K per year for five years. Dr. Amanda Meier (FRCC faculty) and Dr. Sterling Backus (Thorlabs) donate time for the course. Across two years of the program to date—including four full days, with three industrial tours, and one academic tour—there have been 32 student participants who all passed the for-credit class. The demographics of student participants include 50–64% female students, and 50% minorities. Companies visited are Quantinuum (quantum computing), Excelitas (optics manufacturer), Thorlabs (photonics tools), and FRCC. Summer funding/salary for Dr. Meier is also provided in collaboration with Colorado Photonics Industry Association (CPIA) [5] and Optics Manufacturing Consortium, AmeriCOM [6]. They have provided Amanda’s program with ~$1.5M in equipment for the optics manufacturing program. Based on the success of this collaborative program involving industry, high school students, and community colleges, similar programs are being explored in other regions including Valencia Community College in Orlando, Fl [7] and Monroe Community College in Rochester, NY [8].

2) Technician training/pathways for technicians: Exemplar programs demonstrating effective partnerships between two-year colleges, high schools, universities, national laboratories, industry partners, and professional societies:

- The National Center for Optics and Photonics Education (OP-TEC) [9], established in 2006 as an NSF-Advanced Technological Education Program (ATE) National Center of Excellence, is a consortium of eight community and technical colleges in NJ, PA, CA, FL, NC, TX, IA, and SC led by OP-TEC staff at the Center for Occupational Research and Development (CORD);
- Consortium for innovations in technician education through Broadening Institutional Participation in the NSF-ATE program [10];
- DOE-Reaching a New Energy Sciences Workforce (RENEW) [11] - Princeton Plasma Physics Laboratory [12] and other universities and national labs; and
- Apprenticeship program at Princeton Plasma Physics Laboratory [13].

Numerous community colleges around the nation already have excellent optics programs and certification programs in optics and photonics; these are standout candidates for partnership and funding opportunities to further expand laser technology technician training. These community colleges also have region-specific details and forecasts for job opportunities in the laser technology field, including estimated ranges for hourly wages to illustrate earning potential:

- Springfield Technical Community College Laser Electronics Optics Technology (MA) [14];
- Front Range Community College Optics Technology Associate of Applied Science (AAS) degree (CO) [3];
- Monroe Community College Optical Systems Technology AAS (NY) [8];
- San Jose City College laser technology program (CA) [15]; and
- Cañada College photonics and laser technology program (CA) [16].

The professional society SPIE and trade journal Photonics Spectra maintain running lists of community colleges and training programs, which are useful to grasp the prevalence of laser-specific workforce development opportunities particularly for technicians and entry points into laser careers, though they may not be fully up to date:

- SPIE.org lists programs offering Technician Certification [17]; and
- Photonics Spectra has a Community College Listing in its Education Section [18].

3) Undergraduate training for industry careers. Exemplar programs to train undergraduates for industry:

- Bridgewater State University in Massachusetts offers a four-year undergraduate degree program in optical engineering [19] that includes internship opportunities and support [20]; and
- Arizona State University's Sundial Project [21] shows first-year physics students what cutting-edge science and scientific research looks like by taking students to tour research labs, exposing them to applications and technologies beyond the classroom.

4) Undergraduate training for academic careers. Exemplar programs that focus on providing undergraduate training for academic research and careers in laser science include:

- Partnerships for Research and Education in Materials (PREM): Partnership between California State University Northridge (CSUN) and Princeton for Quantum Materials [22];
- American Physical Society (APS) Bridge Program [23];
- Brookhaven National Laboratory (BNL) has established a number of partnerships between the lab and minority serving institutions (MSIs). For laser technology, a recently signed Memorandum of Understanding (MOU) between the New York City College of Technology (CityTech) and BNL expands on pre-existing engagements between BNL's Accelerator Test Facility (ATF) for an accelerator and laser course hosted at the ATF. BNL currently has MOUs in place or in progress with the following MSIs to provide physics/engineering opportunities for their students:
    - Dillard University
    - Howard University
    - North Carolina A&T State University
    - Wellesley College
    - Texas Southern University
    - University of Texas, El Paso
    - New York College of Technology
    - Jackson State University
    - Norfolk State University
    - Ford A&M University
    - Morgan state University
- Lawrence Livermore National Laboratory (LLNL) has a Minority Serving Institute Partnership Program (MSIPP) consortium with three historically black colleges and universities (HBCUs, Norfolk State University, Virginia State University, and Elizabeth City State University) that centers around photonics and material science:

  - LaserNetUS partnership with Morehouse, University of California, Merced, and Florida A&M University (FAMU) funded via DOE-RENEW [24]

5) Early career (pre-tenured) workforce development and graduate student training. Exemplar programs include:

- BNL's mentoring program and post-doc resources [25];
- Graduate Research Student Internship Program (GRSI) at Oak Ridge National Lab (ORNL) [26];
- Siegman International School on Lasers [27];
- Directed Energy Professional Society (DEPS) Graduate Student Research Grants [28]; and
- U.S. Particle Accelerator School at Fermilab [29]

6) Laser facility networks

Exemplar programs include:

- Laserlab-Europe, a network of 35 facilities in 18 countries [30];
- LaserNetUS, a network of 10 facilities in the US and Canada [31];
- X-lites, a network of 12 facilities in 9 countries [32]

LaserNetUS as a model for workforce development and scientific advancement

An important model for workforce development that works across the five distinct development opportunities listed above is LaserNetUS. The LaserNetUS network was established in 2018 by the DOE FES to provide U.S. scientists increased access to midscale, high intensity laser facilities. The laser and support facilities are located at universities and national laboratories distributed geographically throughout the U.S. with one in Canada (see Fig. 13). LaserNetUS is designed as a step towards addressing reduced U.S. leadership in high-intensity laser research and related applications [33]. It benefits the field of ultrashort pulse, high-power laser-based science by providing broad access to flexible, state-of-the-art laser systems. The capabilities of the LaserNetUS facilities [34] enables researchers to perform experiments at conditions not available at their home institutions.

An independent review process of proposals for facility time, overseen by DOE FES, assesses both scientific merit and broader impact, including development of laser technology and, especially, workforce development. This includes the potential for advancing the careers of students, young technicians and scientists, and advancing diversity. Users are strongly encouraged to place qualified students and post-docs in leadership positions on proposals, on experiments, and in representing their teams at the LaserNetUS annual meetings. At the 2023 annual meeting, 47% of the 217 attendees were students and postdocs. At the conclusion of its 4th cycle of user runs, 46% of run participants were students and postdocs. The LaserNetUS network was built on existing facilities that together had previously not played such a large role in workforce development. The potential was there, but unrealized. The new network has led to strengthened relationships between national laboratories and universities, provided more cross-collaboration opportunities, and engaged a broader community including industrial users and members from under-represented groups. With support from the DOE RENEW program, cohorts of students from three minority serving institutions attended the 2023 annual meeting, which included mentors to help them navigate a scientific conference, and this was followed by their summer research. LaserNetUS has become a model for a growing number of other networks based on other technologies such as ZNetUS [35] and MagNetUS [36]. This role has been recognized in recent reports [37] and serves as a model for how the U.S. can better address workforce development using the infrastructure it already has.

LaserNetUS facilities include: CSU's ABL, ALLS, LBNL's BELLA, UT-Austin's CHEDS, UN-Lincoln's ELI, LLNL's Jupiter, Rochester's OMEGA EP, SLAC's MEC, OSU's Scarlet, and UCF's iFAST.

REFERENCES

[1] Bonggu Shim, Binghamton University, Binghamton, NY, USA, Email: bshim@binghamton.edu, Available: https://www.binghamton.edu/physics/research/profile.html?id=bshim

[2] Boulder Prep High School, "About Us." Available: https://boulderprep.org/about.php

[3] Front Range Community College, "Optics Technology." Available: https://www.frontrange.edu/programs-courses/program-list/optics-technology.html

[4] Sterling Backus, Thorlabs, Inc., Lafayette, CO, USA, Email: SBackus@thorlabs.com

[5] Colorado Photonics Industry Association. Available: https://coloradophotonics.org/

[6] American Center for Optics Manufacturing (AmeriCOM). Available: https://americom.org/

[7] L. Shrieves, "Valencia to offer short-term optics technician training program," Valencia College News, May 2023. Available: https://news.valenciacollege.edu/valencia-to-offer-short-term-optics-technician-training-program/

[8] Monroe Community College, "Optical Systems Technology." Available: https://www.monroecc.edu/depts/eomctech/programs/optical-systems-technology/

[9] U.S. National Science Foundation, "Award Abstract # 1144377: OP-TEC: The National Center for Optics and Photonics Education," Aug. 2011, Available: https://www.nsf.gov/awardsearch/showAward?AWD_ID=1144377

[10] U.S. National Science Foundation, "Award Abstract # 2018198: Broadening Institutional Participation in the NSF Advanced Technological Education Program," May 2020 Available: https://www.nsf.gov/awardsearch/showAward?AWD_ID=2018198&HistoricalAwards=false

[11] U.S. Department of Energy, "Reaching a New Energy Sciences Workforce (RENEW)." Available: https://science.osti.gov/Initiatives/RENEW

[12] J. J. DeVoe, "PPPL to lead collaborative center aimed at supporting efforts to bring more underserved communities into plasma science and the fusion energy field," Princeton Plasma Physics Laboratory, Mar. 2023. Available: https://www.pppl.gov/news/2023/pppl-lead-collaborative-center-aimed-supporting-efforts-bring-more-underserved

[13] Princeton Plasma Physics Laboratory (PPPL), "Apprenticeships." Available: https://www.pppl.gov/work-with-us/apprenticeships

[14] Springfield Technical Community College, "Optics and Photonics." Available: https://www.stcc.edu/explore/programs/leot.as/

[15] San José City College, "Laser Technology." Available: https://sjcc.edu/dept/laser-technology.aspx

[16] Cañada College, "Photonics and Laser Technology (PALT)." Available: https://canadacollege.edu/palt/index.php

[17] SPIE, "Programs Offering Technician Certification." Available: https://spie.org/education/technician-resources/community-college-programs

[18] Photonics Spectra, "Community College Listing | Education Special Section." Jul.-Aug. 2018. Available: https://www.photonics.com/Articles/Community_College_Listing/a63623

[19] Bridgewater State University, "Undergraduate degrees in photonics & optical engineering." Available: https://www.bridgew.edu/academics/majors-minors-undergraduate/photonics-optical-engineering

[20] Bridgewater State University, "Beyond the Classroom – Physics, Photonics, and Optical Engineering." Available: https://www.bridgew.edu/department/physics-photonics-optical-engineering/beyond-the-classroom

[21] Arizona State University Department of Physics, "The Sundial Project." Available: https://physics.asu.edu/sundial

[22] U.S. National Science Foundation, "Award Abstract # 1828019: PREM: Partnership between CSUN and Princeton for Quantum Materials," Aug. 2023. Available: https://www.nsf.gov/awardsearch/showAward?AWD_ID=1828019&HistoricalAwards=false

[23] American Physical Society (APS), "APS Bridge Program." Available: https://www.aps.org/programs/minorities/bridge/index.cfm

[24] University of California, Merced, "Reaching a New Energy Workforce grant awarded to CfHEDS team," Dec. 2022. Available: https://cfheds.ucmerced.edu/news/2022/reaching-new-energy-workforce-grant-awarded-cfheds-team

[25] Brookhaven National Laboratory, "Association of Students & Postdocs: Career Resources." Available: https://www.bnl.gov/asap/career-resources.php

[26] Oak Ridge National Lab, "Graduate Research Student Internships." Available: https://education.ornl.gov/grsi/

[27] Optica, "Siegman International School on Lasers." Available: https://www.optica.org/events/topical_meetings/siegman_international_school_on_lasers/

[28] Directed Energy Professional Society, "DEPS Graduate Research Grant Awards." Available: https://protected.networkshosting.com/depsor/DEPSpages/scholarships.html

[29] U.S. Particle Accelerator School. Available: https://uspas.fnal.gov/

[30] Laserlab Europe. Available: https://www.laserlab-europe.eu/

[31] LaserNetUS. Available: https://lasernetus.org/

[32] X-lites. Available: https://opticalscience.osu.edu/x-lites

[33] National Academies of Sciences, Engineering, and Medicine. 2018. *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light*. Washington, DC: The National Academies Press. https://doi.org/10.17226/24939

[34] See https://lasernetus.org/ for an up-to-date list of facilities and their capabilities.

[35] https://znetus.eng.ucsd.edu/

[36] https://sites.google.com/view/frontier-science-magnetus/magnetus

[37] National Academies of Sciences, Engineering, and Medicine. 2023. *Fundamental Research in High Energy Density Science*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26728. See, for example, Box 4-6, "Access to Premier U.S. Facilities in High Energy Density Science Is Essential for the Workforce."