High average power ultrafast laser technologies for driving future advanced accelerators

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Introduction

Large-scale laser facilities are needed to advance the energy frontier in high energy physics (HEP) and accelerator physics. A laser-plasma accelerator (LPA) could in principle reach high energies with an accelerating length that is ~1000× shorter than in conventional RF based accelerators [1]. LPAs have produced multi-GeV electron beams in ~20 cm with relative energy spread of about 2% [2], supported by highly developed laser technology [3]. This validates key elements of the US DOE strategy for such accelerators to enable future colliders [4]. Furthermore, compact LPAs will enable new previously inaccessible applications in medicine, national security, and industry, which will broaden and strengthen the HEP community.

Applications will require rates of kHz to tens of kHz at Joules of energy and high efficiency, and a collider would require ~100 such stages, a leap from current Hz-class LPAs. In the near term, diode pumped, actively cooled Ti:sapphire systems [5] offer a path to higher rates. This will enable active correction for instabilities such as pointing, pulse energy/shape, and machine learning [6,7] optimization to realize precision LPA potential. To reach collider luminosities, repetition rates would need to increase to tens of kHz and efficiencies to tens of percent which requires new laser technologies. Several techniques have been proposed to achieve these goals, but all need sustained R&D to reach technical readiness as LPA drivers [8, 9, 10]. Further development will also require ongoing research in novel materials, optics, and techniques to support laser systems that exceed present optical damage thresholds. All realistic approaches should be pursued. Many of these new laser designs are highly efficient which is important to make future LPAs economical. They also improve laser spatial and temporal pulse qualities, which in turn enables improvements to the particle beam properties [6, 11].

Precision accelerator, laser and science capabilities are needed in the near-term

Continued progress along the LPA development roadmap requires that we both increase laser and LPA performance towards theoretical limits, which requires active correction, and that we address the challenges of operation at high rates while using those rates to enable early applications such as photon sources [4, 12]. A near-term kHz system is needed to address these requirements. Ti:sapphire is the only mature laser technology that can realize the required laser at the 3 Joule, 30 femtosecond level and can be built on the five year time scale [8, 9, 10]. Scaling the LPA driver laser to kHz repetition rate and corresponding average power level relies on four key elements: diode pump lasers, cryogenically cooled Ti:sapphire amplifiers, laser beam/pulse stabilization based on active feedback, and low-loss dielectric pulse compression gratings. This is a major milestone on the US plasma accelerator roadmap [4] and timely execution is critical to continue strong progress on that roadmap. One approach uses OPCPA front end, cryogenically cooled Ti:sapphire, and incoherently combined fiber pump lasers. The hybrid OPCPA/Ti:sapphire design has the potential for scaling by an order of magnitude in power increasing the pump rate to 10 kHz with the thousands of fiber-based pump lasers [9]. At the same time, moving towards even higher repetition rates (10-50kHz) will require new laser technologies due to fundamental limits in Ti:sapphire properties. A facility should support both a near term kHz system and future multi-kHz technologies.

Efficient lasers for driving future LPAs beyond kHz require ongoing development

Support is needed for focused laser R&D to push beyond current laser driver limitations. Diode-pumped solid-state lasers (DPSSLs) are particularly attractive for high efficiencies and robustness. Multiple DPSSL-based laser technologies have been proposed as mid-term solutions towards higher-efficiency laser drivers that can address HEP community needs in the sub-100fs, few J regime. All candidate techniques require development of active control techniques to realize stable and controllable pulse parameters for efficient high-quality LPAs. Development of high peak and average power handling optics will be required for high rate LPAs as well. Furthermore, the need for broadly available modeling software that captures self consistently the required physics of gain, thermal loading and lensing, spectral shaping and other effects required to quantitatively design such lasers has been highlighted in several recent community planning activities [8,9,10].

The fiber laser path to LPA drivers beyond kHz is through combining many ultrashort pulses generated from fiber lasers, in multiple domains. A fiber LPA driver is based on a combination of temporal pulse stacking [13] and spatial beam combining [14] to achieve LPA relevant pulse energies, and spectral combining [15] to achieve short pulse durations. This approach requires additional R&D to demonstrate further power and energy scaling, while maintaining robust and high-fidelity coherently combined output, and pulse duration reduction to 10s of fs. A collaboration between LBNL, LLNL and the University of Michigan is developing combining techniques for an LPA driver. The baseline technology operates at 1µm and 2µm is an alternate. Fiber lasers offer very high wall-plug efficiencies, simple thermal management, high beam quality, and system compactness and robustness.

Large, single-aperture DPSSLs require additional R&D to achieve higher wallplug efficiency, in thermal management while maintaining sufficient beam quality to drive LPA, and in generating sub-100fs laser pulses in relevant solid-state media [16, 17, 18]. A flexible multi-kHz LPA driver utilizing bulk Tm:YLF crystals [16,19] near 2µm is an inherently high-efficiency, single laser beam solution. It has spatial and temporal characteristics more closely matched to LPA needs (including being able to use conventional techniques for sufficient pre-pulse contrast), but more complex thermal management. LLNL is currently developing thermal management techniques for this material system that will enable high average power required for LPA applications, as well as improved understanding of material properties under use conditions. An LLNL and OSU research effort is also studying laser damage in 2 µm gratings.

Another proposed path to efficient multi-Joule sub-100 fs lasers operating at multi-kHz repetition rate relies on diode pumped cryogenically cooled Yb:YAG as the amplifier gain medium. Cryo-cooled Yb:YAG laser technology demonstrated by Colorado State University (CSU) and XUV Lasers [20] has already been used to generate >1 J pulses at 1 kHz repetition rate that were compressed into pulses of < 5ps duration. However, the gain bandwidth of Yb:YAG limits the pulsewidth of these cryogenically cooled kW average power lasers to > 3 ps. Spectral broadening and compression of Yb:YAG ps pulses in long, large diameter hollow-core fibers can provide a path forward for the direct generation of sub-100 fs high energy laser pulses at high average powers [21,22]. A collaboration between CSU and Few-Cycle is currently investigating how to combine all performance aspects into one system [23].

Another approach relies on a MOPA architecture that is being developed by Fraunhofer ILT. Starting with an Innoslab front end and a ThinDisc booster [24] enables Joule class pulses at kHz repetition rate and operation at room temperature [25]. Scaling energy and repetition rate is feasible for both: 1µm and 2µm emission wavelength (gain medium: Yb:YAG and Tm YLF). For further pulse shortening, a highly efficient pulse compression scheme offers a compression efficiency beyond 90% to the required pulse duration in the multi 10 fs range [26, 27]. Further energy scaling at high average power and adapting the pulse compression scheme to J class operation is feasible and requires moderate development efforts. The concept is based on an industrial laser platform, whose precision, repeatability, and maintainability will be of high importance for long term operation and commercialization of LPA and secondary sources.

Lasers for advanced accelerators must produce high-quality focal volumes and pulse shapes that are stable at high-average powers. One challenge is extending the average-power handling capacity of compression gratings and related optics to power densities of ~100 W/cm2, enabling operation at kHz repetition rates. Multiple strategies are being pursued to mitigate these effects [28-30]: (1) substrates with high thermal stability and/or low thermal gradients, (2) active-cooling techniques, (3) low-absorption gratings. Adaptive conditioning of the near-field beam is needed for optimal focal-spot profiles, and avoiding optical damages. Closed-loop systems based on spatial light modulators (SLM) and wavefront sensing have been developed to provide both amplitude and phase control [31,32]. Extending these systems to high average powers (100 W/cm2) will likely require water-cooled modulators and higher speed control loops for machine safety.

The robustness of optical coatings, i.e. multi-pulse operation without significant performance degradation is crucial for high uptime operation of future LPAs. Ultra-broad band femtosecond optics have the potential to operate reliably at 2-3x higher fluence than currently possible [33,34]. To develop such optics, sustained research is needed to construct ultra-low absorption highly robust interference coating systems, involving dielectrics, metals, and mixed-dielectrics, and to benchmark with realistic computational models of laser induced damage [35-38]. Damage and degradation of optics under multi-pulse irradiation is not well-understood and since only a handful of 10 J class lasers currently exist that can operate at Hz level repetition rates, is not possible to obtain reliable data. Sustained research on how intense laser fields interact with surfaces and interfaces of coating layers at atomic to larger spatial scales, and how these damage spots develop from atomic to microscopic to macroscopic level over multiple shots is required for high repetition rate, high peak power femtosecond laser based facilities to operate with high uptimes comparable to modern accelerator facilities.

Outlook

LPA is an essential technical approach for next-generation particle accelerators relevant for the HEP Energy Frontier. Promising laser technologies exist but require additional R&D to realize LPA drivers capable of enabling TeV colliders. A facility enabling near term kHz experiments that also couples developing laser technologies with LPA experiments is a clear, important and cost-effective next step that will provide a way to investigate challenges and advance the path towards applications.

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