Snowmass2021 Letter of Interest:
Laser-Plasma Accelerator Linear Collider

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Introduction The beam energy reach of a linear collider is limited by the accelerating gradient of the accelerator technology and the power costs to achieve the required luminosity. For example, the proposed Compact Linear Collider (CLIC) relies on conventional metallic RF structures with a peak accelerating gradient of 100 MV/m, and the size of the linac to reach TeV-class center-of-mass energies is tens of kilometers [1]. Laser-driven plasma accelerators (LPAs) [2, 3] have demonstrated gradients 1-100 GV/m, orders of magnitude larger than conventional RF accelerators. A linear collider based on LPAs offers the possibility of orders of magnitude reduction in the size of the collider linacs, and the associated reductions in cost. In addition, LPAs naturally generate ultrashort bunches (sub-100 fs), significantly reducing the beamsstrahlung during the collision, and, hence, reducing the required beam power to reach a luminosity goal [4].

LPAs rely on an intense, ultrashort laser pulses to resonantly excite large amplitude electron plasma waves with relativistic phase velocities. Charged particle beams interact with the fields of the plasma wave, or wakefields, gaining energy. There has been tremendous progress in the field of laser-driven plasma-based accelerators in the last two decades. Much of the progress has been the result of laser technology advances and a more complete understanding of the laser-plasma interaction physics. An important experimental milestone was achieved in 2004 when three laboratories reported [5–7] the trapping and acceleration of background plasma electrons to produce quasi-mono-energetic electron beams at energies of approximately 100 MeV. In 2006, 1 GeV electron beams were produced using 100 TW class laser pulses in a few-cm-long plasma channel [8]. Today, many laboratories around the world routinely achieve laser-plasma-accelerated electron beams with energies ranging from 100 MeV to $\gtrsim$1 GeV. Most recently, electrons were accelerated up to 8 GeV over 20 cm using a PW laser pulse propagating in a plasma channel [9]. Recent research has focused on improved beam quality (e.g., reducing energy spread) and reproducibility.

Given the great potential of compact, high gradient, advanced accelerator technologies, such as laser-plasma acceleration, the DOE HEP Office published a report outlining a R&D roadmap toward a collider [10]. As envisioned in this Roadmap, realizing a laser-plasma-based e^+e^-/e^-e^-/gamma linear collider will only be possible with a sustained R&D effort over the next two decades. The Roadmap includes R&D plans for laser-driven plasma-accelerator R&D, beam-driven plasma accelerator R&D [11], and beam-driven structure-based accelerator R&D [12, 13], as there are many commonalities between these three advanced accelerator approaches.

Beyond linear colliders, LPAs may have applications for muon creation and acceleration owing to the high gradients. In general, laser-plasma-based acceleration is of potential interest to any application where there is a premium on compactness. For example, there is worldwide interest in using these beams to drive x-ray free-electron lasers—reducing the accelerating distance from the km-scale using a conventional linac, to m-scale using a laser-plasma accelerator [14]. Nearer-term light source application of LPAs is considered an important demonstration of this technology on the path toward a collider. These LPA-based compact light-sources have cross-cutting applications across the DOE, for instance probing of materials for Basic Energy Sciences or exploration of high-energy density states created in laboratory astrophysical experiments of interest to Fusion Energy Sciences.

LPA-based collider design A conceptual design of LPA-based collider has not been completed. However, several preliminary studies [4, 15] have been completed to guide the accelerator R&D. These studies have identified the operational plasma density regime that minimizes the overall collider power requirements, while keeping the beamsstrahlung at the collision point at an acceptable level for a target luminosity. Owing to the short plasma wavelength ($\sim$100 μm), plasma accelerators are best suited to accelerate ultra-short (sub-100-fs duration) beams, which aids in beamsstrahlung reduction. An LPA-based collider would consist of many LPA accelerating stages with multi-GeV energy gain per stage. Plasma mirrors can allow for compact coupling of lasers between stages, yielding geometric/average accelerating gradients of few GV/m.

Laser technology For resonant excitation, the required laser properties (e.g., peak power, energy, duration, etc.) to drive the plasma accelerator are determined by the operational plasma density. Preliminary collider studies [4, 15], assuming a plasma density of $\sim 10^{17}$ cm^{-3}, indicate each LPA stage is powered by a 100-fs laser, with $\sim$10 J energy, operating at tens of kHz repetition rate (hundreds of kW average power).

At this average power, laser efficiency is critical, and the wall-to-laser efficiency must be in the tens of percent. There is freedom in laser wavelength choice, as the plasma wave is excited by the ponderomotive force (wavelength-averaged intensity gradient), and the required total power is independent of laser wavelength. However, for fixed plasma density, the number of accelerator stages is proportional to the square of the laser wavelength. Present LPA experiments are driven by lasers relying on Ti:Al_2O_3 as an amplifying medium, operating at a few Hz. The technology for kHz Ti:Al_2O_3 systems is available today [16], and such a system would greatly advance precision LPA technology using active feedback at kHz repetition rates with machine learning and artificial intelligence algorithms, as well as enabling near-term applications. Detailed control of the spatio-temporal laser profile may provide a path to optimizing the laser-plasma coupling [17]. Coherent combination of fiber lasers (at 1 μm wavelength) and Tm:YLF (at 1.9 μm wavelength) are two promising laser technologies that have the potential to deliver the high average and peak power requirements for a collider [18]. Driving the wakefield with a modulated long pulse, or a train of pulses, may allow the laser drive energy to be provided by novel, efficient laser technologies [19, 20]. Long-term investment in the development of high average and high peak power short-pulse laser technology is required to realize a collider.

Accelerator technology development toward a collider For HEP applications, the method of laser excitation of plasma waves must be highly efficient, transferring a large fraction of laser energy into the wakefields and subsequently into the particle beam. This requires strong laser-plasma coupling such that the laser energy is depleted into the plasma. The energy reach of a single LPA stage is thus ultimately limited by laser energy depletion–once the laser has depleted a large fraction of its energy into the plasma, a fresh laser pulse must be coupled into the accelerator. For example accelerating a 1 nC of charge to 1 TeV requires 1 kJ, and achieving this beam energy in a single stage would require >kJ of energy in a short-pulse laser. Also to achieve the luminosity, this laser would have to operate at >kHz. Hence, staging of laser-plasma accelerators is considered to reach high energy beams for HEP applications. Initial proof-of-principle staging experiments using plasma mirrors have been performed [21]. Methods for coupling beams with high charge capture and preservation of beam quality must be developed further, in addition to beyond start-of-the-art beam and laser alignment methods relying on kHz feedback. Note that several different staging configurations may be considered, and one may also consider coupling new laser pulses into a continuous plasma channel [22]. Energy recovery may be employed to improve the overall efficiency [20], including recovery of energy remaining in the plasma wave and the depleted laser driver.

In addition to the main plasma-based linacs, R&D is required on the collider subsystems (e.g., injector, positron generation, cooling sections, beam delivery system, final focus, etc.) to optimize compatibility with the laser-plasma accelerator linacs. For example, laser-plasma-based injection methods may be employed to generate ultra-low (tens of nm) emittance beams, linear cooling sections may be considered (using the ultra-high plasma accelerating gradients) to replace damping rings, plasma-based de-chirpers may be considered to manipulate the longitudinal beam phase space, and strong plasma-based focusing elements may be considered for the final focus.

Summary Realizing the challenge of a laser-driven plasma-based collider will only be possible with a sustained, decades-long R&D effort, involving international partners. The worldwide advanced accelerator community has begun to organize and to identify a path to address this challenge through the ALEGRO framework [23, 24]. Advancing LPA technology in the next decade will require new experimental facilities, and new systems providing kHz, Joule-class laser pulses will enable a leap in LPA performance. Investment in longer term development of new laser architectures, such as coherent combining of fiber lasers or using Tm:YLF, is required for collider applications. With further LPA technology development and the emergence of laser architectures that deliver the required high peak and average power, a full system-integrated design study for the linac and all collider subsystems should be performed to assess the potential energy reach of this technology.

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