Snowmass2021 Letter of Interest:
Plasma sources for laser plasma accelerators

A. J. Gonsalves*[1], B. Cros[2], E. Esarey[1], H, M. Milchberg[3], C. B. Schroeder[1], M. Turner[1], A. Zigler[4]

[1]*Lawrence Berkeley National Laboratory, Berkeley, California 94720 USA*
[2]*CNRS, LPGP, Université Paris-Saclay, 91405 Orsay, France*
[3]*University of Maryland, College Park, MD 20742 USA*
[4]*Hebrew University of Jerusalem, Israel*

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The need for plasma channels Laser plasma accelerators (LPAs) [1, 2] have been proposed as the basis for electron-positron colliders with TeV energy since they offer the possibility of orders of magnitude reduction in the size, and therefore a potential reduction in cost [3–7]. For a collider, the method of laser excitation of plasma waves must be highly efficient, transferring a large fraction of laser energy into the plasma and subsequently into the particle beam. This requires strong laser-plasma coupling such that the laser energy is depleted in the plasma. In addition, to maximize the luminosity per beam power requires high charge per bunch (up to the limits set by the beam-beam interaction). One method to achieve these requirements of gradient, bunch charge, and efficiency, is to use staged, channel-guided LPAs. The use of a preformed plasma channel [8, 9] to mitigate diffraction of the laser pulses is advantageous compared to self-guiding because it allows operation at lower density for a fixed laser energy, yielding more energy gain per stage. In addition it allows for operation at a lower laser intensity, providing a plasma wave suitable for the acceleration of positrons.

Preliminary studies [4] of a laser-plasma-based collider indicate the operational plasma density that minimizes the power requirements. These studies guide the LPA R&D and determines the plasma waveguide parameters. The plasma channel length should be tens of cm to $\approx 1\,\mathrm{m}$, and support guiding of laser pulses with radius tens to $\approx 100\,\mu\mathrm{m}$ in a plasma of density $\approx 1 \times 10^{17}\mathrm{cm}^{-3}$ at >kHz repetition rate. The highest energy LPA to date operated at 1 Hz and employed a plasma channel with density $2.7{\times}10^{17}\mathrm{cm}^{-3}$ and matched laser spot size $61\,\mu\mathrm{m}$ [10]. Operating at lower density (which may be challenging with the inverse bremsstrahlung heating employed in Ref. [10]) could allow for increased energy gain [11]. Perhaps of greater importance, flexibility in achieving controlled guiding at density near $1{\times}10^{17}\mathrm{cm}^{-3}$ could allow for operation in the quasi-linear regime with petawatt laser pulses, avoiding dark current from self-injection, and improving beam emittance and energy spread. This, in combination with advanced injection techniques [12] could provide beams with collider-relevant emittance. This Letter of Interest discusses the various plasma channel technologies and associated R&D that could enable this. We note that the challenges not only include achieving the plasma parameters, but also achieving the high degree of longitudinal and transverse density control and stability that a collider will require. It should also be noted that some of the plasma channel technology developed for laser guiding can also be used for the transport of electron beams for staging [13], laser incoupling for staging [14], emittance measurements, and the realization of extremely compact high-resolution multi-GeV spectrometers [15].

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*ajgonsalves@lbl.gov

Types of plasma channels Plasma channels can have a refractive index (plasma density) profile that changes smoothly away from the axis, or can have a step in refractive index due to a plasma or solid. They are typically formed inside capillaries or by heating of plasma with laser pulses.

In dielectric capillaries, the laser pulse is guided by grazing incidence reflections at the optically smooth inner wall of the capillary, so that laser guiding can be achieved either in vacuum or at low plasma density [16]. Laser pulses with intensity up to $3{\times}10^{17}\mathrm{Wcm}^{-3}$ have been guided over $\approx 10\,\mathrm{cm}$ using this technique, and wakefield generation measured using laser red shifts [17, 18]. Laser guiding quality depends strongly on the coupling of the laser pulse at the entrance of the waveguide [19], defining requirements on the input laser pulse quality and stability. The intensity at the capillary entrance walls should be lower than the material ablation threshold which sets tolerances on the laser pointing fluctuations and symmetry variations. As an example, the displacement of the laser spot center to the capillary center should be 0.1 times lower than the capillary radius. Capillary guiding may also provide means of generating hollow plasma channels, for example by ionization of the inner walls [20].

The issue of damage to capillary walls has motivated the use of capillary discharge waveguides [21, 22], for which damage is mitigated through the use of capillaries with significantly larger diameter. In this type of waveguide, an approximately parabolic plasma density profile is formed by Ohmic heating of a current pulse. Demonstration of plasma channel formation at kHz repetition rate has also been demonstrated [23]. However even with diameter an order of magnitude larger than the laser spot size, the non-ideal laser pulse spatial mode and pointing at the entrance of the waveguide can cause significant damage to the capillary walls. Further increase in capillary diameter can be achieved by employing a laser pulse to heat the plasma on-axis [24] and has allowed for guiding of petawatt laser pulses and electron acceleration to 8 GeV [10].

As the repetition rate of LPAs increases, mitigation of capillary damage becomes increasingly difficult for both capillary discharge and grazing incidence capillary waveguides. Laser-based channels [9] that do not employ a capillary simplify the design of a high repetition rate system. Recent advances using optical field ionization allow for small matched laser spot sizes at low density that can maximize energy gain for a given laser system [25] and more recently allowed for low leakage over meters [26]. The coupling of laser energy into this type of waveguide is currently 50 percent owing to non-optimized laser modes, and the channel stability and symmetry requires further beam stabilization and laser phase front correction. Advances in laser pulse control, some of which are only possible at kHz repetition rates, are expected to readily overcome these limitation with continued R&D.

In order to reach the luminosity required for a high energy physics collider, the beam emittance must be extremely low. For an LPA the emittance can grow via Coulomb scattering with background ions. High intensity laser pulses propagating in hollow [27] or near hollow [5] plasma channels can offer an accelerating gradient that is transversely uniform and focusing fields that are linear with the radial coordinate. This can allow for matched beam propagation without significant emittance growth via scattering. Despite the potential advantage of hollow plasma channels for LPAs, this has yet to be demonstrated experimentally.

Summary There are several types of plasma channels under investigation for application to an LPA-based collider. If a capillary-based solution is adopted, one of the key issues to be addressed is damage to the structure, both from non-ideal laser energy distribution in the focal plane, as well as from heating of the plasma. The former may be addressed from future high power laser system enhancements, and the latter could be addressed via photon acceleration of a trailing pulse (which will likely be required anyway when one considers efficiency requirements). Recent advances in laser-produced plasma channels can allow for meter-scale laser propagation without significant leakage [26], and are easily scalable to high repetition rate. Future improved laser control available at kHz repetition rates should allow for a breakthrough in the control of this type of waveguide, for example improving channel symmetry and transverse location.

Regardless of the technology under consideration, a sustained R&D effort is required to produce plasma channels suitable for colliders. Exquisite control over the plasma density profile over tens of cm to $\approx 1\,\mathrm{m}$, including tailoring the ends of the plasma channel, as well as operation at collider-relevant repetition rate are yet to be demonstrated.

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