Snowmass21 Letter of Interest:

High-Brightness Laser-Plasma-Based Injectors

C. Benedetti*, S. S. Bulanov, E. Esarey, C. G. R. Geddes, A. J. Gonsalves, K. Nakamura, C. B. Schroeder, and J. van Tilborg

Lawrence Berkeley National Laboratory, Berkeley, California 94720 USA

August 31, 2020

Introduction. Plasma-based accelerators have received significant interest owing to their ability to sustain large acceleration gradients, enabling compact accelerating structures [1, 2]. In a laser plasma accelerator (LPA), a short and intense laser pulse propagating in an underdense plasma, ponderomotively drives an electron plasma wave (or wakefield). The plasma wave has a relativistic phase velocity and can support large accelerating and focusing fields. LPAs have demonstrated the production of high-quality (quasi mono-energetic, with relative energy spreads $\gtrsim 1-10\%$) electron bunches, and the generation of accelerating gradients in the range of 10s to 100 GV/m [3–5], several orders of magnitude larger than that obtained in conventional accelerators. The rapid development and properties of LPAs make this accelerator technology an interesting candidates for future, compact, high-energy linear colliders [6–9]. In the US this potential is recognized and the DOE HEP Office has published a report outlining an R&D roadmap towards this goal [10]. In parallel, through the ALEGRO framework [11, 12], the worldwide advanced accelerator community has begun to self-organize and to identify a path to address the many challenges posed by the realization of a plasma-based collider.

Even though the properties of future colliders will be determined by high-energy physics experiments that are currently underway, it has been anticipated that a center-of-mass energy $\gtrsim 1$ TeV and a luminosity $\gtrsim 10^{34}$ cm^{-2}s^{-1} will be required [13, 14]. Typically, this implies using (polarized) electrons and positron bunches with $N_b \sim 10^9 - 10^{10}$ particles, normalized horizontal and vertical emittances such that $(\varepsilon_{n,x}\varepsilon_{n,y})^{1/2} < 100$ nm, and small relative energy spreads, $\ll 1\%$, in order to effectively transport the bunch among subsequent plasma stages without emittance degradation, and to guarantee a sufficiently small bunch size at the interaction point [7, 15].

In addition to HEP applications, LPAs are being considered as drivers for x-ray free-electron-lasers (FELs) [16], with possible cross-cutting applications across the DOE. Application of LPA beams to light sources represents an important intermediate step on the path towards a collider. As in the collider case, in order to realize an LPA-based x-ray free-electron-laser, electron beams with a very high quality [i.e., with high current (> 1 kA), small (slice) energy spread ($\ll 1\%$), and small emittances (< 1 mm mrad)] are required.

Plasma-based injectors: self-injection. Electron beams can be produced in an LPA via self-injection by trapping and accelerating a portion of background plasma electrons [1]. Even though low emittances ($\sim$ 0.1 mm mrad) [17] and energy spreads at the percent level can be obtained using this injection technique, it is unlikely that all the bunch parameters of interest for a future LPA-based collider (or even an LPA-based x-ray FEL) can be achieved simultaneously with this scheme. Using self-injection, bunch production and acceleration are coupled and so there is limited tunability. Additionally, owing to the nonlinear nature of the self-injection mechanism, the bunch parameters are sensitive to small changes in the laser-plasma parameters.

*cbenedetti@lbl.gov

Controlled injection methods. Over the years several controlled/triggered injection techniques have been proposed, e.g., colliding-pulse injection [18, 19], ionization-induced injection with one [20–22] or multiple pulses [23–25], and density gradient injection [26–30]. Although experimentally more complex compared to self-injection, these schemes have the potential to significantly improve the quality, stability, and tunability of LPA-generated beams. Some of these injection techniques have already been implemented experimentally in some form (e.g., colliding pulse, ionization induced injection with one pulse, density gradient), while others, until now, have only been studied theoretically (e.g., two-color laser ionization injection [23]).

While further analysis and optimization of all these schemes is underway, preliminary studies show that, for instance, two-color laser ionization injection can produce beams with normalized emittances of the order of tens of nm, with charges of $\sim$100 pC, and a small energy spread [23]. In this scheme, a long-wavelength pump pulse (with a large ponderomotive force and small peak laser electric field) excites a large plasma wake without fully ionizing a high-Z gas, and a short-wavelength injection pulse (with a small ponderomotive force and large peak laser electric field) co-propagating and delayed with respect to the pump laser, ionizes a fraction of the remaining bound electrons of the high-Z gas at a trapping wake phase, generating an electron beam that is accelerated in the wakefield. The emittance is determined by the strength of the ionizing laser (which depends on the choice of the high-Z gas and the long-wavelength pump laser), the trapped charge scales with the forth power of the ionizing laser spot size (a trade-off between charge and emittance is present), and the energy spread can be controlled by changing the length of the high-Z gas [24, 31]. Owing to its potential and interest for HEP applications, a vigorous R&D devoted to the implementation and optimization of this injection scheme should be carried out. A first experimental test could be done with a simple frequency doubled (e.g., Ti:sapphire, 0.4 μm) injection pulse delayed with respect to a (0.8 μm) pump pulse. However, the full potential of this scheme is realized with longer wavelength drive lasers (e.g., CO_2 or Tm:YLF).

Density gradient injection has already had several successful experimental implementations [27–29], demonstrating the stable production of bunches with tunable energy and low absolute energy spread. In this scheme, injection is triggered by inducing a localized decrease of the plasma wake phase velocity. The slow down is generally realized by properly tailoring the background plasma density profile. However, control of the phase velocity via the laser driver is also possible [28]. The slice energy spread of the bunches obtained with this injection technique is generally small due energy-position correlations arising from the way background plasma particles are trapped. The total energy spread can be controlled by tuning the length of the density gradient and by optimizing the acceleration distance after injection. The emittance can be small owing to the fact that trapped particles have a small transverse momentum. Simulations show that the production of beams with a slice energy spread $\lesssim 0.15$ MeV, peak current of $\simeq 8$ kA, and $\simeq 10$ nm emittance is possible [30]. Reaching all the parameters required for HEP applications requires further study.

Generation of polarized beams. Several concepts to generate polarized electron beams via the laser-plasma interaction have been proposed. One concept considers trapping spin polarized electrons generated by ionizing pre-aligned highly polarizable molecules using density gradient injection [32]. Another concept proposes to generation of a polarized bunch via ionization injection using spin-dependent ionization rates [33]. These concepts require further R&D to determine their viability for HEP applications.

Summary. In summary, recent theoretical and experimental research has focused on improving the quality of electron bunches produced in an LPA through controlled injection. Several techniques to reduce energy spread and emittance, and increase charge and reproducibility have been proposed. If the ultra-low emittance and energy spread can be maintained (this requires, among other things, shaping the bunch current profile, and proper care when in-coupling or extracting the bunch from each LPA stage [34]) cooling of the electron bunch might not be required. However, in the case where cooling is needed, compact plasma-based cooling techniques have been proposed [35]. Plasma-based generation of high brightness, polarized positron beams is more challenging and will require significant R&D [35]. It is vital to continue R&D along this path towards HEP applications.

References

[1] E. Esarey, C. B. Schroeder, and W. P. Leemans, Rev. Mod. Phys. **81**, 1229 (2009).

[2] S. M. Hooker, Nature Photon. **7,** 775 (2013).

[3] X. Wang *et al.*, Nat. Commun. **4**, 1988 (2013).

[4] W. P. Leemans *et al.*, Phys. Rev. Lett. **113**, 245002 (2014).

[5] A. J. Gonsalves *et al.*, Phys. Rev. Lett. **113**, 245002 (2014).

[6] W. P. Leemans and E. Esarey, Phys. Today **62**, 44 (2009).

[7] C. B. Schroeder *et al.*, Phys. Rev. ST Accel. Beams **13**, 101301 (2010).

[8] K. Nakajima *et al.*, Phys. Rev. ST Accel. Beams **14**, 091301 (2011).

[9] C. B. Schroeder *et al.*, Letter of Interest submitted to Snowmass2021, 2020.

[10] Advanced Accelerator Development Strategy Report, US Department of Energy, Office of High Energy Physics, 2016.

[11] Towards a Proposal for an Advanced Linear Collider, Report on the Advanced and Novel Accelerators for High Energy Physics Roadmap Workshop No. CH-1211, CERN Report, 2017.

[12] B. Cros and P. Muggli, Letter of Interest submitted to Snowmass2021, 2020.

[13] J. Ellis and I. Wilson, Nature **409**, 431 (2001).

[14] I. Hinchliffe and M. Battaglia, Phys. Today **57**, No. 9, 49 (2004).

[15] J. P. Delahaye *et al.*, in Proceedings of IPAC2014 (JACoW, 2014) p. THPRI013.

[16] J. van Tilborg *et al.*, Letter of Interest submitted to Snowmass2021, 2020.

[17] G. R. Plateau *et al.*, Phys. Rev. Lett. **109**, 064802 (2012).

[18] E. Esarey, R. F. Hubbard, W. P. Leemans, A. Ting, and P. Sprangle, Phys. Rev. Lett. **79**, 2682 (1997).

[19] J. Faure, C. Rechatin, A. Norlin, A. Lifschitz, Y. Glinec, and V. Malka, Nature **444**, 737 (2006).

[20] A. Pak *et al.*, Phys. Rev. Lett. **104**, 025003 (2010).

[21] C. McGuffey *et al.*, Phys. Rev. Lett. **104**, 025004 (2010).

[22] M. Chen *et al.*, J. Appl. Phys. **99**, 056109 (2006).

[23] L. Yu *et al.*, Phys. Rev. Lett. **112**, 125001 (2014).

[24] C. B. Schroeder *et al.*, Proceedings of SPIE Optics + Optoelectronics, 2015, Prague, Czech Republic.

[25] P. Tomassini *et al.*, Phys. Rev. Accel. Beams **22**, 111302 (2019).

[26] S. Bulanov, N. Naumova, F. Pegoraro, and J. Sakai, Phys. Rev. E **58**, R5257 (1998).

[27] C. G. R. Geddes *et al.*, Phys. Rev. Lett. **100**, 215004 (2008).

[28] A. J. Gonsalves *et al.*, Nature Phys. **7**, 862 (2011).

[29] K. K. Swanson *et al.*, Phys. Rev. Accel. Beams **20**, 051301 (2017).

[30] X. L. Xu *et al.*, Phys. Rev. Accel. Beams **20**, 111303 (2017).

[31] C. B. Schroeder *et al.*, Phys. Rev. ST Accel. Beams 17, 101301 (2014).

[32] M. Wen, M. Tamburini, and C. H. Keitel, Phys. Rev. Lett. 122(21), 214801 (2019).

[33] A. Hartung *et al.*, Nat. Photonics 10(8), 526 (2016).

[34] S. Barber *et al.*, Letter of Interest submitted to Snowmass2021, 2020.

[35] S. S. Bulanov *et al.*, Letter of Interest submitted to Snowmass2021, 2020.