Snowmass2021 Letter of Interest:
Compact laser-based positron creation, capture, and cooling

S. S. Bulanov[*], D. Amorim, C. Benedetti, E. Esarey, C. G. R. Geddes, A. Gonsalves, A. Huebl, K. Nakamura, C. B. Schroeder, J. van Tilborg, J.-L. Vay

Lawrence Berkeley National Laboratory, Berkeley, California 94720 USA

August 31, 2020

Introduction. Rapid progress in the field of laser-plasma acceleration allowed the demonstration of laser wakefield acceleration (LWFA) of high-quality multi-GeV electron beams using tens of cm-scale plasmas [1] at BELLA Center, LBNL. This has increased interest and confidence in the idea of using laser-plasma acceleration as a path toward building a compact TeV-class lepton (electron-positron) linear collider [2, 3, 4]. A second path is being pursued with particle-beam-driven wakefield acceleration (PWFA), using high energy electron or positron beams from conventional accelerators to drive the plasma wave [3]. PWFA positron acceleration was demonstrated utilizing conventional means to produce positron beams [5, 6]. Progress on R&D toward laser-plasma-based positron accelerators would greatly benefit from a compact, laser-plasma-based source of positrons. Such a need was highlighted in the U. S. Advanced Accelerator Concepts (AAC) R&D Roadmap, published in the Advanced Accelerator Development Strategy Report (2016) [7]. This report stated that future AAC research should focus on demonstration and understanding of positron acceleration and rapid cooling methods to deliver short (tens of microns) beams, and in particular "with the completion of a 10 GeV electron LWFA stage, the 10 GeV beam may be employed for electron-positron pair creation and subsequent positron beam capture and LWFA. Development of an LWFA-based positron source would enable compact experiments on LWFA and focusing of positron beams". Moreover, it is a part of a near-term R&D at BELLA Center, as detailed in Ref. [8].

Positron creation methods. To advance the LWFA roadmap [7], novel, compact methods of positron beam generation using intense lasers, need to be studied both theoretically and using computer modeling. Several positron creation methods can be considered: positron beam creation via an LWFA electron beam interaction with either a solid target or a high intensity laser pulse, and via laser-solid interactions. Critical to this investigation will be the evaluation of capture methods for post-acceleration of the positron beam. In addition to positron beam creation and capture, novel methods of positron beam cooling can also be explored, including radiative cooling by electromagnetic fields (e.g., laser and/or plasma waves). We note that similar approaches can be applied to the muon beam creation, capture, and cooling, thus, providing an alternative to the conventional scheme of muon acceleration.

First, a thin (less than a radiation length) high-Z target such that the electron beam is not strongly perturbed before exiting the target, can be used. Then the positrons are created via electron beam Bremsstrahlung in a high Z-target followed by photon to electron-positron pair conversion. The high-Z target can be followed by a gas cell, such that the electron beam ionizes the gas and generates a plasma wave. The produced positrons are then captured in the accelerating and focusing phase of that wave and

---

[*] SBulanov@lbl.gov

are rapidly accelerated to high energies in the ultra-high plasma wave gradient. The plasma density in the gas cell following the target is chosen to be greater than the LPA electron beam density, $n_{beam}/n_e < 1$, so that the beam-driven plasma wave is in the linear regime. This regime contains a larger accelerating and focusing phase region for the positrons. The electrons from created pairs will be lost (defocused) in the same phase region of the plasma wave. To operate in the linear region in the high-density plasma requires intense, ultra-short beams such that the length of the beam satisfies $L_{beam} \sim c/\omega_p$, and thus takes advantage of the ultra-short beams created by laser-plasma acceleration. A short drift space between the high-Z target and gas cell is required to place the positrons in the proper phase of the plasma wave. This positron beam creation and capture method results in positron beams with the desired time structure and phase-space characteristics compatible with laser-plasma accelerators.

Second, positron beams may be generated by an intense laser pulse interacting with a solid target [9, 10, 11, 12]. When intense lasers interact with solid targets a large number of fast electrons (>MeV) are created, and these hot electrons may create positrons by two primary processes. One is the Trident process, where electrons interact directly with nuclei and produce pairs. The second process is the Bethe–Heitler process, where fast electrons make high-energy bremsstrahlung photons, which, in turn, interact with nuclei to produce electron-positron pairs. In principle, this scheme can be enhanced by laser interaction with an underdense (near-critical) plasma preceding the solid target.

Third, positron beams may be generated in the interaction of the LPA electron beam with a counter-propagating high intensity laser pulse via the cascade of multiphoton Compton and Breit-Wheeler processes [13, 14]. In this case high energy electrons will first emit photons, which will decay into electron-positron pairs, with both processes happening inside the laser pulse.

The evaluation of the potential of these three methods of positron beam creation, capture, and acceleration would require the consideration of multidimensional effects, coupling of different computational codes, which describe either creation or capture and acceleration, as well as improved computational models for high intensity laser - electron beam interaction [15]. Such R&D is well aligned with the effort to built modular community ecosystem for multiphysics particle accelerator modeling and design [19].

Positron beam cooling. It can be anticipated that positron production by the above methods will yield positron beams with relatively poor phase space properties (i.e., large energy spread and emittance), and that such positron beams would benefit from beam cooling. Cooling is accomplished in conventional devices by using radiation generation by permanent magnetic undulators followed by acceleration, typically performed in damping rings. Laser cooling has been proposed as a possible method of radiation generation via Thomson or Compton scattering. Cooling by Compton scattering can be limited for high (or moderate) energy beams by the quantum-statistical nature of scattering, because the discrete scattering of a photon results in beam energy spread [16, 17, 18]. Another possibility for radiation generation is to use a plasma wave. By using a plasma wave the wavelength of the oscillation can be of the order of the plasma wavelength (e.g., 100 micron), compared to conventional undulators, with cm-scale wavelengths, or lasers, with micron wavelengths. This will enable compact cooling at higher beam energies than can be achieved with lasers.

Summary. Research and Development of laser-plasma-based lepton accelerators would greatly benefit from a study of a compact laser-based positron creation and capture. In addition to that the development of advanced, compact cooling techniques could potentially benefit any future electron-positron collider. This is well aligned with the near term R&D at the BELLA Center [8], modular community ecosystem for multiphysics particle accelerator modeling and design [19], and is necessary component of the plasma-based TeV-class lepton linear collider R&D [4]. Moreover, the results of this R&D can be applied to the design of the muon source for either a conventional or plasma based accelerator.

References

[1] A. J. Gonsalves, et al., Phys. Rev. Lett. 122, 084801 (2019).

[2] W. P. Leemans and E. Esarey, Physics Today 62, 44 (2009).

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

[4] C. B. Schroeder et al., Letter of Interest submitted to Snowmass21, 2020.

[5] S. Corde, et al., Nature 524, 442 (2015).

[6] A. Doche, et al., Sci. Rep. 7, 14180 (2017).

[7] http://science.energy.gov/hep/community-resources/reports/

[8] A. G. Gonsalves et al., Letter of Interest submitted to Snowmass21, 2020.

[9] E. Liang et al., Phys. Rev. Lett. 81, 4887–4890 (1998).

[10] K. Nakashima and H. Takabe, Phys. Plasmas 9, 1505 (2002).

[11] H. Chen et al., Phys. Rev. Lett. 102, 105001 (2009).

[12] H. Chen et al., Phys. Rev. Lett. 105, 015003 (2010).

[13] A. Di Piazza, et al., Rev. Mod. Phys. 84, 1177–1228 (2012).

[14] S. S. Bulanov, et al., Phys. Rev. A 87, 062110 (2013).

[15] T. G. Blackburn, et al., Phys. Plasmas 25, 083108 (2018).

[16] E. Esarey, Nucl. Instrum. Methods Phys. Res. A 455, 7 (2000).

[17] C. B. Schroeder, E. Esarey, W. P. Leemans, Phys. Rev. Lett. 93, 194801 (2004).

[18] T. G. Blackburn, D. Seipt, S. S. Bulanov, and M. Marklund, Phys. Rev. A 101, 012505 (2020).

[19] J.-L. Vay et al., Letter of Interest submitted to Snowmass21, 2020.