Snowmass21 Letter of Interest:

Laser-driven Injectors for Future Colliders

M. Fuchs[1], B. A. Shadwick[1], C. B. Schroeder[2],

[1] *University of Nebraska, Lincoln, NE 68588 USA*
[2] *Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA*

September 1, 2020

INTRODUCTION

Novel laser-driven accelerators have the potential to become an essential part of future high-brightness accelerator technology. In particular, laser-wakefield accelerators (LWFA), which are based on laser-plasma interactions, can produce electron bunches with an emittance comparable to that of conventional accelerators and with a pulse duration of only a few femtoseconds[1–4]. However, LWFA electron beams currently do not have some of the parameters required by many applications, such as a sufficiently small energy spread or a sufficiently high pulse repetition rate. Other parameters, such as the transverse emittance can be even further improved. The parameters of LWFA electron beams are mainly determined by the electron injection into the accelerating plasma structure and the acceleration process itself. For simplicity, the majority of current LWFAs use a self-injection scheme, which leads to electron beams with a relatively large energy spread and that are typically of lower reproducibility compared to conventional accelerator technology. Furthermore, to achieve electron self-injection requires a comparably high laser intensity, which is currently limiting the repetition rate at which LWFA beams can be produced. Different schemes of controlled injection have been demonstrated, including colliding laser pulses[5], plasma density modulations[6, 7] and ionization injection[8–10]. Although first promising results have been obtained, these methods still require further improvements and some experimental implementations are challenging.

Novel approaches for a front-end injector for a future plasma-based collider are required to address these limitations. In particular, this includes methods that increase the laser-to-electron beam efficiency, enable controlling and manipulating the phase-space of ultrashort LWFA electron bunches with high accuracy and high-resolution diagnostics.

LWFA IN THE BUBBLE REGIME

One of the main challenges for LWFAs are improvements in the electron beam brightness, including the energy spread and transverse emittance and increasing the accelerator repetition rate. Due to simplicity, the majority of LWFAs are driven in the highly nonlinear (bubble) regime and use electron self-injection[11–13]. Operating in this regime requires laser pulses with relativistic intensities. Specifically, the normalized vector potential $a_0 = eE\lambda/mc^2 \simeq \lambda[\mu\mathrm{m}](I_0[\mathrm{W/cm}^2]/1.4 \times 10^{18})^{1/2}$ of the pulse, where E is the laser electric field, λ the laser wavelength, mc^2 the electron rest mass and I_0 the laser intensity, needs to be significantly in excess of 1. To achieve these intensities with a matched laser spot size requires laser pulses with a power of hundreds of terawatts to petawatts [11, 14, 15]. This severely limits the repetition rate at which current state-of-the art laser systems can operate, thus limiting the repetition rate of the accelerator. Furthermore, the highly nonlinear bubble regime increases the difficulty of control over the electron beam properties. This includes the control of the injection process and also the acceleration process. For the latter, this is because of the highly nonlinear evolution of the laser pulse due to the laser-plasma interaction. Due to the stronger interaction of the laser with the plasma at higher intensities, this also leads to low laser-to-electron-bunch efficiencies.

PHASE-SPACE SHAPING

The generation of LWFA electron bunches with a sufficiently high beam quality requires control over the beam phase space with very high temporal and spatial precision. This includes control over both, the electron injection process and the acceleration process. This can only be achieved by a combined theoretical and experimental effort that includes the development of novel simulation and experimental methods. In particular, this also includes the development of novel phase-space diagnostic with high spatial and temporal resolution. This approach will allow the comparison of experimental results with simulation to a high degree and can help improve the ability for predictions based on simulations. Efforts to shape the electron bunch phase-space include the development of advanced method of electron injection including beam tapering and the investigation of acceleration in different regimes, such as a more linear regime. Methods to control the phase space include the design of sophisticated driver lasers, such as high control over the laser spatial and temporal higher-order shapes, multiple pulses, potentially of different colors or the incoherent addition of multiple pulses for example from fiber lasers. Furthermore, novel target designs have the potential to increase the beam quality and shot-to shot stability.

DIAGNOSTICS

Despite ever-more sophisticated attempts to measure the LWFA electron bunch phase space, it is still far from being fully characterized. In particular, the sub-femtosecond time resolution that is require is very challenging. The determination of the success of certain approaches requires novel diagnostic methods for both, the accelerated electron bunch and the accelerating plasma structure itself. These methods need to have a very high temporal and spatial resolution and ideally work in a single shot. Furthermore, they need to be capable of measuring the full 6D phase-space distribution of the electron bunches, including their temporal energy distribution.

CONCLUSION

The injector is a critical element of a high-energy collider. HEP-relevant Laser-plasma accelerator scenarios, require the injector to produce electron bunches with carefully tailored characteristics that have yet to be relazised in the laboratory. Developing the necessary injector technology will require a combined effort to advance the forefront of phase space diagnostics, laser technology, computational modeling of injection, and basic plasma physics.

---

[1] E. Esarey, C. B. Schroeder, and W. P. Leemans, Reviews of Modern Physics **81** (2009).

[2] C. G. R. Geddes, C. Toth, J. van Tilborg, E. Esarey, C. B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary, and W. P. Leemans, Nature **431**, 538 (2004).

[3] J. Faure, Y. Glinec, A. Pukhov, S. Kiselev, S. Gordienko, E. Lefebvre, J. P. Rousseau, F. Burgy, and V. Malka, Nature **431**, 541 (2004).

[4] S. P. D. Mangles, C. D. Murphy, Z. Najmudin, A. G. R. Thomas, J. L. Collier, A. E. Dangor, E. J. Divall, P. S. Foster, J. G. Gallacher, C. J. Hooker, D. A. Jaroszynski, A. J. Langley, W. B. Mori, P. A. Norreys, F. S. Tsung, R. Viskup, B. R. Walton, and K. Krushelnick, Nature **431**, 535 (2004).

[5] J. Faure, C. Rechatin, A. Norlin, A. Lifschitz, Y. Glinec, and V. Malka, Nature **444**, 737 (2006).
[6] C. G. R. Geddes, K. Nakamura, G. R. Plateau, C. Toth, E. Cormier-Michel, E. Esarey, C. B. Schroeder, J. R. Cary, and W. P. Leemans, Physical Review Letters **100**, 215004 (2008).
[7] K. Schmid, A. Buck, C. M. S. Sears, J. M. Mikhailova, R. Tautz, D. Herrmann, M. Geissler, F. Krausz, and L. Veisz, Phys. Rev. ST Accel. Beams **13**, 091301 (2010).
[8] C. McGuffey, A. G. R. Thomas, W. Schumaker, T. Matsuoka, V. Chvykov, F. J. Dollar, G. Kalintchenko, V. Yanovsky, A. Maksimchuk, K. Krushelnick, V. Y. Bychenkov, I. V. Glazyrin, and A. V. Karpeev, Phys. Rev. Lett. **104**, 025004 (2010).
[9] A. Pak, K. A. Marsh, S. F. Martins, W. Lu, W. B. Mori, and C. Joshi, Phys. Rev. Lett. **104**, 025003 (2010).
[10] C. E. Clayton, J. E. Ralph, F. Albert, R. A. Fonseca, S. H. Glenzer, C. Joshi, W. Lu, K. A. Marsh, S. F. Martins, W. B. Mori, A. Pak, F. S. Tsung, B. B. Pollock, J. S. Ross, L. O. Silva, and D. H. Froula, Phys. Rev. Lett. **105**, 105003 (2010).
[11] A. Pukhov and S. Gordienko, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences **364**, 623 (2006), http://rsta.royalsocietypublishing.org/content/364/1840/623.full.pdf+html.
[12] I. Kostyukov, E. Nerush, A. Pukhov, and V. Seredov, Phys. Rev. Lett. **103**, 175003 (2009).
[13] S. Kalmykov, S. A. Yi, V. Khudik, and G. Shvets, Phys. Rev. Lett. **103**, 135004 (2009).
[14] T. Tajima and J. M. Dawson, Phys. Rev. Lett. **43**, 267 (1979).
[15] W. Lu, C. Huang, M. Zhou, W. B. Mori, and T. Katsouleas, Phys. Rev. Lett. **96**, 165002 (2006).