Confined Continuous-Flow Plasma Source For High-Average-Power Laser Plasma Acceleration

B. Farace, R. J. Shalloo, K. Põder, W. P. Leemans

Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany
University of Hamburg, Department of Physics, Jungiusstr. 9, 20355 Hamburg, Germany

Abstract

Over the last decades, significant advances in high-power laser systems have enabled rapid progress in the development of laser-driven plasma accelerators. Today, the results obtained in beam stability and reproducibility present laser plasma acceleration as a viable and promising alternative to conventional accelerators. As several electron beam and secondary sources applications require high average currents, a major focus is now on increasing the beam’s repetition rate. In the following, we introduce a novel plasma source for kHz electron acceleration, providing a continuous and spatially confined gas flow, while minimising the gas load in the acceleration chamber.

Particle accelerators are a fundamental tool in science, medicine and industry. In conventional accelerators, particles gain energy in the electric fields generated between two electrodes or in an electromagnetic (radio frequency) cavity, where accelerating fields as high as \(\sim 100\) MeV/m can be reached [1]. This value though, appears to be the upper limitation: increasing the accelerating field further will cause electrons to be stripped off from the cavity wall, leading to what is usually addressed as “electrical breakdown” and damaging the accelerating structure [2]. Ever-increasing machine sizes are then needed for generating higher energy particles.

In the last decades, plasmas opened the path towards much higher electric field gradients. In plasma-based accelerators an intense laser pulse, or a high density particle beam, is propagated through a tenous plasma. There, while the ions, in first approximation, can be considered at rest, the free electrons, being less massive, are pushed away from their original position by the ponderomotive (laser pulse) or electrostatic (particle beam) force. They are then pulled back again by the restoring force of the positive ions, yet their momentum makes them overshoot and oscillate around their initial position. The pulse (or the beam), hence, excites an electron oscillation inside the plasma, an electron density wave, known as “plasma wakefield” [3], as depicted in Fig. 1. As fully ionized plasma cannot suffer from electrical breakdown, this wave can sustain much higher field gradients, up to hundreds of GeV/m [4], promising to shrink the machine size by a factor 1000.

High quality electron beams in the 100 MeV range were already produced in plasma accelerators nearly two decades ago [5] [6] [7]. The GeV scale was reached soon after [8], paving the way towards the multi-GeV regime [9] [10] [11].

Figure 1: In panel (a), a laser pulse of moderate intensity (red) is made to propagate, from right to left, inside a plasma (blue) and excites a trailing linear plasma wave. The same interaction is depicted in panel (b) from a different angle, showing the density perturbation \(\delta n/n_0\) (blue) and the resulting electric field (green) along the spatial coordinate \(\xi\).
To date, electrons up to 8 GeV have been produced, employing a Petawatt-class laser system focused into a 20 cm long plasma channel [14]. Among the different challenges that this technique is facing [15, 16, 17, 18], increasing the repetition rate of the machines is essential, in order to drive applications where many pulses per second are needed.

In laser-driven plasma accelerators (LPAs), 1 kHz operation can now be routinely achieved [12] and, on this path, great effort is being made in optimizing the plasma source, which is key in the acceleration process. The source geometry, as well as its gas density and composition, have a major impact on the accelerated electron beam properties, including charge, energy spectrum and divergence. In the following, we present a novel plasma source which provides a continuous, controllable, 100 micron scale confined gas region. Its interaction with an intense laser pulse is able to produce few MeV electron beams at kHz repetition rates.

Currently, most plasma-based accelerators are operated in the “blow-out” regime, where the fields generated in the plasma wave are particularly suitable for electron acceleration [19, 20]. This regime requires highly relativistic intensities, which are usually delivered by focusing down joule-class Ti:Sa laser systems, typically operating with repetition rates \( \lesssim 10 \) Hz. High repetition rate plasma accelerators, on the other hand, make use of kilohertz laser systems, where the maximum pulse energy is limited to the millijoule level. With these lower energies the blow-out regime is still accessible, provided that all the other parameters are correctly scaled. As an example, Tab. 1 shows the characteristics of a typical plasma source suitable for such systems. In order to accelerate electrons at kHz repetition rates, the plasma source must provide high gas density \( n_e \sim 1 \times 10^{20} \text{ cm}^{-3} \) and must be limited to tens of micrometers scale [21, 22, 23, 24]. Such sources are usually gas nozzles, with inner diameter < 100 µm. Because of their bigger outer diameter, though, these are very prone to be damaged by the tightly focused driving laser, therefore the laser height above the nozzle must be finely tuned and is typically \( \sim 100 \) µm. This inevitably means that a very high backing pressure is needed (up to 60 bar [24]) in order to achieve the desired gas density. Gas load inside the acceleration chamber is then one of the major issues in such experiments, potentially limiting the applicability of these novel accelerators.

The novel source proposed here is able to supply continuous gas flow (required for kHz operation) in a confined spatial region at the 100 µm scale. It consists of a hollow, thin-walled, micro-capillary tube, where gas is flowing at a controlled pressure. As shown in Fig. 2, the driving laser intersects the capillary transversely, drives a plasma wave and accelerates electrons (a). Panel (b) shows the results of a PIC simulation. The upper section depicts a typical density profile obtainable with the presented source geometry (simulated in ANSYS-FLUENT). In the lower one, a mJ laser pulse with the parameters of Tab. 1 is made to propagate through it. Injected electrons are highlighted in pink. Panel (c) shows the electrons spectrum at the end of the propagation. The total accelerated charge in this example is around 0.5 pC. The PIC simulation has been carried out with FBPIC [13].

Table 1: Laser plasma accelerators scaling in the blowout regime, assuming \( \lambda_0 = 800 \) nm, adapted from [12]. The main parameters that define the laser-plasma interaction are outlined for different energy regimes (\( E \)): the pulse temporal duration \( \tau \), the normalised vector potential \( a_0 \), the electron density \( n_e \), the achievable energy gain \( \Delta E \), the laser spot size \( \omega_0 \), the Rayleigh length \( Z_R \), and the dephasing length \( L_{dep} \).

| \( E \) (J) | \( \tau \) (fs) | \( a_0 \) | \( n_e \) (\( \text{cm}^{-3} \)) | \( \Delta E \) (GeV) | \( \omega_0 \) (µm) | \( Z_R \) (mm) | \( L_{dep} \) (mm) |
|---|---|---|---|---|---|---|---|
| 30 | 60 | 4.8 | \( 0.66 \times 10^{18} \) | 4.2 | 26 | 2.6 | 4.5 |
| 1.3 | 25 | 3.5 | \( 4.2 \times 10^{18} \) | 500 | 10 | 0.4 | 2.8 |
| 3 mJ | 5 | 2 | \( 1 \times 10^{20} \) | 10 MeV | 2.1 | 18 | 25 |
laser intersects the capillary transversely, ionizing the gas, exciting the plasma wave and providing electron injection. The gas is in a closed system for capture and recirculation and, thus, the leakage into the chamber can be minimised. Controlling the input pressure allows, then, for tuning the desired gas density at the interaction point and the transverse geometry results in very short ramps, which are needed for optimising the coupling of the driver into the gas. Moreover, features could be added inside the capillary in order to induce shocks or other flow manipulations which could improve the acceleration process.

The novel plasma source proposed, hence, promises to increase the LPA stability and optimise the gas load during the production of few MeV electron beams at kHz repetition rate. Such systems have the potential to deliver multi-GeV electron beams from capillary-discharge-guided subpetawatt laser pulses in the self-trapping regime. Phys. Rev. Lett. 113:245002, Dec 2014. doi: 10.1103/PhysRevLett.113.245002

J. Faure, D. Gustas, D. Guenot, A. Vernier, F. Böhle, M. Ouelle, S. Haessler, R. Lopez-Martens, and A. Lifschitz. A review of recent progress on laser-plasma acceleration at kHz repetition rate. Plasma Physics and Controlled Fusion, 61(1):014102, nov 2018. doi: 10.1088/1361-6587/aae047. URL https://link.aps.org/doi/10.1103/PhysRevLett.113.245002

Remi Lehe, Manuel Kirchen, Igor Andriyash, Brendan B. Godfrey, and Jean-Luc Vay. A spectral, quasi-cylindrical and dispersion-free particle-in-cell algorithm. Computer Physics Communications, 230:86–82, 2016. ISSN 0010-4655. doi: https://doi.org/10.1016/j.cpc.2016.02.007. URL https://www.sciencedirect.com/science/article/pii/S0010465516300224

A. J. Gonsalves, K. Nakamura, J. Daniels, C. Benedetti, C. Pieronek, T. C. H. de Raadt, S. Steinke, J. H. Bin, S. S. Bulanov, J. van Tilborg, C. G. R. Geddes, C. B. Schroeder, Cs. Tóth, E. Esarey, K. Swanson, L. Fan-Chiang, G. Bagdasarov, N. Bobrova, V. Gasilov, G. Korn, P. Sasorov, and W. P. Leemans. Petawatt laser guiding and electron beam acceleration to 8 gev in a laser-heated capillary discharge waveguide. Phys. Rev. Lett., 122:084801, Feb 2019. doi: 10.1103/PhysRevLett.122.084801. URL https://link.aps.org/doi/10.1103/PhysRevLett.122.084801

Lintong Ke et al. Wentao Wang, Ke Feng. Free-electron lasing at 27 nanometres based on a laser wakefield accelerator. Nature, 595, 516 520 (2021), 595(7868):516–520, jul 2021. doi: 10.1038/s41586-021-03678-x. URL https://www.nature.com/articles/s41586-021-03678-x

S. Diederichs, C. Benedetti, E. Esarey, J. Osterhoff, and C. B. Schroeder. High-quality positron acceleration in beam-driven plasma accelerators. Phys. Rev. Accel. Beams, 23:121301, Dec 2020. doi: 10.1103/PhysRevAccelBeams.23.121301. URL https://link.aps.org/doi/10.1103/PhysRevAccelBeams.23.121301

Markus Bäschler, Anna Hützen, Liangliang Ji, and AndreasLehrach. Generation of polarized particle beams at relativistic laser intensities. High Power Laser Science and Engineering, 8: e6, 2020. doi: 10.1017/hpl.2020.35.

A. Pukhov and J. Meyer ter Vehn. Laser wake field acceleration: the highly non-linear broken-wave regime. Applied Physics B: Lasers and Optics, 74(4-5):355–361, apr 2002. doi: 10.1007/s003400200207.

W. Lu, C. Huang, M. Zhou, B. W. Mori, and T. Katouleas. Nonlinear theory for relativistic plasma wakefields in the blowout regime. Phys. Rev. Lett., 96:165002, Apr 2006. doi: 10.1103/PhysRevLett.96.165002. URL https://link.aps.org/doi/10.1103/PhysRevLett.96.165002

References

[1] V. Shiltsev and F. Zimmermann. Modern and future colliders. Rev. Mod. Phys., 93:015006, Modern and future colliders. Rev. Mod. Phys., 93:015006, Mar 2021. doi: 10.1103/RevModPhys.93.015006. URL https://link.aps.org/doi/10.1103/RevModPhys.93.015006

[2] A. Grudiev, S. Calatroni, and W. Wuensch. New local field quantity describing the high gradient limit of accelerating structures. Phys. Rev. ST Accel. Beams, 12:102001, Oct 2009. doi: 10.1103/PhysRevSTAB.12.102001

[3] T. Tajima and J. M. Dawson. Laser electron accelerator. Phys. Rev. Lett., 43:267–270, Jul 1979. doi: 10.1103/PhysRevLett.43.267. URL https://link.aps.org/doi/10.1103/PhysRevLett.43.267

[4] E. Esarey, C. B. Schroeder, and W. P. Leemans. Physics of laser-driven plasma-based electron accelerators. Rev. Mod. Phys., 81:1229–1288, Aug 2009. doi: 10.1103/RevModPhys.81.1229. URL https://link.aps.org/doi/10.1103/RevModPhys.81.1229

[5] S. F. 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. C. Hooker, J. A. Daraoszyński, J. A. Langley, W. B. Mori, P. A. Orreys, F. S. Tsung, R. Viskup, B. R. Walton, and K. Krushelnick. Monoenergetic beams of relativistic electrons from intense laser–plasma interactions. Nature, 431(7008):535–538, sep 2004. doi: 10.1038/nature02939.

[6] C. G. R. Geddes, Cs. Tóth, J. van Tilborg, E. Esarey, C. B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary, and W. P. Leemans. High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding. Nature, 431(7008):538–541, sep 2004. doi: 10.1038/nature02990.

[7] J. Faure, Y. Glinec, A. Pukhov, S. Kiselev, S. Gordienko, E. Lefebvre, J.-P. Rousseau, F. Burgy, and V. Malka. A laser–plasma accelerator producing monoenergetic electron beams. Nature, 431(7008):541–544, sep 2004. doi: 10.1038/nature02963.

[8] W. P. Leemans, B. Nagler, A. J. Gonsalves, Cs. Tóth, K. Nakamura, C. G. R. Geddes, E. Esarey, C. B. Schroeder, and S. M. Hooker. GeV electron beams from a centimetre-scale accelerator. Nature Physics, 2(10):696–699, sep 2006. doi: 10.1038/nphys418.

[9] Hyung Taek Kim, Ki Hong Pae,Hyuk Jin Cha, I Jong Kim, Tae Jun Yu, Jae Hee Sung, Seong Ku Lee, Tae Moon Jeong, and Jongmin Lee. Enhancement of electron energy to the multi-GeV regime by a dual-stage laser-wakefield accelerator pumped by petawatt laser pulses. Phys. Rev. Lett., 111:165002, Oct 2013. doi: 10.1103/PhysRevLett.111.165002. URL https://link.aps.org/doi/10.1103/PhysRevLett.111.165002

[10] Xiaoming Wang, Rafael Zgadzaj, Neil Fazel, Zhengyan Li, S. A. Yi, Xi Zhang, Watson Henderson, Y.-Y. Chang, R. Koszyk, H.-E. Tai, C.-H. Pai, H. Quevedo, G. Dyer, E. Gai, M. Martinez, A. C. Bernstein, T. Borger, M. Spinks, M. Donovan, V. Khudik, G. Shvets, T. Ditmire, and M. C. Downer. Quasi-monoenergetic laser-plasma acceleration of electrons to 2 GeV. Nature Communications, 4(1), jun 2013. doi: 10.1038/ncomms2988.
[21] D. Guénot, D. Gustas, A. Vernier, B. Beaurepaire, F. Böhle, M. Bocoum, M. Lozano, A. Jullien, R. Lopez-Martens, A. Lifschitz, and J. Faure. Relativistic electron beams driven by kHz single-cycle light pulses. *Nature Photonics*, 11(5):293–296, apr 2017. doi: 10.1038/nphoton.2017.46.

[22] F. Salehi, M. Le, L. Railing, M. Kolesik, and H. M. Milchberg. Laser-accelerated, low-divergence 15-meV quasimonoenergetic electron bunches at 1 kHz. *Phys. Rev. X*, 11:021055, Jun 2021. doi: 10.1103/PhysRevX.11.021055. URL [https://link.aps.org/doi/10.1103/PhysRevX.11.021055](https://link.aps.org/doi/10.1103/PhysRevX.11.021055).

[23] L. Rovige, J. Huijts, I. Andriyash, A. Vernier, V. Tomkus, V. Girdauskas, G. Raciukaitis, J. Dudutis, V. Stankevic, P. Gecys, M. Ouille, Z. Cheng, R. Lopez-Martens, and J. Faure. Demonstration of stable long-term operation of a kilohertz laser-plasma accelerator. *Phys. Rev. Accel. Beams*, 23:093401, Sep 2020. doi: 10.1103/PhysRevAccelBeams.23.093401. URL [https://link.aps.org/doi/10.1103/PhysRevAccelBeams.23.093401](https://link.aps.org/doi/10.1103/PhysRevAccelBeams.23.093401).

[24] D. Gustas, D. Guénot, A. Vernier, S. Dutt, F. Böhle, R. Lopez-Martens, A. Lifschitz, and J. Faure. High-charge relativistic electron bunches from a kHz laser-plasma accelerator. *Phys. Rev. Accel. Beams*, 21:013401, Jan 2018. doi: 10.1103/PhysRevAccelBeams.21.013401. URL [https://link.aps.org/doi/10.1103/PhysRevAccelBeams.21.013401](https://link.aps.org/doi/10.1103/PhysRevAccelBeams.21.013401).

[25] Y. Glinec, J. Faure, L. Le Dain, S. Darbon, T. Hosokai, J. J. Santos, E. Lefebvre, J. P. Rousseau, F. Burgy, B. Mercier, and V. Malka. High-resolution gamma-ray radiography produced by a laser-plasma driven electron source. *Phys. Rev. Lett.*, 94:025003, Jan 2005. doi: 10.1103/PhysRevLett.94.025003. URL [https://link.aps.org/doi/10.1103/PhysRevLett.94.025003](https://link.aps.org/doi/10.1103/PhysRevLett.94.025003).

[26] Germán Sciaini and R J Dwayne Miller. Femtosecond electron diffraction: heralding the era of atomically resolved dynamics. *Reports on Progress in Physics*, 74(9):096101, aug 2011. doi: 10.1088/0034-4885/74/9/096101. URL [https://doi.org/10.1088/0034-4885/74/9/096101](https://doi.org/10.1088/0034-4885/74/9/096101).