Electron beam manipulation, injection and acceleration in plasma wakefield accelerators by optically generated plasma density spikes

G. Wittig[a], O. Karger[a], A. Knetsch[a], Y. Xi[b], A. Deng[b], J. B. Rosenzweig[b], D.L. Bruhwiler[c,d], J. Smith[e], Z.-M. Sheng[f], D.A. Jaroszynski[f], G.G. Manahan[f], B. Hidding[a,f]

[a] *Institute of Experimental Physics, University of Hamburg, 22761 Hamburg, Germany*
[b] *Particle Beam Physics Laboratory, UCLA, Los Angeles, California 90095, USA*
[c] *RadiaSoft LLC, Boulder, Colorado 80304, USA*
[d] *RadiaBeam Technologies LLC, USA*
[e] *Tech-X UK Ltd, Daresbury, Cheshire WA4 4FS, UK*
[f] *Physics Department, SUPA, University of Strathclyde, Glasgow G4 0NG, UK*

Abstract

We discuss considerations regarding a novel and robust scheme for optically triggered electron bunch generation in plasma wakefield accelerators [1]. In this technique, a transversely propagating focused laser pulse ignites a quasi-stationary plasma column before the arrival of the plasma wake. This localized plasma density enhancement or optical "plasma torch" distorts the blowout during the arrival of the electron drive bunch and modifies the electron trajectories, resulting in a controlled injection. By changing the laser pulse parameters such as beam waist and intensity, and by moving the focal point of the laser pulse, the shape of the plasma torch can be tuned easily. The proposed method is much more flexible and faster in generating gas density transitions when compared to hydrodynamics-based methods, and it accommodates experimentalists needs as it is a purely optical process and straightforward to implement.

Keywords:
PACS: 52.40.Mj, 29.27.Ac, 52.50.Dg, 52.65.

1. Introduction

The dynamics of electron injection in plasma wakefield accelerators is a main focus of research in the plasma accelerator community, both experimentally and theoretically. The quality of the extracted witness bunches strongly depends on the process of trapping in the plasma wave. Several injection techniques have been proposed and have partially been demonstrated in LWFA as well as in PWFA such as [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16] as well as in the form of hybrid Trojan Horse-type methods [17, 18, 19, 20, 21, 22]. The "plasma torch" technique, as recently introduced in [1], is a flexible and simple technique for injection and trapping of electron bunches into the accelerating phase of plasma wakefield accelerators (predominantly, for PWFA, but potentially also for LWFA) and exploits a combination of optically generated density transitions as well as ionization injection and localized blowout amplification effects.

Here, a focused laser pulse propagating perpendicularly (or at an arbitrary angle) to the driver beam axis (z) is used to ionize homogeneously distributed gas media in advance of the drive beam arrival, leading to a sharply spiked plasma density profile where the ionization threshold is exceeded by the electric field of the laser pulse. We refer to this region of optically excited, shapable plasma density volume as "plasma torch." This optical torch also has potential application in shaping of plasma cell boundaries and in the realization of ultrafast electron bunch kickers [23]. The density elevation may be created on fs to many ps and up to ns time scale before the arrival of the electron-driven wakefield, using a modestly intense laser pulse, e.g. at the $I \sim 10^{15}\mathrm{W/cm^2}$ level in case of Ti:Sapphire laser pulses. The shape of the density profile is tunable by directly controlling parameters such as the energy and intensity profile of the laser pulse. Furthermore, this method does not require hydrodynamic expansion after optical excitation by a near-relativistic intense laser pulse, which is the prerequisite of the laser-driven (LWFA) scheme as discussed in Ref. [24, 5, 25]. In the plasma torch scheme, the plasma density shape does not rely on motion of ions and is a direct imprint of the applied laser profile and intensity, therefore very steep density transitions can be created on fs time scales. For example also between driver-witness electron bunch pairs even if they have few micrometer-scale distances, which may be useful to separate the drive beam from the witness. The plasma density spikes generated by the torch have ultrafast (fs-scale) rise times, and decay times of the order of the recombination timescale. The electron beam drives the plasma wave which is based on a low ionization threshold (LIT) gas species, while another (or more) gas component, which needs a higher ionization threshold (HIT), is left unaffected.

Both using a laser pulse at LIT or HIT ionization threshold intensities can be used to manipulate the beam-plasma interaction, including triggering injection of electrons, but the purely

LIT-based plasma torch is limited to self-ionized PWFA cases because in the preionized cases the LIT medium is preionized per definition and the plasma torch laser does not make any difference at these intensities unless it additionally ionizes the HIT level.

2. Trapping and acceleration of electron bunches for different plasma compositions and laser intensities

Three possible scenarios of electron bunch trapping via the plasma torch scheme, supported by three dimensional particle-in-cell VSim/VORPAL[26] simulations, are considered. The plasma torch approach requires – as all PWFA schemes – an electron beam that can create a high-gradient plasma wake to trap electrons, while its electric fields must not ionize the HIT component. This is experimentally possible using a large range of electron beams, including those generated in LWFA stages. Here we use a FACET-class electron beam [27], having the following parameters: charge $Q = 3$ nC, energy $E = 23$ GeV, energy spread $\Delta E/E = 2$ %, bunch length $\sigma_z = 27\ \mu$m, transverse size $\sigma_r = 8.5\ \mu$m, and normalized emittance $\epsilon_n = 2.25$ mm-mrad. A mixture of hydrogen and helium is implemented as the plasma source, where hydrogen with its low ionization energy is the LIT component and helium is the HIT component. Using the formula for the tunneling ADK rates [28], a peak field in the range of ~90 GV/m is required to quickly ionize helium, which is hardly achievable even by a FACET-class electron beam. Therefore He will generally stay in the neutral state as long as the plasma torch laser does not ionize it purposefully

The use of a hydrogen/helium gas mixture allows for three qualitatively different possible main scenarios: (i) initially hydrogen and helium are in the neutral state, and the electron beam driver ionizes hydrogen on axis, while the plasma torch laser pulse does pre-ionize hydrogen locally in front of the drive beam. Helium is left in neutral state throughout the process; (ii) same as case (i), i.e. no general preionization but self-ionization by the drive bunch, but the torch laser ionizes both hydrogen and helium locally; and (iii) hydrogen is completely preionized, for example by an on-axis laser pulse (focused by a lens, an axicon or advanced diffractive optics), and the torch laser ionizes additional helium locally in the pathway of the drive beam. It shall be noted that by using diffractive optics, it may be possible to adjust the on-axis intensity profile of the preionization laser pulse such that an intensity spike is generated which then acts to a similar effect as an independently tunable plasma torch laser, albeit without its flexibility. In all selected simulations, a laser pulse propagates perpendicular to the electron beam and generates the plasma torch approximately 1 ps before the electron-beam driven plasma wave arrives – this is to save computational costs by keeping the simulation window sufficiently small. In reality, it does not matter much if the plasma torch laser pulse arrives few hundred femtoseconds or many picoseconds before the electron beam driven plasma wave, as long as neither recombination effects nor ion and hydrodynamic motion sets in. This is advantageous because it means that the requirements put on the synchronization between electron beam driver and plasma torch laser pulse can be easily met. In the considered cases, the plasma torch laser pulse is based on a Ti:sapphire laser system, with central wavelength of $\lambda = 800$ nm and a pulse duration (FWHM) of $\tau = 64$ fs. The delay between the torch laser and the electron driver was carefully chosen in the simulation such that the optical plasma torch is allowed to build up before the arrival of the electron beam, while at the same time the simulation box window length is minimized.

All given densities are free electron densities (when ionized), and atomic densities (when in neutral state), because only single ionization occurs both are equal. The actual parameters for the three cases are chosen based on analytical calculations of ionization levels and yields. All simulations of electron trapping triggered by optical plasma torches are compared with simulations without a plasma torch to confirm that the trapping is solely due to the plasma torch density perturbation. The combinations of laser waist w_0 and dimensionless amplitude a_0 have been chosen in all scenarios such that the torch width is equal or greater than the plasma wavelength $\lambda_p = 2\pi c\sqrt{\epsilon_0 m_e/n_e e^2}$ within the plasma torch, in order to allow for the plasma wave to interact at increased density at least over one λ_p (m_e being the electron mass, c speed of light in vacuum, e electron charge, n_e the electron density, and ϵ_0 the vacuum permittivity). On the other hand, a compact torch allows for a rapid density transition. It is known that the downramp length should be shorter than the plasma skin depth $k_p^{-1} = c/\omega_p$ [29] for electron bunch injection in PWFA. This criterion is fulfilled in each case.

Figure 1 shows the injection process of the first scenario, where neutral hydrogen is used and the torch laser is only ionizing hydrogen locally in the drive beam's path. In this case, the drive beam has to self-ionize hydrogen outside of the plasma torch region in order to generate a plasma, which is only possible near the center of the bunch, where the peak fields are high enough to exceed the hydrogen ionization threshold. Consequently, further ahead in the drive bunch there is no plasma, because the electric fields are much lower due to the smaller density, and outside the plasma torch region, the front part of the drive beam is simply unused.

The effective ionization front determines the beginning of the plasma wave, which is shifted rapidly to the front of the drive beam when entering the preionized region produced by the torch laser. Additionally, during the passage of the torch, the wakefield is significantly amplified, as now more drive beam current is contributing to the excitation. When the plasma torch volume is left and the drive beam exits the locally preionized hydrogen plasma region, the blowout shifts back again, since hydrogen once more needs to be self ionized by the drive beam. This snapping back of the plasma wave results in trapping of electrons very effectively. It is remarkable to note that neither the hydrogen gas density nor the plasma wavelength are changed during this process, which is a fundamental difference to gas density downramp injection.

After $z \approx 5$ mm of propagation (≈ 4.6 mm behind the torch), the generated witness bunch with energies exceeding 100 MeV has normalized emittance of $\epsilon_n = 3.5$ mm mrad, $Q = 34$ pC, mean energy of $E = 160$ MeV, energy spread $\sigma_E/E = 12.5\%$;

and a peak current of $I_{\text{peak}} = 2.0$ kA. Also evident in Figure 1 (c) is the lensing effect of the plasma on the drive bunch which supports the wake's acceleration field strength.

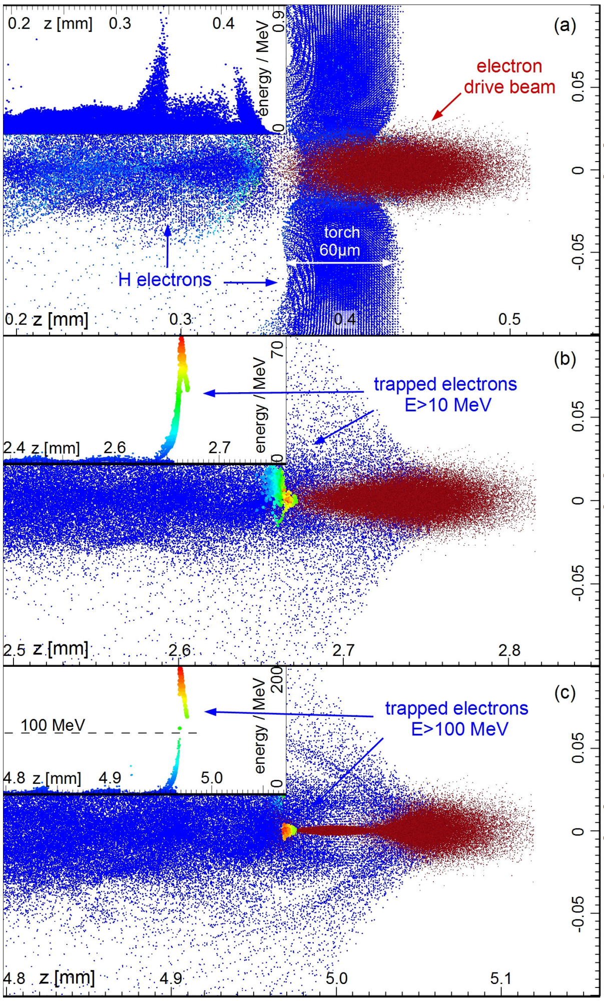

Figure 1: Optical plasma torch injection for scenario (i), using a hydrogen density of $n_{\text{H}} = 4 \times 10^{17}$ cm^{-3} (hydrogen electrons are visualized as blue dots, y,z are the torch laser, and drive beam propagation axes). The plasma torch is generated in the path of the drive beam (red dots), and crossed in (a), leading to blowout amplification and injection. Applying a laser pulse with $w_0 = 35\ \mu$m, and $a_0 = 0.015$ a torch of approximately 60 μm width is created. The injected hydrogen electrons (color coded spheres) are shown in (b) $\approx$ 2.2 mm after the torch, and in (c) after z $\approx$ 4.6 mm of acceleration, where maximum energies of E $\approx$ 194 MeV are reached.

In Figure 2 the second scenario is illustrated, similar to Figure 1. Here, the torch laser intensity is increased to $a_0 = 0.03$ in order to allow the local laser ionization of both helium and hydrogen. Obtained witness bunch parameters at z $\approx$ 5 mm, counting electrons with energies exceeding 60 MeV are: normalized emittance $\epsilon_n = 1.0$ mm mrad; charge $Q = 274$ pC; mean energy $E = 118$ MeV; energy spread $\sigma_E/E = 12.0\%$; and a peak current at $I_{peak} = 11.1$ kA. Electrons of both elements are trapped and form the witness bunch. The total amount of trapped charge can be independently tuned via the helium gas density (up to beam loading levels) in contrast to scenario (i). In fact, here the accelerating filed is lowered, compared to case (i), due to the much higher trapped charge and consequently the energy gain is decreased. In Figure 3 the last scenario is illustrated, which applies preionized hydrogen (LIT). Using the same plasma densities as in cases (i) and (ii), uncontrolled electron injection would occur due to strong electric fields of the blowout [10, 21, 15] that would partly ionize and trap helium. To mitigate this effect, reduced gas densities for hydrogen and helium are used: $n_{\text{H}} = 5 \times 10^{16}$ cm^{-3}, and $n_{\text{He}} = 1 \times 10^{17}$ cm^{-3}, since the longitudinal fields are proportional to the ambient plasma density $E_z \propto n^{1/2}$. The reduction of the plasma density decreases the electric field, avoiding dark current generation at the rear of the blowout. It shall be noted that alternatively, one may also use a weaker driver bunch but elevated hydrogen densities. This would generate smaller blowouts, but nevertheless small enough wakefields as required to avoid He ionization or, more importantly, dark current trap-

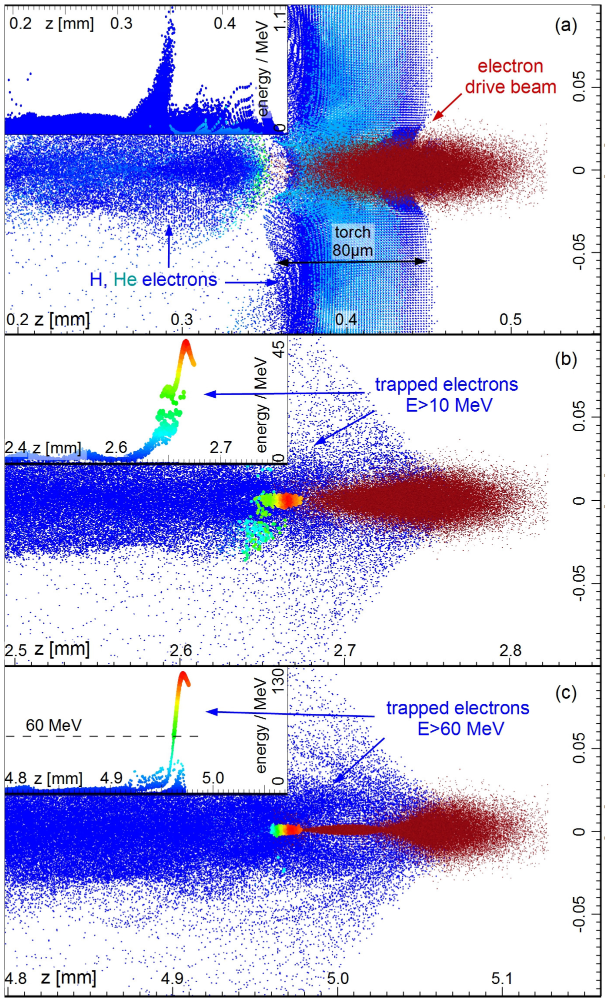

Figure 2: Optical plasma torch injection in scenario (ii), where a hydrogen density of $n_{\text{H}} = 4 \times 10^{17}$ cm^{-3}, and helium density of $n_{\text{He}} = 3 \times 10^{17}$ cm^{-3} was used. Same as in scenario (i), but in addition the plasma torch also comprises helium electrons (light blue spheres), which leads to a double trapezoidal density shape. The plasma torch is generated in the path of the drive beam, where the laser intensity has been adjusted to ionize helium as well. A laser pulse $w_0 = 35\ \mu$m and $a_0 = 0.03$ is used. In (a) the torch is crossed, leading to blowout amplification and injection. The injected electrons are shown in (b) $\approx$ 2.2 mm behind the torch, and (c) after z $\approx$ 4.6 mm of acceleration, where the maximum energy of E $\approx$ 128 MeV is reached.

ping. In this scenario, electron bunch injection and trapping is because of the extension of the plasma wavelength when leaving the plasma torch, resulting in electron injection due to the plasma downramp at the end: a process similar to standard gas density downramp injection. Obtained witness bunch parameters after $\approx$ 7.7 mm of acceleration, counting electrons with energies exceeding 60 MeV are: normalized emittance $\epsilon_n = 1.8$ mm mrad; charge $Q = 1.9$ nC; mean energy at $E = 106$ MeV; energy spread $\sigma_E/E = 12.6\%$; and a peak current at $I_{peak} = 22$ kA.

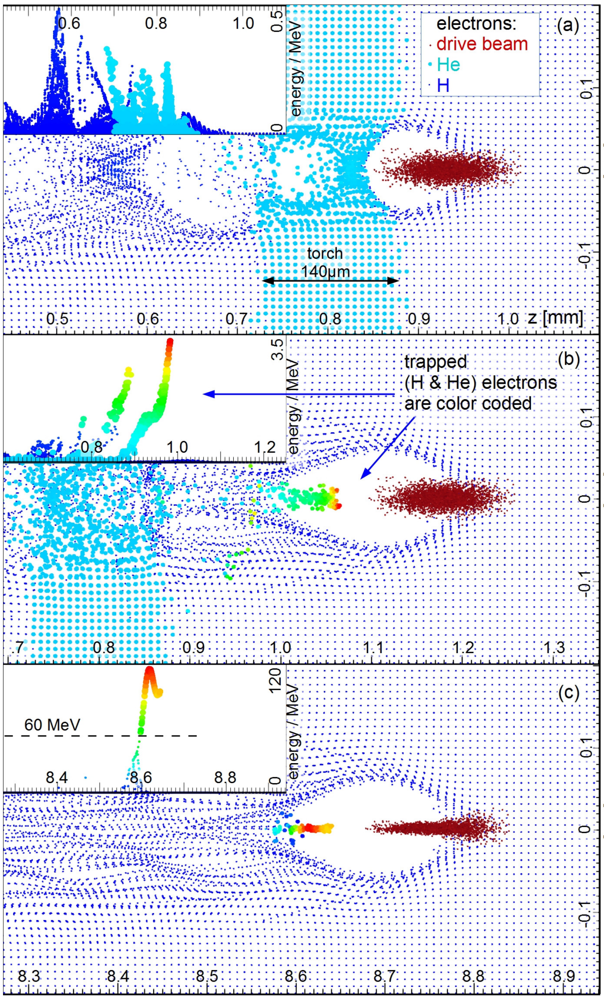

Figure 3: Optical plasma torch injection in scenario (iii) with preionized hydrogen. At gas densities of $n_{\mathrm{H}} = 5 \times 10^{16}$ cm^{-3}, and $n_{\mathrm{He}} = 1 \times 10^{17}$ cm^{-3}, a pronounced blowout is generated. The tunable helium electron torch (a) downramp leads to dark-current free witness bunch formation (b) and allows for massive charge at substantially beam-loaded levels (c). A laser pulse with $w_0 = 100\mu$m and $a_0 = 0.033$ is used to ignite the optical plasma torch (y,z are the torch laser, and beam propagation axes, respectively).

3. Experimental realization of the optical plasma torch

The technique presented in this paper can be experimentally realized for example in 90° geometry, as illustrated in Figure 4 and as used for the presented simulations. Spatial alignment of the order of the torch laser beam waist or the plasma blowout width, respectively, is comparably easily achieved. Temporal synchronization between the electron driver beam and plasma torch laser pulses, as mentioned above, is also easily satisfiable. An energy of the plasma torch laser of the order of a mJ at pulse durations of a few tens of fs can be sufficient, since such pulses can be focused to the intensities of $10^{14-15} W/cm^2$ at the interaction point. This is the intensity level for ionization of either hydrogen (case i) or hydrogen and helium (case ii and iii). For scenario (iii), an additional laser arm is required which is needed to produce a preionized hydrogen plasma channel around the electron beam axis (or any other means of selective preionization). This general preionization laser needs much higher energy, but as it will be much softer focused than the plasma torch laser (in case of Gaussian focusing optics), or by diffractive optics, will reach much lower peak intensities than the plasma torch laser.

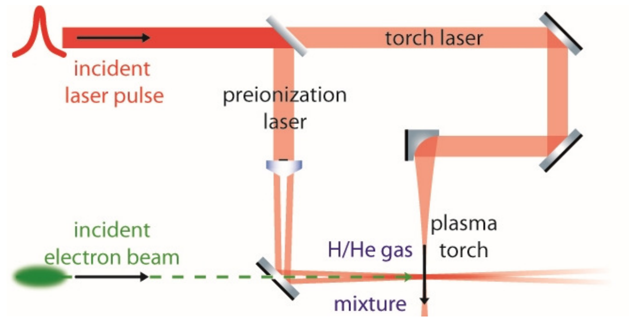

Figure 4: Experimental setup: An electron beam driver and one (scenario i, and ii) or two (scenario iii) moderately synchronized laser pulses interact in an underdense two component gas mixture such as hydrogen and helium. One laser pulse is focused to intensities of the $I \approx 10^{14-15} W/cm^2$ level in order to generate the localized hydrogen/helium plasma torch in the path of the electron beam driven blowout. In contrast to the self-ionized scenario (i) and (ii), for scenario (iii) another, high-energy fraction of the laser pulse is used to preionize the hydrogen.

It shall be noted that while the above has been simulated and discussed with respect to electron beam driven PWFA, it could also be used for LWFA. This is not easy for Ti:Sapphire drive pulses, as the high intensities of $I > 10^{18} W/cm^2$ which are required in order to excite a strong enough bubble, will ionize most media and many higher level ionization states even in the rising slope of the laser pulse driver. However, longer wavelength laser systems such as in the mid-IR and at CO2 wavelength are showing much progress, and may be intense enough to drive strong wakefields in the future. Such laser pulses, due to their much lower peak electric fields $E = (2\pi m_e c^2/e)a/\lambda$ (λ being the laser wavelength, a the normalized amplitude of the laser vector potential), may then allow for plasma density spikes to be generated by short wavelength torch lasers. For example frequency-doubled or tripled Ti:Sapphire laser pulses [19], or even higher harmonics, as the peak electric fields in such laser pulses may be much higher when compared to the drive laser pulse while at the same time having much lower ponderomotive force $F_p \simeq -m_e c^2 \Delta a^2/2$ [30, 31].

4. Summary

We have discussed a fully optically-steered method to generate tunable plasma density transitions. The torch width was chosen to exceed at least one plasma wavelength in order to allow the blowout to close within the torch volume. This defines the ability to trap electrons, e.g. for high torch densities the plasma wavelength within the torch is shorter, allowing for a smaller torch width. Different scenarios have been examined: In scenario (i) injection occurs entirely due to the forward and backward shifting of the plasma cavity, due to the jumping ionization front position and amplification of the wake. In scenario (iii), where preionized hydrogen is used, the front of the wakefield does not change with respect to the electron beam driver. Here electron injection occurs due to distortion of the plasma wavelength, which is similar to conventional downramp injection. Scenario (ii) is a mixture of both, shifting the front of the wakefield combined with a change in the plasma wavelength. In the optical plasma torch technique a large range of field strengths are covered by the accelerating electrons, which results in a rather large energy spread. However, by using a second component (scenario ii and iii) the amount of trapped charge and the bunch length can be controlled, as well as the trapping position. Therefore beam loading can be utilized, e.g. by adjusting the shape of the downramp, to lower the energy spread along with the possibility to trap very short bunches in the very rear of the blowout, leaving space for optimization of this technique. Additionally different laser profiles and intensities can be applied to create diverse plasma profiles and ramp lengths, to tune the current profile and length of the witness bunch and to further optimize the bunch quality. Asymmetric plasma torch profiles and multiple plasma torches may allow for further enhanced flexibility.

[1] G. Wittig, O. Karger, A. Knetsch, Y. Xi, A. Deng, J. B. Rosenzweig, D. L. Bruhwiler, J. Smith, G. G. Manahan, Z.-M. Sheng, D. A. Jaroszynski, B. Hidding, Optical plasma torch electron bunch generation in plasma wakefield accelerators, Phys. Rev. ST Accel. Beams 18 (2015) 081304, doi:\bibinfo{doi}{10.1103/PhysRevSTAB.18.081304}, URL `http://link.aps.org/doi/10.1103/PhysRevSTAB.18.081304`.

[2] S. Bulanov, N. Naumova, F. Pegoraro, J. Sakai, Particle injection into the wave acceleration phase due to nonlinear wake wave breaking, Phys. Rev. E 58 (1998) R5257–R5260, doi:\bibinfo{doi}{10.1103/PhysRevE.58.R5257}, URL `http://link.aps.org/doi/10.1103/PhysRevE.58.R5257`.

[3] H. Suk, N. Barov, J. B. Rosenzweig, E. Esarey, Plasma Electron Trapping and Acceleration in a Plasma Wake Field Using a Density Transition, Phys. Rev. Lett. 86 (2001) 1011–1014, doi:\bibinfo{doi}{10.1103/PhysRevLett.86.1011}, URL `http://link.aps.org/doi/10.1103/PhysRevLett.86.1011`.

[4] C. G. R. Geddes, K. Nakamura, G. R. Plateau, C. Toth, E. Cormier-Michel, E. Esarey, C. B. Schroeder, J. R. Cary, W. P. Leemans, Plasma-Density-Gradient Injection of Low Absolute-Momentum-Spread Electron Bunches, Phys. Rev. Lett. 100 (21) (2008) 215004, doi:\bibinfo{doi}{10.1103/PhysRevLett.100.215004}.

[5] J. Faure, C. Rechatin, O. Lundh, L. Ammoura, V. Malka, Injection and acceleration of quasimonoenergetic relativistic electron beams using density gradients at the edges of a plasma channel, Physics of Plasmas 17 (8) 083107, doi:\bibinfo{doi}{http://dx.doi.org/10.1063/1.3469581}, URL `http://scitation.aip.org/content/aip/journal/pop/17/8/10.1063/1.3469581`.

[6] K. Schmid, A. Buck, C. M. S. Sears, J. M. Mikhailova, R. Tautz, D. Herrmann, M. Geissler, F. Krausz, L. Veisz, Density-transition based electron injector for laser driven wakefield accelerators, Phys. Rev. ST Accel. Beams 13 (9) (2010) 091301, doi:\bibinfo{doi}{10.1103/PhysRevSTAB.13.091301}.

[7] A. J. Gonsalves, K. Nakamura, C. Lin, D. Panasenko, S. Shiraishi, T. Sokollik, C. Benedetti, C. B. Schroeder, C. G. R. Geddes, J. van Tilborg, J. Osterhoff, E. Esarey, C. Toth, W. P. Leemans, Tunable laser plasma accelerator based on longitudinal density tailoring, Nat Phys advance online publication (2011) 862–866, URL `http://dx.doi.org/10.1038/nphys2071`.

[8] M. Chen, Z.-M. Sheng, Y.-Y. Ma, J. Zhang, Electron injection and trapping in a laser wakefield by field ionization to high-charge states of gases, Journal of Applied Physics 99 (5) 056109, doi:\bibinfo{doi}{http://dx.doi.org/10.1063/1.2179194}, URL `http://scitation.aip.org/content/aip/journal/jap/99/5/10.1063/1.2179194`.

[9] D. Umstadter, J. K. Kim, E. Dodd, Laser Injection of Ultrashort Electron Pulses into Wakefield Plasma Waves, Phys. Rev. Lett. 76 (1996) 2073–2076, doi:\bibinfo{doi}{10.1103/PhysRevLett.76.2073}, URL `http://link.aps.org/doi/10.1103/PhysRevLett.76.2073`.

[10] E. Oz, S. Deng, T. Katsouleas, P. Muggli, C. D. Barnes, I. Blumenfeld, F. J. Decker, P. Emma, M. J. Hogan, R. Ischebeck, R. H. Iverson, N. Kirby, P. Krejcik, C. O'Connell, R. H. Siemann, D. Walz, D. Auerbach, C. E. Clayton, C. Huang, D. K. Johnson, C. Joshi, W. Lu, K. A. Marsh, W. B. Mori, M. Zhou, Ionization-Induced Electron Trapping in Ultrarelativistic Plasma Wakes, Physical Review Letters 98 (8) 084801, doi:\bibinfo{doi}{10.1103/PhysRevLett.98.084801}, URL `http://link.aps.org/abstract/PRL/v98/e084801`.

[11] 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, A. V. Karpeev, Ionization Induced Trapping in a Laser Wakefield Accelerator, Phys. Rev. Lett. 104 (2) (2010) 025004, doi:\bibinfo{doi}{10.1103/PhysRevLett.104.025004}.

[12] A. Pak, K. A. Marsh, S. F. Martins, W. Lu, W. B. Mori, C. Joshi, Injection and Trapping of Tunnel-Ionized Electrons into Laser-Produced Wakes, Phys. Rev. Lett. 104 (2010) 025003, doi:\bibinfo{doi}{10.1103/PhysRevLett.104.025003}, URL `http://link.aps.org/doi/10.1103/PhysRevLett.104.025003`.

[13] 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, D. H. Froula, Self-Guided Laser Wakefield Acceleration beyond 1 GeV Using Ionization-Induced Injection, Phys. Rev. Lett. 105 (10) (2010) 105003, doi:\bibinfo{doi}{10.1103/PhysRevLett.105.105003}.

[14] M. Chen, E. Esarey, C. B. Schroeder, C. G. R. Geddes, W. P. Leemans, Theory of ionization-induced trapping in laser-plasma accelerators, Physics of Plasmas (1994-present) 19 (3) 033101.

[15] A. Martinez de la Ossa, J. Grebenyuk, T. Mehrling, L. Schaper, J. Osterhoff, High-Quality Electron Beams from Beam-Driven Plasma Accelerators by Wakefield-Induced Ionization Injection, Phys. Rev. Lett. 111 (2013) 245003, doi:\bibinfo{doi}{10.1103/PhysRevLett.111.245003}, URL `http://link.aps.org/doi/10.1103/PhysRevLett.111.245003`.

[16] N. Bourgeois, J. Cowley, S. M. Hooker, Two-Pulse Ionization Injection into Quasilinear Laser Wakefields, Phys. Rev. Lett. 111 (2013) 155004, doi:\bibinfo{doi}{10.1103/PhysRevLett.111.155004}, URL `http://link.aps.org/doi/10.1103/PhysRevLett.111.155004`.

[17] B. Hidding, G. Pretzler, D. Bruhwiler, J. Rosenzweig, Method for generating electron beams in a hybrid plasma accelerator, german Patent DE 10 2011 104 858.1, US/PCT patent Ser. No. PCT/US12/043002, 2011.

[18] B. Hidding, G. Pretzler, J. B. Rosenzweig, T. Königstein, D. Schiller, D. L. Bruhwiler, Ultracold Electron Bunch Generation via Plasma Photocathode Emission and Acceleration in a Beam-Driven Plasma Blowout, Phys. Rev. Lett. 108 (2012) 035001, doi:\bibinfo{doi}{10.1103/PhysRevLett.108.035001}, URL `http://link.aps.org/doi/10.1103/PhysRevLett.108.035001`.

[19] B. Hidding, J. B. Rosenzweig, Y. Xi, B. O'Shea, G. Andonian, D. Schiller, S. Barber, O. Williams, G. Pretzler, T. Königstein, F. Kleeschulte, M. J. Hogan, M. Litos, S. Corde, W. W. White, P. Muggli, D. L. Bruhwiler, K. Lotov, Beyond injection: Trojan horse underdense photocathode plasma wakefield acceleration, AIP Conference Proceedings 1507 (1) (2012) 570–575, doi:\bibinfo{doi}{10.1063/1.4773760}, URL `http://link.aip.org/link/?APC/1507/570/1`.

[20] Y. Xi, B. Hidding, D. Bruhwiler, G. Pretzler, J. B. Rosenzweig, Hy-

brid modeling of relativistic underdense plasma photocathode injectors, Phys. Rev. ST Accel. Beams 16 (2013) 031303, doi:\bibinfo{doi}{10.1103/PhysRevSTAB.16.031303}, URL http://link.aps.org/doi/10.1103/PhysRevSTAB.16.031303.

[21] F. Li, J. F. Hua, X. L. Xu, C. J. Zhang, L. X. Yan, Y. C. Du, W. H. Huang, H. B. Chen, C. X. Tang, W. Lu, C. Joshi, W. B. Mori, Y. Q. Gu, Generating High-Brightness Electron Beams via Ionization Injection by Transverse Colliding Lasers in a Plasma-Wakefield Accelerator, Phys. Rev. Lett. 111 (2013) 015003, doi:\bibinfo{doi}{10.1103/PhysRevLett.111.015003}, URL http://link.aps.org/doi/10.1103/PhysRevLett.111.015003.

[22] X. L. Xu, et al., Phase-Space Dynamics of Ionization Injection in Plasma-Based Accelerators, Phys. Rev. Lett. 112 (2014) 035003, doi:\bibinfo{doi}{10.1103/PhysRevLett.112.035003}, URL http://link.aps.org/doi/10.1103/PhysRevLett.112.035003.

[23] P. Muggli, S. Lee, T. Katsouleas, R. Assmann, F. J. Decker, M. J. Hogan, R. Iverson, P. Raimondi, R. H. Siemann, D. Walz, B. Blue, C. E. Clayton, E. Dodd, R. A. Fonseca, R. Hemker, C. Joshi, K. A. Marsh, W. B. Mori, S. Wang, Collective refraction of a beam of electrons at a plasma-gas interface, Phys. Rev. ST Accel. Beams 4 (2001) 091301, doi:\bibinfo{doi}{10.1103/PhysRevSTAB.4.091301}, URL http://link.aps.org/doi/10.1103/PhysRevSTAB.4.091301.

[24] T.-Y. Chien, C.-L. Chang, C.-H. Lee, J.-Y. Lin, J. Wang, S.-Y. Chen, Spatially Localized Self-Injection of Electrons in a Self-Modulated Laser-Wakefield Accelerator by Using a Laser-Induced Transient Density Ramp, Phys. Rev. Lett. 94 (2005) 115003, doi:\bibinfo{doi}{10.1103/PhysRevLett.94.115003}, URL http://link.aps.org/doi/10.1103/PhysRevLett.94.115003.

[25] P. Brijesh, C. Thaury, K. T. Phuoc, S. Corde, G. Lambert, V. Malka, S. P. D. Mangles, M. Bloom, S. Kneip, Tuning the electron energy by controlling the density perturbation position in laser plasma accelerators, Physics of Plasmas 19 (6) 063104, doi:\bibinfo{doi}{http://dx.doi.org/10.1063/1.4725421}, URL http://scitation.aip.org/content/aip/journal/pop/19/6/10.1063/1.4725421.

[26] C. Nieter, J. R. Cary, VORPAL: a versatile plasma simulation code, Journal of Computational Physics 196 (2) (2004) 448–473, ISSN 0021-9991, URL http://www.sciencedirect.com/science/article/pii/S0021999103006041.

[27] M. Litos, E. Adli, W. An, C. I. Clarke, C. E. Clayton, S. Corde, J. P. Delahaye, R. J. England, A. S. Fisher, J. Frederico, S. Gessner, S. Z. Green, M. J. Hogan, C. Joshi, W. Lu, K. A. Marsh, W. B. Mori, P. Muggli, N. Vafaei-Najafabadi, D. Walz, G. White, Z. Wu, V. Yakimenko, G. Yocky, High-efficiency acceleration of an electron beam in a plasma wakefield accelerator, Nature 515 (7525) (2014) 92–95, ISSN 0028-0836, URL http://dx.doi.org/10.1038/nature13882.

[28] D. L. Bruhwiler, D. A. Dimitrov, J. R. Cary, E. Esarey, W. Leemans, R. E. Giacone, Particle-in-cell simulations of tunneling ionization effects in plasma-based accelerators, Physics of Plasmas (1994-present) 10 (5) (2003) 2022–2030, doi:\bibinfo{doi}{http://dx.doi.org/10.1063/1.1566027}, URL http://scitation.aip.org/content/aip/journal/pop/10/5/10.1063/1.1566027.

[29] H. Suk, N. Barov, J. B. Rosenzweig, E. Esarey, Plasma Electron Trapping and Acceleration in a Plasma Wake Field Using a Density Transition, Phys. Rev. Lett. 86 (6) (2001) 1011–1014, URL http://link.aps.org/doi/10.1103/PhysRevLett.86.1011.

[30] D. Umstadter, J.-K. Kim, E. Dodd, Method and apparatus for generating and accelerating ultrashort electron pulses, uS patent Ser. No. 5,789,876, 1995.

[31] L.-L. Yu, E. Esarey, C. B. Schroeder, J.-L. Vay, C. Benedetti, C. G. R. Geddes, M. Chen, W. P. Leemans, Two-Color Laser-Ionization Injection, Phys. Rev. Lett. 112 (2014) 125001, doi:\bibinfo{doi}{10.1103/PhysRevLett.112.125001}, URL http://link.aps.org/doi/10.1103/PhysRevLett.112.125001.