DENSITY DOWNRAMP INJECTION INTO A DISCHARGE-BASED PLASMA ACCELERATION STAGE

L. Boulton[1*], J. C. Wood, J. Beinortaitė[2], J. Björklund Svensson, S. Bohlen, G. Boyle, J. M. Garland, P. Gonzalez Caminal[3], C. A. Lindstrøm, G. Loisch, S. M. Mewes[3], T. Parikh, F. Peña[3], K. Põder, S. Schröder, M. Thévenet, S. Wesch, M.Wing[2], J. Osterhoff, R. D'Arcy
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
[1]also at SUPA, Department of Physics, University of Strathclyde, Glasgow, United Kingdom
[2]also at University College London, London, United Kingdom
[3]also at Institute of Experimental Physics, Universität Hamburg, Hamburg, Germany

Abstract

Electron bunches internally injected into plasma accelerators reach relativistic energies in giga-volt-per-metre-level fields, reducing emittance growth due to space charge and ultimately yielding high-brightness beams. Density downramps with steep gradients have provided an effective method of controllable injection into beam-driven plasma-wakefield accelerators, but previously have relied on the fields of an intense particle beam or laser to preionise the acceleration stage. Here, injection using downramps formed via optical ionisation is experimentally shown to be compatible with discharge-based-acceleration stages, producing bunches with up to six times higher energy than with laser-only preionisation. Results demonstrating injection of charge using a purely discharge-preionised acceleration stage and a low-energy injection laser suggest the feasibility of a scalable, high-repetition-rate injection stage—potentially attractive for high-average-power applications.

INTRODUCTION

Plasma accelerators driven by intense laser [1] or particle beams [2, 3] can generate giga-volt-per-metre level accelerating gradients, making them a promising technology for future compact light sources and particle colliders [4]. However, plasma accelerators can also serve as a source of high-quality particle bunches, where the rapid acceleration of injected particles to relativistic energies can drastically mitigate emittance growth due to space-charge forces. Although several schemes exist for the injection of particles into a plasma wake, Density Downramp Injection (DDRI) [5–7] has been identified as a particularly robust option that can yield transverse normalised emittances on the 100 nm-level [8, 9]. In this scheme, as the driver traverses a negative plasma density gradient, the plasma wake elongates. Plasma electrons at the back of the wake that have a high enough longitudinal velocity can then sample the accelerating phase of the wakefield long enough to reach the same velocity as the driver, which in beam-driven plasma wakefield acceleration (PWFA) propagates at approximately the speed of light. This enables controlled, dark-current-free injection [10], but also necessitates either the use of steep downramps [11] or high-current drivers that can generate the accelerating gradients necessary to successfully trap injected electrons.

Several experimental demonstrations of DDRI in PWFA have been performed, using beam drivers from both conventional [12–14] and laser-wakefield [15–17] accelerators. In particular, Ref. [18] details a PWFA experiment in which electron bunches were injected via steep density downramps generated by optical ionisation [19]. A high injection success rate allowed for a thorough, multi-shot characterisation of the injected bunches which simultaneously displayed low horizontal emittances and high spectral densities, resulting in a high 3D brightness. The injected bunches, however, achieved relatively low energy gains of 30 MeV, primarily attributed to ionisation defocusing of the laser beam that generated the plasma channel used for acceleration [20].

Here we expand upon the results presented in Ref. [18] with preliminary measurements of density-downramp-injected electron beams accelerated in a discharge-preionised plasma stage. Energy gains that were multiple times higher than the laser-only-preionised case were demonstrated, albeit at the expense of the charge of the injected bunches. In the following sections, we describe the setup and results from two experimental campaigns. In the first, injection and acceleration of charge up to energies of (176 ± 4) MeV was observed, but only in the presence of the discharge plus both the preionisation and injection lasers. In the second, the intermittent production of 90 MeV electron bunches is shown using only the discharge and injection laser. We discuss the advantages of such discharge-based plasma stages for internal injection in PWFA, as well as future work.

EXPERIMENTAL SETUP

The experiment was performed at the FLASHForward facility at DESY [21]. The experimental setup is shown in Fig. 1, with more details provided in Ref. [18]. To summarise, drive electron bunches were delivered by the FLASH linac [22]. At the optimal injection working point found in Ref. [18], the bunches had an energy of 689 MeV and charge of (304 ± 2) pC and were compressed to a duration of (96 ± 6) fs rms, with peak currents reaching (1.9 ± 0.2) kA. The beam was focused at the entrance of the plasma stage by a collection of final-focusing quadrupoles. The hori-

* lewis.boulton@desy.de

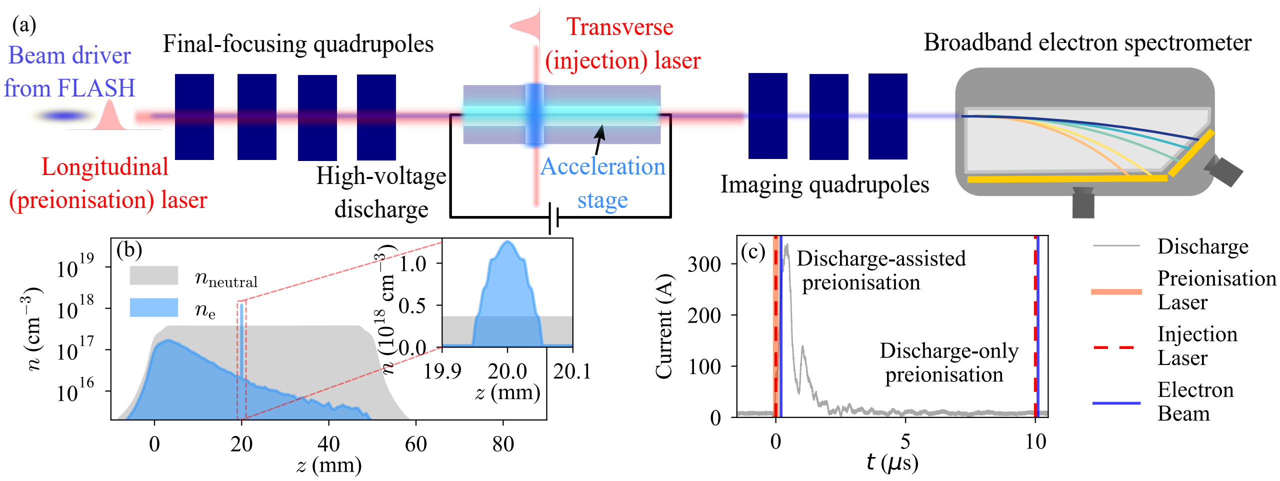

Figure 1: Experimental setup. (a) Electron bunches from FLASH were focused into a plasma cell—injected bunches were measured downstream with an imaging spectrometer. (b) Simulations reveal the plasma profile (blue filled curve) generated via the ionisation of the neutral gas (grey filled curve) by the preionisation and injection lasers. (c) Discharge pulses (grey curve) were introduced in two different contexts, with the beam (blue vertical line) and lasers (red vertical lines) arriving at different times.

zontal normalised emittance of the driver was typically (20 ± 2) mm mrad; the emittance in the vertical direction could not be measured, as this was the dispersion direction of the spectrometer dipole. Spectral measurements of the plasma-interacted driver—and internally injected trailing bunches—were provided by a broadband imaging spectrometer downstream of the interaction point.

Plasma was generated in this experiment in a 50 mm-long, 1.5 mm-diameter plasma cell [23], supplied with a predominantly argon mixture from a 46 mbar buffer volume. As was the case in Ref. [18], the default ionisation method in this experiment used laser pulses from a Ti:sapphire system with a full-width-half-maximum (FWHM) duration of (32.6 ± 0.2) fs. Propagating along the electron beam axis, the longitudinal arm of this laser was focused with a long-focal-length optic to a spot size of (430 ± 10) µm × (350 ± 10) µm, reaching peak intensities of (3.0 ± 0.1) × 10^{14} Wcm^{-2}. The transverse arm of the laser, traveling perpendicular to the electron beam direction, was tightly focused through a small hole located 20 mm downstream of the plasma cell entrance, reaching a minimum spot size of (48 ± 1) µm × (43 ± 1) µm and a peak intensity of (5.2 ± 0.1) × 10^{15} Wcm^{-2}. Simulations performed in FBPIC [24] [see Fig. 1(b)] show that the transverse laser was able to ionise up to Ar^{4+}, providing a sharp density gradient suitable for downramp injection. The longitudinal laser on the other hand did not have a high enough intensity to fully ionise the first level of argon. Furthermore, ionisation defocusing led to a reduction in intensity as the laser propagated, resulting in a plasma density decrease along the length of the cell [20].

Another ionisation source supported by the plasma cell in this experiment was current pulses from a high-voltage discharge. Typically, these pulses were able to fully ionise the argon to the first level along the length of the cell [25]—the density experienced by the electron beam could then be controlled by changing the delay between the discharge and the bunch arrival time [26]. In the following sections, we describe two scenarios, depicted in the diagram in Fig. 1(c), where a discharge was used to generate the plasma in the acceleration channel with a higher ionisation fraction than the longitudinal laser alone. In the first case, which we refer to here as "Discharge-assisted preionisation", both the longitudinal and transverse lasers arrived at around the same time as the discharge was ignited. In the case of "Discharge-only preionisation", the longitudinal laser was removed and injection was observed with the transverse laser firing around 10 µs after discharge ignition.

DISCHARGE-ASSISTED PREIONISATION

In this case, a 20 kV discharge pulse was introduced to the optimal working point described in Ref. [18]. As shown in Fig. 2(a–b), at a discharge ignition time of $\Delta t_d = 0$ ns—just after the arrival of the driver and lasers—the injected beams remained the same as with no discharge, with a median energy gain of (28 ± 1) MeV, where the quoted uncertainty is the median absolute deviation.

By gradually bringing the discharge pulse earlier in time, the energy gain of the injected charge increased to (176 ± 4) MeV at a discharge arrival time 110.77 ns earlier than the driver and lasers—a six-fold increase compared to the laser-only case. This, however, came at the expense of injection success rate, which dropped to as low as 25 % over the range of this scan. Moreover, analysing only shots where a beam was detected (i.e. those with measured charges of > 0.1 pC), the median charge dropped to (0.3 ± 0.2) pC at $\Delta t_d = -110.77$ ns. The maximum charge measured at this timing was 2.5 pC. Although discharge preionisation resulted in the beams experiencing a higher plasma density after injection, the relative height of the downramp with

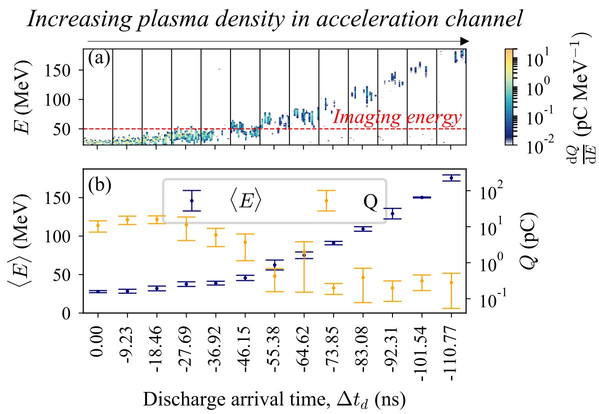

Figure 2: Downramp-injected bunches with discharge-assisted preionisation. (a) Spectra of the injected bunches, measured with the broadband spectrometer. Note that the imaging energy during this measurement was 50 MeV (red dashed line). (b) As the discharge arrived earlier, the mean electron energy of the injected bunches (blue points) increased, whilst the injected charge (orange points) decreased.

respect to the base density is also reduced, likely explaining the decrease in injected charge.

Interestingly, in these results, injection was not observed with the longitudinal laser arm blocked. A suggested reason for this is that the laser is able to ionise neutral gas that exists outside of the plasma cell extent. This could then result in long, low density ramps at the exit of the plasma cell that reduce the divergence of the injected bunches before being transported to the spectrometer [27]. Although the need for both laser arms in these measurements is sub-optimal in terms of energy efficiency and experimental complexity, these results serve as initial confirmation that discharge-preionisation of the acceleration stage is compatible with optically-generated downramp injection.

DISCHARGE-ONLY PREIONISATION

In measurements from a separate experimental campaign, downramp injection was observed with the longitudinal laser blocked. Here, a 21 kV discharge pulse created the acceleration stage and, as shown in Fig. 1(c), the beam arrived 10 µs later. The driver had (301 ± 20) pC of charge and an energy of 924 MeV. Based on a comparison of bunch compression monitor readings in the linac, the bunch length here was around 1.36 times longer than the previous case, leading to an estimated peak current of 1.4 kA. The transverse laser was set up to generate the density downramp promptly before beam arrival. However, due to electromagnetic interference between the discharge and the laser synchronisation system, the exact timing of the laser with respect to the beam was unfortunately not known and was prone to drifts and jitters over time. Nevertheless, intermittent downramp injection of electron beams was observed with this configuration. Similar to the previous section, the charge level of these beams was low; the example bunch in Fig. 3 has a charge of 1.2 pC, with a peak spectral density of 0.3 pCMeV^{-1}. On the other hand, the energy gain of this bunch was 91 MeV, exceeding that of the laser-only case by at least a factor of 3.

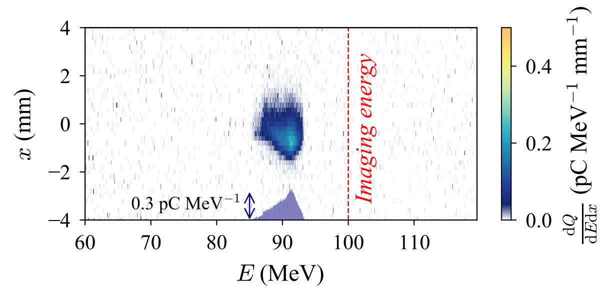

Figure 3: An example of a downramp injected bunch using discharge-only preionisation. The imaging energy in this measurement (red dashed line) was 100 MeV.

Crucially, this provides experimental evidence that an injection stage based on discharge-preionisation and a low energy injection laser is possible. Whilst able to scale to longer plasma lengths, discharge plasma sources are also seen as a promising solution to generating plasmas at the high repetition rates (kHz–MHz) required by high-average-power applications [28]. With the energy demand on the laser reduced to the 10 mJ-level needed for the injection arm, a dedicated laser system with the ability to match the repetition rate of the beam driver becomes more viable.

OUTLOOK

The results presented in this paper demonstrate that, in principle, optically-triggered density downramp injection is compatible with a discharge-generated acceleration stage. Future work should aim to re-establish an injection stage based on discharge-preionisation and a low energy laser injector with the drive beam optimised specifically for this operation mode. This way, the limits of the injected bunch quality can be properly determined. Other methods of generating the sharp downramps required, e.g. via laser-generated hydrodynamic shocks [16], could also be explored in the context of discharge-preionisation. Furthermore, the compatibility of optically-generated downramp injection with high-repetition rate PWFA should also be investigated, with the aim to build an injection stage capable of fully utilising the bunch timing structure of modern linacs.

ACKNOWLEDGEMENTS

The authors thank M. Dinter, S. Karstensen, S. Kottler, K. Ludwig, F. Marutzky, A. Rahali, V. Rybnikov and A. Schleiermacher for their engineering and technical support. They additionally thank M. Meisel and T. Staufer for sharing their laser expertise. This work was supported by Helmholtz ARD, Helmholtz ATHENA, the Helmholtz IuVF ZT-0009 programme and the Maxwell computational resources at DESY. L.B. was supported by an Engineering Physical Sciences Research Council (EPSRC) Studentship.

REFERENCES

[1] T. Tajima and J. M. Dawson, "Laser Electron Accelerator", *Phys. Rev. Lett.*, vol. 43, no. 4, pp. 267–270, Jul. 1979. doi:10.1103/PhysRevLett.43.267

[2] P. Chen, J. M. Dawson, R. W. Huff, and T. Katsouleas, "Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma", *Phys. Rev. Lett.*, vol. 54, no. 7, pp. 693–696, Feb. 1985. doi:10.1103/PhysRevLett.54.693

[3] R. D. Ruth, A. W. Chao, P. L. Morton, and P. B. Wilson, "A Plasma Wake Field Accelerator", SLAC National Accelerator Laboratory, Menlo Park, CA, Tech. Rep., Jul. 1984. doi:10.2172/1447278

[4] B. Foster, R. D'Arcy, and C. A. Lindstrøm, "A hybrid, asymmetric, linear Higgs factory based on plasma-wakefield and radio-frequency acceleration", *New J. Phys.*, vol. 25, no. 9, p. 093037, Sep. 2023. doi:10.1088/1367-2630/acf395

[5] T. Katsouleas, "Physical mechanisms in the plasma wake-field accelerator", *Phys. Rev. A*, vol. 33, no. 3, pp. 2056–2064, Mar. 1986. doi:10.1103/PhysRevA.33.2056

[6] S. Bulanov, N. Naumova, F. Pegoraro, and J. Sakai, "Particle injection into the wave acceleration phase due to nonlinear wake wave breaking", *Phys. Rev. E*, vol. 58, no. 5, pp. R5257–R5260, Nov. 1998. doi:10.1103/PhysRevE.58.R5257

[7] C. G. R. Geddes *et al.*, "High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding", *Nature*, vol. 431, no. 7008, pp. 538–541, Sep. 2004. doi:10.1038/nature02900

[8] X. L. Xu *et al.*, "High quality electron bunch generation using a longitudinal density-tailored plasma-based accelerator in the three-dimensional blowout regime", *Phys. Rev. Accel. Beams*, vol. 20, p. 111303, Nov. 2017. doi:10.1103/PhysRevAccelBeams.20.111303

[9] C. Zhang *et al.*, "Effect of fluctuations in the down ramp plasma source profile on the emittance and current profile of the self-injected beam in a plasma wakefield accelerator", *Phys. Rev. Accel. Beams*, vol. 22, p. 111301, Nov. 2019. doi:10.1103/PhysRevAccelBeams.22.111301

[10] G. G. Manahan *et al.*, "Hot spots and dark current in advanced plasma wakefield accelerators", *Phys. Rev. Accel. Beams*, vol. 19, p. 011303, Jan. 2016. doi:10.1103/PhysRevAccelBeams.19.011303

[11] H. Suk, N. Barov, J. B. Rosenzweig, and E. Esarey, "Plasma Electron Trapping and Acceleration in a Plasma Wake Field Using a Density Transition", *Phys. Rev. Lett.*, vol. 86, no. 6, pp. 1011–1014, Feb. 2001. doi:10.1103/PhysRevLett.86.1011

[12] D. Ullmann *et al.*, "All-optical density downramp injection in electron-driven plasma wakefield accelerators", *Phys. Rev. Research*, vol. 3, p. 043163, Dec. 2021. doi:10.1103/PhysRevResearch.3.043163

[13] A. Knetsch *et al.*, "Stable witness-beam formation in a beam-driven plasma cathode", *Phys. Rev. Accel. Beams*, vol. 24, p. 101302, Oct. 2021. doi:10.1103/PhysRevAccelBeams.24.101302

[14] C. Zhang *et al.*, "Plasma-wakefield accelerator simultaneously boosts electron beam energy and brightness", *Nat. Commun.*, vol. 16, no. 1, p. 10719, Nov. 2025. doi:10.1038/s41467-025-65742-8

[15] T. Kurz *et al.*, "Demonstration of a compact plasma accelerator powered by laser-accelerated electron beams", *Nat. Commun.*, vol. 12, no. 1, p. 2895, May 2021. doi:10.1038/s41467-021-23000-7

[16] F. M. Foerster *et al.*, "Stable and High-Quality Electron Beams from Staged Laser and Plasma Wakefield Accelerators", *Phys. Rev. X*, vol. 12, p. 041016, Nov. 2022. doi:10.1103/PhysRevX.12.041016

[17] F. M. Foerster *et al.*, "Efficient Acceleration of High-Quality GeV-Electron Bunches in a Hybrid Laser- and Beam-Driven Plasma Wakefield Accelerator", *arXiv*, no. 2602.24107, 2026. arxiv.org/abs/2602.24107

[18] J. C. Wood *et al.*, "Bright electron bunches from a plasma-wakefield accelerator with a steep density down-ramp", *Nat. Commun.*, vol. 17, no. 1, p. 1588, Feb. 2026. doi:10.1038/s41467-026-69283-6

[19] G. Wittig *et al.*, "Optical plasma torch electron bunch generation in plasma wakefield accelerators", *Phys. Rev. ST Accel. Beams*, vol. 18, p. 081304, Aug. 2015. doi:10.1103/PhysRevSTAB.18.081304

[20] S. C. Rae, "Ionization-induced defocusing of intense laser pulses in high-pressure gases", *Opt. Commun.*, vol. 97, no. 1, pp. 25–28, 1993. doi:10.1016/0030-4018(93)90611-8

[21] R. D'Arcy *et al.*, "FLASHForward: plasma wakefield accelerator science for high-average-power applications", *Philos. Trans. R. Soc. A*, vol. 377, no. 2151, p. 20180392, 2019. doi:10.1098/rsta.2018.0392

[22] B. Faatz *et al.*, "Simultaneous operation of two soft x-ray free-electron lasers driven by one linear accelerator", *New J. Phys.*, vol. 18, no. 6, p. 062002, Jun. 2016. doi:10.1088/1367-2630/18/6/062002

[23] D. J. Spence and S. M. Hooker, "Investigation of a hydrogen plasma waveguide", *Phys. Rev. E*, vol. 63, p. 015401, Dec. 2000. doi:10.1103/PhysRevE.63.015401

[24] R. Lehe, M. Kirchen, I. A. Andriyash, B. B. Godfrey, and J.-L. Vay, "A spectral, quasi-cylindrical and dispersion-free Particle-In-Cell algorithm", *Comput. Phys. Commun.*, vol. 203, pp. 66–82, 2016. doi:10.1016/j.cpc.2016.02.007

[25] J. M. Garland *et al.*, "Combining laser interferometry and plasma spectroscopy for spatially resolved high-sensitivity plasma density measurements in discharge capillaries", *Rev. Sci. Instrum.*, vol. 92, no. 1, p. 013505, 2021. doi:10.1063/5.0021117

[26] C. A. Lindstrøm *et al.*, "Energy-Spread Preservation and High Efficiency in a Plasma-Wakefield Accelerator", *Phys. Rev. Lett.*, vol. 126, p. 014801, Jan. 2021. doi:10.1103/PhysRevLett.126.014801

[27] R. Ariniello, C. E. Doss, K. Hunt-Stone, J. R. Cary, and M. D. Litos, "Transverse beam dynamics in a plasma density ramp", *Phys. Rev. Accel. Beams*, vol. 22, p. 041304, Apr. 2019. doi:10.1103/PhysRevAccelBeams.22.041304

[28] G. Loisch, J. Kahl, F. Obier, and J. L. Teichgräber, "Kilohertz repetition rate capillary discharge pulse modulator with energy recuperation and energy deposition monitoring", *Plasma Phys. Control. Fusion*, vol. 68, no. 2, p. 025007, Feb. 2026. doi:10.1088/1361-6587/ae3ad6