PROGRESS TOWARDS HIGH-REPETITION-RATE PLASMA WAKEFIELD ACCELERATION AT FLASHFORWARD

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Abstract

Radiofrequency linacs accelerate thousands of bunches per second, which should be matched by beam-driven plasma wakefield accelerators (PWFAs) if their benefits as high-acceleration-gradient energy boosters are to be fully exploited. However, demonstrations to date have accelerated only ~ 10 bunches per second. At FLASHForward, key issues are being solved to bridge this gap. Analytic models have been developed to show how to generate bunch pairs from the photocathode with the longitudinal shape optimised for plasma acceleration, thus reducing stray radiation compared to a collimator system. To deal with large energy depositions from rapid plasma creation and acceleration events, benchmarked models have been built to determine the heating of the plasma source at kHz repetition rates, so that remedial measures can be developed. Furthermore, we have seen that ionisation induced by the wakefield-perturbed plasma can limit the maximum repetition rate. Finally, PWFAs must produce large energy gains for photon science or particle physics applications. We recently demonstrated acceleration of bunches from 1.2 to > 1.7 GeV over 0.5 m of plasma, with < 2% energy spread.

INTRODUCTION

A GeV-per-metre acceleration gradient, surpassing radiofrequency (RF) technology by at least an order of magnitude, can be achieved in plasma-wakefield accelerators (PWFAs) by using an electron bunch to drive a plasma wave, in whose wakefield a trailing electron bunch can be accelerated [1–3]. Such acceleration in plasma can be utilised to shrink the size of future particle linear colliders or increase the photon energy reach of free-electron lasers, provided that other accelerated bunch parameters are preserved. These include the accelerated bunch brightness, energy spread, and repetition rate, which contribute to collider luminosity or average free electron laser (FEL) brightness. The energy transfer efficiency of the acceleration process is a vital consideration to further reduce the environmental impact of future facilities. To prove its applicability, plasma acceleration must either match the burst-mode MHz acceleration of superconducting machines such as FLASH, EuXFEL or ILC [4–6], or GHz acceleration of CLIC [7]. Alternatively, it could be operated continuously at multi-kHz repetition rate to match the average output of these facilities. However, to date, most demonstrations have been performed at 10 Hz or less. High-repetition-rate, high-average-power PWFA stages with high energy gains are also central components of proposals for future compact colliders such as HALHF [8,9], or free-electron lasers such as EuPRAXIA@SPARC_LAB [10], and thus require significant further research.

FLASHForward is a plasma-wakefield acceleration experiment at DESY, focussing on demonstrating the applicability of PWFA for future accelerator facilities by researching the GeV/m acceleration of FEL-quality electron bunches [11,12]. FLASHForward is driven by bunches from the FLASH linac, which are normally used to produce extreme UV and soft x-ray FEL radiation down to 3.2 nm in the fundamental for user experiments. The electron bunches have charges up to 1 nC, energies up to 1.35 GeV and typical emittances of approx. 1 µm [4, 13]. Due to the superconducting radiofrequency architecture of the FLASH linac, the electron bunches arrive in trains of up to 800 bunches with, typically, 1 µs spacing. The trains repeat at 10 Hz. To date, driver-trailing bunch pairs at FLASHForward have been generated with an energy collimator system in a dispersive part of the beamline [14]. Typically the driver has 300-500 pC of charge and a peak current of 1 kA, while the trailing bunch, the front of which trails the centre of the driver by ~ 600 fs, has tens of pC of charge and 0.3-0.5 kA peak current. The bunches are focussed to a β-function of 10-20 mm into discharge-generated plasmas with densities of order 1×10^{16} cm^{-3} to generate the wakefield [15].

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FLASHForward has performed multiple proof-of-principle experiments, including demonstrations of per-mille-level energy spread preservation during GeV/m acceleration [16] and the preservation of mm-mrad-level normalised emittance during acceleration by 40 MeV in a 50 mm long plasma [17]. Regarding energy efficiency, it has been shown that 42% of the energy deposited into the plasma by the driver can be transferred to the accelerating bunch [16], and separately that 57% of the driver energy can be deposited into the plasma [18]. Similar results have been obtained at SLAC [19, 20]. Furthermore, 30 MeV high-quality (mm-mrad emittance and per-cent-level energy spread) bunches were injected into a PWFA via a plasma-density downramp, furthering a proposed scheme for ultrabright bunch generation in plasma wakefields [21]. Finally, a $\mathcal{O}(100)$ ns plasma recovery time was measured, suggesting that a maximum possible burst-mode frequency of PWFA could be 10 MHz for those settings [22].

After comparing the progress outlined above with the goals of the plasma accelerator community, as well as the electron-bunch-train structures accelerated by the FLASH linac, we set two main priorities for FLASHForward:

1. Demonstrating bunch-quality preservation with energy gains towards energy doubling, which will also improve the overall efficiency of the PWFA process.
2. Demonstrating high-average-power PWFA, ultimately utilising as many of the bunches available from FLASH as possible.

In this paper we will first outline the upgrades that have been made to FLASHForward since they were last discussed in the literature in 2019 [12]. Secondly, recent progress towards higher-overall-efficiency PWFA with higher electron energy gains will be presented. Finally, multiple ongoing projects contributing to the development of a high-average-power FLASHForward will be detailed.

UPGRADES

Interaction Chamber and Plasma Sources

FLASHForward houses its plasma capillary in a vacuum chamber embedded in the beamline, which is sketched in Fig. 1. In 2022, a new, larger chamber was installed with an inner length of 935 mm, meaning that longer plasma capillaries can be used. An additional hexapod was added to the chamber so that the positions of two capillaries can be independently controlled: one for plasma-wakefield acceleration and one for a plasma lens. To maintain sufficiently high vacuum in the chamber, top-mounted turbo pumps are installed; the ambient pressure is typically around 10^{-3} mbar at gas flowrates of a few mbar L s^{-1}. More chamber ports allow the use of additional diagnostics, for example, extended plasma light imaging for non-invasive PWFA efficiency measurements [18, 23]. Furthermore, light from the plasma is collected by an optical fibre at the capillary and transported to a spectrometer for on-shot diagnosis of the plasma density [15, 24, 25].

Up to three accelerating plasma capillaries can be mounted simultaneously on the first hexapod. A 50-mm capillary, shown in Fig. 3(a), is formed from two milled sapphire slabs with internally-embedded electrodes. Typically, 24 kV, 400 ns pulses are used to break down the gas and form the plasma. In addition, a long, 500-mm sapphire tube for large-energy-gain PWFA experimentation is housed in the chamber and is detailed in Ref. [26]. In this case, a 5 kV constant voltage is used to form a glow discharge, which allows for an easier and more stable breakdown for the pulsed discharge. Then typically a 12 kV, 130 A, 400 ns FWHM pulse is used to ignite a plasma with a high enough density for gigavolt-per-metre acceleration. A third capillary of length 250 mm has been installed based on the tube design of the 500 mm capillary, which will allow us to experiment with MHz-repetition-rate plasma acceleration with ~ 250 MeV energy gains. Finally, a 15 mm-long capillary is mounted on the second hexapod and is used for plasma lens experimentation. Recently it was shown that a passive plasma lens, where the wake of a driving bunch strongly focuses the trailing bunch, can preserve the slice emittance of the trailing bunch [27].

Electron Bunch Diagnostics

Investigations of emittance preservation after accelerating or focussing in plasma necessitate high-resolution diagnostics, which have been upgraded at FLASHForward. The accelerated bunch is captured around 1 m after the interaction by five high-gradient quadrupoles acting as a triplet [28]. An additional dipole was installed downstream of the first electron spectrometer [12], 5 m after the plasma capillary, meaning the bunch can now be imaged with a magnification up to 12. This is an improvement from magnification of 3 achievable with the first electron spectrometer, increasing the energy resolution from around 0.2 % to 0.02 %. The horizontal beam width is measured as a function of energy, and scanning the object plane of the imaging system provides an energy-resolved measure of the horizontal emittance. The bunches are imaged onto an in-vacuum gadolinium-aluminium-gallium-garnet (GAGG) screen imaged by a high-resolution camera with Scheimpflug optics [29], providing an optical resolution of ~ 7 µm and enabling 0.1 mm normalised emittances to be measured [27, 30]. Since then, the magnification and thus resolution of the diagnostic was further increased by a factor of 1.5 by the installation of an additional quadrupole between the five high-gradient quadrupoles and the spectrometer dipole. Moreover, a new on-axis screen station was installed downstream of the second spectrometer to measure the quality of the focus and the projected emittance in both transverse planes.

In the final diagnostic section, the longitudinal phase space of the bunch is measured via a dipole and a PolariX variable-polarisation transverse deflecting structure, which was developed by a collaboration between DESY, PSI and CERN [31]. The X-band RF fields can resolve few-femtosecond features in the bunch longitudinal profile, while the microsecond-level modulator pulse length allows,

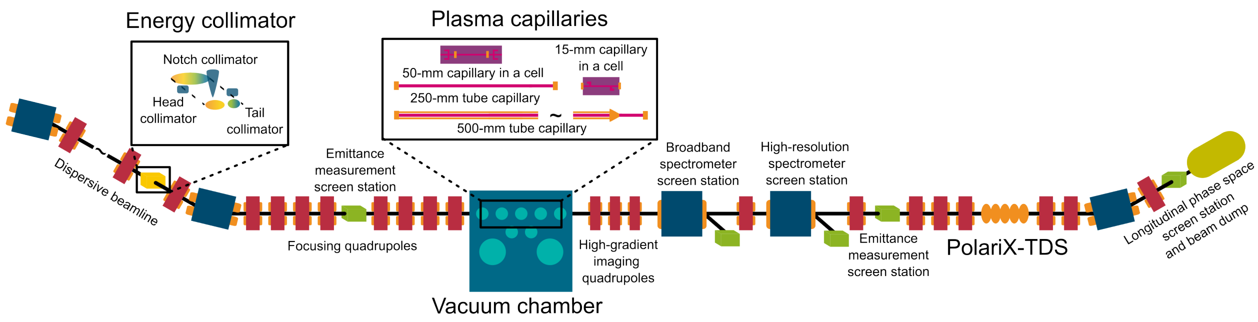

Figure 1: FLASHForward beamline. Electron bunches travel from left to right, first entering a dispersive section where the driving and trailing bunch pairs are created. Bunches are then focused into one of the plasma capillaries in the vacuum chamber. The accelerated bunches are captured by the high-gradient quadrupoles and imaged onto one of the screen stations. The bunches can be transported further downstream to PolariX-TDS and the longitudinal-phase-space screen station.

in principle, for deflection of individual single bunches from a MHz bunch train [12]. The PolariX-TDS has now been fully commissioned [32], and by utilising the variable polarity and its accompanying quadrupoles, a 5D tomographic reconstruction of a bunch's phase space was performed [33].

Plasma Source Characterisation Laboratory

In order to develop, test and characterise plasma capillaries at FLASHForward, and to support other plasma-based technologies, a separate laboratory called the ADVANCE lab was set up at DESY [34]. The lab is equipped with high voltage pulser units and diagnostics that are as similar to FLASHForward as possible. As in FLASHForward, the plasma density is measured via optical-emission spectroscopy [15,24,25]. In the ADVANCE lab it is also imaged lengthways onto the entrance slit of an imaging spectrometer to provide longitudinal resolution. The minimum measurable density is approx. $5 \times 10^{14}\,\mathrm{cm^{-3}}$. A gated, intensified CMOS camera provides a temporal resolution of ~ 50 ns. In addition, a two-colour-interferometry instrument, driven by a 3 mJ Ti:Sa laser, is being constructed to radially resolve the plasma density in discharge capillaries [35]. A reflectometry-based temperature diagnostic is fibre-coupled to the capillary to monitor heating during operation [36]. Capillaries developed in the ADVANCE lab have supported other studies, such as a plasma lens for high-transmission focussing of attosecond UV pulses [37].

LARGER ENERGY GAINS AT FLASHFORWARD

Future PWFA applications require large energy gains, necessitating the use of longer plasma capillaries at the typical FLASHForward working point, where bunches can be accelerated at ~ $1\,\mathrm{GeV\,m^{-1}}$ [16]. In this experiment, a bunch accelerated to 1205 MeV in the FLASH linac and bisected into a bunch pair in the FLASHForward beamline was focussed into the 500 mm capillary, which was filled with discharge-ionised argon. The accelerated trailing bunch was imaged onto a spectrometer screen, and the results are shown in Fig. 2. Plasma-wakefield acceleration over 500 mm resulted in approximately 44% mean electron energy gain, with a trailing bunch of $Q = (22 \pm 2)$ pC being accelerated to (1730 ± 30) MeV, exceeding the maximum energy of FLASH, with an rms energy spread of (1.2 ± 0.1)% (errors are standard deviations from 200 shots).

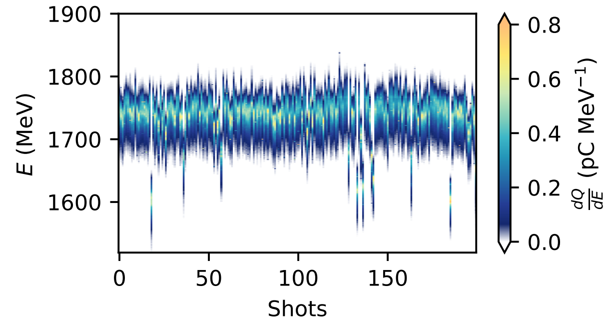

Figure 2: Electron energy spectra of 200 consecutive shots exhibiting energy gain from 1205 to 1730 MeV

Future studies will focus on maintaining this high energy gain but improving charge coupling to increase energy-transfer efficiency, and ensuring the preservation of beam quality. This will involve a multi-parameter optimisation of beam-plasma interactions. Machine learning and Bayesian optimisation methods are being explored for this [26].

DEVELOPMENTS TOWARDS A HIGH AVERAGE POWER FLASHFORWARD

To demonstrate high-average-power PWFA operation at FLASHForward, several studies are being carried out on high-repetition-rate plasma generation, capillary heating, linac operation and beamline adjustments for delivering long bunch trains.

MHz Plasma Generation and Characterisation

In order to generate plasma for consistent plasma acceleration of microsecond-spaced bunches, a new pulsing system has been designed, which will be detailed further in an upcoming publication. The key technology change is the use of a solid-state switch that can operate at MHz frequencies and is capable of supporting 5 kV, about 100 A discharge pulses lasting hundreds of nanoseconds each. A new trigger generator has been installed, which can generate triggers matched to the FLASH bunch train with variable width and independent timing in 0.66 ns steps. This allows the plasma density that each bunch interacts with to be precisely controlled.

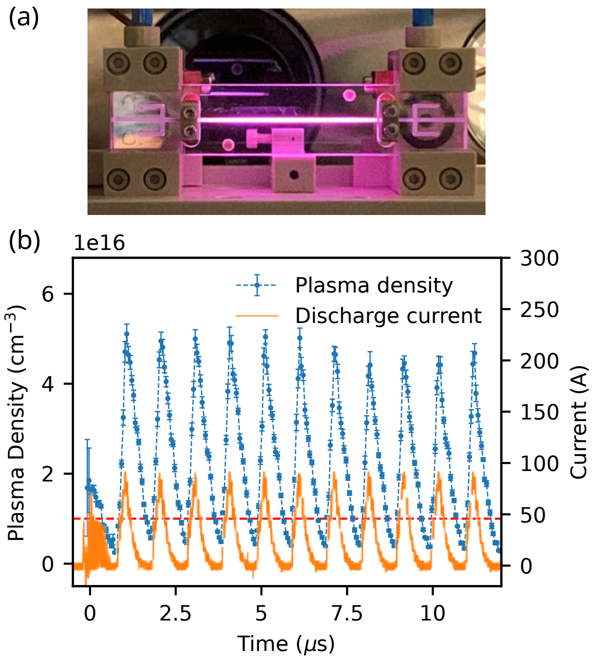

Figure 3: (a) The 50 mm FLASHForward plasma capillary with internally-embedded electrodes being operated with hydrogen plasma. (b) Measured plasma density and discharge current over 12 microsecond-spaced pulses. The red dashed line denotes a plasma density of 1×10^{16} cm^{-3}.

MHz-repetition-rate plasma generation is performed in the 50-mm capillary shown in Fig. 3 (a). The properties of the rapidly generated plasma are characterised both in the FLASHForward beamline with and without electron beam interaction, and in the ADVANCE lab. Key parameters to control are the gas pressure in the capillary, the discharge voltage and the gas species, where rapidly recombining gases have advantages for rapid pulser usage, while heavier ions suppress ion motion effects on the accelerating bunch [38]. Plasma density stability is usually taken as the key figure of merit. An example of a characterised working point with measured plasma density and pulse current is shown in Fig. 3 (b). The required plasma density for gigavolt-per-metre accelerating gradients is reliably produced by each consecutive discharge pulse, except the first, which is used to break down the gas.

Plasma Source Temperature

When plasma is generated, heat is deposited into the capillary mainly via the cooling of the plasma at the capillary wall. In addition, the wakefield acceleration process deposits energy since it is not 100% efficient. During long, high-average-power PWFA runs, the capillary heating may be so extreme that it will result in its damage. Therefore, temperature trends need to be understood and remedial measures taken, such as the minimisation of energy input during the plasma creation process and active capillary cooling. For this reason, capillary temperature measurements were carried out in the ADVANCE lab.

In the study presented here, plasma was created at 40 Hz by a high-voltage pulser delivering 380 A, 0.53 µs FWHM pulses that deposited approx. 180 mJ per pulse into the capillary (7.2 W average power). The energy deposition was estimated from a benchmarked plasma hydrodynamic code [39]. In a second experiment, a kHz-repetition-rate-capable pulser, detailed in Ref. [40], delivering 155 A, 0.36 µs FWHM pulses and depositing ~ 40 mJ per pulse was used (1.6 W average power), allowing us to study different levels of power delivery. For the low-power case, a lower degree of ionisation was reached, which may be problematic for multi-kA driver bunches as they further ionise the plasma. The capillary temperature for both power deposition levels, measured at the surface of the sapphire block, is plotted in Fig. 4(a). Such a measurement allows the estimation of the heating rate and asymptotic temperature for a specific pulser setting. A map of the steady-state temperature reached by the capillary in the high-power case is shown in Fig 4(b). A constant heating power of 7.2 W was applied at the inner wall of the capillary. Good agreement with the experimental data was found, meaning these simulations provide the basis for studying much higher heating powers and informing the cooling requirement for high-average-power PWFA sources.

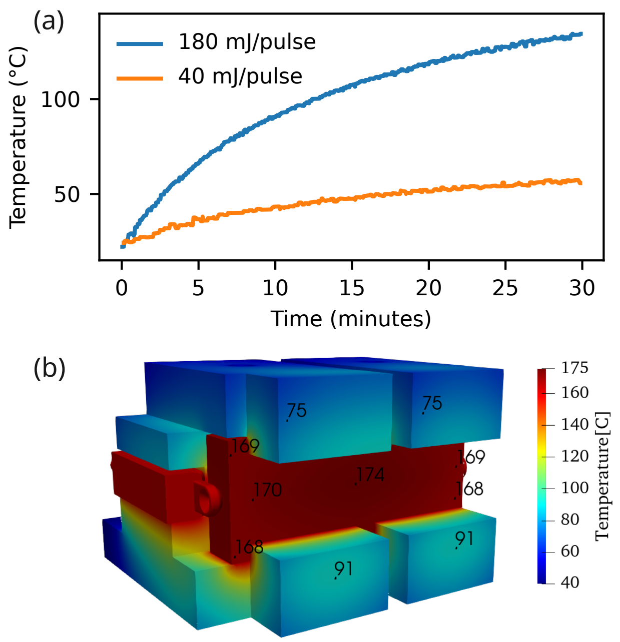

Figure 4: (a) Capillary temperature over 30 min during 40 Hz plasma generation with differing energy deposition per pulse, given in the legend. (b) Steady-state temperature map from an ANSYS simulation of a FLASHForward capillary with 7.2 W average heating power applied on-axis.

Twin Bunch Generation at the Photocathode

High-average-power PWFA at FLASHForward would irradiate the energy collimator that creates the driver-trailing bunch pair at an unacceptably high rate. Therefore, it will be necessary to create a temporally separated bunch pair at the FLASH photocathode using two synchronised laser pulses [41], and accelerate them in a single RF bucket before delivering them to the plasma stage. PWFA is performed with two bunches spaced by a large fraction of the plasma wavelength, typically many hundreds of femtoseconds. This separation should be variable for tuning of the interaction. Furthermore, the trailing bunch must be appropriately shaped to optimally beam-load the wakefield to maintain its small energy spread [16, 42], which is also dependent on the precise plasma properties. Therefore, fine control of the injection and acceleration of two bunches from the photocathode is vital for FLASHForward and other PWFA projects [43]. It also has applications for twin-pulse free-electron lasing [44, 45].

Modelling of twin-bunch creation and acceleration has been undertaken for the combined FLASH and FLASHForward lattices [46], where it was also found that the choice of acceleration and compression parameters allows for additional control of the twin-bunch current profile. Subsequently, the first successful experiments have been performed. Two temporally-separated bunches were generated at the photocathode, accelerated, compressed in two bunch compressors and then measured at the PolariX TDS in the FLASH2 FEL beamline. The resulting longitudinal phase space and current profile are shown in Fig. 5. A leading 308 pC, ~1 kA bunch was trailed by a 82 pC, ~0.5 kA bunch, with their centres of mass at sub-picosecond separation. The central bunch energy was E_0 = 920 MeV. The charges, currents and separation are similar to the standard FLASHForward operating point [16]. Future studies will focus on driving a PWFA with these bunches and optimising the current profile of the trailing bunch by shaping the injector laser.

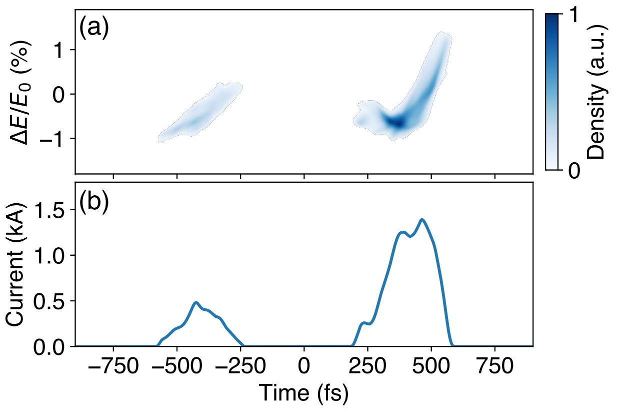

Figure 5: (a) The longitudinal phase space of the twin bunch structure. (b) The current profile of the bunches.

Driving and Trailing Bunch Separation

To accelerate long bunch trains, dedicated beam dumps for the depleted, large-energy-spread driver and the accelerated witness bunches will be needed. A design study is underway. The driver and witness beams will be separated in a chicane shortly after the plasma capillary. High-energy accelerated bunches will then be captured by quadrupoles and transported to an upgraded electron spectrometer with a beam dump, or to the existing beam dump at the end of the FLASHForward beamline. Having already dumped the driver, accelerated bunches can be measured at the TDS without significant irradiation of the environment. A redesign of the dump section of the FLASHForward beamline will allow us to select individual bunches from a train to be kicked and streaked by the TDS for bunch-by-bunch measurements.

Required Diagnostic Development

A high-average-power PWFA at FLASHForward will require diagnostics adapted to MHz repetition rates. At the broadband electron spectrometer station, screens and cameras with the ability to resolve bunches arriving with microsecond spacing are required. For this, screens were tested at the ARES facility [47], and it was concluded that the fastest decay time was observed with a LYSO scintillating screen. Furthermore, a microsecond-exposure-time CMOS camera was installed to record images of the LYSO screen as the dispersed bunches from the FLASH MHz train are imaged onto it. Owing to the fast signal decay time of the screen and the camera exposure time, the spectra of any bunch in the train can be recorded without significant signal pollution from preceding bunches.

CONCLUSION

This work presented the upgrades that have taken place at FLASHForward since the last reports in the literature, which are necessary to demonstrate that plasma wakefields can accelerate electron bunches with high gradient and sufficient quality for future applications. Furthermore, the recent milestone of almost 50% electron energy gain over 500 mm of plasma with low energy spread was reported, with a future outlook to improve the acceleration quality. Finally, plans were outlined which are steps towards experimentation on high-repetition rate PWFA at FLASHForward.

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