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FLASHForward X-2: Towards beam quality preservation in a plasma booster

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ABSTRACT

Beam quality preservation in the external injection scheme is one of the key missing milestones towards staging of plasma-wakefield accelerators, a prerequisite for their utilisation in particle physics or other applications requiring high energy beams. This topic will be studied at FLASHForward, a unique beam-driven plasma wakefield acceleration facility currently under construction at DESY (Hamburg, Germany), in the frame of the FLASHForward X-2 experiment. High-quality 1 GeV-class electron beams from the free-electron laser FLASH with μm-emittances, kA-scale currents, and less than 100 fs durations will be utilised to generate driver–witness pairs by using a mask in a dispersive section. In this contribution the physics case and the current status of the FLASHForward X-2 experiment are reviewed. The experimental installation is described, with a focus on the electron beamline. Electron beam dynamics and particle-in-cell simulations are presented.

1. Introduction

Plasma-based accelerators have demonstrated accelerating fields orders of magnitude greater than in conventional radio-frequency cavities and thus can lead to compact and accessible particle accelerators for various applications such as particle physics, free-electron lasers, or medicine. In the *beam-driven* scheme, an intense charged-particle beam (*drive* beam) excites a plasma-wakefield which accelerates a trailing or *witness* beam. The witness beam can either be generated *internally*, from plasma background electrons [1] or by controlled ionisation of a dopant gas species [2], or injected *externally*. The latter process is crucial for staging of multiple plasma-accelerating modules, as required to achieve high beam energies.

The extreme accelerating gradients, prevalent in plasma-wakefield accelerators were demonstrated for the first time at SLAC [3]. The front part of a 6 mm-long 42 GeV electron bunch drove a wakefield while electrons in the back of the bunch were accelerated by this field and reached energies of around 80 GeV after propagating through an 85 cm long plasma, implying an accelerating field of the order of 50 GV/m. Injection of a separate witness beam was, for the first time, performed at the FACET experiment [4]. The beam gained 1.6 GeV within a plasma length of around 36 cm, which corresponds to a 4.4 GV/m accelerating gradient. The average energy spread of the witness beam after the acceleration was 2%, compared to the initial energy spread of 1%. Additionally, high efficiency of the energy transfer from the wakefield to the witness beam was demonstrated.

Both measurements represent important milestones, however, several challenges need to be addressed before plasma-wakefield acceleration of externally injected beams can be applied in practice. A key requirement is the preservation of the beam quality, that is, conservation of the energy spread and emittance. A non-negligible increase of the energy spread was seen in [4], while the emittance was not characterised. Moreover, the transfer of a significant fraction of the total driver energy to the witness needs to be demonstrated. This, in addition to the high energy-transfer efficiency [4], requires *driver depletion*, that is, a loss of the significant fraction of its energy. These issues are the key goals of the FLASHForward X-2 experiment, where 1 GeV driver–witness pairs will be sent to a plasma to study the external injection scheme. Acceleration of witness beams to energies of 2 GeV or more is anticipated.

This paper reviews the status of the X-2 experiment. An overview of the FLASHForward facility is given in Section 2. The generation of the driver–witness pairs is discussed in Section 3, while Section 4 describes the first commissioning of the electron beamline.

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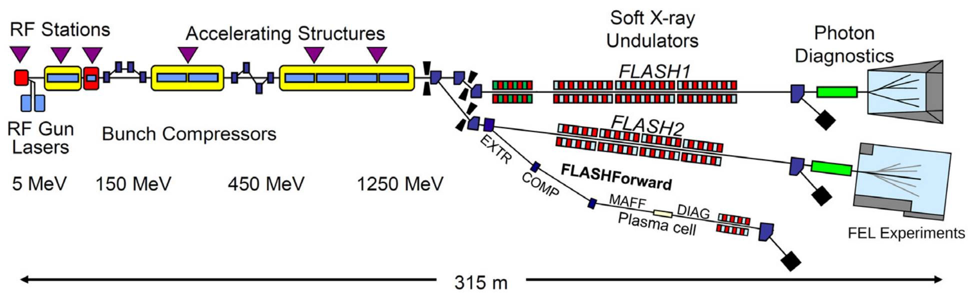

Fig. 1. Schematic overview of FLASH and FLASHForward. See text for more details.

2. FLASHForward overview

FLASHForward is a unique beam-driven plasma-wakefield acceleration (PWFA) facility at the FLASH free-electron laser (DESY, Hamburg, Germany) aiming to produce high-quality electron beams from a plasma-wakefield accelerator and to demonstrate free-electron laser gain with these beams [5]. A schematic overview of FLASH and FLASHForward is given in Fig. 1. The machine consists of a superconducting radio-frequency (SRF) linac, two undulator beamlines (FLASH1, FLASH2) and a third beamline, FLASHForward, dedicated to plasma-wakefield experiments. Beams with durations of 1–7 ps r.m.s. and charges of up to 1 nC are generated in a laser-driven photocathode RF-gun and accelerated to a maximum energy of 1.25 GeV by seven 1.3 GHz SRF modules [6]. Longitudinal compression down to sub-100 fs durations takes place in two magnetic chicanes. A third-harmonic 3.9 GHz SRF module allows linearisation of the longitudinal phase-space to provide a linear compression. However, it also provides additional flexibility to shape the phase-space, e.g. to produce triangular-shaped longitudinal profiles [7] for high-transformer ratio PWFA [8]. The linac works at a repetition rate of 10 Hz with a maximum of 800 bunches per bunch train.[1] After the linac the beam is distributed between the FLASH1 and FLASH2 undulator beamlines: a fraction of the bunches within each bunch train can be sent to FLASH2 using a combination of a fast kicker and a Lambertson septum, while the remaining bunches propagate to FLASH1 (see Fig. 1).

2.1. FLASHForward electron beamline

The purpose of the FLASHForward electron beamline is to extract beams from FLASH2, transport them with desired properties to the plasma target, capture and diagnose the beams after the interaction with plasma, and ultimately transport them to the FEL undulators. Conceptually, it consists of the following sections:

- *Extraction (EXTR)* begins with two dipole magnets deflecting the beams from FLASH2 to FLASHForward with an 8 degree angle between the beamlines. Currently, static magnets are used, precluding parallel operation of FLASH2 and FLASHForward. However, they will be upgraded to pulsed dipoles (half-sine, rise time of 130 μs), allowing extraction of 1–2 bunches from each bunch train and thus allowing parallel operation of FLASH2 and FLASHForward.
- *Compression (COMP)* starts directly downstream of the radiation safety wall separating the FLASH linac and FLASH2 undulator tunnels. This section features a reverse −0.8 degree bend, allowing a flexible tuning of the longitudinal dispersion R_{56}: the beamline can be made isochronous, however, positive or negative values of R_{56} are also possible, allowing post-compression of the bunch. The section ends with two bends providing a total deflection of −7.2 degrees, which removes the dispersion generated in EXTR and COMP and makes the following beamline sections parallel to FLASH2.
- *Matching and Final Focusing (MAFF)* is the last section before the plasma target. It allows for focusing of the beam at the entrance of the plasma cell down to sizes lower than 10 μm and features an emittance measurement section with a quadrupole scan.
- *Diagnostics (DIAG)* starts directly downstream of the chamber hosting the PWFA module (see Section 2.2). It captures, transports, and diagnoses the witness and driver beams after the plasma interaction. A broadband electron spectrometer allows reconstruction of the energy distribution of both driver and witness at a few-percent level resolution [9]. However, it can also operate in a high-resolution narrow-band mode by utilising the upstream quadrupoles.

The beamline features various diagnostics, such as cavity, button, and stripline beam-position monitors, charge monitors, scintillating screens for beam profile measurement, and beam loss monitors. The overall length of the beamline is around 55 m. The DIAG section will be extended to accommodate an X-band transversely-deflecting RF-cavity for fs-resolution longitudinal diagnostics of both driver and witness beams [10], and ultimately FEL undulators, to demonstrate gain from plasma-accelerated beams.

2.2. Plasma target

The plasma target is a sapphire capillary with gas inlets supporting hydrogen, helium, or other gases. Plasma densities of up to $5\times10^{17}\mathrm{cm}^{-3}$ and capillary lengths of up to 250 mm are foreseen, allowing depletion of 1 GeV drivers. The windowless design avoids emittance degradation of the witness beam which is a key goal of FLASHForward X-2. Gas ionisation can be performed either using a Ti:sapphire laser with a maximum peak power of 25 TW, situated in a dedicated laboratory nearby the tunnel [5], or alternatively with a discharge.

The plasma cell is located in a cylindrical vacuum chamber of 500 mm diameter, placed closely after the final quadrupole of the MAFF section. The chamber houses a hexapod allowing micrometer-precision alignment of the plasma cell in all 6 dimensions (three coordinates and three rotation angles).

3. Double-bunch generation

The driver–witness pairs with a maximum overall charge of 1 nC and a separation of 50–150 μm will be generated with a mask in a dispersive section as proposed in Ref. [11]. In order to compress the beams in the magnetic bunch compressors (see Fig. 1), an energy chirp – a correlation between the energy and the longitudinal coordinate within the bunch – is imposed in the accelerating modules. The COMP section features a horizontal dispersion, therefore this energy chirp translates into a

[1] This corresponds to 1 MHz intra-bunch train repetition rate. Smaller repetition rates are also possible, reducing the maximum number of bunches per train due to a maximum train duration of 800 μs; a limitation posed by RF-modules.

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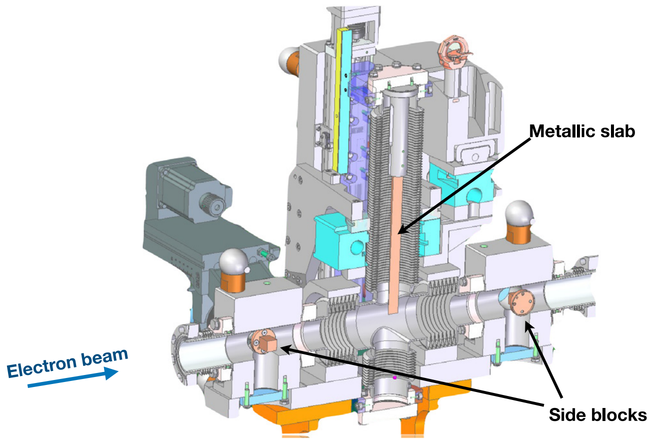

Fig. 2. A CAD-model of the metallic mask for generation of driver–witness pairs together with its mover system. Side blocks are also visible.

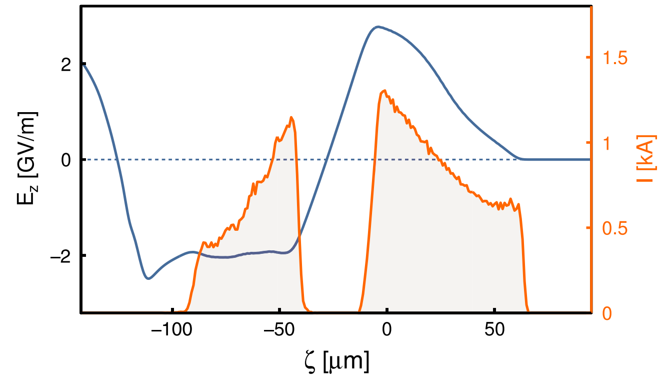

Fig. 3. Drive and witness beam current profiles at the entrance to the plasma cell (orange line) and the longitudinal electric field from a particle-in-cell simulation (blue line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

correlation between the longitudinal (ζ) and horizontal (x) coordinates. By inserting vertically a thin metal slab, electrons within a certain range of x can be removed,[2] which leads to longitudinally separated witness and drive bunches in the dispersionless sections (MAFF, DIAG). The slab has a wedge shape which is 150 mm high, 15 mm thick (in the beam propagation direction) and has a maximum (minimum) width of 3 mm (0.1 mm). Additionally, two blocks can be inserted horizontally from either side of the beamline. This allows further tuning possibilities, such as the removal of unwanted parts of phase-space, reducing the length of drive or witness beams, or blocking them completely. A CAD-model of the system is shown in Fig. 2.

Start-to-end simulations were performed in order to assess feasibility of the double-bunch generation with the mask method as well as to determine the linac and slab parameters that lead to optimal shape and duration of the driver–witness pair for a given plasma density. The RF-gun was simulated using the ASTRA space-charge code [12]. The linac, FLASH2 extraction, and FLASHForward beamline were simulated with elegant [13]. Passage of particles through the slab was modelled using GEANT4 [14]. An example of the longitudinal profile of the beam at the plasma cell entrance, optimised for a density of 5×10^{16} cm^{-3}, is given in Fig. 3. It shows well-separated drive and witness bunches with the overall length of 150 μm. The charge of the driver (witness) is 215 pC (115 pC).

The resulting beams were imported into a particle-in-cell simulation with the HiPACE quasi-static code [15], setting the plasma density to 5×10^{16} cm^{-3}. Fig. 3 shows the longitudinal electric field on the beam propagation axis. The witness beam shape was chosen in such a way that it provides sufficient *beam loading* — flattening of the electric field at the location of the witness. This ensures that the energy spread of the bunch is not increased during the acceleration, which is one of the crucial goals of FLASHForward X-2.

Particle-in-cell simulations of beams with sufficiently small centroid offsets and similar longitudinal properties show emittance and energy spread preservation at the level of 0.1 μm and 0.1%, respectively.[3] Influence of coherent-synchrotron radiation [16] generated in the bends of the FLASH bunch compressors as well as in the FLASH2 and FLASH-Forward extraction arcs (see Section 2) on the hosing instability [17] and thus potential impact on the emittance are under investigation.

[2] These electrons lose a fraction of their energy in the slab and are therefore lost on the way to the plasma target.

[3] In an exemplary simulation the horizontal (vertical) emittance increased from 2 μm to 2.1 (2.02) μm while the relative energy spread enlarged from 0.1% to 0.2%.

4. First beamline commissioning campaign

The beamline installation started in December 2015, when concrete magnet supports were installed in the FLASH2 tunnel. In 2016, the majority of magnets were installed, as well as the magnet power supplies and cabling for magnets and other components such as beam diagnostics. A large part of the ionisation laser beamline was also installed. In Summer 2017, during a six-week shutdown of FLASH dedicated to FLASHForward, the vacuum system was installed, up to a few metres upstream of the plasma chamber. This includes the beam pipes, diagnostics vacuum components, pumps, as well as the majority of the laser beamline components.

Shortly after the shutdown, the first commissioning campaign took place. After initial tests, such as magnet polarity measurements with a Hall probe, the beam was sent to the FLASHForward beamline. After beam transmission was achieved, the beam-based commissioning of the diagnostics, in particular setup of the timing system, took place. This allowed absolute charge measurement in the EXTR section and confirmed that the full charge generated in the linac was transported to FLASHForward. Orbit response matrices were recorded and compared to theoretical prediction. Reasonable agreement was found, however, full data analysis is ongoing.

5. Conclusions and outlook

FLASHForward X-2 is a beam-driven plasma-wakefield experiment with the primary goal of demonstrating witness beam quality preservation in external injection, in particular emittance and energy spread preservation, as well as showing driver depletion. Both items would represent major milestones on the way towards future applications of plasma-wakefield acceleration technology, such as particle physics colliders or free-electron lasers.

The beamline installation is expected to be finished in January 2018 during the next scheduled shutdown of the FLASH machine. This will include installation of the plasma target chamber and completion of the vacuum system including the DIAG section. The beam time for the final commissioning of the beamline is allocated to February 2018.

The installation of the thin slab for generation of the driver–witness pairs is foreseen for Summer 2018. First external injection experiments will start shortly thereafter.

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