FLASHFORWARD - FUTURE-ORIENTED WAKEFIELD-ACCELERATOR RESEARCH AND DEVELOPMENT AT FLASH

R. D'Arcy *[1], A. Aschikhin[1], C. Behrens[1], S. Bohlen[1,2], J. Dale[1], L. Di Lucchio[1], M. Felber[1],
B. Foster[1,2,3], L. Goldberg[1], J.-N. Gruse[1,2], Z. Hu[1], G. Indorg[2], A. Knetsch[2], O. Kononenko[1],
V. Libov[2], S. Karstensen[1], K. Ludwig[1], A. Martinez de la Ossa[2], F. Marutzky[1], T. Mehrling[2],
P. Niknejadi[1], C.A.J. Palmer[1], P. Pourmoussavi[1,2], M. Quast[1,2], P. Winkler[1,2], J.-H. Röckemann[1,2],
L. Schaper[1], J. Schaffran[1], H. Schlarb[1], B. Schmidt[1], S. Schröder[1], J.-P. Schwinkendorf[1,2],
B. Sheeran[1,2], M.J.V. Streeter[1], G. Tauscher[1,2], J. Thesinga[1,2], V. Wacker[1,2], S. Weichert[1,2], S. Wesch[1],
S. Wunderlich[1], J. Zemella[1], and J. Osterhoff[1]
[1]Deutsches Elektronen-Synchrotron, Hamburg, Germany
[2]University of Hamburg, Hamburg, Germany
[3]University of Oxford, Oxford, United Kingdom

Abstract

FLASHForward is a beam-driven plasma wakefield acceleration facility, currently under construction at DESY (Hamburg, Germany), aiming at the stable generation of electron beams of several GeV with small energy spread and emittance. High-quality 1 GeV-class electron beams from the free-electron laser FLASH will act as the wake driver. The setup will allow studies of external injection as well as density-downramp injection. With a triangular-shaped driver beam electron energies of up to 5 GeV from a few centimeters of plasma can be anticipated. Particle-In-Cell simulations are used to assess the feasibility of each technique and to predict properties of the accelerated electron bunches. In this contribution the current status of FLASHForward, along with recent experimental developments and upcoming scientific plans, will be reviewed.

INTRODUCTION

The FLASHForward facility [1] at DESY aims to accelerate electron beams to GeV energies over a few centimetres of ionised gas through the principle of Plasma Wakefield Acceleration (PWFA) [2]. The FLASHForward beam line utilises sections of the FLASH linac [3] to generate and deliver compressed electron bunches for injection into the plasma. The electron bunches used to drive this acceleration process are produced with a photo-cathode gun, accelerated to a maximum of 1.25 GeV with 1.3 GHz SCRF modules, then transmitted through the FLASH2 extraction line and pulsed dipoles to the FLASHForward beam line. The planned FLASHForward beam line can be seen in Fig. 1, leading to the plasma target chamber and beyond to the diagnostics and undulator section.

The primary goal of FLASHForward is to deliver beam-driven PWFA electron bunches of sufficient quality to demonstrate exponential FEL gain. To reach this target the project is planned in a staged manner, with the components and scientific phases shown in Fig. 1. The overarching goals of the experiment are outlined in detail in [1]. This paper will expound both experimental developments and hardware additions made since its publication, as well as present the immediate scientific outlook of the upcoming first-commissioning of the experiment later this year.

EXPERIMENTAL DEVELOPMENTS

Driver Bunch Schemes

The FLASH facility allows novel techniques to be used to shape the longitudinal phase-space of the driver beam, thus optimising the bunch properties for the PWFA process. Longitudinal bunch shaping can be achieved through the use of 1.3 GHz and 3.9 GHz accelerating cavities, in combination with two bunch compressors. Recent dedicated FLASH beam time has been used to refine this bunch shaping: triangular current profiles for optimised transformer ratios >2 [4] and high peak currents of >2.5 kA for driving density-downramp injection [5]. The results of this study can be seen in Fig. 2 with the current profile illustrated for these two cases. With further post-compression achievable in the variable longitudinal dispersion FLASHForward extraction section, these types of driver bunches will aid commissioning of the preliminary beam line later this year.

Double Bunch Production

As well as internal injection techniques [5, 6] where the witness bunch is created from the plasma electrons, FLASHForward also intends to inject a pre-formed witness bunch into the plasma bubble for acceleration. This external injection gives far more flexibility over witness beam parameters, such as transverse emittance; essential for stable post-plasma transport in e.g. staged experiments. This technique requires precise selection of the longitudinal current profile, proposed in FLASHForward's case through the inclusion of a beam scraper [7, 8] in the variable longitudinal dispersion extraction section, with a linear chirp induced upstream in the FLASH linac.

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* richard.darcy@desy.de

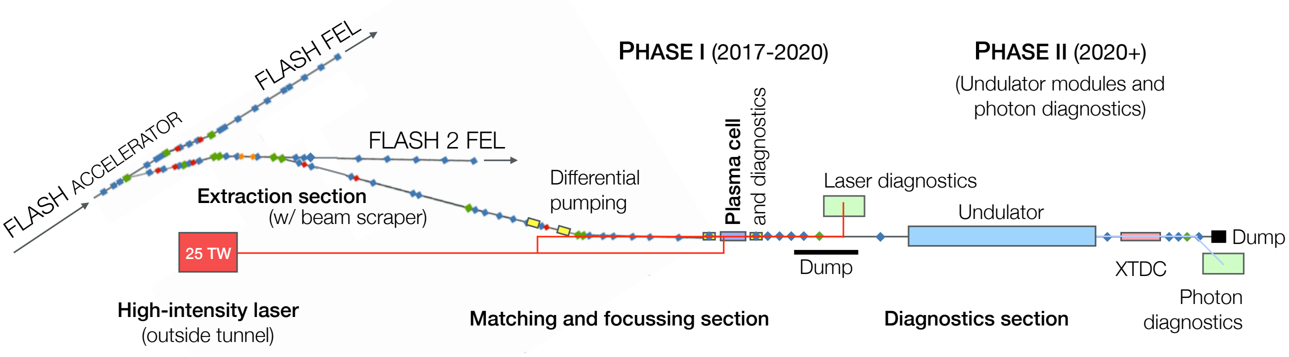

Figure 1: A sketch of the FLASHForward beam line, highlighting key features and phases of installation/commissioning.

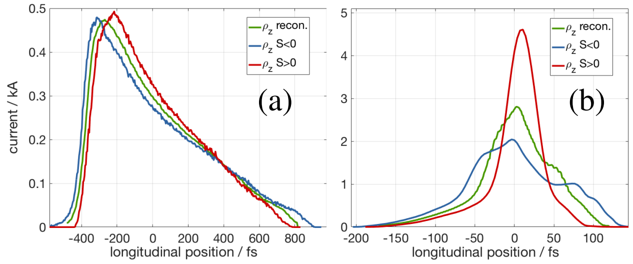

Figure 2: Current profile plots for the a) triangular, and b) high peak current bunches achievable at FLASH. The longitudinal properties of the 700 MeV, 0.3 nC bunches were diagnosed using the S-band TDS at both zero crossings, with the reconstructed profile (green) shown.

The present beam scraper design has a wedge-shape, with dimensions 150 mm (H) x 3 mm (W, tapered to 0 mm) x 15 mm (D), and will be composed of a 50:50 Tungsten-Copper alloy to minimise secondaries, limit heating effects, and for ease of manufacture. The wedge will be inserted vertically into the beam line using a stepper motor. Initial studies – modelling the electron gun in ASTRA [9], propagating the bunch in elegant [10], and simulating the beam scraping with GEANT4 [11] – can be seen in Fig. 3. Two benefits of this scheme are a variable driver-to-witness bunch separation, as defined by the plasma wavelength, and a triangular driver bunch current profile for transformer ratios >2, as described in the previous subsection.

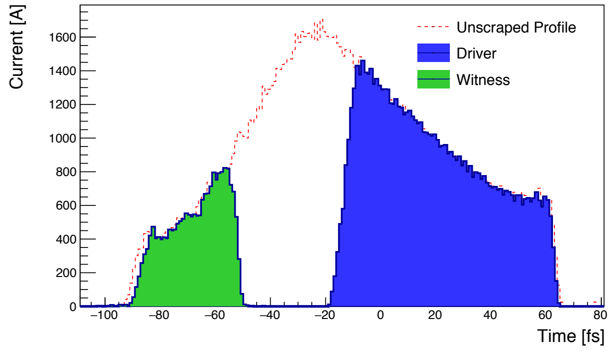

Figure 3: A demonstration of longitudinal bunch selection with a beam scraper, using a simulated FLASHForward driver bunch. The scraper removes approx. 30% of the total charge.

Plasma Generation

FLASHForward will require plasma capillaries of lengths up to 30 cm to run a full suite of PWFA experiments. To successfully generate plasmas over this length it is necessary to uniformly ionise the entire length of the gas with a well-collimated and stable high-intensity laser. To test this scheme before installation in the experimental tunnel a test-bed was set up in a dedicated laboratory located above the extraction area. This test-bed uses similar laser parameters, path lengths, and focussing elements to emulate the scheme intended for FLASHForward. Figure 4 shows a CCD image taken of the final 50 mm of this ionisation test channel (total length 500 mm and radius 500 μm). No corruption of the ionisation process over this downstream section suggests stable ionisation over the entire plasma channel. In this particular case the channel was filled with 3 mbar of Hydrogen gas with the incident laser power attenuated to approx. 3 TW.

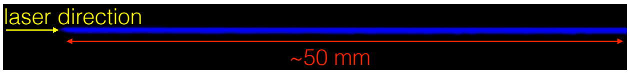

Figure 4: A CCD image of the end of the FLASHForward test-bed plasma channel, inferring sustained plasma production over the full plasma channel length of 500 mm.

X-Band Transverse Deflecting Cavity

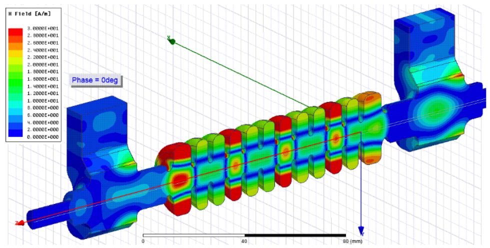

Figure 5: A 3D plot of the H-field within a 10 cell version of the CERN-designed XTDC cavity for implementation at FLASHForward in early 2019 [14].

ISBN 978-3-95450-182-3

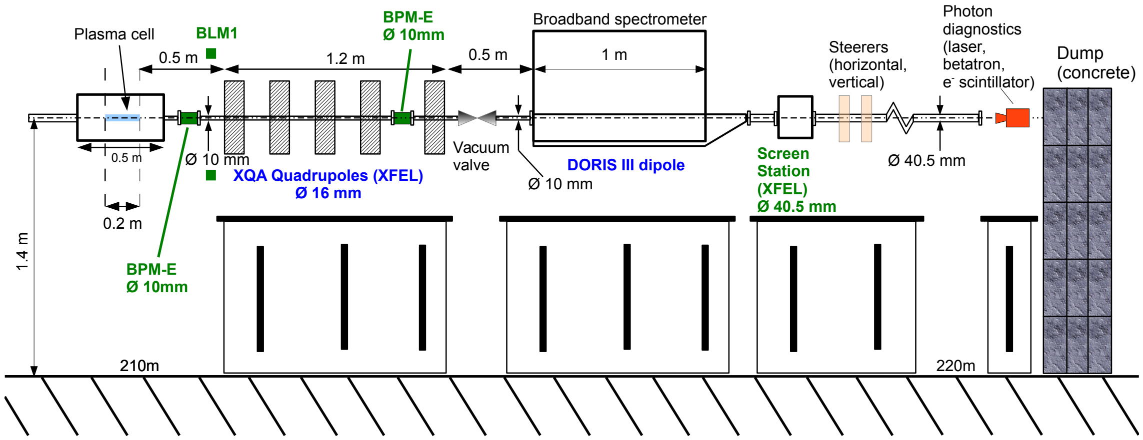

Figure 6: A schematic of the FLASHForward plasma cell and post-plasma beam line, planned for installation in Q3 2017.

Phase I of FLASHForward will culminate with the installation and commissioning of an X-band Transverse Deflecting Cavity (XTDC) system, the proposed location of which is highlighted in Fig. 1. This piece of diagnostic equipment, operating in the X-band frequency range, has already been used with much success for longitudinal phase space profiling of ultra-short electron bunches at other international laboratories [12]. However, its implementation downstream of the FLASHForward plasma cell will provide the configuration required to perform the first sub-fs measurement of its type with a plasma accelerated witness bunch. In addition, the XTDC will play a crucial role in the understanding and commissioning of FLASHForward through longitudinal profiling of the different driver bunch schemes, such as those described in the first section of this paper.

This novel XTDC scheme and cavity design is being pursued by a collaboration between DESY, CERN, and PSI (further details on e.g. the novel dual polarisation capability of the cavity or broad range of planned experimental implementation can be found in [13]). A 3D plot of the H-field inside such a structure with only 10 cells (the complete structure will have 96 cells) can be seen in Fig. 5. Through the use of this cavity, tailored beam line design, optimised optics, and a pulse-compressed peak RF power of approx. 25 MW, the XTDC could unlock temporal resolutions at the sub-fs level. For example, the FLASHForward witness bunch working point, with pertinent bunch parameters $\varepsilon_{n,y} = 0.5\ \mu\text{m}$ and $E = 1.5$ GeV, may be measured with a temporal resolution $R_t > 0.9$ fs. A more comprehensive breakdown of schematic implementation can be found in [15].

UPCOMING SCIENTIFIC PLANS

As previously mentioned, FLASHForward is planned in a staged approach, allowing for commissioning of the beam line in a stepwise manner. The preparatory studies outlined in this paper will be utilised in the commissioning of the first Phase I beam line configuration: the extraction section from FLASH2; matching and focussing; plasma target area; and initial diagnostics section. The latter part of this beam line, from the plasma cell to the beam dump, can be seen in Fig. 6. This, and all preceding sections, will be installed and commissioned during dedicated accelerator shutdown and R&D periods later in the year. Highlights of commissioning will include extraction and transmission of FLASH electron bunches through the entire beam line; laser in-coupling and focal spot optimisation; ionisation tests; differential pumping studies with the plasma cell; commissioning of diagnostics before and after the plasma cell (BPMs, BLMs, scintillator screens, toroids, and magnetic spectrometers); compression schemes; matching and focus optimisation at the plasma cell; and ultimately demonstration and characterisation of a plasma wake.

CONCLUSIONS

The developmental scientific studies of bunch shaping and plasma generation demonstrate meaningful steps towards the successful implementation of the FLASHForward experiment at DESY. The knowledge and expertise gained from these studies will be utilised with immediate effect once the first stages of experimentation begin later this year.

Nascent longitudinal profile selection studies with a wedge-shaped beam-scraper have shown promise. The addition of external injection techniques afforded by this scheme will provide important information for the efficacy of stable and reproducible beam-driven PWFA bunches. The information from this and other injection techniques will be rigorously analysed by the X-band TDC, providing a world first measurement of witness bunch longitudinal profiles on the sub-fs level.

The results outlined in this paper indicate a strong development of the targets and goals of FLASHForward since its inception. This cogent progress is expected to continue with the first stages of commissioning later this year.

ACKNOWLEDGEMENTS

Thanks to Alexej Grudiev for providing Fig. 5. The authors would also like to thank the Helmholtz ARD program and the VH-VI-503 for their funding and support.

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