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PLASMA WAKEFIELD ACCELERATED BEAMS FOR DEMONSTRATION OF FEL GAIN AT FLASHFORWARD *

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Abstract

FLASHForward (**FF►►**) is the Future-ORiented Wakefield Accelerator Research and Development project at the DESY free-electron laser (FEL) facility FLASH. It aims to produce high-quality, GeV-energy electron beams over a plasma cell of a few centimeters. The plasma is created by means of a 25 TW Ti:Sapphire laser system. The plasma wakefield will be driven by high-current-density electron beams extracted from the FLASH accelerator. The project focuses on the advancement of plasma-based particle acceleration technology through the exploration of both external and internal witness-beam injection schemes. Multiple conventional and cutting-edge diagnostic tools, suitable for diagnosis of short electron beams, are under development. The design of the post-plasma beamline sections will be finalized based on the result of these aforementioned diagnostics. In this paper, the status of the project, as well as the progress towards achieving its overarching goal of demonstrating FEL gain via plasma wakefield acceleration, is discussed.

PLASMA WAKEFIELD ACCELERATORS

As opposed to conventional particle accelerators, where the accelerating electric gradients are generated by radio waves in superconducting (SRF) or nonsuperconducting (RF) structures, plasma wakefield accelerators (PWFA) employ a charged particle beam to create a charge-density "wake" in a plasma. With accelerating gradients on the order of 10-100 GeV/m, about three orders of magnitude greater than those produced by SRF methods, plasma wakefield accelerators allow for significant reduction of length, ultimately scaling down the size of future high energy accelerators for future light sources and colliders [1, 2]. Hence, PWFA is a promising alternative to conventional accelerators, worthy of further investigation.

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FLASHFORWARD FACILITY

FLASHForward [3] is one of the few facilities in the world that is dedicated to studying and overcoming the technical and scientific challenges of beam-driven plasma wakefield acceleration. FLASHForward has as its main feature a new electron beamline in the FLASH2 tunnel, which consists of beam extraction, beam matching and focusing, a plasma cell, beam diagnostics, and undulator sections. This beamline is shown in Fig. 1. The first three sections of the beamline leading to the plasma cell are currently being installed. The project is planned in two phases so that progress and understandings gained in the first phase can benefit the second phase. Demonstration of high-quality electron beams, with small emittance and energy spread, is the goal of this first phase of the FLASHForward project. This phase will conclude with measurements of the longitudinal phase space of plasma-accelerated beams with femtosecond resolution via an X-band transverse deflecting cavity (XTDC) [4]. The design for the sections beyond the plasma cell, the diagnostics and undulator section, will be finalized after demonstration and characterization of PWFA beams. The commissioning of the second phase is expected to begin in 2020.

As previously mentioned, FLASHForward is an extension to the FLASH facility, to be operated in parallel with FLASH1 and FLASH2. As such, FLASHForward already benefits from features that are unique to linear accelerators designed for high-gain single-pass FEL sources. These features include a beam of sufficient quality to drive an FEL (up to 1.25 GeV energy, ~ 0.1% energy spread, ~ 2 μm transverse normalized emittance) with a peak current of 2.5 kA and variable current profile.

Through the use of FLASH bunches, which are already used to generate FEL pulses, the efficiency of a PWFA stage as an energy booster for FELs will be explored. In this scheme the FLASH beam will receive an energy boost via plasma acceleration while its qualities are preserved to produce FEL gain. Preservation of beam quality during accel-

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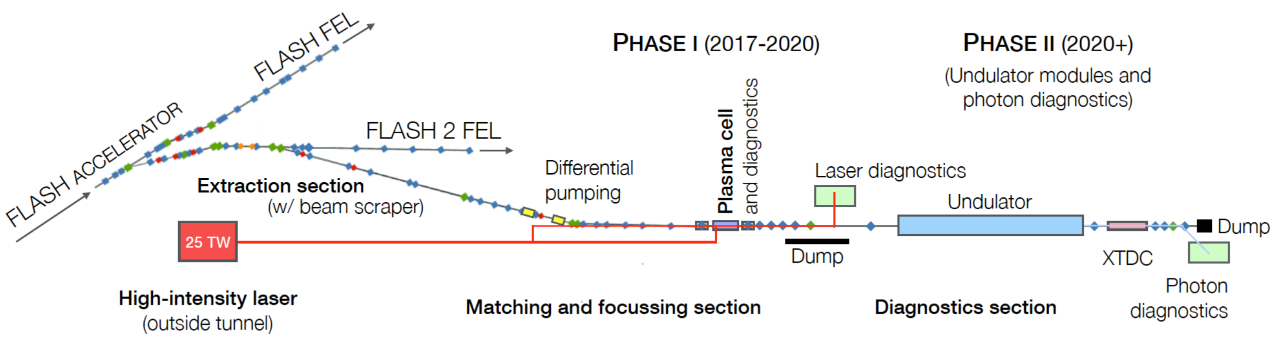

Figure 1: Outline of the FLASHForward beamline. The distance from the extraction unit to the dump is ~ 100 m. The space allocated to the undulator modules would be between 15-20 meters.

eration, extraction of the beam from the plasma stage, and transportation to the diagnostics and FEL regions all present challenges.

Furthermore, the L-band superconducting cavities at FLASH are capable of generating beams at MHz repetition rates. This is an important feature for high-average-power and high-average-brilliance applications of PWFA. Through the use of a pulsed kicker magnet, two bunches within one FLASH bunch train may be extracted to FLASHForward. An example of such a FLASH bunch train scheme is shown in Fig 2. This will allow the stability of the plasma-acceleration process at μs time intervals between two acceleration events to be tested; this is a crucial test for the future of PWFA in applications requiring high average power.

The ultimate scientific goal of FLASHForward is to demonstrate FEL gain. However, to achieve this end, a broad range of scientific milestones need to be reached before future FEL facilities can benefit from this technology. The development and testing of plasma cells, plasma-based beam optics, and femtosecond phase-space measurement [4] are among some of the challenges currently under investigation. Details of planned and achieved milestones can be found in [3] and [5].

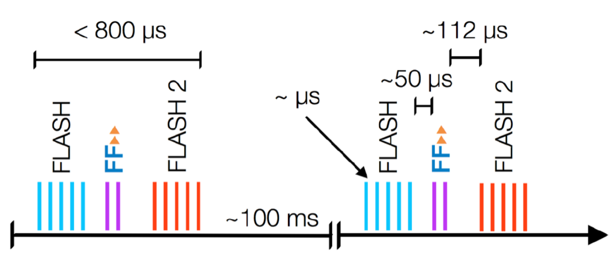

Figure 2: An example of a possible timing scheme for FLASH1, FLASH2 and **FF►►** bunch-train.

PLANNED INJECTION MECHANISMS FOR FLASHFORWARD

Injection mechanisms for PWFA can be divided into two main categories: external and internal injection. External injection is a two-bunch scheme, in which a drive bunch excites a wake while a second trailing witness bunch "surfs" the wake. If the witness is placed in the accelerating phase of the wake it will accelerate. PWFA via external injection is also referred to as a Plasma Booster. At FLASHForward, longitudinal bunch selection by means of a beam scraper [6] is being studied for the production of the double bunch. Internal injection, on the other hand, uses one bunch only. In this scheme, the drive-bunch generates wakefields that trap and accelerate a witness beam composed by electrons either from the background plasma or from a neutral dopant species coexisting with the plasma. Several internal injection mechanisms were studied by particle-in-cell (PIC) simulations using OSIRIS [7]: beam-induced ionization injection [8,9], wakefield-induced ionization injection [10,11], density-downramp (DDR) injection [12,13] and laser-induced ionization injection (Trojan horse) [14]. Of these methods, DDR has been shown to be the most suitable candidate for demonstrating FEL gain by an internal injection scheme at FLASHForward. PWFA via internal injection is also referred to as Plasma Cathode. Beam parameters from the PIC simulations for both external injection and DDR are compared to the FLASH beam in Table 1.

DEMONSTRATION OF FEL GAIN FROM PWFA

For Phase II of the FLASHForward project, a demonstration of FEL gain will be defined as a 100-fold magnification of the self-amplified spontaneous emission (SASE) signal. Therefore, a FLASHForward FEL would operate in the exponential regime. To satisfy the conditions for exponential power growth, it is important that the electron-beam emittance is less than the photon beam emittance and that beam energy spread is less than the FEL bandwidth. Minimizing both of these parameters will minimize the FEL gain length. A number of modules of Tesla Test Facility (TTF) undulators will be available for use. A preliminary scan of the parameter space via the Xie formalism [15] for the TTF undulators ($K = 1.27$, $\lambda_u = 27.3$ mm, 4.5 m long with upper bound of ~ 3 meters for FEL gain length) and PWFA beams from the PIC simulations have beam performed. These show that PWFA beams are suitable for demonstration of FEL gain, particularly if strong focusing [16] is implemented (Fig. 3).

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Table 1: Comparison Between the FLASH Beam Parameters and the Predicted FLASHForward Beams

Beam Parameter	**Symbol**	**FLASH Driver Bunch**	**FF►► Internal Injection Witness Bunch (DDR)**	**FF►► External Injection Shaped Witness Bunch (w/ Scraper)**	**Unit**
Energy	E	0.6-1.25	~1.6-2.0	>1.6	GeV
Sliced Energy spread	Δ_E	~0.1	0.3-0.5	~0.2	%
Normalized emittance	ϵ_n	<2	0.3-0.5	~2	mm-mrad
Peak current	I_p	1-2.5	~0.5-1.0	>2	kA
Bunch duration	σ_b	100-500	~20-40	~10	fs

The contour plot in Fig. 3 is a generalized parameterization via Xie formalism. The vertical axis shows the average β-function for the undulator beam line. For a natural-focusing undulator beamline, the average β function is close to the undulator length. An alternating gradient (FODO) lattice can be used to provide strong focusing along the undulator line. The region meeting the 3 meter gain-length requirement in Fig. 3 falls around the contour lines for the 2 GeV beam and an average beta function of 2 meters. In addition to the 3D effects considered via Xie formalism, strong slippage effects must be avoided. Therefore the PWFA bunch lengths must be longer than the slippage length. For external injection parameters, the minimum bunch length is ~ 5 fs and for DDR parameters, ~ 9 fs. These initial criteria have been met in the preliminary studies. Full 3D simulations are planned to further investigate this scheme. Additionally, since the slice energy spread is the most critical parameter for minimizing FEL gain length, precise measurements of longitudinal phase space—planned in 2018 after the installation of the X-band transverse deflecting cavity—will be the final determining factor for FLASHForward undulator beamline design. The ultimate objective of Phase II will be to investigate the possibility of FEL gain at shorter wavelengths than that of FLASH, which will demonstrate the utility of a PWFA stage.

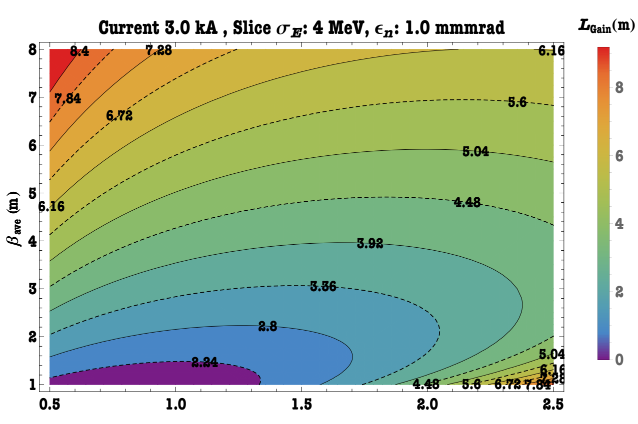

Figure 3: Initial FEL parameter study using the Xie formalism shows that the TTF undulators would be a suitable candidate for the predicted beams from the PIC simulations.

START-TO-END SIMULATIONS

To understand the effects of the beamline components on the quality of generated electron beams, as well as performance and operation of the FEL, complete start-to-end simulations are being performed. At present, the majority of these studies consider an idealized beam. However, as future experimental measurements at FLASH are made, more realistic features of the beam will be included. The final start-to-end simulations will include coherent synchrotron-radiation, space-charge, and wakefield effects. In addition to the studies of the conventional accelerator sections of FLASH, the plasma-wakefield acceleration of the electron beams is simulated by OSIRIS [7] and HiPACE [17], while the transport and diagnostics of the electron beam is simulated by elegant [18]. Finally, the passage and interaction of the electrons through the undulator modules and the FEL radiation are modeled by GENESIS [19] and Puffin [20].

OUTLOOK AND SUMMARY

The FLASHForward beamline will be the third beamline at the existing FLASH accelerator facility and will benefit from the unique characteristics of FLASH electron beams that are suitable for PWFA investigations. Installation of the electron and laser beamlines up to and including the experimental chamber and the plasma cell is ongoing and will be completed by the end of 2017. Of the various injection techniques that have been studied, DDR and external injection have been selected for the first experiments in 2017 and 2018. Full parameter optimization by means of start-to-end simulation is ongoing and will benefit from the forthcoming experimental results. The first demonstration of an FEL, driven by electron beams from PWFA, is planned for the period beyond 2020.

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