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STATUS OF THE TRANSVERSE DIAGNOSTICS AT FLASHForward*

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Abstract

Density modulations in plasma caused by a high-intensity laser or a high charge density electron pulse can generate extreme acceleration fields. Acceleration of electrons in such fields may produce ultra-relativistic, quasi-monoenergetic, ultra-short electron bunches over distances orders of magnitudes shorter than in state-of-the-art radio-frequency accelerators. FLASHForward is a beam-driven plasma wakefield accelerator (PWFA) project at DESY with the goal of producing, characterizing, and utilizing such beams. Temporal characterization of the acceleration process is of crucial importance for improving the stability and control in PWFA beams. While measurement of the transient field of the femtosecond bunch in a single shot is challenging, in recent years novel techniques with great promise have been developed [1, 2]. This work discusses the plans and status of the transverse diagnostics at FLASHForward.

FLASHFORWARD

The Future-ORiented Wakefield Accelerator Research and Development (FLASHForward FF►►) is a project at the DESY free-electron laser (FEL) facility which aims to produce high-quality, GeV-energy electron beams within a plasma cell of a few centimeters. The plasma can be created by means of a 25 TW Ti:Sapphire laser system or by a high voltage discharge mechanism. The high-current-density electron beams extracted from the FLASH2 accelerator will be the driver for the plasma wakefield in several injection schemes [3]. The current focus of the project is on the advancement of plasma-based particle acceleration technology through the exploration of both external and internal witness-beam injection schemes as well as developing cutting-edge diagnostic tools. The characterization of the PWFA electron beams is the aim of several of such diagnostic tools. The latest layout of FF►► is shown in Fig. 1.

Several core and novel diagnostics and prototype experiments are envisioned for FF►►. Of the core experiments, the investigation of internal [4,5] and external injection [6,7] mechanisms are scheduled to begin in the summer of 2018 and will be followed with transformer ratio optimization and hosing study/mitigation in 2018-2019. Additionally, several in-house R&D prototypes and diagnostics for indirect characterization of electron beams, (i.e. from their radiation profile [8, 9]), measurement of longitudinal phase-space by an X-band Transversely Deflecting Structure (XTDS) [10], and electro-optical sampling (EOS) [11] are also planned.

The simulation studies of different injection mechanisms have shown that with a FLASH2 driver bunch [12], with parameters indicated in Table 1, typical witness bunches produced in FF►► would have a rms length of 10-50 fs. Summary of the expected beam parameters such as energy, slice energy spread, normalized emittance, peak current, and bunch duration are listed in Table 1. TDS diagnostics [13] have achieved resolutions on the order of 10 fs at FLASH and with additional upgrades (i.e. X-band frequency), and optimized imaging optics can provide as low as 1 fs resolutions [10]. EOS, although a nondestructive diagnostic method, is not of practical use for the short FF►► witness beams. The best temporal resolutions achieved by EOS detection is ~ 50 fs [11]. Therefore the EOS setup is reserved for providing an arrival time trigger signal and characterizing the drive bunch.

RECONSTRUCTION OF LONGITUDINAL BEAM PROPERTIES

In addition to the X-band TDS, which will measure the drive and witness beam parameters 25 meters downstream of the plasma target, and the EOS, which can measure the drive beam parameters before it enters the plasma, two novel diagnostic methods for studying the longitudinal profile of the beam inside the plasma are also being considered. Based on the Table 1 parameters, the optimal resolution for diagnostics, allowing for emittance consideration, at the position of the plasma target is a few fs. The methods discussed here have the potential to achieve this resolution.

The strong nonlinear defocusing fields at the back of the wave are detrimental to the quality of the electron beam produced in the PWFA structure. The witness bunch, which meets the required emittance and energy spread of a high brightness beam, is typically smaller than one half of the accelerating structure of the plasma. Therefore, in plasma accelerators, the high peak current beam is confined to a distance at least a factor of two shorter than the plasma wave-

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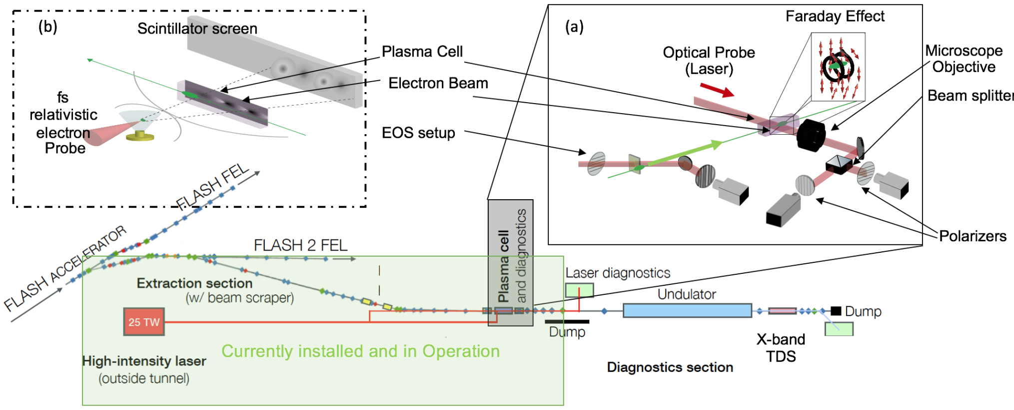

Figure 1: Bottom: Layout for FF►►, Top a): the currently in commission transverse probe diagnostics for Faraday Rotation measurement and EOS setup, Top b): the concept illustration of a novel fs relativistic electron beam probe which is being considered for FF►►.

Table 1: FLASH2 and Predicted FF►► Beam Parameters

Beam Parameter	FLASH Driver	Internal / External FF►► Witness
E (GeV)	0.4-1.25	~1.6-2.0 / >1.6
Δ_E (%)	~0.1	0.3-0.5 / ~0.2
ϵ_n (mm-mrad)	>1	0.1-0.5 / ~2
I_p (kA)	1-2.5	~0.5-1.0 /~2
σ_b (fs)	50-500	~20-40 / ~10-80

length. For a plasma with a density of 10^{18} cm^{-3} this would mean that several 10s or 100s of pC of charge are confined within 10 µm (30 fs). The axial electric field of such beams would deflect an electron probe beam crossing perpendicular to it from the probe path. Similarly, the azimuthal magnetic field of the main beam and its surrounding medium (plasma) would alter the polarization of an optical beam crossing perpendicular.

The envisioned novel transverse diagnostics for the interaction regime at the FF►► plasma target include a 30 fs, near-IR optical beam and electron bunches of 100s of MeV that would cross perpendicular to the main beam and ultimately provide snapshots of the magnetic and electric fields produced in the plasma and, in some parameter ranges, those of the electron beam as well. In the following sections, recent developments in the field that have inspired the transverse measurements at FF►► will be briefly reviewed. The current and possible future experiments will be outlined.

TRANSVERSE OPTICAL PROBE

Real-time observation of laser-driven electron acceleration (LWFA) has been possible in recent years [1, 14] by recording the magnetic field of the electron beam and reconstructing the density modulation of the plasma and beam from this recorded data. Unlike frequency domain interferometry (holography), which can provide the time-integrated shape of the plasma [15], this method provides the snapshot of the unaveraged longitudinal profile. It was demonstrated that, when an optical probe beam crosses a LWFA-produced field and electron bunch, which are accelerated by means of a laser passing through a supersonic gas jet, the polarization of the probe beam with few fs cycles (shorter than the plasma period) is rotated. Shadowgrams from the interaction region are recorded simultaneously by two CCD cameras where each camera has a polarizer that is rotated away from the extinction of the original probe polarization where the polarizers are nearly in quadrature with each other (one polarizer is rotated in the counterclockwise and the other in the clockwise direction). The pixel by pixel division of the polarogram intensities recorded from the polarizers. Defines the rotation angle, due to the interaction:

$$\varphi_{rot} = \frac{e}{2m_e c n_c} \int_l n_e \vec{B}_\varphi \cdot d\vec{s}. \quad (1)$$

The setup for Faraday rotation measurement has been adapted for the PWFA experiment FF►►. As shown in the concept illustration in Fig. 1. the supersonic gas jet and the driving laser described in the earlier section are replaced with a specially designed plasma target cell and an electron beam respectively. The different setup geometry, beam parameters, and vacuum requirements for the beam driven case make this adaptation nontrivial. One of the implementation challenges of this measurement is the need for high plasma density that would allow the Faraday rotation signal to be detected by means of the available optical beam. Since FF►► is connected to the FLASH2 user facility and must comply with the vacuum requirements of FLASH2, a specialized plasma target has been designed that would separate the high-density plasma from the ultra-high vacuum beamline of FLASH2 with foil windows. The experimental setup with a plasma target which requires the optical beam to go through additional surfaces, unlike a supersonic gas jet which does not have windows, and the expected beam parameters also require a different optical and imaging setup.

For the summer of 2018, an initial test of probing the magnetic field of the plasma with a 1-2 mJ, >30 fs long laser

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pulses of both 800 nm and of longer near-IR wavelength is scheduled. The required optical system for this measurement is being built, tested, and characterized at Institut für Optik und Quantenelektronik and will be transferred to DESY to be implemented at FF►►.

The fast shadowgraphy and polarimetry images recorded from the beam driven plasma wakefield alone would provide valuable insights into the acceleration process and allows for monitoring and better understanding of the linear and non-linear effects within the plasma. Additionally, imaging the longitudinal charge density of the beam, measuring the jitter between the laser and the electron beam, and calibration of upstream beamline elements such as emittance spoilers and scrapers against the electron parameters could be achieved. Further exploration would also allow for study of hosing [16] and its systematic mitigation [17].

TRANSVERSE ELECTRON PROBE

In a very recent experiment, electron bunches generated from one LWFA were used successfully to probe the plasma structure of another LWFA setup. This method utilizes a few femtosecond long relativistic electron bunches to probe the wake produced in a plasma. Since the electric field of the accelerating structure is ~GV/m, it can deflect the probe electron bunch traversing the wake, which then experiences a momentum modulation induced by the electric field of the wake. This modulation causes a density variation in the probe beam which is recorded after some free-space propagation. This variation of density produces a snapshot that can reproduce many of the wake structure information and its evolution. In Eq. (2), $\vec{\theta}$ is the deflection angle due to the field of the main beam. The denominator refers to the parameters of the probe and the numerator refers to the parameters of the wakefield/main beam [2].

$$\vec{\theta}(y,z) = \int_{-s}^{s} \frac{-e\vec{E}(x,y,z-x\beta_{\text{main}})}{cp_0\beta_{\text{probe}}}dx. \tag{2}$$

Unlike the optical probe discussed earlier, in this case, the fs electron probe can characterize electron beams without a plasma background and make study of plasma dynamics in densities lower than 10^{18} cm^{-3} possible. Therefore, implementing this method at FF►► has the advantage of allowing study of density profiles that would result in the production of better quality beams via PWFA at FF►►. However, for the FF►► beams of 1 GeV energy with 1.5 kA peak current, the axial electric field is an order of magnitude higher than beams studied in [2,18] and would likely require a very small drift distance and/or higher probe energy which would not be feasible. Nevertheless, a proof of principle experiment at FF►►, in the beam energy range of 400-600 MeV can be possible and valuable. Fig 2. illustrates simulations in which the fs transverse electron probe provides qualitative information about a wake in the nonlinear regime (c,d) as well as detecting a 10 fs witness bunch on a virtual screen (e) confirming it is placed closed to the optimum position for beam loading. Adaptation and implementation of this setup

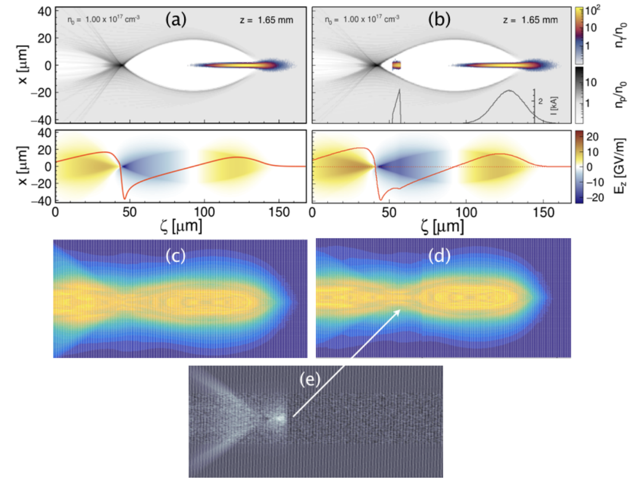

Figure 2: a): An example of a simulation run in HiPACE with 500 MeV drive beam for achieving high transformer ratio at FF►►, b): a shaped witness beam of 400 MeV is added near the optimum position for beamloading to the case (a), c): simulation of the density variation from a 220 MeV probe with 15% energy spread is projected on a virtual screen after traversing the wake in case (a), d) same as (c) for the case in (b). Subtracting the modulations recorded in (c) and (d) to discern a shaped 10 fs witness bunch of 35 pC.

for FF►► will be a big challenge, therefore, a detailed study of the realistically simulated beams in HiPACE [19] and in OSIRIS [20] is underway to obtain the working parameters for the probe (e.g. max energy spread, emittance,...) and to allow for study and evaluation this method and feasibility of its implementation at FF►►.

CONCLUSION AND OUTLOOK

In plasma acceleration nonlinear focusing and defocussing forces, which can reduce the quality of the accelerating electron bunch, are present. Therefore, direct probing of the field structure of plasma wakes and their evolution, as well as measuring electron parameters in real time is of high value. The setups discussed in this work use extremely short laser/electron beam bunches to provide an understanding of the transient electric and magnetic fields of the plasma and electron beam and can be used to optimize the process of plasma acceleration. The proof of principle transverse beam probe experiments at FLASHforward, using the currently available technologies and equipments, within the constraints of the already existing structure of FLASH2 can be used to determine the utility and feasibility of these novel probing methods as an alternative diagnostic tool for future PWFA/LWFA facilities.

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