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PROGRESS TOWARD A HIGH-TRANSFORMER-RATIO DIELECTRIC-WAKEFIELD EXPERIMENT AT FLASH*

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Abstract

Dielectric wakefield accelerators offer many advantages over conventional RF accelerators such as higher acceleration gradients and cost effectiveness. In this paper we describe our experimental plans to demonstrate an enhanced transformer ratio with drive and witness bunches. The experiment, pending its approval, is foreseen to be performed at the Free-electron LASer in Hamburg (FLASH) and utilizes unique pulse shaping capabilities using the dual-frequency superconducting linac to produce high transformer ratios ($\mathcal{R} > 2$). The beam-driven acceleration mechanism will be based on a cylindrical-symmetric dielectric-lined waveguide (DLW). The experimental setup is described, and start-to-end numerical simulations of the experiment will be presented.

INTRODUCTION

The last decade has witnessed an increasing interest toward the development of compact electron accelerators. These accelerators could serve as backbone for compact short-wavelength light sources that could have a wide range of applications. A popular configuration consists of a "drive" electron bunch with suitable parameters propagating through a high-impedance structure or plasma medium thereby inducing an electromagnetic wake. A following "witness" electron bunch, properly delayed, can be accelerated by these wakefields [1].

Collinear beam-driven acceleration techniques have demonstrated accelerating fields in excess of GV/m [2, 3]. The fundamental wakefield theorem [4] limits the transformer ratio – the maximum accelerating field over the decelerating field experienced by the driving bunch – to 2 for bunches with symmetric current profiles. Tailored bunches with asymmetric , e.g. a linearly-ramped, current profiles can lead to transformer ratio $\mathcal{R} > 2$ [5]. Only recently new methods to shape a bunch below picosecond timescales have been developed [6, 7], opening the path toward high-frequency (THz) beam-driven acceleration schemes with enhanced transformer ratios. Most recently, a simple technique that uses a radiofrequency (rf) linear accelerator (linac) operating at two frequencies was shown to be capable of generating electron bunches quasi-ramped current profiles [8] which could produce a transformer ratio ~ 6 when combined with dielectric wakefield acceleration using dielectric-lined waveguides (DLW's). The shaping technique was demonstrated at the Free-electron LASer in Hamburg (FLASH) facility [11] and an experiment to demonstrate an enhanced transformer ratio is being planned [9].

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EXPERIMENTAL SETUP

The main goal of the experiment being planned at the FLASH accelerator is to demonstrate acceleration in a DLW with $\mathcal{R} > 2$. In addition the beam structure available at FLASH could also enable the investigation of dynamical effects in DLWs. Description of the FLASH facility can be found in Ref. [11, 12]. In short, the electron bunches are generated via photoemission from a cesium telluride photocathode located on the back plate of a 1+1/2 cell normal-conducting rf cavity operating at 1.3 GHz.

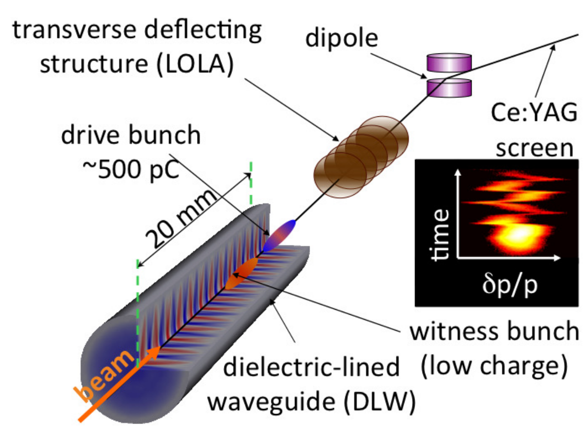

Figure 1: Overview of the enhanced-transformer-ratio experiment under preparation at FLASH. The nominal beam energy is $\sim$ 700 MeV.

The bunch is then accelerated in a 1.3-GHz and 3.9-GHz superconducting accelerating modules (respectively ACC1 and ACC39) before passing through a bunch compressor (BC1). The ACC39 3rd-harmonic module was installed to nominally correct for nonlinear distortions in the longitudinal phase space (LPS) and enhance the final peak current of the electron bunch. Downstream of BC1, the bunch is accelerated and can be further compressed in BC2. A last acceleration stage (ACC4/5/6/7) brings the beam to its final energy (maximum of $\sim$ 1.2 GeV but nominally set to $\sim$ 700 MeV). The beam's direction is then horizontally translated using a dispersionless section referred to as dogleg beamline (DLB). Nominally, the beam is sent to a string of undulators to produce ultraviolet light via the self-amplified stimulated emission free-electron laser (FEL) process. For our experiment, the bunches will instead be vertically sheared by a 2.856-GHz transverse deflecting structure (TDS) operating on the TM_{110}-like mode and horizontally bent by a downstream spectrometer [10]; see Fig. 1. Consequently the transverse density measured on the downstream Cerium-doped Yttrium Aluminum Garnet (Ce:YAG) scintillating screen is representative of the LPS density distribution. The horizontal and vertical coordinates at the Ce:YAG screen are respectively $x_s \simeq \eta\delta_F$, where $\eta \simeq 0.75$ m is the horizontal dispersion function, and $y_s \simeq \kappa z_F$ where $\kappa \simeq 20$ is the vertical shearing factor and (z_F, δ_F) refers to the LPS coordinate upstream of the TDS.

PHOTOINJECTOR GENERATION OF DRIVE AND WITNESS BUNCHES

The produced ramped bunches have been shown to be capable of producing high-peak electric fields with transformer ratios significantly higher than 2 using a dielectric-loaded waveguide (DLW) structure [9]. In order to demonstrated the capability of the generated ramped bunch to support an enhanced transformer ratio, the wakefield would have to be driven by a high-charge (drive) bunch followed by a low-charge (witness) bunch. Ideally the drive bunch would only lose energy while the witness bunch would be delayed to only sample the accelerating portion of the wakefield. The latter would also imply that the witness bunch length should be shorter than the wavelengths of the excited wakefield modes. For the first round of experiment we instead plan on having a larger witness bunch behind the drive bunch thereby sampling both the accelerating and decelerating field. This choice stems from the lack of flexibility in the witness-bunch generation: producing two bunches with controllable spacing and individual duration at the DLW experiment location is challenging in the current FLASH photoinjector configuration. The witness bunch will be generated by temporally splitting the photocathode uv laser pulse with a birefringent α-BBO crystal [13, 14]; see Fig. 2 (a). Such a method would provide two identical pulses with temporal separations given by $\delta\tau = \mathcal{G}L$ where L is the crystal thickness and $\mathcal{G} \simeq -0.96$ ps/mm is the group velocity mismatch. A 21-mm thick crystal would therefore provide a $\delta\tau \simeq 20$ ps which is longer than the laser rms duration $\sigma_t = 6$ ps and allows for a clear separation between the two electron bunches according to simulation performed with ASTRA [15]; see Fig. 2 (b). In addition, the ratio of the drive- and witness-pulse intensities could be controlled by varying the angle between the optical axis of the crystal and the incoming laser polarization. Therefore such a simple modification of the laser system would therefore provide a drive bunch followed by a low-charge population that would be energy-modulated by the drive-bunch's wakefields.

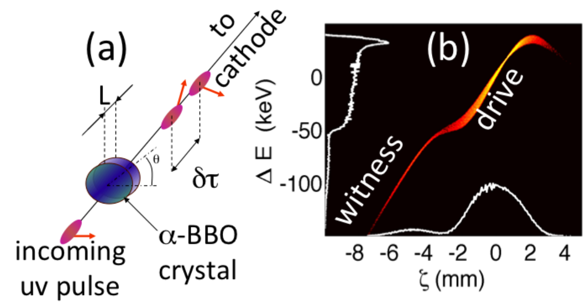

Figure 2: Photocathode drive laser manipulation scheme to produce the drive-witness bunch set (a) and corresponding simulated electron beam LPS 0.5-m downstream of the photocathode using the FLASH photoinjector setup (b).

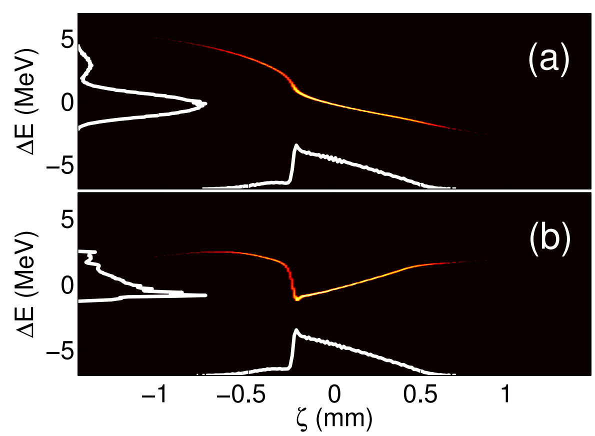

Figure 3: Longitudinal phase spaces (false color images) and associated current and energy profiles (white traces) downstream of the first stage compression (a) and at the location of the planned DWFA experiment (b).

Simulations with ASTRA and a 1D-1V model were performed to explore whether a shaped drive bunch followed by a witness bunch could be achieved at the anticipated location of the DLWA experiment. The resulting LPS provides the needed shape as shown in Fig. 3. In the simulations, the drive and witness bunches have a respective charge of 500 and 50 pC. The 500-pC drive-bunch charge is consistent with previous shaping experiment [8] while the 50-pC charge for the witness bunch is large enough to be observable on a Ce:YAG screens such as the one used in the single-shot LPS diagnostics.

SIMULATION OF THE EXPERIMENTAL SETUP

To understand the effects of the DLW on the bunches with drive-witness distributions shown in Fig. 3 (b), we used VORPAL [16] to simulate the propagation of the bunch through the DLW. The three-dimensional particle-in-cell program VORPAL uses the finite difference-time domain (FDTD) method to solve Maxwell's equations and includes an advanced technique known as cut-cell boundaries to allow accurate representation of curved geometries within a rectangular grid.

An example of the simulated LPS downstream of the DLW is compared to the initial LPS in Fig. 4. For all our simulations a DLW diamond structure (with relative permittivity $\epsilon_r = 5.7$) is considered. The initial and final LPS are fitted using a spline and the energy modulation due to the DLW is inferred using a difference technique. The typical induced modulation with peak-to-peak amplitude in excess of $\sim$ 1 MeV which should be easily resolved using the time-resolved single-shot LPS described in the previous section; see Fig. 5.

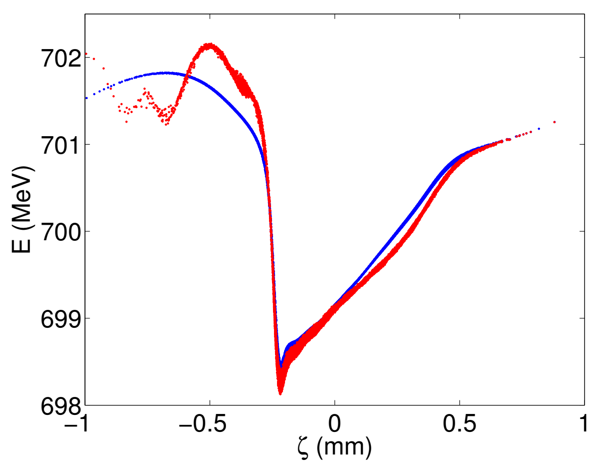

Figure 4: Longitudinal phase spaces upstream (blue) and downstream (red) the DLW structure with inner and outer radius of respectively $a = 180$ and $b = 240$ μm.

HARDWARE STATUS

The experimental setup will consist of three DLW structures with different dielectric layer thicknesses that will be remotely insertable in the beam's path. Beside being mounted a bi-axis translational stage for transverse alignment, two rotational stages will also enable the precise angular alignment of the structure. Currently, the exact location of the experiment remains to be specified. On option is to locate the DWFA experimental station downstream of the last accelerating module (ACC7). The close proximity of our experiment to superconducing cavities put stringent requirements on the vacuum quality. Therefore the final choice for the mechanism to control the structures position and alignment will depend on the outcome of vacuum tests aim at evaluating the compatibility with the needed sustained ultra-high vacuum. A Ce:YAG screen upstream of the structure along with other available diagnostics at FLASH (beam position monitor, beam-loss detectors) will enable precise centering and focusing of the electron beam through the DLW.

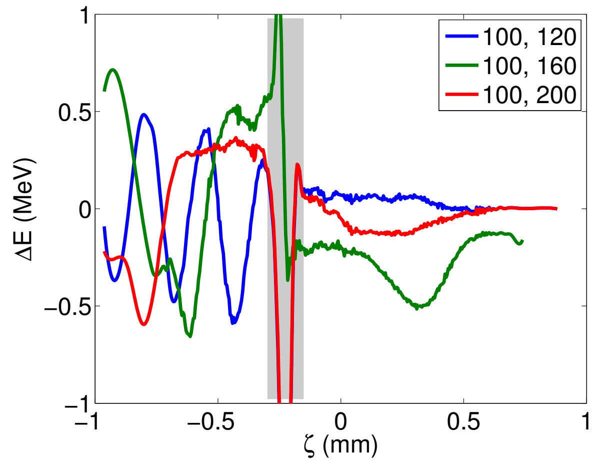

Figure 5: Reconstructed time-dependent energy loss along the bunch's longitudinal ordinate ζ for three DLW with inner and outer radii (in μm) shown in the legend. The shaded area indicate a region where the energy loss is not accurately reconstructed due to the large LPS slope (see Fig. 4).

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