EXPERIMENTAL PLANS TO EXPLORE DIELECTRIC WAKEFIELD ACCELERATION IN THE THZ REGIME*

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Abstract

Dielectric wakefiel accelerators have shown great promise toward high-gradient acceleration. We investigate the performances of a possible experiment under consideration at the FLASH facility in DESY to explore wakefiel acceleration with an enhanced transformer ratio. The experiment capitalizes on a unique pulse shaping capability recently demonstrated at this facility. In addition, the facility incorporates a superconducting linear accelerator that could generate bunch trains with closely spaced bunches thereby opening the exploration of potential dynamical effects in dielectric wakefiel accelerators.

INTRODUCTION

The rapidly developing fiel of accelerator physics is showing great promise for applications to many other technologies and sciences such as high energy physics, medicine, imaging, material sciences, energy production and propulsion. Today's conventional accelerators use radiofrequency (rf) cavities which have maximum acceleration gradients of $\sim$ 100 MV/m [1]. The emergence of high-gradient accelerating structures such as plasma or dielectric wakefiel accelerators [2, 3] opens the door towards more compact and cost effective accelerators.

This paper concentrates on beam-driven wakefiel accelerators that employ dielectric-loaded waveguides (DLW). In such a scheme, a high-charge drive bunch excites electromagnetic wakes in the DLW allowing a properly delayed witness bunch to experience a strong accelerating field Collinear beam-driven acceleration techniques have demonstrated accelerating field in excess of 1 GV/m [2, 4]. The fundamental wakefiel theorem [5] limits the transformer ratio ($\mathcal{R} \equiv E_+/E_-$) – where E_+ is the maximum accelerating fiel in the wake, and E_- is the maximum decelerating fiel experienced by the driving bunch – to 2 for bunches with symmetric current profiles Tailored bunches with asymmetric (e.g. a linearly-ramped) current profile can lead to a transformer ratio > 2 [6].

* This work was sponsored by the DTRA award HDTRA1-10-1-0051 to Northern Illinois University, the German's Bundesministerium für Bildung und Forschung and by the DOE contract DE-AC02-07CH11359 to the Fermi research alliance LLC.

In the following, we consider two types of dielectric structures shown in Fig. 1. The structures consist of a cylinder (resp. slab) with aperture radius (resp. half gap) a and dielectric layer thickness $\delta = b - a$. The dielectric layer has a relative electric permittivity ϵ. In this paper, we explore the performances of these two types of structures in the (a, b, ϵ) parameter space using experimentally generated bunches with ramped current profile [7].

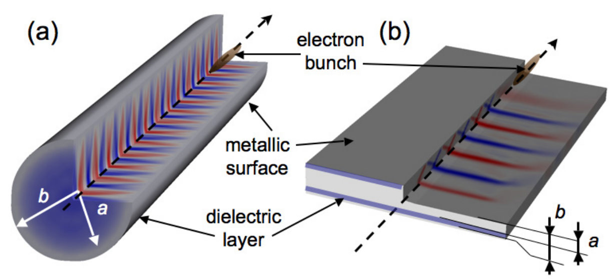

Figure 1: Geometries of interest: (a) An electron bunch passes through a cylinder with inner radius a, and outer radius b. (b) Similarly an electron bunch passes through a slab-symmetric geometry of inner length a, and outer length b. In both instances, the dielectric material is located in the region $\delta = b - a$, the geometries are surrounded by a conducting sheet, and the region $< a$ is vacuum.

SIMULATIONS AND RESULTS

We have developed several numerical models capable of simulating wakefield generated as a bunch of electrons passes through a cylindrical or slab structure. Our model is based on a semi-analytical approach developed in Ref. [8] for the cylindrical DLWs and on an extension of the work reported in Ref. [9] for the slab DLWs [10]. The developed models were benchmarked against the three-dimensional electromagnetic particle-in-cell program VORPAL [11]. VORPAL uses the finit 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.

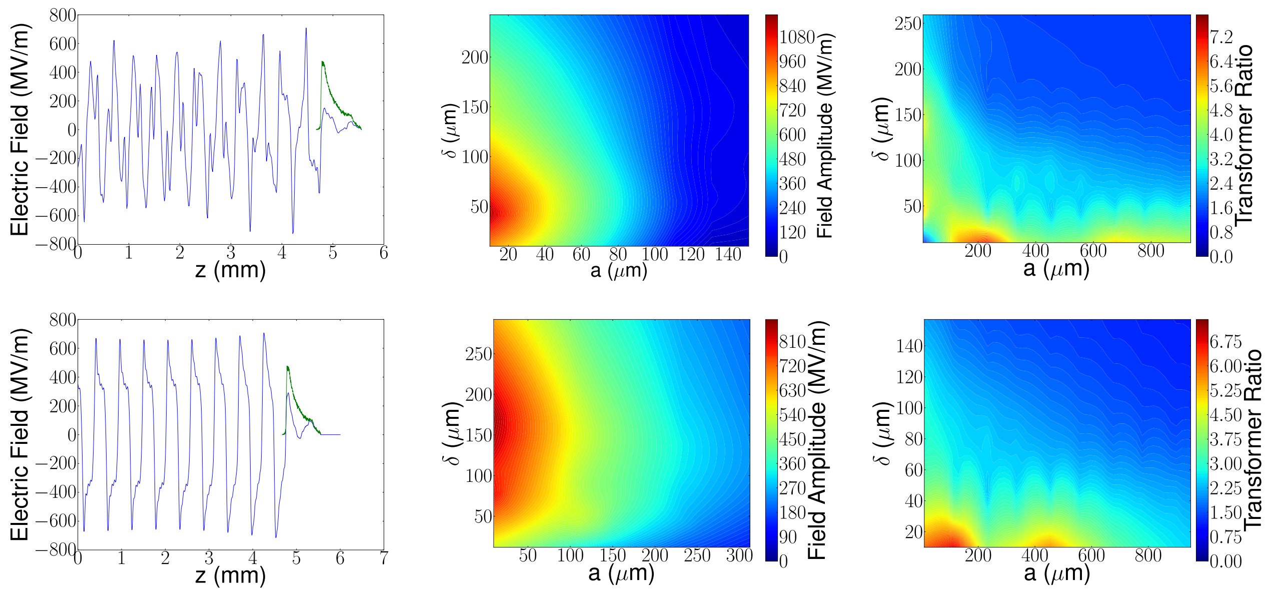

Figure 2: Wakefield (blue trace) produced by a 500-pC bunch with ramped current distribution (green trace) [left column], scan of the peak accelerating fiel (E_+) [middle column], and scan of the transformer ratio ($\mathcal{R}$) [right column], in the (a, δ) parameter spaces. The top and bottom rows respectively correspond to cylindrical and slab DLWs. The wakefield plotted in the left column correspond to $(a, \delta) = (20, 60)$ μm.

The $(a, \delta \equiv b - a)$ parameter space was scanned and the values $\mathcal{R}$ and E_+ were recorded. The dielectric layer material was chosen to be made of diamond ($\epsilon = 5.7$) due to its exceptional heat coefficien [> 2000 W/(mK)].

We present simulation results pertaining to one of the ramped current profile measured during a current shaping experiment conducted at the Free-electron LASer in Hamburg (FLASH) facility [12]; see details in [7]. The resulting performances in the (a, δ) parameter space are gathered in Fig. 2 for both a cylindrically-symmetric and slab-symmetric structures. As expected from its shape, the current profil yields a $\mathcal{R}$ in excess of ~ 6, with peak currents on the order of ~ 1 GV/m. For both types of structures the $\mathcal{R}$ evolution in the (a, δ) parameter space displays similar features and especially several maxima. Some of these maxima correspond to high electric–fiel amplitudes (for small values of a), while others are attained for more conservative values of $a \sim 200 - 300$ μm with significantl weaker (but still attractive) fiel amplitudes $|E_+| \sim 100$ MV/m.

We also considered the wakefiel properties resulting from bunches obtained using the typical nonlinear bunch compression settings at FLASH. These bunches can generate electric field in excess of 2 GV/m (at the expense of poor $\mathcal{R}$ values); see an example of produced wakefiel in Fig. 3.

Finally, in an effort to understand the more-intricate dependence of the wakefiel properties on the dielectric constant ϵ, we scanned its value for fi ed a, b parameters (see Fig. 4). We found that E_+ and $\mathcal{R}$ were extremely sensitive to changes in ϵ and could potentially achieve values

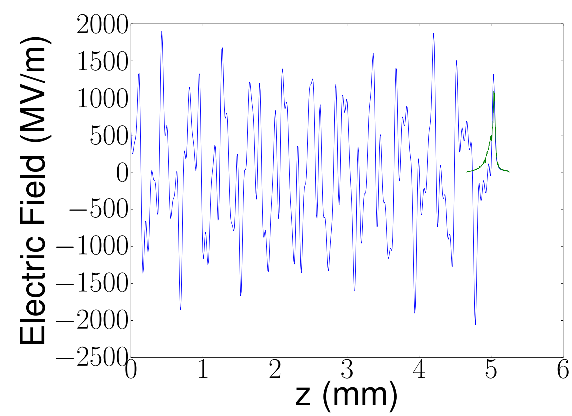

Figure 3: Example of wakefiel (blue trace) produced by a 500-pC bunch (green trace) obtained via typical non-linear bunch compression at FLASH. The structure is a cylindrical DLW with $(a, \delta) = (20, 60)$ μm.

$\mathcal{R} > 10$. These high values of $\mathcal{R}$ are associated to values of ϵ which are not a priori available in conventional materials. Synthetizing materials with the required ϵ while having a low tan-loss factor might be very challenging. It is however worth stressing that the current profil has also a significan impact. In particular, we showed that maxima of the $\mathcal{R}(\epsilon)$ function could be shifted to different ϵ values by altering the current profiles We plan on investigating such a feature closer with the end goal of establishing a set of possible materials. Such a multivariate optimization in the (a, b, ϵ) parameter space will be performed using a genetic algorithm. The overall optimization goals will be to fin compromises between high values of $\mathcal{R}$ and $|E_+|$.

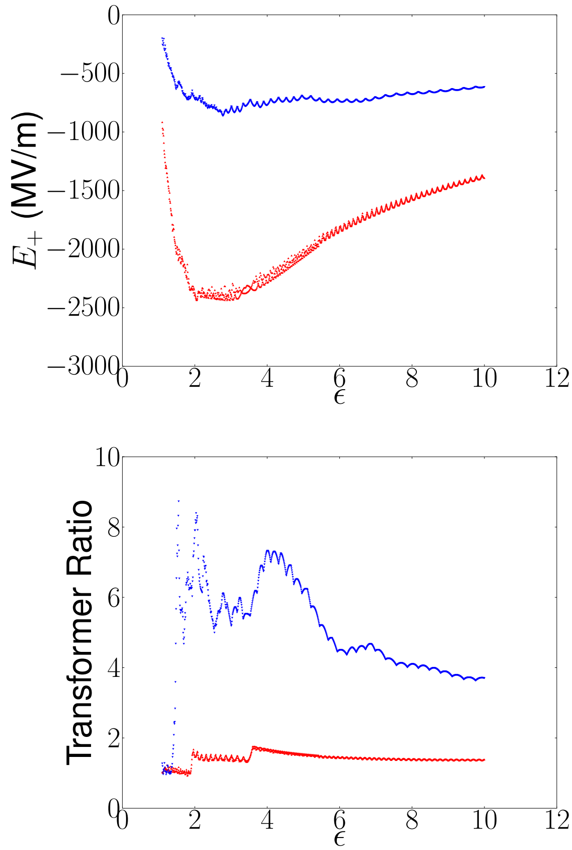

Figure 4: Accelerating fiel E_+ (top) and transformer ratio $\mathcal{R}$ (bottom) as a function of ϵ. The blue and red traces respectively correspond to the current profile shown in Fig. 2 and 3. For these calculations, $(a, \delta) = (20, 60)$ μm.

POSSIBLE EXPERIMENT AT FLASH

Based on the simulation results presented in the previous sections we are planing an experiment aimed at measuring an enhanced transformer ratio using the ramped bunches produced at the FLASH facility. In such an experiment, the dielectric structure would be located downstream of the last accelerating stage once the beam has been accelerated to $\sim$ 700 MeV. After the beam passes through a remotely insertable DLW structure it will be vertically sheared by a transverse deflectin structure (TDS) and then horizontally bent with a dipole magnet (spectrometer); see Fig. 5. A Cerium-doped Yttrium Aluminium Garnet screen (Ce:YAG) located downstream of the dipole magnet will provide a single-shot measurement of the longitudinal phase space distribution thereby allowing for a time-resolved measurement of the drive bunch's energy loss. Given the typical rms fractional momentum spread measured during the ramped bunch experiment reported in Ref. [7], we expect that a DLW structure with a conservative 2-cm length and its geometric parameter chosen to provide a conservatively-low peak fiel of $E \simeq 200$ MV/m. This would result in, at least, a 2-fold increase in fractional momentum spread to $\sim 200 \times 0.02/700 \simeq 0.6 \times 10^{-3}$. Such an increase is well within the resolution of the spectrometer. In addition, the time-resolved nature of our measurement should allow for a sensitivity to even smaller increase as details of the correlated energy developing due to the wakefiel will be observable.

Finally, the availability of an 800-μm macropulse comprising of 2400 electron bunches could also enable the investation of dynamical effects in the DLW. Such a capability is unique to a super-conducting linac.

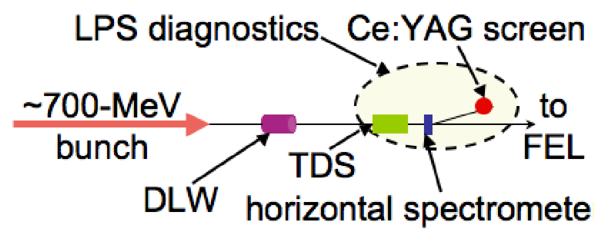

Figure 5: Possible DLW test experimental configuratio at the FLASH facility. The drive and witness bunches longitudinal phase space (LPS) is directly measured at the Ce:YAG screen after the beam has been vertically sheared in a transverse deflectin structure (TDS) and horizontally bent in a spectrometer.

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