TOWARD A DIELECTRIC-WAKEFIELD ENERGY DOUBLER AT THE FERMILAB'S ADVANCED SUPERCONDUCTING TEST ACCELERATOR*

F. Lemery [1], D. Mihalcea [1], P. Piot [1,2], C. R. Prokop [1], P. Stoltz [3]
[1] Department of Physics, and Northern Illinois Center for Accelerator & Detector Development, Northern Illinois University DeKalb, IL 60115, USA
[2] Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[3] Tech-X Corporation, Boulder, CO 80303, USA

Abstract

The Advanced Superconducting Test Accelerator (ASTA), presently under construction at Fermilab, will produce high-charge ($\sim$ 3 nC) electron bunches with energies ranging from 50 to eventually 750 MeV. The facility is based on a superconducting linac capable of producing up to 3000 bunches in 1-ms macropulses repeated at 5 Hz. In this paper we explore the use of a short dielectric-lined-waveguide (DLW) linac to significantly increase the bunch energy. The method consists in (1) using advanced phase space manipulation techniques to shape the beam distribution and enhance the transformer ratio, and (2) optimize the generation and acceleration of a low-charge witness bunches. Piecewise simulations of the proposed concept are presented. This DLW module could also be used to test some aspects of a recently proposed concept for a multiuser short-wavelength free-electron laser utilizing a series of DLW linacs.

INTRODUCTION

Fermilab is currently constructing a superconducting electron accelerator, the advanced superconducting test accelerator (ASTA), with the end goal of eventually supporting a user-driven advanced accelerator R&D program [1]. ASTA consists of a high-brightness photoinjector coupled with superconducting accelerating modules. In addition, the design accommodates advanced phase-space manipulation such as a round-to-flat beam transformer and eventually a transverse-to-longitudinal phase space exchanger.

These manipulation techniques could be used to shape the beam current profile and repartition its emittance within the three degrees of freedom, as needed for some advanced acceleration mechanisms, such as dielectric-wakefield acceleration in dielectric-lined waveguides (DLWs) with slab geometries. In its first phase of operation, ASTA will provide beam energies limited to 250 MeV. We are interested in significantly increasing the beam energy using a simple and cheap beam-driven mechanism based on DLW acceleration and in this paper, we explore the addition of slab-symmetric DLW modules in ASTA. In such a configuration, the layout of the ASTA facility would be as schematized in Fig. 1. In brief, the $\sim$5-MeV beam produced by a 1.3-GHz rf gun would be accelerated to $\sim$ 50 MeV using two TESLA-type superconducting cavities (CAV1 and 2). The bunch could then be manipulated using a 3rd harmonic cavity (CAV39), a chicane-based magnetic bunch compressor (BC1) and with the RFTB transformer, before undergoing further acceleration to $\sim$ 250 MeV in one accelerating module. Finally, the bunch current profile could be tailored using a phase space exchanger (PEX) or second bunch compressor (BC2) and be injected into the DLW module.

PARAMETERS AND DLW CHOICES

The choice of the DLW structure geometry sets the maximum achievable accelerating field for a given bunch current distribution but is also constrained by the beam's transverse emittances. Here, we impose the DLW module to accelerate the incoming 250-MeV beam to 500 MeV within a maximum footprint of 10 m assuming a filling factor of 30% (3 meter total of active acceleration length). This sets a moderate requirement of $\sim$ 100 MV/m for the accelerating field. Taking a cylindrical-symmetric DLW would impose stringent requirements on the normalized transverse emittance $\varepsilon_\perp$ for a given betatron function. Considering a structure with aperture radius a and length L and imposing the condition $6\sigma_\perp \leq 2a$ (where $\sigma_\perp$ is the transverse beam size at the entrance/exit of the DLW) yields the requirement on the normalized transverse emittance:

$$\varepsilon_\perp \leq \frac{4\gamma a^2 \beta^{*2}}{9(4\beta^{*2} + L^2)}, \qquad (1)$$

where γ is the Lorentz factor and β^* is the value of the betatron function at the center of the DLW (assumed to correspond to the beam's waist). For anticipated betatron functions of $\sim$ 1 m, the required transverse emittance would be $\varepsilon_\perp \simeq 0.5$ μm; see Fig. 2 (b). Such a low-emittance is challenging to achieve for the anticipated nC charge need in the drive bunch. Simulations indicate that a minimum emittance of $\varepsilon_\perp \sim 5$ μm is achievable at the ASTA photoinjector for $Q = 3.2$ nC.

Therefore the use of round DLW structures operating in the THz regime is difficult for our beam parameters. Instead, we explore the use of a drive beam with asymmetric transverse emittances to excite wakefields in a slab-

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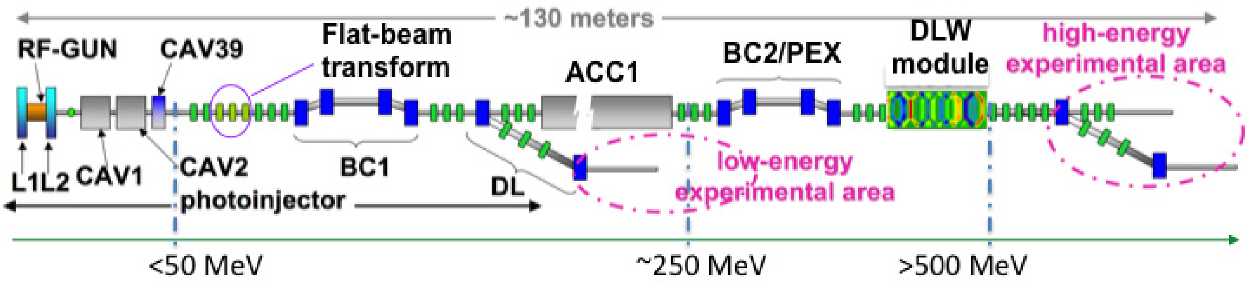

Figure 1: Overview of the Advanced Superconducting Test Accelerator (ASTA). The legend is "L1" "L2" stand for solenoids, "CAV1", "CAV2", and "CAV39" correspond to accelerating cavities, "ACC1" to an accelerating module (composed of 8 accelerating cavities), "BC1" and "BC2" to bunch compressors, and "DL" to a dispersionless translating beamline termed as dogleg. "PEX" represents a possible reconfiguration of "BC2" to act as a transverse-to-longitudinal phase space exchanger; see text for details.

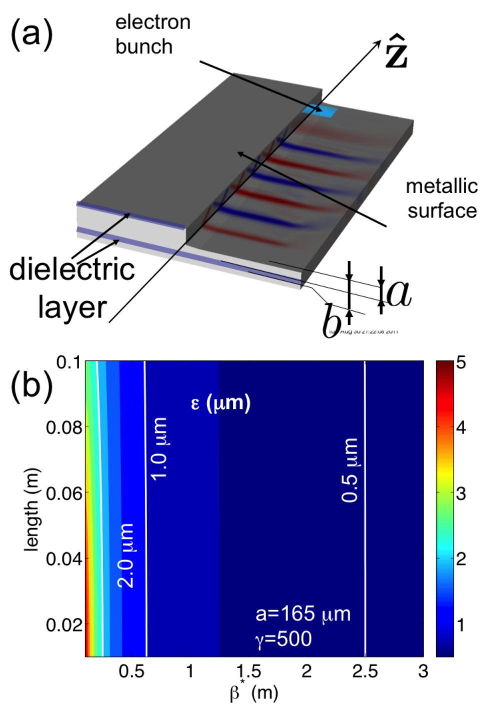

Figure 2: Schematic rendition of the slab-symmetric structure under consideration (a) and required normalized transverse emittance as a function of β^* function and DLW structure length. The DLW inner aperture is taken to be $a = 165$ μm and the beam Lorentz factor is $\gamma = 500$.

symmetric DLW structure with geometry depicted in Fig. 2 (a) [2].

GENERATION OF A FLAT DRIVE BUNCH WITH SHAPED CURRENT PROFILES

A critical element to acceleration in slab-symmetric DLWs is the production of flat electron beams. These types of beams can be formed using simple linear transformations directly out of a photoinjector as proposed in Ref. [3]. This method consists in generating an angular-momentum-dominated beam (also termed as "magnetized" beam) by immersing the photocathode in an axial magnetic field. After acceleration, the round beam is transformed into a flat beam using a set of skew quadrupoles. Upon proper tuning of the transformer, the expected normalized flat-beam emittances, $\varepsilon_n^{\pm}$, are given by [4]:

$$(\varepsilon_n^+, \varepsilon_n^-) = \left(\frac{(\varepsilon_n^u)^2}{2\beta\gamma\mathcal{L}}, 2\beta\gamma\mathcal{L}\right), \tag{2}$$

where $\varepsilon_n^u \equiv \beta\gamma\varepsilon_u$ is the normalized uncorrelated emittance of the magnetized beam prior to the transformer, $\beta = v/c$, γ is the Lorentz factor, $\mathcal{L} \equiv \langle L\rangle/2p_z$, p_z is the longitudinal momentum, and $\langle L\rangle \equiv eB_0\sigma_c^2$, where e is the electron charge, B_0 the axial magnetic field on the photocathode surface, and σ_c is the root-mean-square (rms) transverse size of the drive-laser spot on the photocathode. An experimental investigation of angular-momentum-dominated beams and their flat-beam conversion was reported in Ref. [5, 6]. At ASTA the beam emittance for charge $Q \in [0.02, 3.2]$ nC scales as $\varepsilon_\perp^n = 2.11Q^{0.69}$ μm (where Q is the charge in nC) according to optimization performed in Ref. [7]. Taking the round-beam emittance value to correspond to $\varepsilon_u = \varepsilon_\perp$, the flat beam emittances will be ε_-^n and $\varepsilon_+^n = (\varepsilon_u^n)^2/\varepsilon_-^n$. Therefore requiring the smallest emittance to be $\varepsilon_-^n = 0.5$ μm implies that $\varepsilon_+^n = 50$ μm to be consistent with a round-beam emittance of 5 μm yielding to an emittance ratio $\rho \equiv \varepsilon_+^n/\varepsilon_-^n = 100$. Numerical simulation of the ASTA photoinjector setup to provide flat beams have confirmed this type of scaling.

In beam driven acceleration, the use of a shaped drive bunch can significantly enhance the transformer ratio – the maximum accelerating wakefield E_+ over the decelerating field E_- experienced by the driving bunch – to $\mathcal{R} \equiv |E_+/E_-| \leq 2$ for bunches with symmetric current profiles. Tailored bunches with asymmetric , e.g. a linearly-ramped, current profiles can lead to $\mathcal{R} > 2$ [8]. Achieving large transformers ratios is beneficial for beam-driven acceleration as it enables longer interaction times and increases the overall efficiency of the method; however, large values of R compromise large values of values of E_+. Since ASTA will eventually incorporate a 3.9-GHz

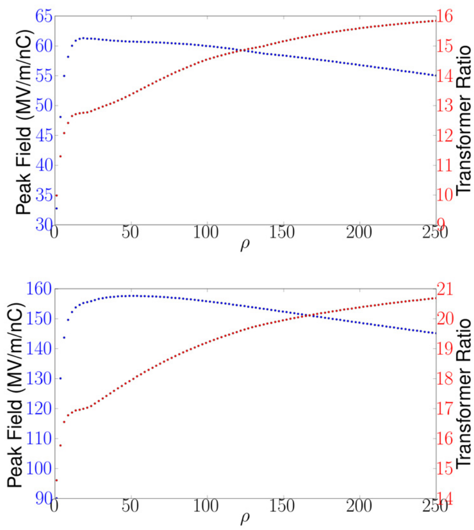

Figure 3: Peak accelerating electric field (blue trace) and transformer ratio (red trace) as a function of emittance ratio $\rho = \varepsilon_n^+/\varepsilon_n^-$ for a 1 nC electron bunch with 4D emittance $\varepsilon_n^u \equiv \varepsilon_n^+\varepsilon_n^- = 5\ mu$m. The structure parameters is $a = 165\ mu$ and $b - a = 30\ \mu$m (top) and taken to be variable such that $a = 4\sigma_y$ and $b - a = 30\ \mu$m (bottom). The bunch is taken to be linearly-ramped with total length of 1.2 mm.

accelerating cavity, the multi-frequency method described in Ref. [9] could be implemented. Alternatively, the use of a transverse-to-longitudinal phase space exchanger (PEX) is under investigation [10]. We plan on eventually using a high-energy PEX which will be located downstream of the first cryomodule at 250 MeV. A shaped mask located upstream of the PEX will enable the tailoring of the current profile [11]. To test the influence of the beam flatness on the performances of the wakefield induced in the DLW, we use a 3-D model adapted from Ref. [12] and previously benchmarked [2]. For the set of simulations presented below we take an electron bunch with $\varepsilon_n^u = 5\ \mu$m. Figure 3 (top) presents the evolution of the transformer ratio and peak accelerating field for a 1-nC drive bunch given a structure with half-gap $a = 165\ \mu$m and dielectric thickness of 20 μm. If we vary the DLW structure's gap for different flatness, $a = 4\sigma_y$ higher accelerating fields are possible; see Fig. 3 (bottom). In both studies, the total bunch length was fixed to 1.2 mm which increases the transformer ratio as a (and consequently the fundamental-mode wavelength) decreases.

COLLINEAR ACCELERATION IN A FODO CHANNEL

An important issue related to collinear acceleration is the management of the drive-bunch and witness-bunch optics while the energy of both bunches is changing [13]. A FODO channel with energy tapered quadrupole-magnet strengths can provide a decent control over the drive bunch; see Fig. 4 (top) while still enabling transport of a lower-charge drive bunch Fig. 4 (bottom). These calculations only include a kick approximation for the beam energy change and do not account for the large energy spread potentially generated during the drive-bunch deceleration. The witness bunch was accelerated from 250 to 500 MeV over the 5-m long channel while the drive bunch was decelerated by approximately 25 MeV (a transformer ratio of 10 was assumed).

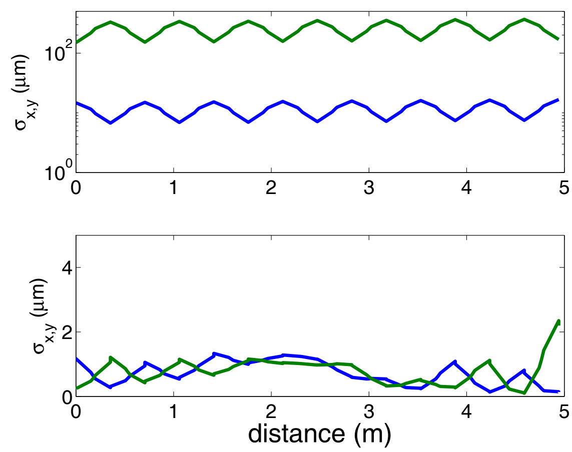

Figure 4: Drive (top) and witness (bottom) bunch rms transverse beam size evolution along a 5-m FODO channel. The two bunches are assumed to have the same initial Courant-Snyder parameters. The witness bunch is accelerated from 250 to 500 MeV while the drive bunch is decelerated from 250 to 225 MeV.

In summary, a piecewise numerical simulation of a possible energy doubling scheme for the ASTA facility has been explored and indicate such an experiment is possible. Further investigations are needed and a full start-to-end simulation is being assembled.

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