BEAM PULSE SHAPING EXPERIMENTS FOR UNIFORM HIGH GRADIENT DIELECTRIC WAKEFIELD ACCELERATION*

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Abstract

Dielectric wakefield accelerators (DWA) can produce high accelerating gradients and could possibly be used as afterburners for the accelerators of future free electron lasers (FELs) such as X-ray FEL of the proposed Matter-Radiation Interactions in Extremes (MaRIE) experimental facility at LANL [1]. With a double triangular drive bunch DWAs can produce a high transformer ratio. Also, by slightly customizing the time profile of the accelerated bunch it is possible to achieve high gradient uniformity along the accelerated bunch resulting in a low induced energy spread [2]. We plan to test a DWA which would incorporate all those benefits. The only way to produce the desired current profile of the main and drive bunches is to use current shaping with a beam mask. A variation of this technique is currently used at Accelerator Test Facility (ATF) at Brookhaven National Laboratory (BNL) which is available for outside users' experiments.

We report our recent beam shaping experiments at BNL for a transformer ratio test. We used a 58 MeV energy chirped electron beam and a single dogleg with a beam mask inserted in a region where the beam transverse size was dominated by the correlated energy chirp. Both measurement results and Elegant simulation data are presented.

INTRODUCTION

A demand for compact accelerators has recently resulted in an increased interest in dielectric wakefield accelerators (DWAs). The DWA is formed by one or several co-axial dielectric layers surrounded by metal cladding (Fig. 1) [3]. Wakefields in dielectric structures may reach gradients on the order of 10 GV/m [4] with 100 MV/m being demonstrated in multiple experiments [5]. They also have the remarkable property that the wakefield's axial electric field and the transverse electric field are transversely uniform and linear, respectively. This is due to the fact that the relativistic drive beam and the subsequent wakefield travel very nearly at the speed of light. If one can make the wakefield to be longitudinally constant along the bunch it will result in no induced energy spread within the bunch, leading to an extraordinary condition of preserving the main beam brightness while providing high gradient acceleration. We have realized that by a proper longitudinal customization of the accelerated beam the induced energy spread in a DWA can be made small enough (<0.1%) to satisfy tight requirements for X-ray free electron laser linac afterburner of the proposed Matter-Radiation Interactions in Extremes (MaRIE) facility at LANL [1, 2, 6].

An important characteristic of the wakefield acceleration is a transformer ratio (TR). It is the ratio of the peak accelerating gradient to the peak decelerating gradient experienced by the drive bunch, and thus it determines how long the drive bunch will be stable before some part of it decelerates to low energies. For a finite length longitudinally symmetric bunch the TR can never exceed 2 [7]. An enhanced TR can be achieved with a ramped beam or a ramp-profiled bunch train [7]. Recently a Double Triangular (DT) beam shape was proposed making possible high TRs with almost uniform drive bunch deceleration [8]. In the DT bunch the TR is approximately proportional to the beam length in wavelengths of the induced wakefield radiation and thus can be made very large.

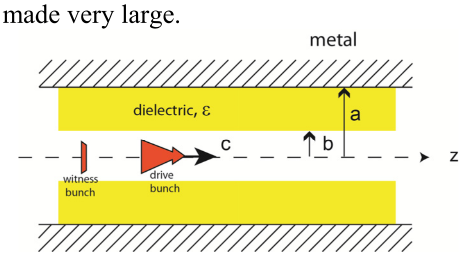

Figure 1: The schematic of a dielectric loaded waveguide with shaped electron bunches traveling on axis.

The main obstacle on the way to experimental demonstration of superior properties of the DWA with a DT drive beam is that the DT bunch shapes are difficult to produce in the submillimeter scale required for ~300 GHz DWAs using conventional methods based on direct beam current modulation. One of the actively popularized methods to shape the beam currents in such a small scale is based on an emittance exchanger technique [9]. It is easy to shape the transverse beam profile using a mask. The emittance exchanger allows to convert a transverse particle distribution into longitudinal. However this method is relatively new and not available at any user accelerator facility although it has already been verified at the Fermilab A0 Photoinjector [10]. A relatively simpler technique is used at Accelerator Test Facility (ATF) of BNL [11] which also allows current shaping on the required scale. It utilizes an energy chirped beam which is cut with a transverse beam mask placed inside of the beamline dispersive region where one transverse coordinate is linearly related to both the particle energy and arrival time.

We studied the possibility of using the ATF facility at BNL for demonstrating high gradient high transformer ratio operation of a DWA with a double triangular beam.

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THE BEAMLINE SET-UP

The electron beam at the ATF is produced with an S-band RF photoinjector followed by an S-band linac. After the linac the beam can be directed to one of three different beamlines. For our experiment in May, 2013 we used the beamline #2. The system parameters relevant to the experiment are listed in Table 1. A linear energy chirp in time was produced by accelerating the beam off the crest of the RF wave.

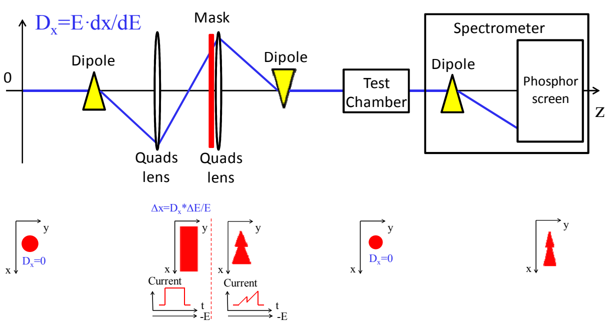

Figure 2: Principal of beam shaping: simplified scheme with only essential beamline elements pictured. Top plot shows dispersion evolution caused by the beamline elements. Bottom plots show particle distributions in different locations along the beamline.

Table 1: ATF Beamline #2 Beam Parameters.

Beam energy	58 MeV
Beam current	100 A
Pulse shape	Square
Pulse duration	5 ps
Repetition rate	1.5 Hz
Beam transverse profile	Gaussian
Normalized transverse emittances	≈ 2 mm*mrad
Typical energy chirp, ΔE/E	1.5%
Beamline dispersion, D_x	≈ 1 m

Figure 2 illustrates the principal of beam shaping employed at the ATF. Several quadrupole magnets are used inside of the dispersion region in the dogleg to minimize the beam x-beta function on the mask to make the beam size due to the dispersion strongly dominate over the beam size caused by a transverse emittance. The dogleg is followed by a zero dispersion region with a vacuum chamber where a DWA can be installed on a motorized mount. The last beamline element is a spectrometer. The spectrometer consists of a single dipole which produces dispersion, a phosphor coated metal screen and a high resolution camera. It also has a set of quadrupole magnets for minimizing the beam x-beta function on the screen. The brightness of pixels in the pictures from the camera is proportional to the density of electrons hitting the surface of the screen. There is also a number of pop-up phosphor screens with cameras along the beamline which are used to visualize the beam during a tuning of magnets process which had to be performed every day after the accelerator was warmed up. The beam parameters, including emittances, varied at the linac output quite substantially from day to day. Figure 3 shows the plots of the beam twiss parameters inside the whole beamline starting from the linac output with magnets' currents optimized in MAD-X [12] for beam shaping for some realistic set of initial beam parameters. At the top of Fig. 3 there is a scheme with all magnets, excluding weak dipole magnets used for fine beam steering, positioned along the beam path.

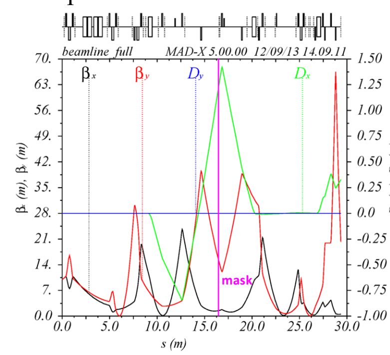

Figure 3: Twiss parameters as modeled in MAD-X vs the beam propagation distance with the mask location marked.

BEAM SHAPING EXPERIMENT

We used a mask on a motorized holder with three openings in the form of arrows, one of them being double triangular (Fig. 4). The mask was mounted on a motorized holder, its orientation corresponded to the tail of the arrows always irradiated by higher energy electrons.

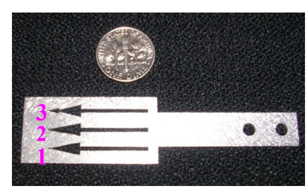

Figure 4: Aluminum mask used in the experiment.

Figures 5-7 show experimental results. The beam had a close to a Gaussian shape with no noticeable x-energy correlation left after the dogleg (Fig. 5). However the spectrometer revealed a strong energy spectrum distortion. Also, depending on the sign of the beam energy chirp the energy spectrum looked either stretched or compressed. The observed behavior was consistent with the coherent synchrotron radiation (CSR) effect making the beam tail lose more energy than the head (Fig. 6).

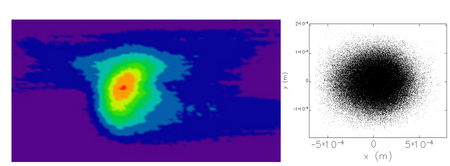

Figure 5: The beam in the test chamber: pictured with a camera using a phosphor screen (left), and simulated (right).

Another evidence denoting the charge related effects was that a low charge bunch transmitted through the off beam center mask opening was reproduced on the spectrometer with minimal distortions (Fig. 7).

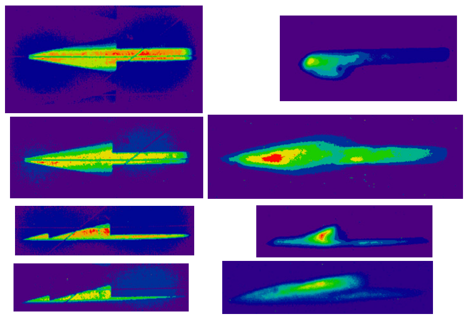

Figure 6: Left column: the beam profiles measured immediately after the mask. Right column: the beam profiles on the spectrometer, all at the same horizontal scale. Upper two rows are for a single triangular arrow mask, lower two rows are for a double triangular arrow mask (due to mechanical constraints only half of it was illuminated with the beam). For each mask the upper two pictures are for the arrow looking forward in the direction of propagation, and the lower two are for the backward arrow orientation.

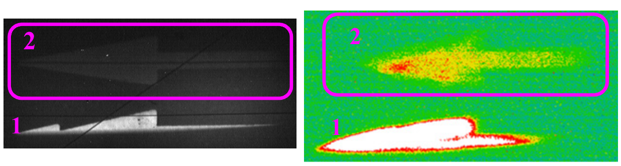

Figure 7: A low charge arrow #2 on the mask (left) is nicely reproduced on the spectrometer (right).

SIMULATIONS

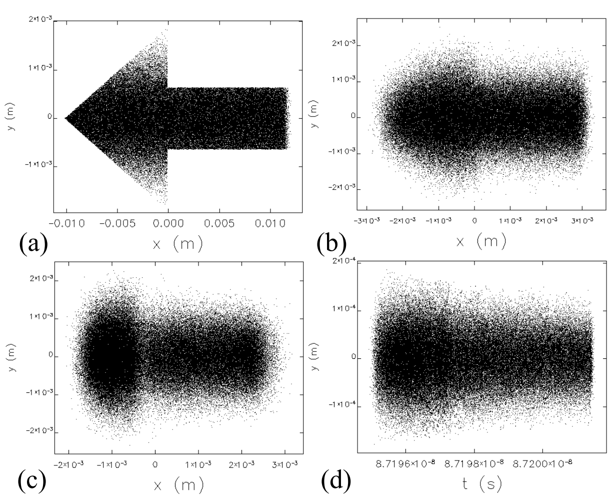

Figure 8: Simulated distribution of electrons in the beam: (a) immediately after the mask; (b) on the spectrometer obtained using the transfer matrix method; (c) on the spectrometer and (d) in the test chamber with account for the LSC effect in drift spaces & CSR in the dipole bends.

In order to confirm the nature of the effects observed in the experiment we performed simulations in Elegant [13]. We converted the MAD-X beamline model with parameters used to obtain the plot in Fig. 3 into Elegant format and wrote a script to incorporate the mask as an x-y filter element in Elegant. Elegant is a matrix code, for each beamline element it uses a transfer matrix in the form of tensors accounting for up to the 3rd order nonlinearities. It can also account for a longitudinal space charge (LSC) and coherent synchrotron radiation (CSR) by doing a specified number of kicks on the length of each beamline element. Figure 8 demonstrates the severity of the beam shape distortion inside the beamline for the initially 100 A beam. The beam energy spectrum looks different compared to its time profile (Fig. 8(c)-(d)).

CONCLUSION

We have carried out a beam shaping experiment at the ATF BNL user facility. We tried two different masks with single and double triangular shapes. For nominal current of 100 A we observed a strong CSR effect which considerably degraded the output beam energy spectrum. At the same time for a low charge beam the shaping seemed to work very well. A simple dipole-based spectrometer installed on the beamline was not helpful in characterizing the beam time profile. An RF deflecting cavity is needed to be able to resolve the beam shape in time. The deflecting cavity is going to be implemented on the beamline in the nearest future. Its addition will allow to acquire both the current shape and the energy spectrum of the beam needed for a DWA experiment with a double triangular beam. However simulations show that obtaining a perfect double triangular beam is challenging due to space charge related effects and beamline nonlinearities. Probably, some of these effects can be taken care of by customizing the mask shape.

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