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DIELECTRIC WAKEFIELD ACCELERATOR EXPERIMENTS AT ATF*

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Abstract

Dielectric wakefield acceleration (DWA) presents us with means to achieve the accelerating gradient high above the limits of conventional accelerators. In a typical DWA scheme a higher energy lower charge main bunch is accelerated in the wakefield produced by a preceding lower energy higher charge drive bunch inside of a hollow metal-encapsulated dielectric tube. To make use of as much energy of the drive bunch as possible, it is highly important that all parts of it decelerate uniformly. Close to uniform drive bunch deceleration can be achieved if its current is properly shaped.

At Accelerator Test Facility (ATF) at BNL we shaped the current of a chirped electron beam with an adjustable mask placed inside of the highly dispersive region in the magnetic dogleg. We passed the shaped beam current through a quartz tube and observed the beam particles' energy modulation at the tube's output with a spectrometer. By tuning the mask we were able to control the beam energy modulation and thus the wakefield profile in the tube.

INTRODUCTION

Dielectric wakefield accelerators are formed by one or several coaxial dielectric layers surrounded by metal cladding (Fig. 1). Wakefields in dielectric structures may reach gradients on the order of 10 GV/m [1] with 100 MV/m demonstrated in multiple experiments. They also have the remarkable property that the wakefield's axial electric field is transversely uniform due to the fact that the relativistic drive beam and the subsequent wakefield travel very nearly at the speed of light. As we noticed previously [2, 3], these unique properties may allow the use of DWAs as high gradient high brightness accelerators for X-ray free electron lasers.

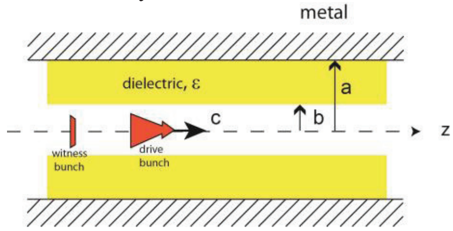

Figure 1: Schematic of the DWA.

An important parameter of each accelerator is its energy transfer efficiency. In case of the DWA it has to do with the transformer ratio (TR), which is the ratio of the accelerating field acting on the main bunch to the maximum deceleration field inside of the drive bunch. For the same accelerating gradient higher TR wakefield will ensure longer use of the drive bunch due to its smaller and more uniform deceleration. For any finite length longitudinally symmetric bunch the TR can never exceed 2 [4]. An enhanced TR can be achieved with a ramped beam or a ramp-profiled bunch train [4]. Recently a double triangular (DT) beam current was proposed [5]:

$$I(t) = \begin{cases} I_0 \cdot f \cdot t, & 0 \le t < \frac{1}{4f}; \\ I_0 \cdot \left(f \cdot t - \frac{1}{2\pi}\right), & \frac{1}{4f} \le t < T. \end{cases}$$

In the above formula, f is the frequency of a single mode accelerator, T – the total bunch duration, t – time, I_0 – a constant with units of current. In a single mode approximation the DT current produces strictly uniform deceleration of the drive bunch except for its very beginning part (Fig. 2). In reality, due to the finite thickness of the dielectric tube, more than one mode is exited; as a result, the TR is generally reduced (Fig. 2). For very long DT drive bunches the TR becomes proportional to the bunch length expressed in wavelengths of the induced wakefield radiation and thus the TR can be made very large.

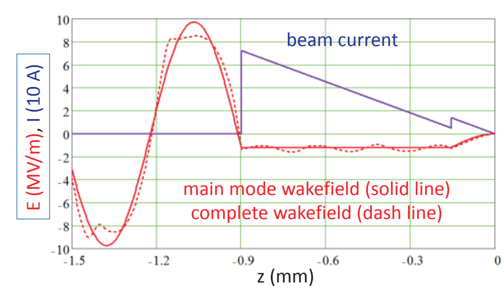

Figure 2: DT current and its wakefield in the tube chosen for the experiment: a=550 μm, b=400 μm, ε=3.8.

Even though the DT bunch has no steep rising edges, it is still difficult to produce with all the features in subpicosecond scale required for the accelerator operation at 300 GHz or higher frequencies.

At ATF we used an indirect method of current modulation employing a transverse DT beam mask [6]. The mask was made adjustable to compensate for beam parameters which were hard to control. An energy chirped beam was shaped with the mask, passed through a metal encapsulated quartz tube and visualized on a spectrometer. We tuned the mask and observed the beam energy change on the spectrometer. The idea of the experiment was that if the beam has a right DT shape then its picture on the spectrometer incurs minimum changes

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except a translational shift to lower energies as compared to the case with no tube.

EXPERIMENTAL SETUP AT ATF

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 experiments we used the beamline #2. The system parameters relevant to the experiments are listed in Table 1. A linear beam energy chirp was produced by accelerating the beam off crest.

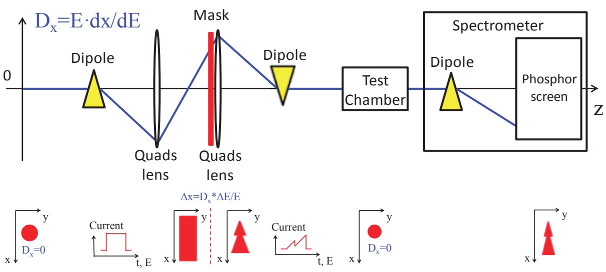

Figure 3: Schematic of beam shaping at ATF.

Table 1: ATF Beam Parameters at Beamline #2

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, each	≈ 2 μm*rad
Typical energy chirp, ΔE/E	1.5%
Beamline dispersion, D_x	≈ 1 m

Figure 3 illustrates the beam shaping technique employed at the ATF. Several quadrupole magnets are used inside of the dispersion region in the dogleg to minimize the beam beta function β_x on the mask to make the beam size in x-plane dominated by the dispersion and not by the transverse emittance. The dogleg is followed by a zero dispersion region with a vacuum chamber where we installed the dielectric tube on a motorized mount for the real time alignment. The last beamline element is the 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 beta function β_x 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. Figure 4 shows the plots of the beam twiss parameters for the whole beamline starting from the linac output with magnets' currents optimized in MAD-X [7] for beam shaping for a set of initial beam parameters close to those which we had in the experiment. It demonstrates low β_x and high dispersion D_x where the mask was located. At the top of Fig. 4 there is a scheme with all the magnets, excluding only weak dipole magnets used for fine beam steering, positioned along the beam path.

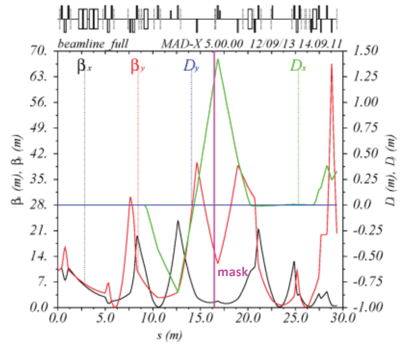

Figure 4: Twiss parameters as modeled in MAD-X vs the beam propagation distance with the mask location marked.

BEAM MASK

In many previous experiments performed at ATF the mask orientation was so that the head of the beam had lower energy than its tail. As we have demonstrated in [8], it resulted in poor resolution on the spectrometer due to the CSR effect in the dipole bends. The CSR effect causes the beam tail to lose more energy than the head thus reducing the overall beam energy spread. Having bigger energy spread improves spectrometer resolution of small features.

The other effect related to the mask orientation is that depending on the beam chirp sign there is either stretching or compression of the beam arriving to the experimental chamber due to nonzero beamline transfer matrix element R_{56}. In our case a beam with positive chirp undergoes stretching due to the quadrupole optics inside of the dogleg that reduces the current and thus lowers the wakefields. As the dielectric tube's length is restricted due to the beam loss increasing with its length (caused by misalignment and beam divergence), it is advantages to increase the beam current by compression to make the wakefields stronger. Our new mask was made to take advantage of these both improvements.

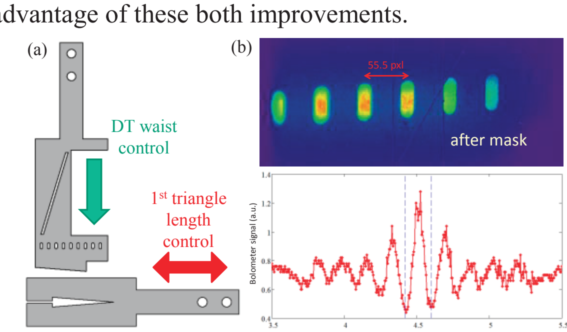

Figure 5: Adjustable beam mask (a). Longitudinal size calibration using coherent transition radiation interferometry (b).

The two critical parameters of the DT bunch current are the length of the first triangle (which must be a quarter of

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the radiation wavelength in vacuum) and the waist between the triangles. In principle, the length of the first triangle can be controlled by adjusting the chirp. The waist between the triangles can be made permanent if the beam density on the mask is known to be uniform. To take better control on those two parameters the mask was made adjustable and consisted of two movable aluminium plates as shown in Fig. 5a. It also allowed to produce equally separated identical bunches and a single triangle bunch with a witness bunch separated by a tuneable distance. Equally separated bunches were used to calibrate a relationship between the beam length in the experimental chamber and the transverse beam size readings in pixels from a removable monitor located behind the mask (Fig. 5b).

EXPERIMENT

In the experiment the horizontal mask turned out to have limited movability in the direction to the left (Fig. 5a). As a result, for energy chirps allowing stable operation the smallest first triangle we could achieve was half of the radiation wavelength with the quarter wavelength required for the optimum DT bunch. Another problem was a not sharp first triangle tip in the beam pictures after the mask. The latter could be partially due to not enough distance from the mask to the diagnostic monitor for the scattered by the mask particles to separate from the rest of the beam.

Due to the above problems the experiment was limited to adjusting the waist between the triangles with the mask and observing the change on the spectrometer with and without the dielectric tube. To get higher wakefields we operated at the maximum charge of 800 pC before the masks for which the operation was still stable. Figure 6 shows an example of the processed experimental data for two different positions of the vertical mask blade: beam profiles after the mask and beam spectrometer pictures for the cases of beam passing through the tube and when the tube was moved out of the way. The beam widths at the location of the tube corresponded to standard deviations of 140 μm and 80 μm. The beam loss caused by the tube's finite diameter of 400 μm and its alignment errors was about 25%. The tube's length was 6 cm. After passing through the tube the beam had a distinct energy modulation, which was determined by the mask shape. Comparison of energy modulations for two different mask openings revealed the difference in wakefields of up to ≈5 MV/m. Wakefield computations with the beam current recovered from the pictures of the transverse beam profile (Fig. 6) gave the maximum wakefield change of ≈4 MV/m.

CONCLUSION

A real time wakefield shaping experiment was carried out. The profile of the wakefield acting on a bunch inside a dielectric tube was mainly characterized through the imposed energy modulation of the output beam having initially only linear chirp. The ultimate goal of creating close to uniform wakefield profile was not achieved. Even though there are ways for improvement of the experiment, this goal is difficult to achieve due to the underlying limits of the beamline, aligning procedures and measuring equipment. For example, the final beam current profile cannot be reliably confirmed with a spectrometer measurement due to the CSR effect. A transverse deflecting cavity would be a very helpful addition for the beam characterization.

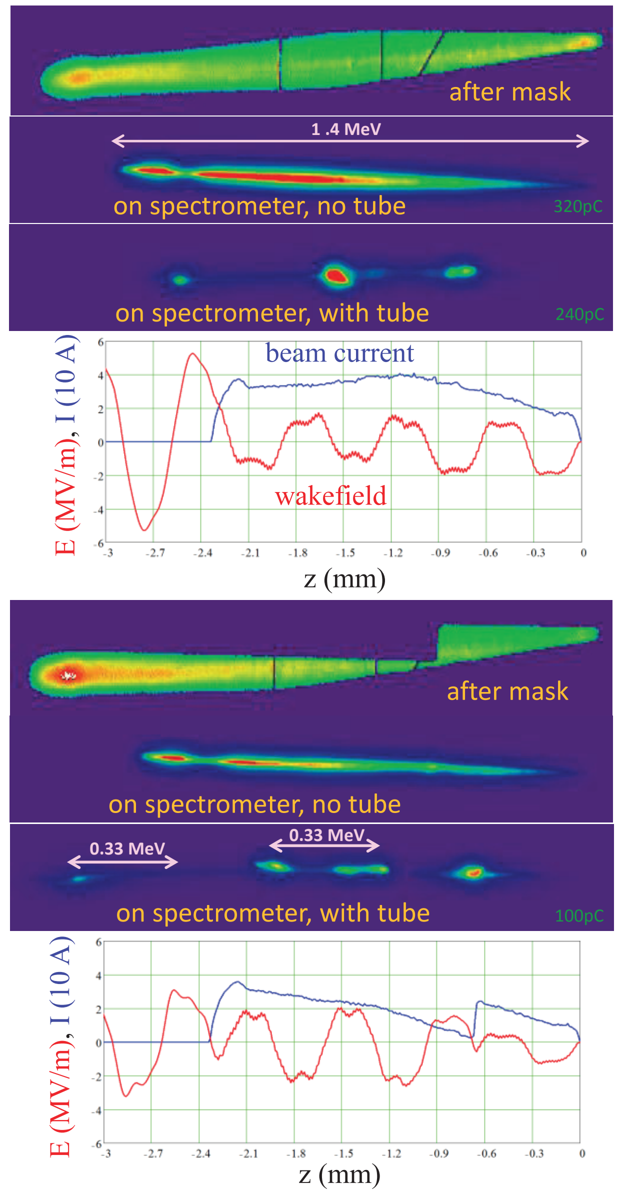

Figure 6: Experimental data for two different mask openings with corresponding computed current and wakefield profiles. Distortions in the form of lines on the transverse beam profile pictures are from wires used for measuring the beam's width.

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