SHAPING ELECTRON BUNCHES FOR ULTRA-BRIGHT ELECTRON BEAM ACCELERATION IN DIELECTRIC LOADED WAVEGUIDES*

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Abstract

We describe a possible design of an Emittance Exchanger (EEX) which may be employed to generate a pair of a double-triangular drive bunch and a trapezoidal witness bunch for a Dielectric Wakefield Accelerator (DWA). We consider the concept of a high-brightness DWA with the gradient of above 100 MV/m and less than 0.1% induced energy spread in the accelerated beam as a possible afterburner for the proposed Los Alamos Matter-Radiation Interactions in Extremes (MaRIE) signature facility. We present the results of simulations with Elegant which take into account non-linear effects of the EEX beamline. Possibilities for producing ideal beam shapes to demonstrate low induced energy spread in a DWA are discussed.

INTRODUCTION

The modern discovery science has an emerging need for a very hard X-ray source, with high-peak fluxes of coherent 42-keV photons (~ 0.3 angstrom wavelength). High energy photons will allow resolving grain boundaries in materials in extreme states such as experiencing shock waves and being able to penetrate μm-to-mm sized samples. High photon energies are also required to prevent samples from disintegrating from a single X-ray pulse, allowing multiple images of transient effects. High-resolution imaging of these effects will optimally require up to 10^{12} photons per X-ray pulse, well above the ability of current technology. Los Alamos National Laboratory (LANL) has identified this discovery science frontier as an important part of its future mission and has proposed the Matter-Radiation Interactions in Extremes (MaRIE) facility [1], which includes an X-ray free electron laser (XFEL) as described in [2].

The number and the energy of photons produced by the XFEL is strongly dependent on the energy of the electron beam produced by the linear accelerator with the more energetic beam delivering more high energy photons to the user. Although generally the baseline design needs to be conservative and rely on existing technology, any future upgrade would immediately call for looking into the advanced accelerator concepts capable of boosting the electron beam energy up by a few GeV in a very short distance without degrading the beam quality. Typical electron beam quality parameters for XFEL applications are electron bunch charges of 0.1 to 1 nC, normalized rms emittances of 0.1 to 1 μm, and rms energy spreads of < 0.1%. By decreasing the bunch energy spread and emittance, it is possible to increase the total X-ray flux by orders of magnitude [2]. Dielectric Wakefield Accelerator (DWA) [3,4] has a potential to satisfy the required constraints of the afterburner and produce acceleration gradients above 100 MV/m and less than 0.1% spread in the gained beam energy [5].

We have initiated a project at LANL to demonstrate the proof-of-principle operation of a DWA with shaped drive and witness bunches at high gradient, and with enhanced transformer ratio and reduced energy spread.

REDUCING WITNESS BUNCH ENERGY SPREADS IN DWAs

DWAs are formed by one or several dielectric layers surrounded by metal cladding (Figure 1). The dielectric constant and the inner and outer radii of the dielectric tubes (or single tube in the simplest case) are chosen so that the phase velocity of the fundamental monopole mode (TM_{01}) is approximately equal to the speed of light and the mode is effectively excited by the beam passing in the central vacuum channel. In a collinear DWA the field generated by a leading, high-charge drive bunch is used to accelerate a trailing, low-charge main bunch which contains a relatively small amount of charge. The wakefields excited by a leading bunch have the remarkable property that the axial electric field and the transverse electric field are transversely uniform and linear, respectively. If one can make the wakefield to be axially 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 it is possible that an accelerated beam in a DWA can achieve the needed small energy spread if the longitudinal witness bunch profile is properly customized [5].

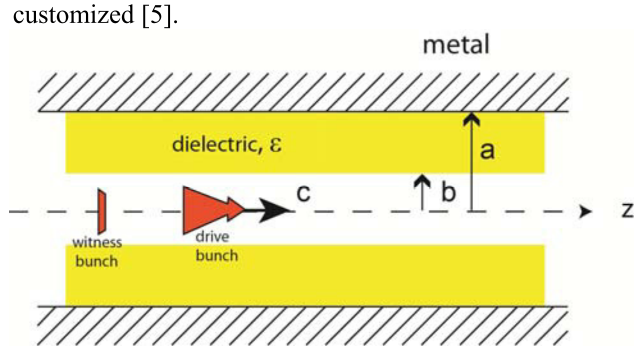

Figure 1: The schematic of a dielectric loaded waveguide with shaped electron beams traveling on axis.

Figure 2 shows the current profiles of the driving double triangular bunch and a trapezoidal witness bunch and their corresponding longitudinal wakefield generated

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in a single mode wakefield accelerator. The wakefield is computed using the Green function method for the DWA geometry with parameters summarized in Table 1. It can be seen from the figure that the wakefield excited by the witness bunch interferes with the wake excited by the drive bunch which results in a uniform gradient experienced by the witness bunch. As a result, the induced energy spread in the witness bunch is below 10^{-5}.

In addition, Figure 2 illustrates the high transformer ratio generated by the double triangular drive bunch. The enhanced transformer ratios which result from generating the wake with the shaped drive bunches are important for achieving high gradients in DWAs.

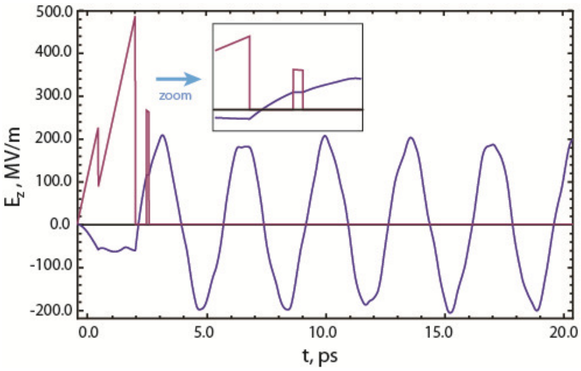

Figure 2: The current profiles of the drive and the witness bunches (red line) and the wakefield (blue line) excited by the pair of bunches in a proposed DWA configuration.

Table 1: Parameters of the 300 GHz Dielectric Wakefield Accelerator Configuration

Beam pipe ID, *2b*	1.14 mm
Dielectric tube ID, *2a*	1.24 mm
Waveguide cutoff	298 GHz
Charge of the drive bunch	5 nC
Length of the drive bunch	2.350 ps
Charge of the witness bunch	250 pC
Length of the witness bunch	100 fs
Time between the bunches	2.8017 ps
Transformer ratio	3.38
ΔG/G	$9*10^{-6}$

PRODUCING SHAPED BEAMS WITH EEX

In order to simultaneously generate the double triangular drive bunch and a trapezoidal witness bunch for a proof-of-principle demonstration, the recently proposed Emittance Exchanger (EEX) [6,7] can be employed. The schematic of a possible beamline is shown in Figure 3. The beamline starts with a mask which has two shaped slots. The slots have special shapes and are optimized to cut out the correct double triangular and trapezoidal beam profiles out of the Gaussian bunch (Figure 4). The mask is followed by an Emittance Exchanger which consists of two identical doglegs, a deflecting cavity in between them, and a number of corrective elements, such as a fundamental mode cavity, quadrupoles and possibly sextupoles. We conducted the extensive tuning of the EEX optics to convert the distribution of particles shaped in x direction into a distribution of particles similarly shaped in z direction.

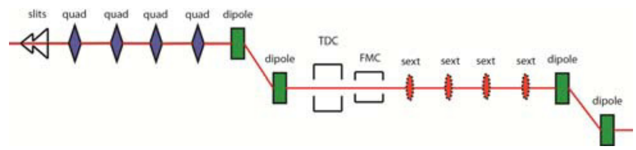

Figure 3: The schematic of a beamline for producing shaped electron bunches.

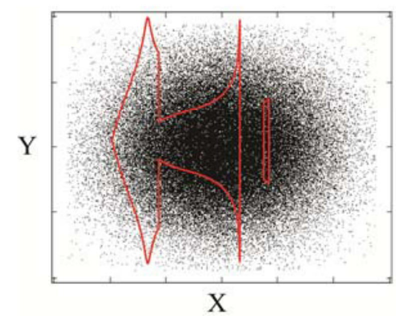

Figure 4: The shape of the mask plotted on top of the Gaussian bunch.

The beamline was modeled with Elegant [8], which is a matrix code. Without accounting for the space charge effect and coherent synchrotron radiation (CSR), the final 6-dimensional phase space coordinates of each particle in Elegant can be obtained from the initial phase space coordinates using different orders of transfer matrices of the beamline:

$$X_i^F = R_{ij}X_j + T_{ijk}X_jX_k + Q_{ijkl}X_jX_kX_l;\ \ i,j,k,l = 1,2,\dots 6.$$

In order to have the perfect transformation of the beam in the first (linear) order described by R-matrix, we want to have R_{5j}=0 except for R_{51}, which determines the stretch factor. The conditions R_{53}=R_{54}=0 are satisfied automatically in this configuration as the y-space remains uncoupled to both x and z spaces. In order to make R_{55}=R_{56}=0 the dispersion of the doglegs has to be matched to the deflecting cavity. Since the deflecting cavity of a finite length produces a time-correlated energy variation in the beam, it is necessary to include a fundamental mode cavity to compensate this effect.

Matrix elements R_{51} and R_{52} can be adjusted with the quadrupole magnets in front of the emittance exchanger. Using just two quadrupoles is sufficient to make R_{52}=0 and R_{51} equal to whatever required stretch factor. However, with only two quadrupoles we do not have any control over the width of the bunch (beta functions) along the beamline. The beta-functions may become quite large and the second order aberrations then become significant.

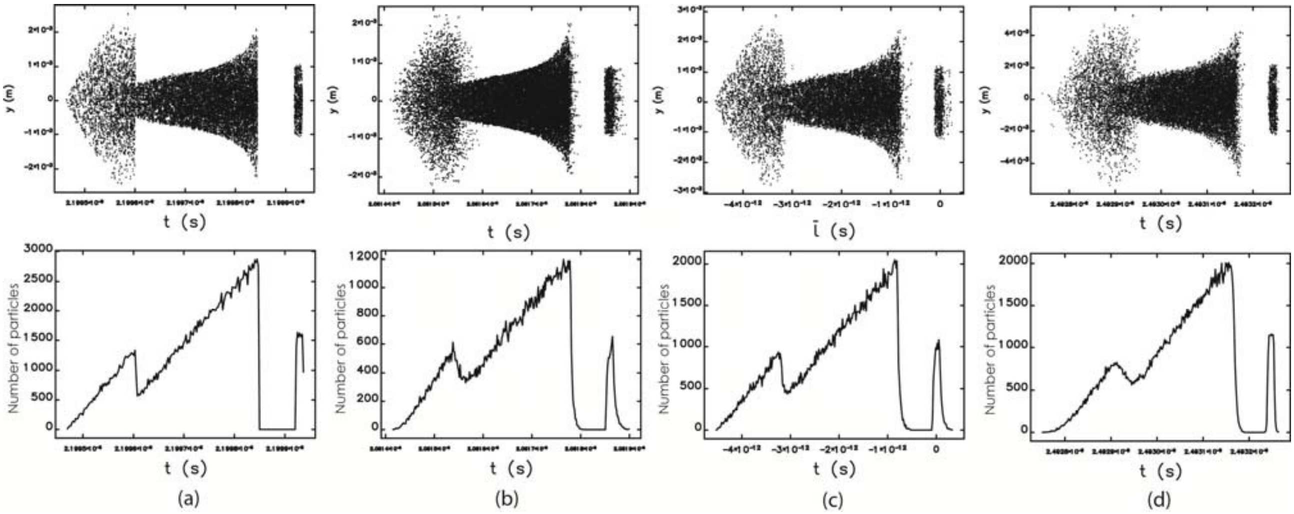

Figure 5: Distributions of the electrons (2D and integrated over y-axis) in the drive and witness bunches after the mask and the EEX as computed by Elegant: (a) in the first order of matrix elements, (b) in the third order of matrix elements, (c) in the first order with the second order matrix element T_{555} artificially included, and (d) in the third order with correcting sextupoles turned on.

With four quadrupole magnets before the EEX we have the control over R_{51}, R_{52}, beta functions and also over R_{61}, which we would like to keep small to avoid a longitudinal momentum chirp in the shaped bunch. Figure 5(a) shows the final distribution of particles and current in the shaped drive and witness bunches as computed with Elegant with only the first order of the transfer matrix.

The phase space exchange looks perfect in the first order simulations. However, when computations were performed to take into account the higher order matrices, aberrations were discovered (Figure 5(b)). We analysed the effects caused by different second and third order matrix elements and concluded that the observed changes in the shape of the witness bunch were mostly due to the effects of the second order matrix elements T_{555} and T_{551}. Figure 5(c) shows the distribution of electrons computed with the first order matrix and the T_{555} element artificially added. The aberrations due to the second order elements could be mitigated by placing a number of sextupole magnets in between the cavities and the second dogleg. Figure 5(d) shows the distribution of electrons with the sextupole corrections.

CONCLUSION

We have designed and optimized a beam shaping beamline to produce a double triangular drive and a trapezoidal witness bunches for a high transformer ratio low induced energy spread dielectric wakefield accelerator experiment. The beamline consisted of a mask followed by a tuned Emittance Exchanger. The EEX provides a unique tool for shaping beam currents in a small time scale. We realized that the EEX method is not perfect, as the higher order nonlinear effects in the beamline distort the desired pulse shape. Suppression of nonlinearities by inserting new elements into the beamline like quadrupoles, sextupoles or even octupoles can help reducing higher order nonlinearities, but will also increase complexity of the system that will eventually make tuning and aligning more difficult. The tighter focused beam may also become more prone to the space charge related effects. An experiment is planned in the near future to fully evaluate the nonlinearities and the space charge effects. We plan to conduct a beam shaping experiment with an EEX to evaluate the effects which are difficult to account for in simulations. This work may eventually evolve into a conceptual design of an afterburner for the proposed LANL future signature facility MaRIE. It also has the potential to advance the DWA technology to a level to make it suitable for a number of national security applications, including compact accelerators for warfighter support and active interrogation.

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