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Possibility for Ultra-bright Electron Beam Acceleration in Dielectric Wakefield Accelerators

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Abstract. We describe a conceptual proposal to combine the Dielectric Wakefield Accelerator (DWA) with the Emittance Exchanger (EEX) to demonstrate a high-brightness DWA with a gradient of above 100 MV/m and less than 0.1% induced energy spread in the accelerated beam. We currently evaluate the DWA concept as a performance upgrade for the future LANL signature facility MaRIE with the goal of significantly reducing the electron beam energy spread. The pre-conceptual design for MaRIE is underway at LANL, with the design of the electron linear accelerator being one of the main research goals. 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's quality. Scoping studies have identified large induced energy spreads as the major cause of beam quality degradation in high-gradient advanced accelerators for free-electron lasers. We describe simulations demonstrating that trapezoidal bunch shapes can be used in a DWA to greatly reduce the induced beam energy spread, and, in doing so, also preserve the beam brightness at levels never previously achieved. This concept has the potential to advance DWA technology to a level that would make it suitable for the upgrades of the proposed Los Alamos MaRIE signature facility.

Keywords: dielectric wakefield accelerator, emittance exchanger, free electron laser.
PACS: 41.60.Cr, 41.75.Lx, 41.85.

INTRODUCTION

Discovery science requirements will drive future X-ray Free-Electron Lasers (XFELs) toward multiple directions. There is a clear need for high-average flux, soft X-ray FELs. There is additionally an emerging need for a very hard X-ray source, with high-peak fluxes of coherent 42-keV photons (~ 0.3 angstrom wavelength). At this frontier, time-resolved materials properties in extreme states (e.g., imaging shock waves to determine transient equation-of-state behavior) will be measured. These effects will be dominated by materials dynamics at grain boundaries. Resolving these grain dimensions and being able to penetrate μm-to-mm sized samples require high-energy photons, on the order of 42 keV. 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 vision and has proposed the Matter-Radiation Interactions in Extremes (MaRIE) facility [1], which includes an XFEL as described here [2].

Typical electron beam quality parameters for modern applications (FELs, XFELs, linear colliders, and national security 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% (where the emittance is a normalized measure of the beam's area in phase space). The graph for the nominal photon power produced by the MaRIE XFEL for a bunch rms current of 3.4 kA is shown in [2]. By decreasing the bunch energy spread and emittance, it is possible to increase the total X-ray flux by two orders of magnitude. New techniques developed at LANL can reduce the bunch emittances to 0.15 μm [3], and are possible to implement if the beam energy spread is sufficiently small (0.01% and below).

In a conventional rf accelerator, an oscillating electromagnetic field is established in a metallic structure or cavity and used to resonantly accelerate the electron beam. Even in the ideal case, there are two effects in an rf cavity that lead to an energy spread in the beam. First, the time variation of the rf fields themselves leads to a curvature in the longitudinal phase space and particles at different transverse positions see different magnitudes of the accelerating fields, which are both proportional to the energy gain of the bunch and independent of bunch energy, typically leading to energy spreads of ~0.1% at rf frequencies at 3 GHz and below. Second, the beam's own space-charge fields lead to additional energy spread. Fortunately, the beam's space-charge fields vanish due to relativistic cancelation as the bunch is accelerated, but that effect is replaced by a more dominant effect. As the bunch is accelerated, the bunch itself drives additional electromagnetic fields in the cavity, known as wakefields. These wakefields include the effect of the energy transfer from the primary cavity field to the bunch's kinetic energy and also the energy in all the other normal modes of the cavity driven by the passage of the bunch. These wakefields interact with the bunch and lead to a significant energy spread that stays proportional to the energy gain and additionally is linearly proportional to the total bunch charge and scales as the square of the accelerating frequency.

In this paper we will discuss the means that may allow us to harness the dangerous phenomena of wakefields and shape the wake produced by a driving bunch in a dielectric wakefield accelerator (DWA) in such a way that the witness bunch is being accelerated by a constant gradient resulting in no energy spread.

USING DWAs FOR REDUCTION OF THE ENERGY SPREAD

Exactly the same phenomena, that causes the dominant energy spread effect in beams can be used to generate extraordinary gradients in plasmas [4,5] and dielectric structures [4, 6-9] via wakefield acceleration. Dielectric wakefield accelerators (DWAs) are formed by one or several co-axial 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 to adjust the phase velocity of the fundamental monopole mode (TM_{01}) to approximately the speed of light so that the mode is effectively excited by the beam passing in the central vacuum channel. In a collinear dielectric wakefield accelerator, the fields generated by a leading, high-charge drive bunch (either a single drive bunch or a train of drive bunches) is used to accelerate a trailing, low-charge main bunch which contains a relatively small amount of charge.

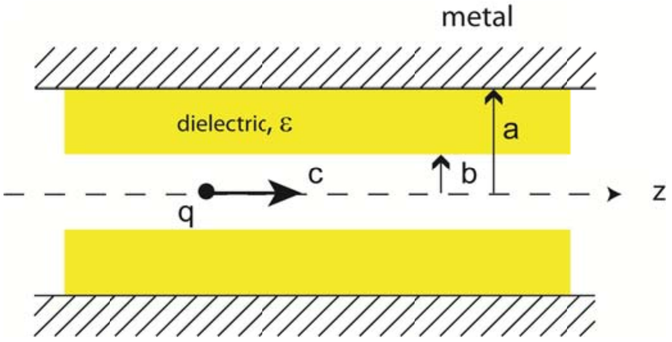

FIGURE 1. The schematic of a dielectric loaded waveguide and an electron beam traveling along the axis.

Wakefields in dielectric structures may reach gradients on the order of 10 GV/m [10], with 100 MV/m being demonstrated in multiple experiments [8]. 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 subsequent wakefield travels very nearly exactly at the speed of light and the wakefield is transversely at cut-off. If one can make the wakefield to be axially constant along the bunch (resulting in no energy spread), all transverse fields on the bunch vanish, leading to an extraordinary condition of preserving the main beam brightness while providing high gradient acceleration.

A good analytical description of the electromagnetic fields excited by an on-axis electron bunch in a dielectric-loaded waveguide is presented in [11]. The eigenmodes of this electromagnetic system are represented by Bessel functions in radial direction with sinusoidal variation in longitudinal direction. And the field excited by an electron bunch of an arbitrary shape can be represented as a sum of those.

An important parameter that influences the performance of a wakefield accelerator is the transformer ratio (*TR)* which is the ratio of the maximum energy gain of the witness bunch to the maximum energy loss of the drive bunch. To accelerate the witness beam to high energy it is desirable to make the TR as large as possible. For a Gaussian-shaped drive beam pulse the transformer ratio cannot exceed two [12]. However, there are techniques that can achieve TR > 2 by breaking the symmetry of the drive beam and creating bunches of triangular shape [13] or its variations (ramped bunch train [14] and double-triangular [15]). Figure 2 illustrates the current profile of the double triangular bunch and its corresponding longitudinal wakefield generated in a single mode wakefield accelerator. Theoretically, the maximum transformer ratio for a double triangular drive bunch is

$$TR = \sqrt{1 + (\omega T - 1)^2} \ , \tag{1}$$

where ω is the characteristic resonant frequency of the wake function and T is the duration of the bunch. The dimensions of the dielectric loaded waveguide, the bunches and the transformer ratios for the geometry with the wakefield of Figure 2 are summarized in Table 1. Figure 2 also shows the longitudinal electric field excited by the two bunches (the high charge double-triangular drive bunch and the lower charge trapezoidal main bunch) on axis of the dielectric-loaded waveguide. The dimensions of the waveguide were chosen so that a 5 nC drive bunch would be capable of exciting a gradient of more than 100 MV/m, which is required for the reasonable afterburner for MaRIE. The shape of the drive bunch was customized to achieve the high transformer ratio of more than 3 and the uniform deceleration within the bunch to effectively utilize its energy. The trapezoidal shape of main bunch was adjusted to achieve the maximum uniformity of the gradient witnessed by the accelerated electrons. We found that in theory, the induced energy spread in the witness bunch on axis could be made as low as $\frac{\Delta G}{G} < 10^{-5}$.

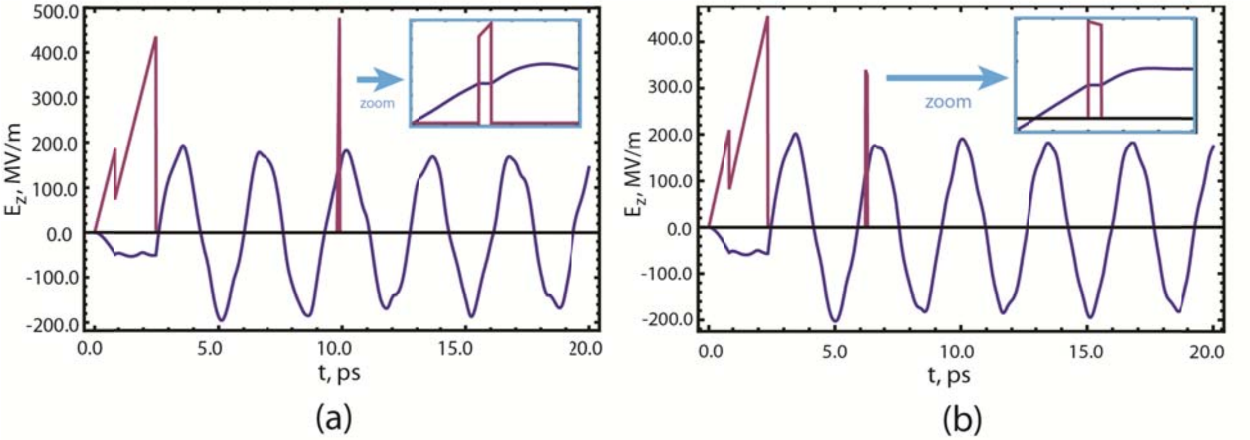

FIGURE 2. The wakefield (blue) from a double-triangular drive bunch, showing a large transformer ratio (the ratio of the peak accelerating gradient to the decelerating gradient experienced by the drive bunch) and the current profiles of the drive and the witness bunches (red). The wakefield inside of a trapezoidal witness bunch (also zoomed in) shows a flat gradient observed by the electrons in the witness bunch. (a) Configuration 1; and (b) Configuration 2.

TABLE 1. Dimensions of the 300 GHz dielectric loaded waveguide, parameters of the double-triangular drive bunch and witness bunch, and the resulting transformer ratio and induced energy spreads for the two high transformer ratio dielectric wakefield acceleration configurations.

	Configuration 1	**Configuration 2**
Beam pipe OD, *2b*	1.14 mm	
Dielectric tube OD, *2a*	1.24 mm	
Waveguide cutoff	298 GHz	
Charge of the drive bunch	5 nC	
Length of the drive bunch	2.127 ps	2.373 ps
Charge of the witness bunch	250 pC	
Length of the witness bunch	75 fs	
Time between the bunches	9.4 ps	6.2 ps
Transformer ratio	3.16	3.34
ΔG/G	$1.5 \cdot 10^{-5}$	$8.5 \cdot 10^{-6}$

The simultaneous double triangular shape of the witness bunch and the trapezoidal shape of the main bunch are now relatively easy to implement using a new accelerator optic called an Emittance EXchanger (EEX), recently proposed [16] and demonstrated [17], if we include a simple multi-slit mask [18]. The EEX optics exchanges one of the transverse planes of the electron beam (for instance the y-plane) with the longitudinal plane. The double-triangular or trapezoidal shapes can be easily produced in the transverse directions with a mask. An adjustable mask with the varied distance between the drive bunch and the witness bunch can be employed to map the wake excited by the drive bunch [19] and to minimize the induced energy spread within the witness bunch.

Tolerances on the parameters of the drive and witness bunches were studied to figure out if the induced energy spread of <0.01% could be realized in an experiment. The tolerances are summarized in Table 2. It can be seen from the table that the tolerances, especially the tolerances on the witness bunch are very tight. The future experiment will demonstrate how close the realistic conditions may be able to reproduce the ideal configuration.

TABLE 2. Tolerances on the dimensions and charges of the drive and witness bunches to keep the induced energy spread below 0.01%.

	Configuration 1	**Configuration 2**
Charge of the drive bunch	4.999 nC < Q < 5.004 nC	
Charge of the witness bunch	249.9 pC < q < 250.1 pC	
Length of the drive bunch	2.1272 ps < T_0 < 2.1277 ps	2.3728 ps < T_0 < 2.3734 ps
Time between the bunches	9.3995 ps < ΔT< 9.4013 ps	6.1997 ps < ΔT< 6.2003 ps
Length of the witness bunch	74.95 fs < T_1 < 75.02 fs	74.96 fs < T_1 < 75.04 fs

Apart from the tolerances on the length and the charges of the bunches, any realistic transverse distribution of the charge within the drive bunch and the witness bunch may cause deviations from the ideal simulations. To analyze this effect, the geometry and the beam was modeled with CST Particle Studio [20]. As an initial step, a simulation was run with all particles on axis and 10^7 mesh points, and the results of the simulation are shown in Figure 3. We learned that the Particle Studio was unable to clearly resolve the 75 fs long trapezoidal witness bunch within the geometry with typical dimensions of 1 mm. The numerical noise was excessive. In spite of being seemingly very simple, this problem has to be modeled by more powerful parallel-computing software, such as VPIC [21] or Vorpal [22], which will be done in the near future.

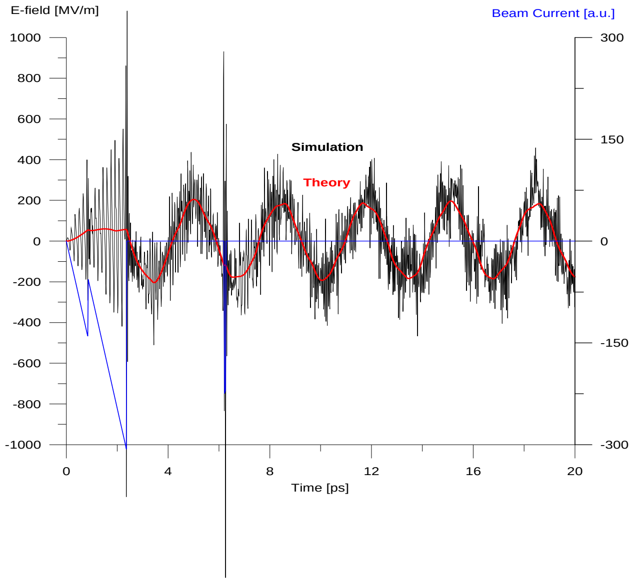

FIGURE 3. Simulations of the wakefield produced by a double-triangular drive bunch and a trapezoidal witness bunch with a Particle Studio with approximately 10^7 mesh points (black curve). The wake derived from the simple Bessel equations following [11] (red curve).

CONCLUSION

We described a conceptual proposal to combine the dielectric wakefield accelerator with the emittance exchanger to shape the drive electron bunch into a double-triangular shape and the main bunch into a special trapezoidal shape. As a result, we plan to demonstrate a high-brightness DWA with the gradient of above 100 MV/m and less than 0.1% induced energy spread in the accelerated beam. In our opinion, an ideal location for such a demonstration is the Advanced Superconducting Test Accelerator (ASTA) facility in Fermilab [23], which produces an electron bunches with a charge up to 10 nC and is perfectly equipped to conduct the beam shaping experiment with EEX. We currently evaluate the DWA concept as a performance upgrade for the future LANL signature facility MaRIE with the goal of significantly reducing the electron beam energy spread. Considering the long time scale associated with the MaRIE project, this technology, if demonstrated now, may provide an approach to boost the energy of the electron beam feeding the MaRIE XFEL from the nominal 12 GeV up to 20.8 GeV with a very low cost upgrade. This upgrade would allow a much greater production of 126-keV photons, now at the third harmonic of 42 keV. With the current 12 GeV MaRIE linac design, generation of the third harmonic photons is suppressed in the wiggler.

However, photon energy above 120 keV is required for the K-shell ionization of uranium and other actinides, an important MaRIE mission and part of its funding justification. An 8.8-GeV DWA afterburner would lead to over an order of magnitude greater production of these high energy photons.

This work 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 (e.g. small weaponized free-electron lasers) and active interrogation (e.g. small and inexpensive electron accelerators as compact front ends for muon active interrogation sources or alternatively to generate bremsstrahlung radiation).

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REFERENCES

1. Matter–Radiation Interactions in Extremes (MaRIE) facility. http://marie.lanl.gov.
2. B. E. Carlsten, K. A. Bishofberger, L. D. Duffy, C. E. Heath, Q. R. Marksteiner, D. C. Nguyen, R. D. Ryne, S. J. Russell, E. I. Simakov, and N. A. Yampolky, *J. of Mod. Optics* **58**(16), 1374 (2011).
3. B. E. Carlsten, K. A. Bishofberger, L. D. Duffy, S. J. Russell, R. D. Ryne, N. A. Yampolsky, and A. J. Dragt, *Phys. Rev. ST – Accelerators and Beams* **14**, 050706 (2011).
4. B.E. Carlsten, E.R. Colby, E.H. Esarey, M. Hogan, F.X. Kärtner, W.S. Graves, W.P. Leemans, T. Rao, J.B. Rosenzweig, C.B. Schroeder, D. Sutter and W.E. White, *Nucl. Instrum. Meth. A*, **622**, 657 (2010).
5. W. P. Leemans, B. Nagler, A. J. Gonsalves, C. Toth, K. Nakamura, C. G. R. Geddes, E. Esarey, C. B. Schroeder, and S. M. Hooker, *Nature Phys*., **2**, 696 (2006).
6. W. Gai, P. Schoessow, B. Coley, R. Konecy, J. Norem, J. Rosenzweig, and J. Simpson, Phys. Rev. Lett., **61**, 2756 (1988).
7. M. Rosing and W. Gai, *Phys. Rev. D*, **45**, 1829 (1990).
8. C. Jing Wei Gai, John G. Power, Richard Konecny, Wanming Liu, Steven H. Gold, Allen K. Kinkead, Sami G. Tantawi, Valery Dolgashev, and Alexei Kanareykin, *IEEE Trans. on Plasma Science*, **38**(6), 1354 (2010).
9. C. Jing, A. Kanareykin, J.G. Power, A. Zholents, *Proceedings of IPAC11*, 1485 (2011).
10. M. C. Thompson, H. Badakov, A. M. Cook, J. B. Rosenzweig, et al, *Phys. Rev. Lett*., **100**, 214801 (2008).
11. C. Jing, *PhD Thesis*, Illinois Institute of Technology (2005).
12. P.B. Wilson, *SLAC Report* No. 296, 273 (1985).
13. K.L.F. Bane, P. Chen, P.B. Wilson, *IEEE Trans. on Nuclear Science*, **32(**5), 3524 (1985).
14. C. Jing, J. G. Power, M. Conde, W. Liu, Z. Yusof, A. Kanareykin, and W. Gai, *Phys. Rev. ST – Accelerators and Beams* **14**, 021302 (2011).
15. C. Jing, J. Power, and A. Zholents, *Report ANL/APS/LS-326* (2011).
16. P. Emma, Z. Huang, K.-J. Kim, P. Piot, Phys. Rev. ST Accel. Beams, **9**, 100702 (2006).
17. A. Johnson, J. Ruan, H. Edwards, T. Koeth, A. Lumpkin, P. Piot, J. Santucci, Y.-E Sun, R. Thurman-Keup, *Proceedings of IPAC10*, 4614 (2010).
18. Y.-E. Sun, P. Piot, A. Johnson, A. H. Lumpkin, T. J. Maxwell, J. Ruan, and R. Thurman-Keup, *Phys. Rev. Lett*., **105**, 234801 (2010).
19. S. Antipov, C. Jing, A. Kanareykin, J. E. Butler, V. Yakimenko, M. Fedurin, K. Kusche, and W. Gai, *Appl. Phys. Lett*. **100**, 132910 (2012).
20. CST Particle Studio, Computer Simulation Technology, www.cst.com.
21. K. L. Bowers, B. J. Albright, L. Yin, B. Bergen, and T. J. T. Kwan, *Phys. Plasmas* **15**, 055703 (2008).
22. Vorpal, Tech-X Corporation, http://www.txcorp.com/products/VORPAL/.
23. Jerry Leibfritz, Richard Andrews, Curtis Baffes, Kermit Carlson, Brian Chase, Michael Church, Elvin Robert Harms, Arkadiy L. Klebaner, Michael Kucera, A. Martinez, Sergei Nagaitsev, Lucy Elizabeth Nobrega, John Reid, Manfred Wendt, Steven Wesseln, Philippe Regis-Guy Piot, *Proceedings of IPAC12,* MOOAC02 (2012).