PARTICLE SIMULATIONS OF A LINEAR DIELECTRIC WALL PROTON ACCELERATOR*+

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Abstract

The dielectric wall accelerator (DWA) is a compact induction accelerator structure that incorporates the accelerating mechanism, pulse forming structure, and switch structure into an integrated module. The DWA consists of stacked stripline Blumlein assemblies, which can provide accelerating gradients in excess of 100 MeV/meter. Blumleins are switched sequentially according to a prescribed acceleration schedule to maintain synchronism with the proton bunch as it accelerates. A finite difference time domain code (FDTD) is used to determine the applied acceleration field to the proton bunch. Particle simulations are used to model the injector as well as the accelerator stack to determine the proton bunch energy distribution, both longitudinal and transverse dynamic focusing, and emittance growth associated with various DWA configurations.

INTRODUCTION

With typical gradients on the order of 100 MV/m, a high gradient dielectric wall accelerator (DWA) has potential applications for proton beam cancer therapy. [1,2] A 3D finite difference time domain (FDTD) electromagnetic simulation code [3] is used to determine the field structure for specific DWA configurations. The initial charged state of the structure is determined from an electrostatic solution for the stacked Blumlein configuration. The structure is then discharged using discrete switches according to a temporal schedule to maintain synchronism with the proton bunch. A volumetric, temporal field map is saved from the simulation in the beam transport region, and these fields are subsequently used to transport particles through the system. A finite element mesh can be superimposed on the charged particle bunch for space charge and image force calculations. Initial particle distributions can be specified, or particle distributions from injector simulations [4] can be loaded for transport through the accelerator structure. While this methodology is not self consistent in terms of modeling the detailed beam interaction with the structure, it does allow for quickly assessing the performance of the accelerator channel design for optimization purposes. After a suitable design is obtained, 3D PIC code modeling [4] using the LSP code can be used to assess detailed performance.

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MODELING

Figure 1 shows a representation of an accelerator channel excited by a pair of stacked stripline Blumlein assemblies on opposite sides of the accelerator axis, which minimizes dipole steering fields in the structure.

The Blumlein stacks are discharged sequentially, according to an acceleration schedule, so that the proton bunch maintains synchronism with the accelerating field at the desired gradient.

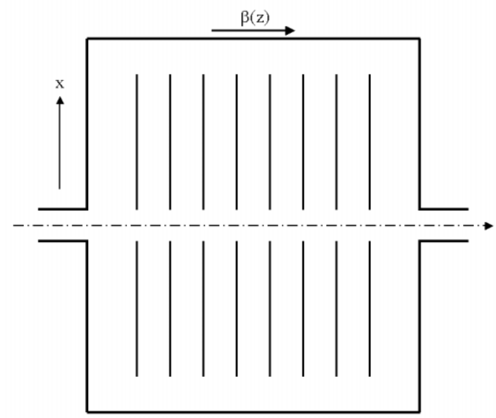

Figure 1: Accelerator geometry.

For a proton bunch that experiences a constant accelerating field, the synchronism condition is defined in Eqs. (1-2)

$$\gamma = \gamma_0 + \frac{E}{mc^2} z \tag{1}$$

$$ct = \frac{mc^2}{E}\left[\left(\gamma^2 - 1\right)^{1/2} - \left(\gamma_0^2 - 1\right)^{1/2}\right] \tag{2}$$

where E is the accelerating field and γ_0 corresponds to the proton bunch injection energy. Figure 2 shows an acceleration schedule for a 780 keV proton in a 40 cm long acceleration channel experiencing a 80 MV/m gradient. For a stacked Blumlein configuration, the peak

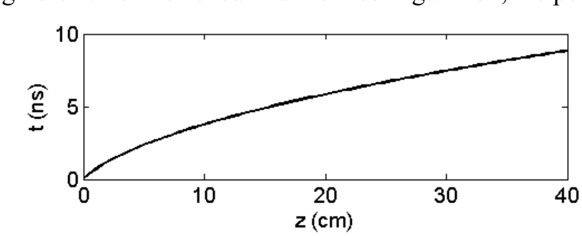

Figure 2: Synchronous timing condition.

accelerating gradient is not uniform through the acceleration channel due to parasitic coupling between individual layers of the Blumlein stack which is a function of the accelerator structure as well as the timing function. This significantly complicates the synchronism condition since the bunch will slip in phase with respect to the Blumlein excitation. Figure 3 shows a typical acceleration pulse near the injection end of the accelerator, and Figure 4 shows the variation of the peak amplitude along the accelerator channel.

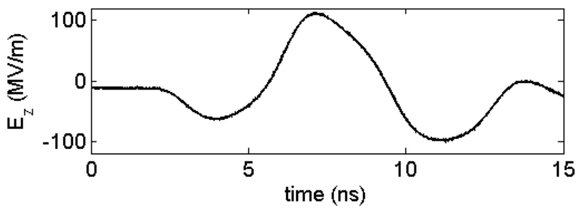

Figure 3: Acceleration pulse.

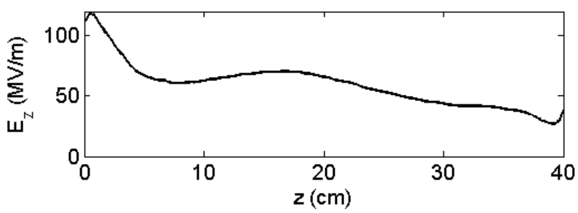

Figure 4: Peak gradient variation along accelerator channel is a function of the channel timing function.

A series of 3D particle simulations were performed to examine the dynamics of the acceleration channel. For all the simulations the bunch was assumed to be at a waist with a radius or 0.5 cm at the entrance to the accelerator. The transverse emittance is 2 cm-mr. These parameters are consistent with injector simulations [4]. Figure 5 shows the transverse phase space at the accelerator entrance. The wall radius of the accelerator channel is 2 cm.

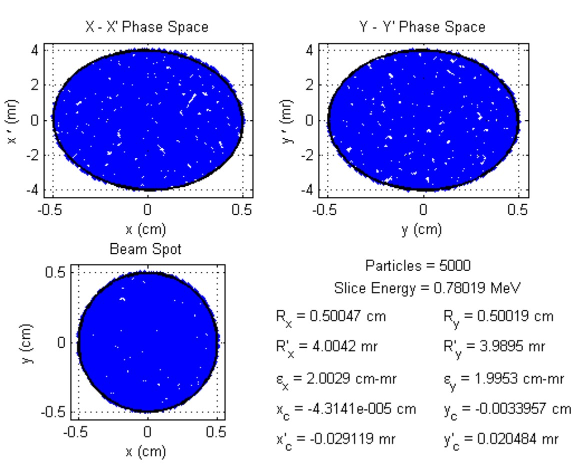

Figure 5: Transverse phasespace at accelerator entrance.

Since the channel has no external focusing elements the bunch injection should be slightly before the peak of the acceleration field (~ 7 ns) to maintain longitudinal focusing of the bunch. At this point there is also a net transverse defocusing force. Figure 6 shows the output energy of the channel as a function of injection time relative to the peak of the field at the accelerator entrance.

The transverse beam size at the output of the accelerator channel is shown in Fig. 7. As can be seen in Fig. 7, the beam intercepts the channel wall if the injection time is too far before the peak of the acceleration waveform. Also, due to the nature of the excitation from the diametrically opposite Blumlein stacks, there is a strong quadupole focusing force on the beam as is evident in the differing size of the beam in x and y as seen in Fig. 7.

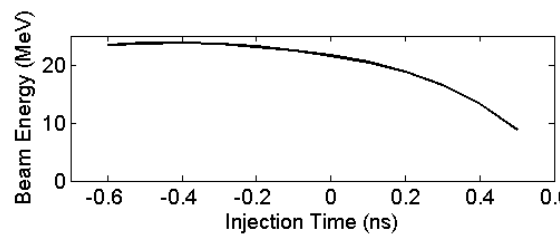

Figure 6: Output energy as function of injection time.

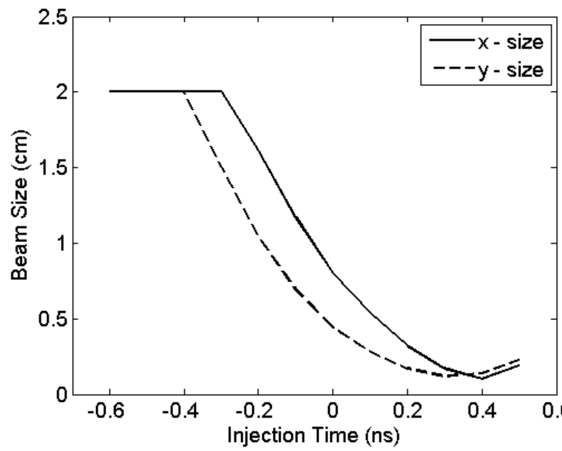

Figure 7: Beam size at output of accelerator channel. The bunch radius is 0.5 cm at the entrance.

Figures 8 and 9 show the output energy and beam size as a function of the injection energy for an injection time near the peak of the accelerating waveform at 7 ns (0 ns relative shift) respectively. To minimize the output beam size, the injection energy should be close to the synchronous design criteria of 780 keV. The transverse phasespace at the accelerator exit for an injection energy of 780 keV at a relative injection time of 0 ns is shown in Fig. 10.

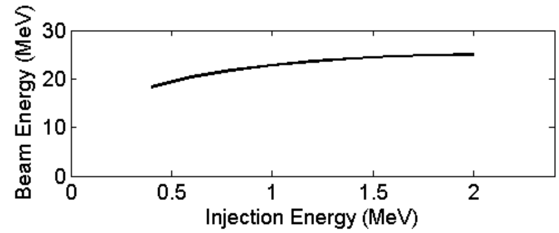

Figure 8: Output energy as function of injection energy.

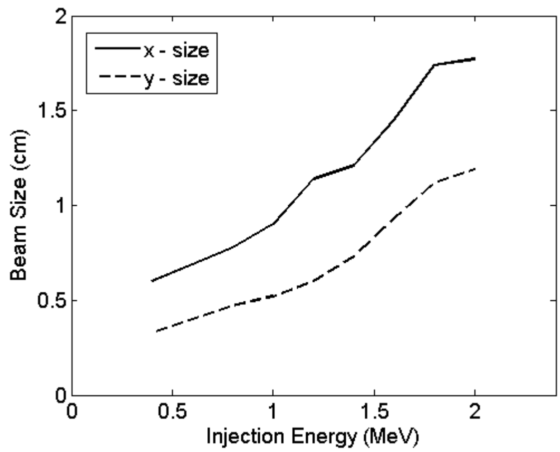

Figure 9: Beam size as function of injection energy.

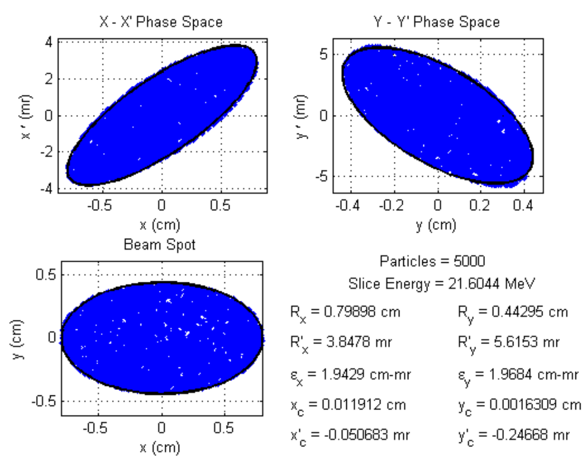

Figure 10: Transverse phasespace at accelerator exit.

Figures 11 and 12 shows the energy variation and temporal shift of the bunch with respect to the accelerating wave along the structure. The energy gain along the channel is less than linear due to the peak gradient variation along the channel and the slippage of the bunch with respect to the accelerating field. Figure 13 shows the transverse beam size variation along the channel. The beam at the accelerator exit is elliptical due to the dynamic quadrupole fields in the structure.

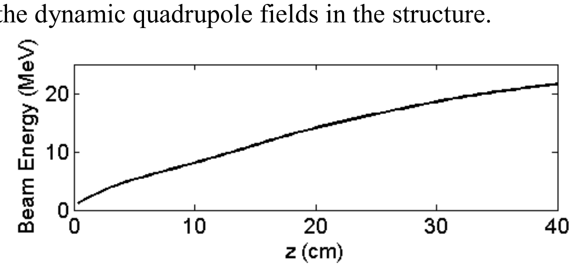

Figure 11: Beam energy along accelerator.

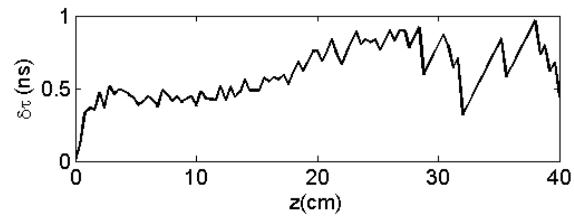

Figure 12: Temporal bunch slippage along accelerator.

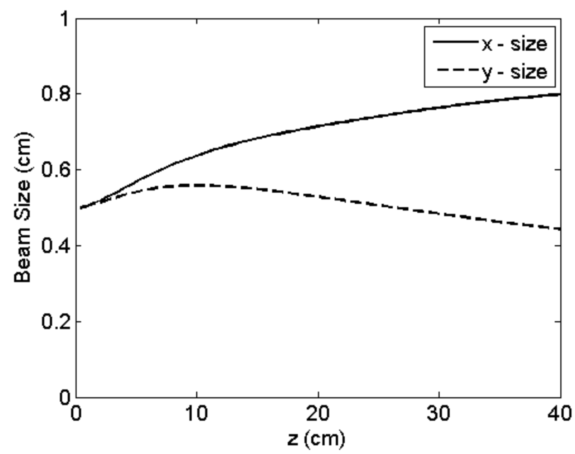

Figure 13: Beam size variation along accelerator.

CONCLUSIONS

In this paper, we have presented 3D particle simulations for a compact, high-gradient DWA proton accelerator. The non-uniformity of the acceleration channel due to parasitic waves complicated the transport of the bunch. Dynamic quadrupole focusing is present due to excitation of the structure from two azimuthal locations. Focusing methodologies are being investigated to transport the bunch over longer distances. In addition, 3D space charge effects are being included in the simulation code for more self-consistent simulations.

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