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BEAM TRANSPORT IN A PROTON DIELECTRIC WALL ACCELERATOR*

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Abstract

The beam tube of the compact dielectric wall (DWA) accelerator, being developed at the Lawrence Livermore National Laboratory [1], is a stack of high gradient insulators, consisting of alternating layers of insulators and conductors. Characteristically, insulators' surface breakdown thresholds go up as the applied voltages' pulse width goes down. To attain the highest accelerating gradient in the DWA accelerator, the accelerating voltage pulses should have the shortest possible duration. This can be done by appropriately timing the switches in the transmission lines, which feed the continuous HGI tube. The accelerating voltage pulses arrive at the accelerator axis along the beam tube at different times so as to appear to the charged particle bunch as a traveling accelerating voltage wave. We have studied the beam transport in a baseline DWA configuration by performing PIC simulations using the 3-D, EM PIC code, LSP [2]. Sensitivity of the output beam parameters to the injector timing jitter is presented. In addition to the baseline configuration, an alternative novel focusing scheme is discussed.

INTRODUCTION

Compact dielectric wall (DWA) accelerator technology is being developed at the Lawrence Livermore National Laboratory [1]. The DWA accelerator's beam tube is a stack of high gradient insulators, consisting of alternating layers of insulators and conductors. Characteristically, insulators' surface breakdown thresholds go up as the applied voltages' pulse width goes down. To attain the highest accelerating gradient in the DWA accelerator, the accelerating voltage pulses should have the shortest possible duration. This can be done by appropriately timing the switches in the transmission lines, which feed the continuous HGI tube. The accelerating voltage pulses arrive at the accelerator axis along the beam tube at different times so as to appear to the charged particle bunch as a traveling accelerating voltage wave bucket (referred as virtual traveling wave later). Depending on the phase of the charge bunch with respect to the short virtual traveling wave bucket, particles are either simultaneously transversely defocused and longitudinally compressed or transversely focused and longitudinally decompressed. Therefore, besides of matching and catching the injected proton bunch into the DWA and flattening the accelerator waveform both temporally and spatially, one of the main challenges for DWA's physics design is to provide simultaneous longitudinal and transverse stability to the charge bunch while maintaining beam quality. In this paper, we present a baseline transport case for a strawman proton therapy machine with timing sensitivity study and an alternative focusing scheme, which indicate that we can meet our design objective.

TRANSPORT IN STRAWMAN DWA

To demonstrate the feasibility of achieving longitudinal and transverse stability simultaneously while maintaining the beam quality, we have studied beam transport in a simple strawman proton DWA therapy machine configuration by performing PIC simulations using the 3-D, EM PIC code, LSP [2]. The strawman machine consists of an injector, a matching section and the DWA. The injecor, such as a RFQ with only a single bucket filled, provides a 2-MeV, 200-ps proton bunch. The 2-m DWA's averaged gradient is about 60 MV/m. The goal of this strawman DWA is to deliver a proton bunch with a nominal energy of 120 MeV and a ±2% energy spread. At the DWA exit, the beam radius is less than a 1-cm and the range for its envelope slope is from -10 mr to 10mr. Finaly, the goal for the normalized Lapostal emittance is not to excess 8π mm-mrad.

To reduce the number of control channels needed in the final system, we group several Blumleins together to form a 1-cm block such that their switches are turned on and off together. To minimize the surface breakdown risk while maximizing the on-axis accelerating field, the wall excitation length on the inner wall of the HGI, roughly equivalent to the virtual traveling wave's traveling velocity (or proton bunch's velocity) times the voltage pulse length, is at least three times of the beam pipe radius through out the entire DWA [1]. At the DWA entrance, the accelerating waveform on the wall has a 3-ns flattop with 1-ns Gaussian rise/fall. As the proton bunch accelerated along the DWA, flattop duration shrinks to maintain the wall excitation length. The waveform reduces to a 1-ns FWHM Gaussian after the flattop duration vanishes at about 20 cm downstream from the DWA entrance (at z = 0 cm). Note that reducing the accelerating pulse to a 1-ns FWHM Gassian pulse does not reduce the accelerating field on the axis since the 1-ns pulse length is much longer than the time required to fill the equilibration ring. The LSP simulated on-axis accelerating waveforms and proton bunch's temporal profiles (narrow spikes) at z = 4.5 cm, 8.5 cm and 55.5 cm are presented in Fig. 1 (a) – (c). The stair-case waveform

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profile at (a) z = 4.5 cm is the result of the long flattop pulse near the DWA entrance and the 1-cm Bulmlein block configuration. As protons being accelerated, the time delay between the turn-on times of the neighboring Blumlein blocks reduces and the voltage pulses approach Gaussian shape. Consequently, the net accelerating field waveform on the axis becomes smoother and Gaussian like as shown in Figs. 1 (b) and (c).

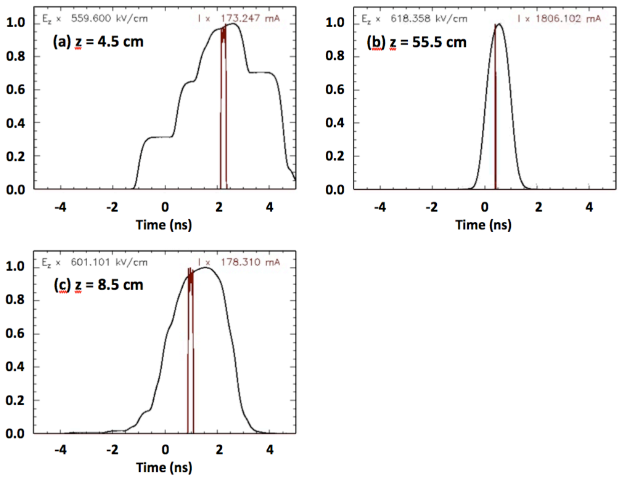

Figure 1: On-axis accelerating field waveforms and proton bunch temporal profiles at (a) z =4.5 cm, (b) 8.5 cm and (c) 55.5 cm.

There is no grid or foil at the entrance of the DWA. Also, no external focusing is used in the DWA. The transport strategy is to employ the entrance fringe fields, switch timing and accelerating voltage. Due to the relatively long accelerating pulse respect to the 200-ps proton bunch at the DWA entrance, the bunch is transversely focused by the fringe field and longitudinally stable at the same time. As the voltage waveform losing its flattop along the machine, the bunch position, or phase, with respect to the virtual traveling wave is controlled by changing the switch timing and the accelerating voltage. After being transversely focused by the frindge field initially, the bunch is positioned in the leading side of the virtual traveling accelerating voltage wave so that the bunch is being longitudinally compressed and transversely defocused. In the second part of the DWA, the proton bunch position is moved to the trailing side of the voltage wave. By alternating the bunch's relative phase respect to the virtual traveling wave, the net focusing could be achieved both transversely and longitudinally.

The LSP simulations for beam transport in the strawman DWA start at 10 cm upstream from the DWA entrance. The initial proton bunch is at its waist with a 5-mm radius. Since the emittance of the initial proton bunch provided by the RFQ is expected to be much smaller than the emittance goal, the initial proton bunch is cold in the simulations. The phase spaces of the LSP simulated beam at the DWA exit are presented in Fig. 2. The r.m.s. beam radius is 2 mm, and the edge radius is 5.5 mm. The r.m.s. beam envelope slope is -0.5 mrad. The normalized Lapostalle emittance is 1.5 mm-mrad. The proton bunch's energy distribution in Figure 3 shows that the exit beam energy is 136 MeV, higher than the goal of 120 MeV, due to that fact that we managed the proton bunch's phase along the DWA by changing the individual Blumlein's voltage in these set of simulations. However, it has demonstrated the feasibility of beam transport without any beam loss and without using any external focusing element. The 1-sigma energy spread is 1.7 MeV.

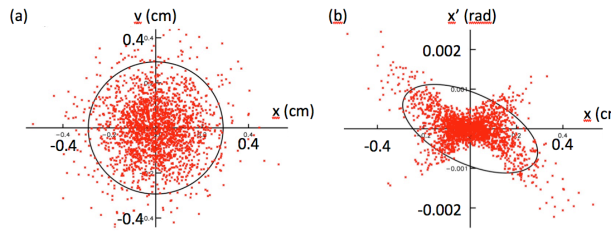

Figure 2: Phase space plots at the DWA exit.

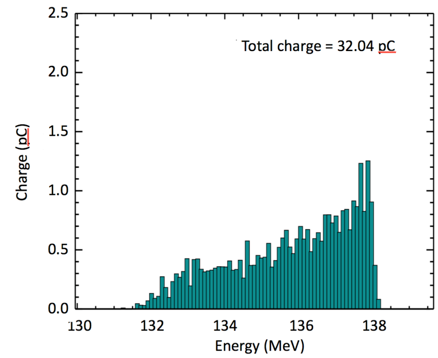

Figure 3: Proton bunch's energy distribution at the DWA exit.

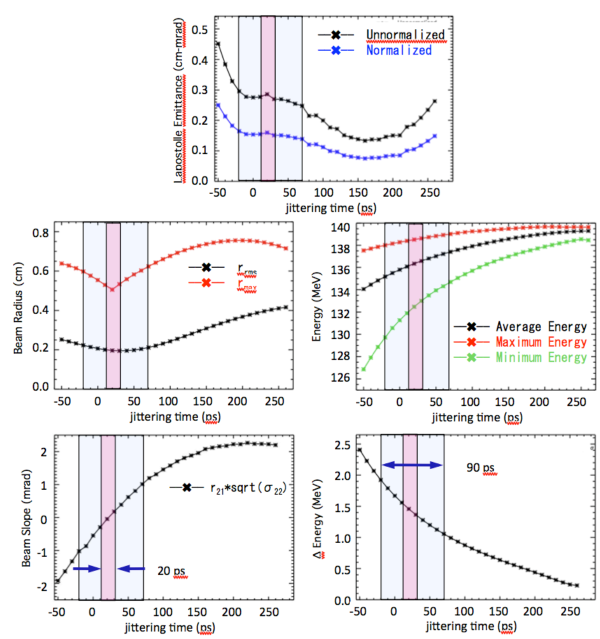

Figure 4: Proton bunch's Lapostoll emittance, beam radius, beam slope, energy and energy variation at the DWA exit versus injector timing jitter .

A synchronization and pulse selection system will be used to phase lock an injected bunch from RFQ to the DWA. To examine the sensitivity of the output beam parameters as a function of the injector-DWA timing jitter, all the parameters in the DWA were frozen except the relative timing between the injected proton bunch and the DWA. Figure 4 shows the output beam parameter variations with respect to the injector timing variations. The goal for the 6-sigma jitter of the synchronization system is 20 ps. The timing sensitivity study reveals that up to approximately 90 ps peak to peak jitter is tolerable.

NOVEL FOCUSING SCHEME

Instead of using the alternate phase focusing scheme to achieve both transverse and longitudinal focusing, we can position the proton bunch at the longitudinally focused phase and generate a strong focusing channel to focus the bunch transversely by deforming the conductors of the HGI. The deformed HGI conductor surface can be described as

$$x = r\cos\phi, \qquad y = r\cos\phi, \tag{1}$$

$$z - z_i = \Delta z\left(\frac{r}{b}\right)^n \cos n\phi. \tag{2}$$

Here r, z and ϕ are the cylindrical coordinates, z_i is the i-th conductor layer's average axial coordinate, Δz is the maximum axial deviation of the conductor along its inner radius, b is its inner radius, and n is an integer.

The deformed conductors, described in the above equations, lie along the equipotentials of a combined axial accelerating and multipole electric field distribution with its axial accelerating field given by

$$E_z = E_o \Big/ \sqrt{1+\left(\frac{n\Delta z}{b}\right)^2} \ , \tag{3}$$

where E_o is the electric field normal to the conductors. Since $\Delta z << b$, the reduction to the accelerating gradient is minimal. The order of the multipole generated by this deformed conductor is n. Conventional HGIs have $n = 0$. For $n = 1$, the HGI will have a dipole field in addition to the accelerating field. For $n = 2$ (shown in Figs. 5 and 6), the HGI will have the acceleration field and quadrupole fields, which are given as

$$E_x = E_o\, x\left(\frac{2\Delta z}{b^2}\right) \Big/ \sqrt{1+\frac{4\Delta z^2}{b^2}} \ , \tag{4}$$

$$E_y = -E_o\, y\left(\frac{2\Delta z}{b^2}\right) \Big/ \sqrt{1+\frac{4\Delta z^2}{b^2}} \ . \tag{5}$$

A stack of these conductors with the same orientation creates a quadrupole lens. Alternating the lens' orientation forms an alternating quadrupole focusing channel. Figure 7 shows a 2-MeV (initially), 1-Amp, 10π mm-mrad beam's envelope in an alternating quadrupole focusing DWA with its period varying through out the accelerator. The peak accelerating field is 100 meV/m. The HGI's inner radius is 2 cm, and the deformation Δz is 0.42 cm. The bunch always rides on the longitudinally stable phase in the entire DWA so that it is subject to a strong radial defocusing force from the accelerating sinusoidal waveform. Figure 7 shows that this alternate focusing scheme can be used to transport the proton bunch successfully.

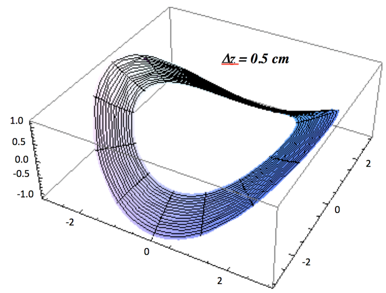

Figure 5: Deformed HGI with n = 2.

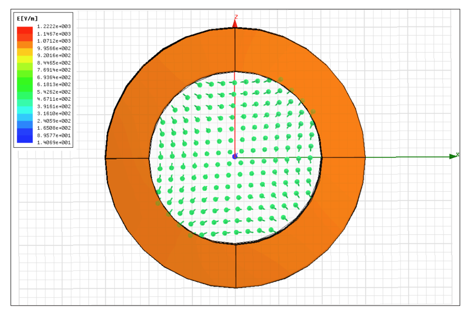

Figure 6: Electric quadrupole field in the interior of a deformed HGI with n = 2.

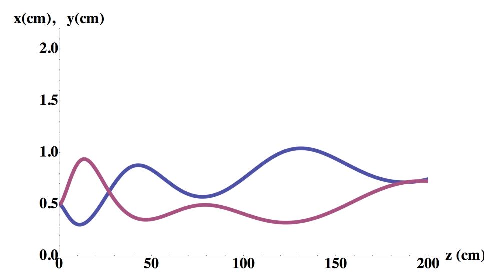

Figure 7: Beam envelope in the DWA with a periodic quadrupole focusing channel provided by deformed HGIs.

SUMMARY

We have established beam transport in a baseline proton therapy DWA configuration without any beam loss and without using any external focusing for sensitivity analysis of the injector timing jitter with respect to the DWA switch timing. We have also developed a novel focusing scheme by deforming the HGI's conducting plates. Preliminary studies of both transport schemes indicate that we can meet our design objective.

REFERENCES

[1] G. J. Caporaso, Y-J Chen and S. E. Sampayan, "The Dielectric Wall Accelerator", Rev. of Accelerator Science and Technology, vol. 2, p. 253 (2009).

[2] Alliant Techsystems Inc., http://www.lspsuite.com/.