BEAM TRANSPORT IN A COMPACT DIELECTRIC WALL ACCELERATOR FOR PROTON THERAPY*

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Abstract

To attain the highest accelerating gradient in the compact dielectric wall (DWA) accelerator, the DWA will be operated in the "virtual" traveling mode [1] with potentially non-uniform and time-dependent axial accelerating field profiles, especially near the DWA entrance and exit, which makes beam transport challenging. We have established a baseline transport case without using any external lenses. Results of simulations using the 3-D, EM PIC code, LSP [2] indicate that the DWA transport performance meets the medical specifications for proton treatment. Sensitivity of the transport performance to Blumlein block failure will be presented.

INTRODUCTION

The high gradient DWA system being developed at LLNL [1] uses fast switched high voltage transmission lines to generate pulsed electric fields on the inside of an accelerator tube, which consists of many alternating fine layers of floating conductors and insulators. To attain the highest accelerating gradient in the accelerator, the DWA will be operated in the "virtual" traveling mode with the shortest possible accelerating voltage pulses. Since only a short section of the HGI wall would be excited, the accelerating field's axial profile could be non-uniform and time-dependent, especially near the entrance and exit of the DWA. Those short accelerating voltage pulses with little or no flattop will either simultaneously transversely defocus and longitudinally compress or transversely focus and longitudinally decompress the charge bunch depending on the bunch's phase with respect to the short virtual traveling wave bucket. Therefore, besides 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. Currently we are developing a short pulse (~ 3 ns) compact proton therapy DWA system with a goal of fitting the system in a conventional treatment vault for intensity modulated proton therapy. In this paper, we discuss the accelerating voltage pulses' width requirement and present a baseline transport case for a strawman proton therapy machine. The sensitivity study of injector timing jitter has revealed that up to approximately 90 ps peak to peak jitter is tolerable while the goal for the 6-sigma jitter of the synchronization system is 20 ps [3]. In this report, we present a sensitivity study of Blumlein block failure.

VOLTAGE PULSE WIDTH

To attain the highest accelerating gradient, the DWA voltage pulses should have the shortest possible duration and be applied to the shortest spatial extent of the HGI tube. However, applying the accelerating voltage to a too small section of HGI tube will result in small accelerating field along the machine axis due to the fringe field effect. In the DWA operated in the "virtual" traveling mode, the spatial extent of the accelerating field on the HGI tube wall is roughly equivalent to the virtual traveling wave's traveling velocity, also proton bunch's velocity, times the voltage pulse length. To ensure that the accelerating field on the axis to be at least 90% of the gradient on the HGI wall, the spatial extent of the accelerating field on the HGI tube wall should be greater than 3 times the beam tube radius divided by the Lorentz factor γ [1]. Therefore, the voltage pulse widths at the injector end need to be longer than those at the higher energy portion of the DWA. For a DWA with a 2-cm radius HGI tube, the required minimum accelerating voltage pulse width as a function of proton energy is shown in Fig. 1. The minimum accelerating voltage pulse width, given by this criterion, decreases monotonically as the proton energy increases. However, the pulse width should always be much longer than the time required for the accelerating field to fill the equilibration ring of the HGI. Otherwise, the on-axis accelerating field will be small also. The minimum voltage pulse width is also limited by the pulsed power technology's ability in producing a very short voltage pulse.

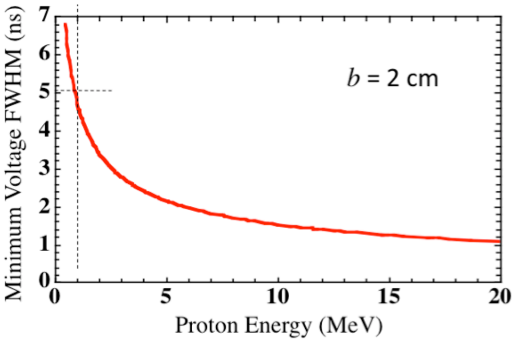

Figure 1: Minimum voltage pulse width requirement versus proton energy.

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TRANSPORT IN STRAWMAN DWA

To demonstrate the feasibility of achieving longitudinal and transverse stability simultaneously while maintaining the beam quality, we have simulated beam transport in a 2-m strawman proton DWA accelerator by using the 3-D, EM PIC code, LSP [2]. A 2-MeV, 200-ps proton bunch is injected into the stawman DWA. The accelerating gradient is about 60 MV/m throughout the DWA. The goal is to deliver a 120-MeV proton bunch with a ±2% energy spread. The exit beam radius is less than 1-cm and the range for its envelope slope is from -10 mr to 10mr. Finaly, the goal for the normalized Lapostolle emittance is not to exceed 8π mm-mrad.

To minimize the number of control channels needed for tuning the DWA, several Blumleins are grouped to form a 1-cm block with their switches being turned on and off together. The accelerating waveform on the wall at the DWA entrance has a 3-ns flattop with 1-ns Gaussian rise/fall. As the proton bunch is 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 the 1-ns pulse length is much longer than the time required to fill the equilibration ring of the HGI. The simulated on-axis accelerating field 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. 2 (a) – (c). The stair-case waveform profile at (a) z = 4.5 cm is the result of the longer flattop pulse near the DWA entrance and the 1-cm Bulmlein block configuration. As protons are accelerated, the time delay between the turn-on times of the neighboring Blumlein blocks decreases 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. 2 (b) and (c).

No external focusing, entrance grid or foil 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 with respect to the 200-ps proton bunch at the DWA entrance, the bunch is transversely focused by the fringe field and is longitudinally stable at the same time. Once the proton bunch enters the DWA, the voltage waveform loses 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 fringe 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 so that the net focusing could be achieved both transversely and longitudinally.

The simulations 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 proton bunch provided by a candidate injector, such as a RFQ with a single filled bucket, is expected to be much smaller than the emittance goal, the initial proton bunch is cold in the simulations. The simulated exit beam's phase spaces with a 2-mm r.m.s. radius and a 5.5-mm edge radius are presented in Fig. 3. The r.m.s. envelope slope is -0.5 mrad. The normalized Lapostolle emittance is 1.5 mm-mrad. The exit beam energy is 136 MeV with a 1.7-MeV 1-sigma energy spread.

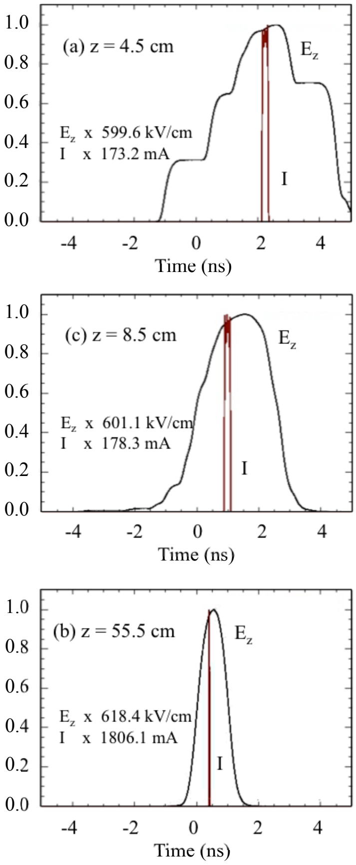

Figure 2: On-axis accelerating field waveforms and proton bunch temporal profiles at (a) z =4.5 cm, (b) 8.5 cm and (c) 55.5 cm.

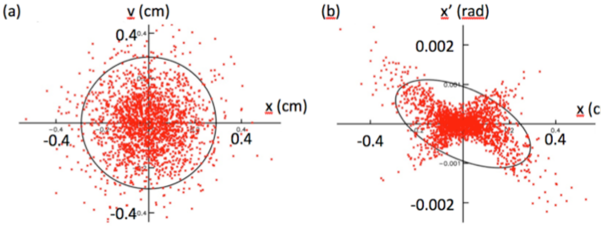

Figure 3: Phase space plots at the DWA exit.

BLUMLEIN FAILURE EFFECTS

In the DWA, the Blumlein charging voltages are chosen to provide the desired acceleration and transport. Once the charging voltages are set for the optimal beam transport performance, the individual switch's turn-on time is chosen so that the accelerating voltage pulse and the charge bunch arrive a given location along the accelerator axis at the same time. Failure of a Blumlein or switch will cause the charge bunch to slip behind the "virtual" traveling wave bucket. We have simulated the effects of Blumlein failure on beam transport by turning off one 1-cm Blumlein blocks at various locations while keeping all other Blumleins' switch timing and charging voltages the same. The simulated exit beam parameters versus the location of the failed 1-cm Blumlein blocks are presented in Fig. 4. The marks at z = 201 cm in all four plots indicate the beam parameters without any Blumlein failure. As expected, failure of Blumlein blocks at the DWA entrance has a large impact on the beam quality since the charge bunch's velocity is drastically reduced when 2-cm of Blumleins failed to fire. Note that a Blumlein consisting of a photoconductive switch is only 2 mm thick. There are two Blumleins feeding into the HGI tube at any given location. One 1-cm Blumlein blocks will consist of 5 pairs of Blumleins and 10 switches. The likelihood of having all 10 switches and 10 Blumleins failing at the same time is very small. Therefore, the Blumlein failure effects on transport reported here is exaggerated. However, transport performance still meets the goal with Blumlein block failure. There are ways to mitigate the impact of Blumlein failure. One is to increase the injected beam' energy so that the energy change due to Blumlein misfire would be small. The other way is to lower the DWA accelerating gradient at the low energy end. As discussed in the previous section, the accelerating gradient is roughly constant throughout the strawman DWA even though the voltage pulse width is longer at the entrance. Characteristically, insulators' vacuum surface breakdown thresholds decrease as the applied voltage pulses' widths increase. Therefore, the accelerating gradient at the DWA entrance should be lower than that in the rest of the accelerator. Consequently, the Blumlein failure effects would be smaller. Ramping up the accelerating gradient at the low energy end of the DWA has an additional benefit. There is a radial electric field accompanying the ramping accelerating field. This radial field potential can provide us the needed focusing. In Ref. 4, we will report a transport strategy by using such field for focusing the proton bunch to a tight spot on the patient without using any external lenses.

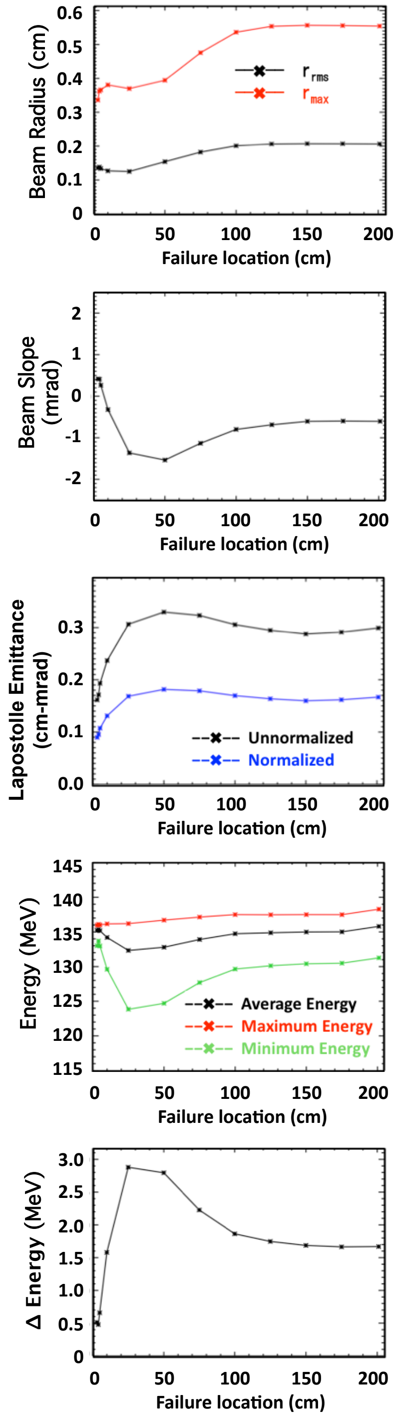

Figure 4: The exit r.m.s. beam radius, beam slope, Lapostolle emittance, energy and energy variation versus the location of the failed two 1-cm Blumlein blocks. The marks at z = 201 cm indicate the beam parameters without any failure.

SUMMARY

We have discussed the accelerating voltage pulse requirement for the "virtual" traveling wave DWA. Without using any external focusing, we have established beam transport in a baseline proton therapy DWA configuration without any beam loss and studied the effects of Blumlein failure on the beam transport. Preliminary studies of the strawman transport indicate that we can meet our design objectives.

REFERENCES

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