BEAM TRANSPORT IN A DIELECTRIC WALL ACCELERATOR FOR INTENSITY MODULATED PROTON THERAPY*,+

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Abstract

We are developing a compact dielectric wall accelerator (DWA) for intensity modulated proton therapy (IMPT) with a goal of fitting the compact proton DWA in a single room [1]. To make the accelerator compact, the DWA needs to have a very high accelerating gradient. Also, beam transport in the DWA should be done with as few external lenses as possible. We have developed a transport scheme to transport the proton bunch in the DWA and to focus the charge bunch on the patient without using any external focusing lenses. The transport scheme would allow us change the proton beam spot size on the patient easily and rapidly. Results of simulations using 3-D, EM PIC code, LSP [2] will be presented.

INTRODUCTION

The high gradient DWA system being developed at LLNL [1] uses fast switched high voltage Blumleins to generate pulsed electric fields on the inside of a high-gradient insulating (HGI) beam tube, which consists of many alternating fine layers of floating conductors and insulators. To attain the highest accelerating gradient, the DWA will be operated in the "virtual" traveling mode with the shortest possible accelerating voltage pulses so that only a short section of the HGI wall is excited. This high gradient DWA technology makes a compact proton accelerator fitting in a conventional treatment room with the patient possible. Furthermore, to make the accelerator compact, beam transport in the DWA should also be done with as few external lenses as possible.

Currently, the conventional proton accelerator for cancer treatment uses magnets for beam transport in the system. Those magnets are very large and costly, and their fields cannot be changed quickly. Focusing the proton beam on the patient and shot-to-shot spot size variation are frequently achieved only by using collimators/masks right before the patient, and those masks generate unwanted neutrons in the treatment room. In contrast, for the DWA system, instead of using external focusing lenses, we have developed a transport system by using an electric DWA lens to provide the needed focusing. The concept of the electric DWA lens is presented in this paper. Methods for shot-to-shot spot size variation without using external lenses and masks are also discussed.

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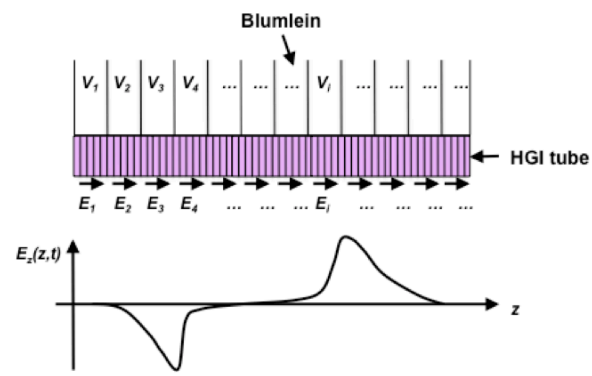

Figure 1: The schematic of a high-gradient electric HGI lens.

DYNAMICS DWA LENS

The accelerating voltage pulses in the DWA are fed into the beam tube by using Blumleins as shown in Fig. 1. Thickness of each Blumleins is only a few millimeters. Either each Blumlein has its own charging system, or a block of Blumleins uses a common charging system. Varying the Blumleins' charging voltages from pulse to pulse leads to pulse-to-pulse variation in both the electric field gradient and the field profile. Such configuration provides a great flexibility for dynamically shaping the on-axis accelerating electric field profile $E_z(z,t)$ along the HGI tube and its corresponding radial electric field. Let $E_z(z,t) = \tilde{E}(z) f(t - \int_{z_0}^{z} dz'/v)$, where $f(t - \int_{z_0}^{z} dz'/v)$ describes the "virtual traveling" wave package moving down the axis with a velocity v, and $\tilde{E}(z)$ is the field gradient along the z axis. The radial electric field at a radial position r << $E_z / |\partial E_z / \partial z|$, is given roughly as

$$E_r(z,t) \approx -\frac{r}{2}\left[\tilde{E}'(z) f(z - vt) + \tilde{E}(z) \frac{df}{dt} \Big/ v\right]. \qquad (1)$$

Depending on the relative position of the charged particle bunch with respect to the peak of the waveform, the second term containing *df/dt* provides a radial focusing or defocusing field. For short pulse applications, a DWA lens can be used as either a focusing lens or defocusing lens simply by controlling the timing of the charged particle bunch with respect to the accelerating wave.

With the flexibility in changing Blumleins' charging voltages, a DWA can provide an additional radial field control capability through the first term in Eq. (1). Since HGIs can sustain at least 3 -4 times higher electric field than conventional insulators, DWA lenses are capable of providing at least 3 -4 times stronger radial electric field than conventional electric lenses. By dynamically adjusting the charging voltage of each Blumlein or block, the DWA lens' accelerating field profile $\tilde{E}(z)$ can be shaped for a specific net radial focusing for a specific shot.

To demonstrate the focusing capability of the first term in Eq. (1), we consider the case that $(df/dt)/v = 0$, which occurs when the beam bunch rides on the crest or the flattop of the electric field pulse or the DWA's accelerating wave is DC. The first 5 cm of the DWA is used as an electric focusing lens with its accelerating field ramping up linearly from 0 to 100 MV/m. The accelerating and radial electric field profiles along a 2-m DWA axis are plotted in Fig. 2 at the left, and the radial field profile is plotted also at the right.

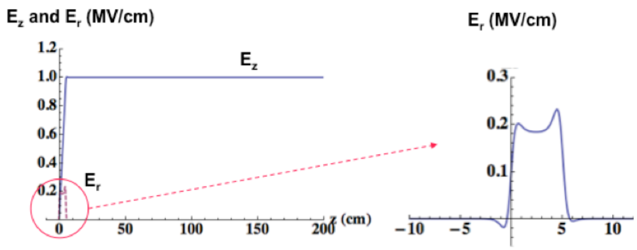

Figure 2: Longitudinal and radial electric field profile.

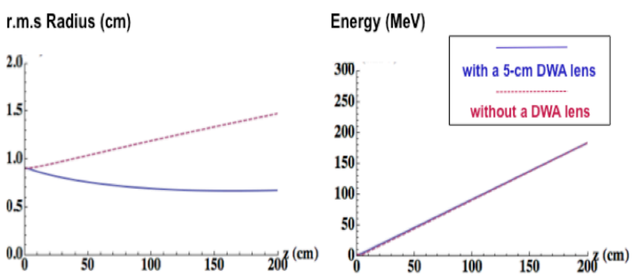

Figure 3: Proton bunch's r.m.s. beam radius and energy in a DWA with a 5-cm electric focusing DWA lens (solid blue) and without a lens.

The r.m.s. envelope equation,

$$R'' + \frac{(\gamma\beta)'}{\gamma\beta} R' = -\frac{q\tilde{E}'}{2\gamma\beta^2 mc^2} R + \frac{I/I_o}{\gamma^3\beta^3 R} + \frac{\varepsilon_n^{\,2}}{\gamma^2\beta^2 R^3}, \quad (2)$$

for a 200-mA, 2-MeV, 1-mm-mr (r.m.s normalized) proton bunch at its waist entering this 2-m DWA is solved, where $\beta = v/c$, R, q, m, γ, I, and ε_n is the beam's r.m.s. beam envelope, charge, mass, Lorentz factor, beam current, and normalized r.m.s. emittance, respectively, and I_o is proton Alfven current. The resulted beam envelope and energy (in Fig. 3 in blue) demonstrate that even just a 5-cm long DWA lens can provide sufficient transverse focusing for a 2-m DWA. For comparison, the beam envelope and energy in a DWA without the 5-cm electric focusing lens are also plotted (in red).

A short DWA lens can be used before any accelerator to focus the beam and boost the energy. A DWA module can also be used as a strong dynamic Einzel lens. Since charging voltages can be set differently from one Blumlein to another dynamically, one can easily shape the electric field profile for a desired focusing effect without the difficulties of shaping the electrodes of a conventional Einzel lens.

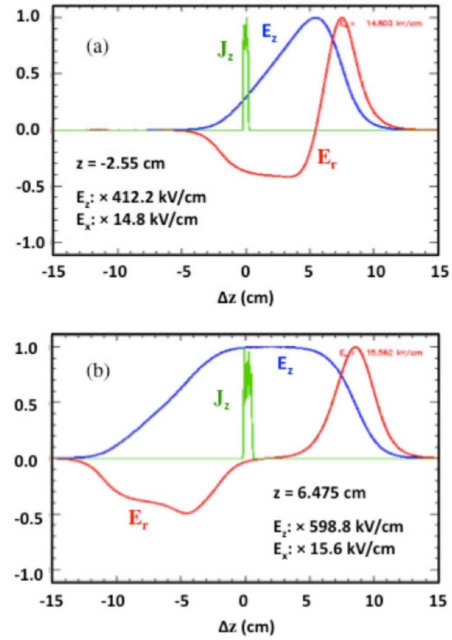

Figure 4: The longitudinal and radial electric field profiles of (a) a strong electric focusing DWA lens at the DWA entrance (z = -2.55 cm) and (b) constant acceleration inside the DWA (z = 6.475 cm) and proton current profiles.

FOCUSING ON THE PATIENT

To demonstrate the feasibility of tightly focusing the proton beam on the patient with a DWA lens, we have simulated beam transport through a 205-cm strawman proton DWA and a 1-m drift space to the patient, by using the 3-D, EM PIC code, LSP. A 2-MeV, 200-ps bunch is injected into the DWA, which does not use any external focusing, entrance grid, or foil. The average accelerating gradient is about 60 MV/m. Blumleins are grouped to form a 1-cm block with their switches being turned on and off together. The charging voltages at the first 10 cm of the DWA (from z = -4 cm to z = 6 cm) are tuned to create a strong linear electric lens to focus the beam on the patient (z = 300 cm). The small fringe field upstream of the DWA provides an additional focusing. With a 1-ns Gaussian rise/fall, the accelerating voltage pulse's flattop decreases from 8 ns at the bottom of the field ramp to 3 ns at the top. After the ramp, the flattop duration shrinks further to maintain the wall excitation length, and the waveform reduces to a 1-ns FWHM Gaussian after the flattop duration vanishes at about z = 20 cm. The accelerating and radial field profiles vs. Δz with respect to (a) z = -2.55 cm (at the DWA entrance) and (b) z = 6.475 cm (after the lens) are shown in Fig. 4 with their scaling factors given in the legend. To show the proton bunch's location, the current profile is also shown. The accelerating pulse is relatively long with respect to the 200-ps proton bunch at the entrance. The bunch is transversely focused and longitudinally stable at the same time (see Fig. 4a). This ramping field is sufficiently strong to focus the proton bunch to a 0.4-mm r.m.s. radius spot on the patient (see Fig. 5.) After the lens, by changing the switch timing and the accelerating voltage, the bunch is placed in the leading side of the "virtual" traveling accelerating voltage wave so that it is being longitudinally compressed and slightly transversely defocused (see Fig. 4b). 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 simulation starts at z = -14 cm, i.e., 10 cm upstream from the DWA entrance. The proton bunch's phase spaces near the DWA entrance and the patient are shown in Fig. 5. The initial proton bunch has a 3-mm radius, a 25.6-mr beam slope and a 0.543-mm-mr normalized edge emittance. The simulated beam on the patient at z = 300 cm has a 0.4-mm r.m.s. radius and -0.2-mr beam edge slope. The final normalized edge emittance is 0.36 mm-mr. Compared with the initial emittance, it is clear that the beam emittance is preserved by the linearly increased E_z field along the z axis at the entrance, which yields a radial electric field linear in r (see Fig. 4). The final beam energy is 121.58 MeV ± 0.0855 Mev (1σ).

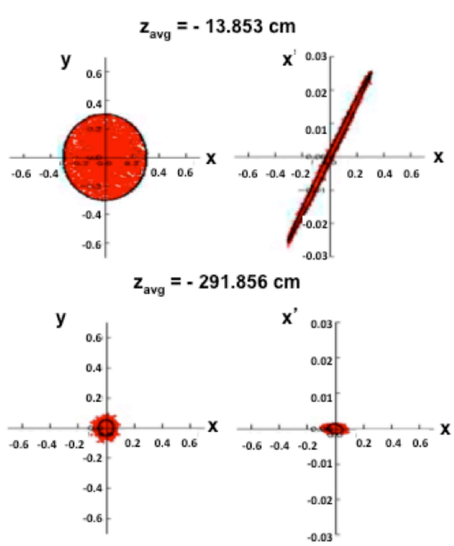

Figure 5: The phase spaces near the DWA entrance (z = -14 cm) and the patient (z = 300 cm).

CHANGING SPOT SIZE FOR IMPT

It is desirable for a DWA system to have shot-to-shot spot size variation capability for intensity modulated proton therapy without using any additional external focusing elements. To do so, first, the baseline beam transport for getting the minimum spot on the patient required by the treatment plan should be established by using a DWA lens at the entrance and an optimal set of timing with respect to the accelerator for the Blumleins and the injector. For such baseline transport, the timing of the traveling accelerating field is synchronized with the proton bunch so that the bunch rides on the crest of the traveling field. If the "traveling" accelerating pulse and the proton bunch are out of sync, the bunch slips off the crest, which will lead to growth in both spot size and emittance. The amount of spot size increase and emittance growth are determined by how far the bunch has slipped off the crest.

An obvious knob for spot size variation is to change the synchronism between the beam and the traveling field. Designing a laser optic distribution system with shot-to-shot switch timing variation capability for Blumleins' charging system is challenging. Leave the DWA's timing setting untouched, we can change the synchronism simply by either varying the injector timing with respect to the DWA or the Blumleins' charging voltages, which changes proton velocity. A previous timing sensitivity study for transport without using a DWA lens indicates that the exit beam parameters, although changed, are suitable for treatment even with up to ± 90 ps injector timing shift [3]. While the injector's timing jitter is expected to be less than ± 20 ps [4], we can purposely change the injector timing for a set of desired beam parameters, including the spot size. The study for Bulmlein failure effects on transport in the same strawman DWA configuration without a DWA lens [5] suggests that we can also change beam spot size by turning off a block of Blumleins at various location near the DWA entrance. Last but not the least, we can also change the electric DWA lens' field ramp at the entrance, which changes the lens' focusing strength in addition to the synchronism. Regardless of which method is used, the charging voltages near the DWA exit could be adjusted from shot to shot to compensate for the small energy shift introduced by changing synchronization between the beam and the field. Since the beam is rigid near the exit, the beam spot size change due to voltage changes there should be negligible.

SUMMARY

The DWA configuration provides a flexibility to create an electric lens with desired radial electric field for focusing. We have demonstrated that the proton bunch can be transported through the DWA and focused on the patient tightly by using only an electric DWA lens at the DWA entrance. We have also discussed methods to achieve spot size variation from shot to shot without using any external focusing lens.

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