PRELIMINARY STUDY OF PROTON BEAM TRANSPORT IN A 10 MeV DIELECTRIC WALL ACCELERATOR*

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Abstract

A novel proton accelerator based on Dielectric Wall Accelerator (DWA) technology is being developed at Institute of Fluid Physics (IFP). The accelerating gradient will be 25 MV/m or even higher based on current high gradient insulator (HIG) performance. Theoretical study and numerical simulation of accelerating the proton beam to 10 MeV by virtual travelling wave method are presented in this paper. The beam injection at the DWA entrance is also discussed.

INTRODUCTION

The proton dielectric wall accelerator is being developed at Institute of Fluid Physics. The DWA system is a block structure which is similar to the linear induction accelerator. Each block of cell is consist of a ring-shape high gradient insulator, parallel-plate Blumlein pulse forming lines and photon conductive switches. To obtain the highest accelerating gradient, the DWA will be operated in the "virtual" travelling wave mode with the accelerating pulse as short as no more than 2 nanoseconds in the majority of the HGI tube [1]. These technologies are now being tested individually and will soon be tested integrally. The proton bunch will first be accelerated to 1 MeV with the accelerating gradient of about 20 MV/m and then upgraded to higher energy by adding more DWA cells. The accelerating gradient is also expected to be 25 MV/m or even higher, which is mainly determined by the performance of the HGI tube.

The major advantageous of a DWA system used for cancer treatment is that the total length of the system will be less than 3 meters so that it can be equipped in a single treatment room and the large and costly gantry can be neglected. Moreover, the energy, spot size of the proton bunch can be changed from shot-to-shot by adjusting the pulsed power system.

ION SOURCE AND LEBT

The layout of a 10-MeV DWA system is shown in Fig.1. It will start with a proton beam generated in an ECR ion source and extracted at about 40 keV. The main purpose of the LEBT is to transport the beam to the entrance of the DWA and match the injection requirements. Since a DWA system should be short and light enough to be rotated for intensity modulated proton therapy (IMPT), a two Einzel lens structure was chosen as the LEBT system. The pulse width of the proton bunch generated by the ion source is expected to be much longer than the DWA requirement. A fast kicker system will be mounted at the exit of the LEBT. Most of the protons will be deflected and hit on the metal wall at the DWA entrance, and only a small part of protons is allowed to enter the DWA. Design and fabrication of the ion source and LEBT is performed by Institute of Heavy Ion Physics, Peking University.

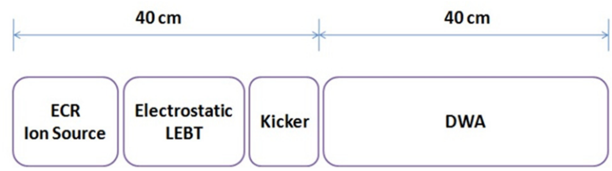

Figure 1: Layout of a 10 MeV DWA.

BEAM INJECTION

Generally, there is no any external focusing element or grid in the DWA system. The proton bunch is supposed to be focused to the downstream of the DWA by the radial electric field produced by the field gradient at the entrance [2]. The focusing effect is generally determined by the beam parameters, the accelerating gradient, the electric field and the time sequence. Chen [3] has demonstrated transporting a 2-MeV (injection energy) proton bunch in a 120-MeV DWA system at the accelerating gradient of 60 MV/m. For a 40-keV proton bunch, the radial electric field can easily cause the bunch pinching at the front of the DWA first and then defocusing. To demonstrate the focusing effect of the radial electric field at the entrance, the envelop equation

$$R'' = -\frac{\gamma'}{\gamma\beta^2}R' - \frac{\gamma''}{2\gamma\beta^2}R + \frac{K}{R} + \frac{\varepsilon_n^2}{\beta^2\gamma^2R^3} \quad (1)$$

for a 40-keV, 20-mA, 1-mm-mrad proton bunch at its waist is solved, where R, β, γ, ε_n and K is the beam's radius, velocity relative to the speed of light, Lorentz factor, normalized edge emittance and generalized perveance, respectively. We consider the case that the length of the DWA is 40 cm and the proton bunch rides on the flattop of the electric field (25 MV/m) except that there is a constant field gradient at the beginning 5 cm of the DWA. The proton bunch envelop as a function of the proton energy is plotted in Fig.2 (a). It is obvious that the focal spot of the beam will move upstream as the proton energy decreases. The focal spot of proton bunch with 2-MeV injection energy just locates at the end of the drift

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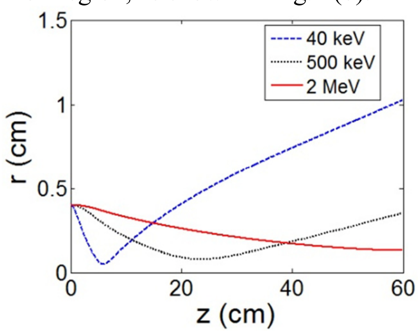
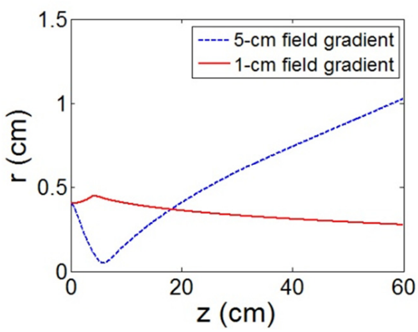
tube, while the proton bunch with 40-keV injection energy will pinch at the front of the DWA and then diverge. If we adjust the injection timing to make only the last 1 cm of field gradient is seen by the bunch, the 40-keV proton bunch will also be tightly focused throughout the simulation region, as shown in Fig.2 (b).



(a)

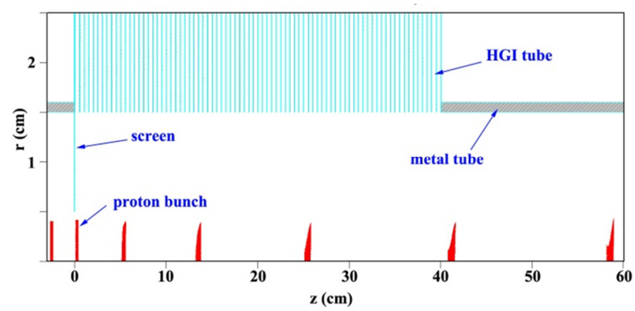


(b)

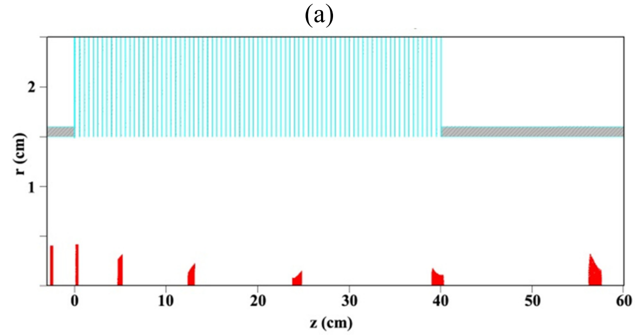
Figure 2: Beam envelop for (a) different injection energies, (b) two different lengths of field gradient at the DWA entrance for a 40-keV proton beam.

TRANSPORT SIMULATION

We have simulated the proton beam transported through a 40-cm DWA by using a self-consistent, 2.5-dimensional particle-in-cell code. The inner radius of the HGI tube is 1.5 cm and the average accelerating gradient is about 25 MV/m. Blumleins are grouped to form a 2-cm block which was triggered together. The accelerating voltage pulse was given a rise/fall time of 1 ns each. The simulation transports a 40-keV, 1-ns proton beam from 3 cm upstream of the DWA entrance to 20 cm downstream of the DWA exits. The flattop of each electric pulse and the triggering sequence were carefully chosen to ensure that the DWA worked in the “virtual” travelling wave mode and the proton bunch just rode on the flattop throughout the DWA except at the entrance and exits. To make sure that the proton bunch was not over-focused, the first two groups of HGI were triggered together when the proton bunch entered the HGI tube. An entrance metal screen was employed to further increase the accelerating field at the entrance and reduce the electric field gradient seen by the proton bunch. The simulation results with and without entrance screen are shown in Fig.3.



(a)



(b)

Figure 3: Beam transports in a 10-MeV DWA, (a) entrance screen can further reduce the focusing force at the entrance, (b) the proton bunch was over-focused when there was no entrance screen.

The bunch was first accelerated by the leading side of waveform, and a radial focusing force is applied on the bunch at the same time. The longitudinal and radial electric field profiles at the DWA entrance are shown in Fig. 4. When the entrance screen was employed, the accelerating field is higher at the entrance comparing to the case when there is no entrance screen. So the protons can be accelerated to higher energy in a shorter distance to avoid over-focusing. And the radial focusing force is also smaller. After that, the virtual travelling wave with a flattop was formed and the proton bunch rode on the flattop of the accelerating waveform, as shown in Fig.5. At this stage, the radial electric field vanished. The shape of the accelerating field nearly kept constant as the proton bunch travelling through the accelerator. However, the electric pulse flattop applied on the HGI reduced from about 4 ns at the entrance to 1.5 ns at the end, as shown in Fig.6. The pulse duration at the second group of Blumleins is longer than the first one since they are triggered together to increase the accelerating field and reduce the length of the waveform leading side at the entrance. At the exits of the DWA, a de-focusing force will be applied on the bunch because of the opposite field gradient to that of the entrance. So the last HGI should be turned off as quickly as possible. For the 10-MeV DWA, the transport systems with or without the entrance screen are both acceptable though the bunch was slightly over-focused when there was no entrance screen. However, the radial focusing force at the DWA entrance is proportional to the accelerating gradient, and the entrance screen could be an alternative method to avoid over-focusing for a longer DWA with higher accelerating gradient,

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The proton energy and current profile at the exits of the DWA is shown in Fig.7. Because the bunch rode on the falling side of the acceleration waveform at the DWA entrance, the bunch underwent longitudinally compressing and the average peak current increased to about 100 mA at the DWA exits. This longitudinally compressing effect is useful in a DWA system for IMPT. It is desirable for such a system to have an accelerating gradient of 100 MeV/m with 1-ns accelerating pulse width. To ensure that the proton bunch rides on the flattop of the accelerating waveform, the bunch length should be sub-nanosecond. And how to extract such a proton bunch is still a challenge. However, by adjusting the charging sequence of the HGI, the proton bunch can be placed at the falling side of the accelerating waveform and the bunch will be compressed longitudinally in the front of the accelerator. Moreover, the proton bunch should be about 200 mA and 0.2 ns for a 50-Hz DWA system for IMPT. It is obvious that the current exceeds the maximum capability of the ion source. And the beam radius at the DWA entrance can't be kept small if the current extracted from the ion source is large enough. Therefore, the proton bunch should be extracted at lower current and then be compressed to higher current and shorter pulse length.

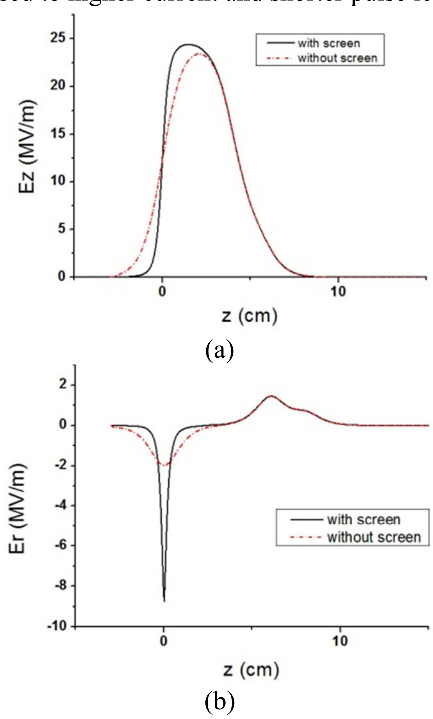

Figure 4: Longitudinal (a) and radial (b) electric field profiles at the DWA entrance with and without entrance screen.

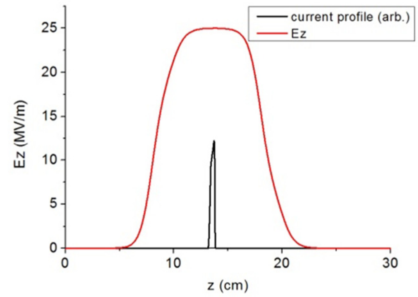

Figure 5: Longitudinal electric field and proton current profile in the middle of the DWA.

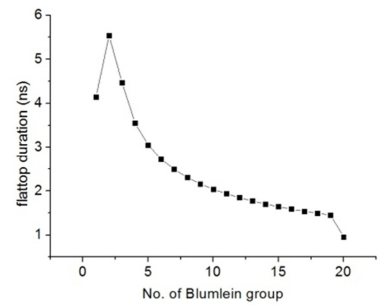

Figure 6: Electric pulse flattop duration as a function of the No. of HGI group.

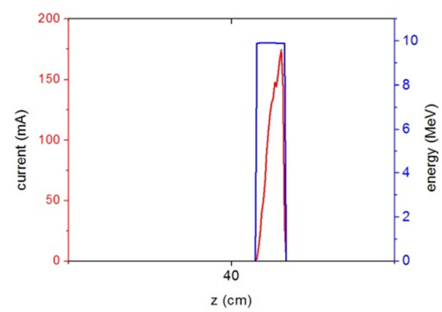

Figure 7: Proton energy and current profile at the exits of the DWA (with screen).

SUMMARY

The design of the ion source and LEBT for a 10-MeV DWA is introduced in this paper. We have discussed the beam injection by using the focusing force produced by the field gradient at the DWA entrance. We also have demonstrated that a 40-keV proton bunch can be transport through a 40-cm-long DWA with an accelerating gradient of 25 MV/m.

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