Beam transport design for a 1 MeV prototype dielectric wall accelerator*

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Abstract: The beam transport design of a novel proton dielectric wall accelerator is introduced in this paper. The protons will be accelerated from 40 keV to nearly 1 MeV under an accelerating gradient that is as high as 20 MV/m. A consideration of the beam line as well as the transport simulation is presented. The influences of the injection timing jitter and the accelerating pulse timing jitter are also discussed.

Key words: beam transport, dielectric wall accelerator, accelerating gradient, transport simulation, timing jitter

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1 Introduction

The fundamental physics features of the proton beam (e.g. it has high dose concentration around the Bragg peak) have made proton therapy a preferable cancer treatment method compared with the conventional radiation treatment [1]. In recent years, more compact machines have been required to reduce the construction and running cost, which will result in a boost of the use of proton therapy around the world [2]. The modern dielectric wall accelerator (DWA) proposed by Carporaso et al. [3] has a potential high accelerating gradient on the order of 100 MV/m for accelerating pulses on the order of 1 nanosecond in duration. The DWA for proton therapy is expected to be installed on a rotating gantry inside a single treatment room, and the energy as well as the spot size of the proton bunches can be changed from shot-to-shot.

A prototype DWA is being developed at Institute of Fluid Physics (IFP). It has been designed to deliver proton bunches of about 1 MeV with an acceleration gradient greater than 20 MV/m at the repetition rate of 50 Hz. The DWA module is a block structure that is similar to the linear induction accelerator [4]. Each module consists of a high gradient insulator (HGI) [5] tube, a stack of parallel-plate Blumlein pulse forming lines (PFL), and is triggered by photon conductive semiconductor switches (PCSS) [6]. The accelerating field is directly coupled to the beam through the wall of the HGI. We have used the ray-tracing code PBGUN and a 2.5 D particle-in-cell (PIC) code to develop the 1 MeV DWA. This paper describes the beam line design for the 1 MeV DWA. Section 2 will briefly outline the general consideration in the design. Section 3 describes the injector including the ion source, the low energy beam transport (LEBT) and the kicker. Section 4 describes the PIC simulation studies of the proton bunch transport downstream of the injector. A discussion and summary is presented in Section 5.

2 General consideration of the DWA module

Due to the inverse dependence of the surface flashover strength on the pulse width, the accelerating voltage pulse width should be as short as possible in order to achieve a high accelerating gradient. Thus, the accelerating voltage should only be on locally when the charge particle bunch arrives along the HGI tube, which was proposed as the virtual traveling wave method [3]. Moreover, to ensure that the on-axis electric field is larger than 90% of the electric field obtained on the wall of the HGI tube, the particle velocity u in non-relativistic case should satisfy

$$u\tau \geqslant 3.3R. \quad (1)$$

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Where τ is the voltage pulse width and R is the inner radius of the HGI tube. In our design, the one-way transit time of the PFL was chosen to be about 4 ns in order to obtain the 20 MV/m accelerating gradient. The inner radius of the HGI tube is expected to be 2 cm for the convenience of inner surface treatment. Since the velocity of protons is too slow to satisfy Eq. (1) at the entrance of the DWA, we proposed to use metal discs with 8 mm radius hole to enhance the on-axis electric field, as shown in Fig. 1.

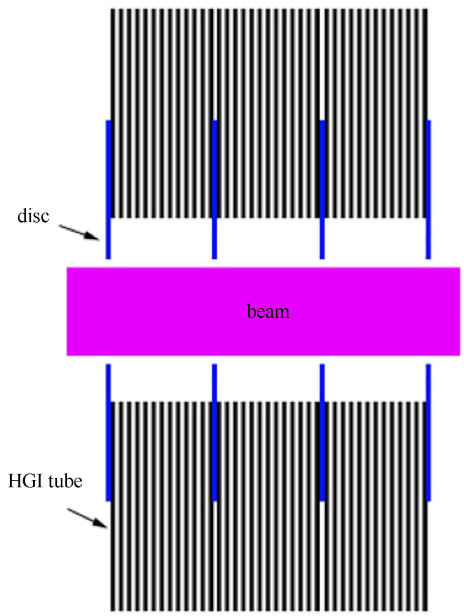

Fig. 1. (color online) Structure of the DWA module.

Unlike the metal structure in convention accelerators, the beam tube of the DWA is a stack of insulators. Beam loss and secondary electron production inside the DWA module may degrade the surface flashover strength of the HGI tube. Therefore, the beam size should be kept small enough to avoid interception by the structure. Hence, the existence of the metal discs also helps to protecting the inner surface of the HGI tube.

In addition, there is no external focusing element in the DWA system. The proton bunch is supposed to be transversely focused by the radial electric field $E_{\rm r}$, which is related to the accelerating field E_z by

$$E_{\rm r}=-\frac{r}{2}\frac{{\rm d}E_z}{{\rm d}z}. \tag{2}$$

According to Eq. (2), the protons will generally be focused at the entrance of the DWA module and defocused at the exit.

3 Injector

The layout of the 1 MeV DWA beamline is shown in Fig. 2. It starts with a proton beam generated in a 50 Hz ECR ion source and is extracted at about 40 keV with bunch length of several hundreds of microseconds. The LEBT with two Einzel lens was designed to transport the proton bunch through the DWA module without intercepting with the metal disc, whether the accelerating field is on or not. The LEBT-electrode shapes were optimized by simulating proton beams using the code PBGUN. The final calculated beam optics are shown in Fig. 3. Since the accelerating voltage pulse width is only about 8 ns, and the performance of the HGI during the beam passage is still unclear, only a small part of protons will be selected by the kicker to enter the DWA module for further acceleration, while the majority of the protons will be deflected and hit the flange at the DWA entrance.

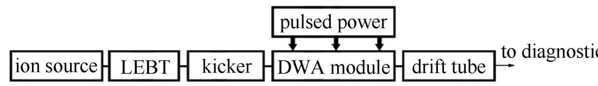

Fig. 2. Layout of the 1 MeV dielectric wall accelerator.

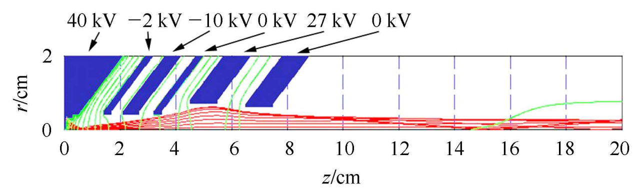

Fig. 3. (color online) PBGUN simulation of the 44 mA production LEBT.

4 Beam dynamics inside the DWA module

The proton bunch transport through the DWA module and a 15 cm drift tube was simulated by using a 2.5 D Particle-in-Cell code. The HGI tube is divided into three 1.45 cm cells connected with four 2 mm-thick metal discs. Each cell was assumed to be charged by a group of PFLs, which were triggered together. Generally, proton bunches with duration of about 0.2 ns or less as well as bunch compression (to increase the proton bunch current) are required for a DWA used for proton therapy [7]. A Radio Frequency Quadrupole (RFQ) linac system was proposed to bunch the low energy protons at the DWA device being developed by Compact Particle Acceleration Corporation [8]. In our 1 MeV DWA, a much longer proton bunch will be selected by the kicker, while the bunching system is supposed be included in the next phase. When a long proton bunch passes through the DWA module, the behavior of protons injected at different time will be totally different because the electric field varies quickly with time. The behavior of a long bunch could be considered as a combination of many short bunches. Thus, the simulation of the short proton bunch transportation will help to understand the beam behavior of a long bunch.

In our simulation, a 40 keV, 50 mA, 0.2 ns, 0.5 mm·mrad (Lapostolle) K-V proton bunch at its waist starts injection from 4 cm upstream of the entrance of the DWA module at $t=-2.2$ ns to 1.2 ns. The voltage pulse on the first cell reaches its center at t=15.8 ns. The arrival times of the voltage pulses on the second and the third cell relative to the first pulse were delayed 2.2 ns and 3.8 ns, respectively, in order to keep pace with the fastest protons. The typical waveforms of the accelerating field on the wall and on the axis are shown in Fig. 4. The maximum value of the 1 ns flattop pulse on the wall is 23.2 MV/m, while the peak value of the electric field on the axis reduces to 21.5 MV/m and the flattop vanishes.

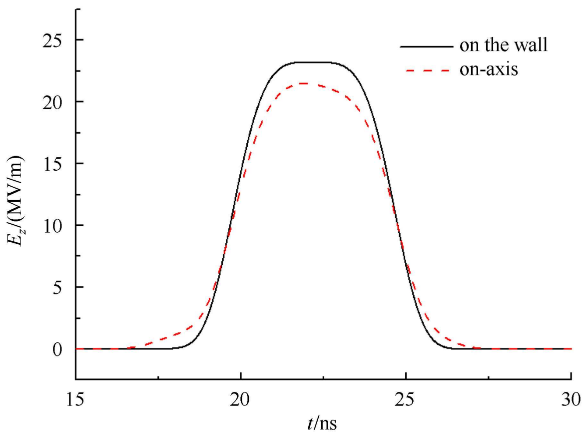

Fig. 4. (color online) Accelerating fields on the wall and on-axis at the second cell.

The energy, radius, beam slope and emittance of the proton bunch at the end of the drift tube as a function of the beam injection timing jitter are shown in Fig. 5. It is found that when the injection timing jitter is 1.4 ns, the output energy variation could be less than 2%. However, the radius and the slope of the bunch varies fast and monotonically in this situation. The beam behavior when the output energy is maximized is shown in Fig. 6(a). The proton bunch strongly converges inside the DWA module and diverges quickly thereafter. The focal spot of the proton bunch could be placed at the end of the drift tube by earlier injection to achieve a balance between the focusing force at the entrance and the defocusing force at the exit of the DWA module. The corresponding beam behavior is shown in Fig. 6(b). However, to obtain a tight focused proton bunch, the injection timing jitter should be less than 0.2 ns. Moreover, in order to maintain the small size of the beam slope, the injection timing jitter should not exceed 0.1 ns. It is obvious that the requirement for the timing jitter to obtain a stable output beam envelope is more strict than that to obtain a stable output beam energy.

In practice, the influence of the injection timing jitter can be neglected because the bunch length will be longer than that of the accelerating voltage pulse. The beam behavior and energy distribution along z-axis for a 8 ns proton bunch injected at $t=-4$ ns is shown in Fig. 7. It is obvious that only part of the protons could be accelerated to nearly 1 MeV. The maximum energy of the protons will still be influenced by the arrival timing

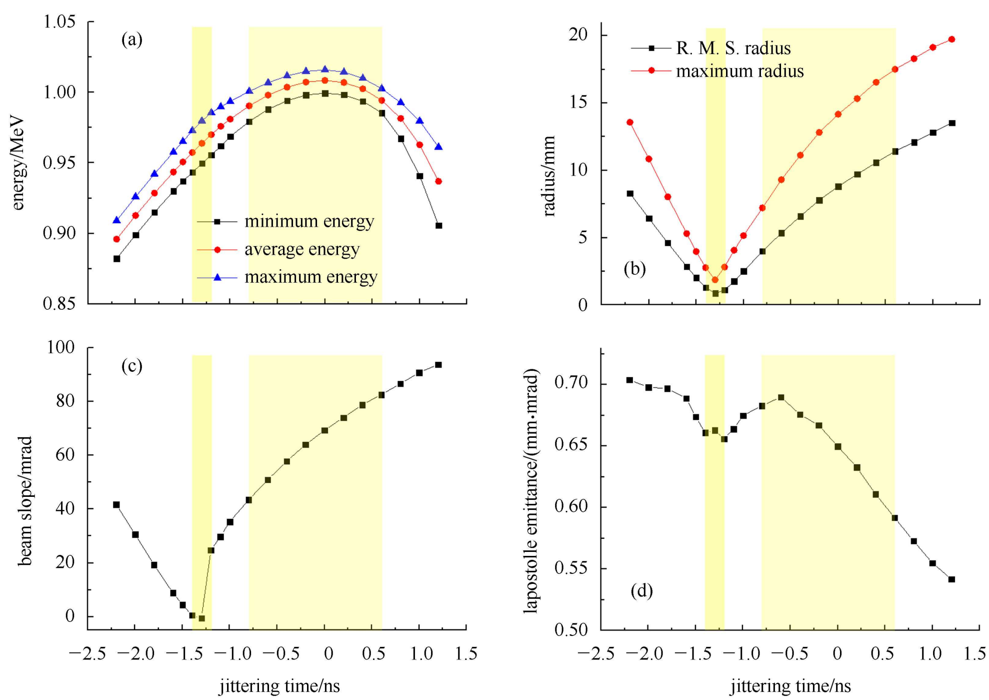

Fig. 5. (color online) Proton bunch's (a) energy, (b) radius (c) beam slope, and (d) Lapostoll emittance at the end of drift tube as a function of injection timing jitter.

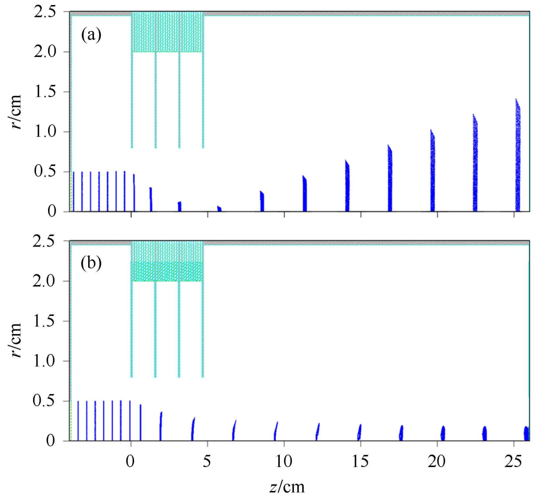

Fig. 6. (color online) Transport simulation of a 0.2 ns proton bunch (a) injected at t=0; (b) inject at t=−1.3 ns, the phasespaces of the protons are plotted every 2 ns.

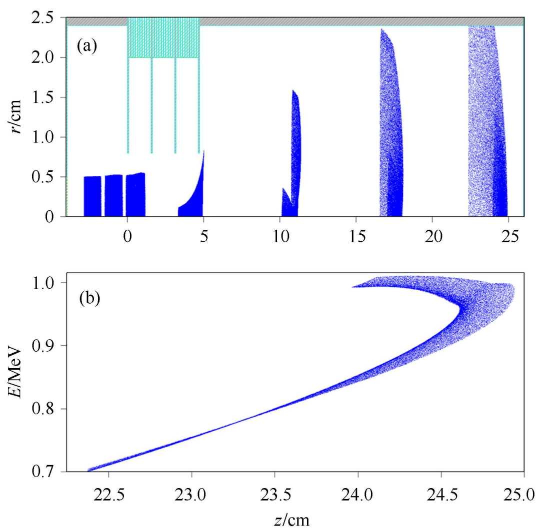

Fig. 7. (color online) Transport simulation of an 8 ns proton bunch, (a) phasespaces plotted every 5 ns; (b) Energy distribution along z-axis at the end of the drift tube.

jitter of the voltage pulses on the second and the third cell. The influences of the timing jitter were studied independently by assuming that one pulse has jittering time and that the timing of the other pulse is fixed. The simulation result is shown in Fig. 8. It is found that the maximum timing jitter allowed is about 2 ns in order to obtain the 20 MV/m or higher accelerating gradient. The maximum timing jitter allowed can be relaxed by increasing the accelerating voltage, which will result in an increased high voltage breakdown risk during the operation. It should be pointed out that the accelerating voltage pulse on each cell of the 1 MeV DWA is expected to be produced by a stack of Blumlein PFLs. Therefore, the jittering time of the PCSSs would not only be determine the timing jitter, but would also be determined by the shape of the output pulse, which will in turn influence the acceleration and focus of the proton beam.

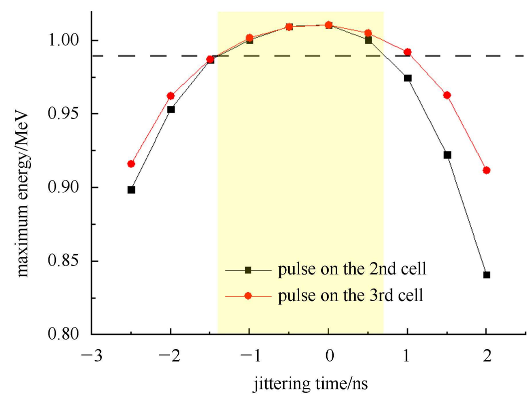

Fig. 8. (color online) The maximum proton energy as a function of the timing jitter of the voltage pulses on the second and the third cell.

5 Summary

In this paper, we present the beam transport design for a prototype DWA, which will provide the proof of principle experiment of the integrated DWA module composed of the HGI tube, the parallel-plate Blumlein PFL and the PSCC. The main purpose of the 1 MeV DWA is to achieve an acceleration gradient as high as 20 MV/m by using a novel acceleration structure. This accelerator does not attempt to cover all of the important aspects of the full machine used for proton therapy. These aspects include the method to produce a sub-nanosecond proton bunch, the realization of virtual traveling wave acceleration, the influence of the timing jitter variation on the output of the beam, and so on.

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