RF DEFLECTOR DESIGN FOR RAPID PROTON THERAPY*

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Abstract

Pencil beam scanning of charged particle beams is a key technology enabling high dose rate cancer therapy. The potential benefits of high speed dose delivery include not only a reduction in total treatment time and improvements to motion management during treatment, but also the possibility of enhanced healthy tissue sparing through the FLASH effect, a promising new treatment modality. We present here the design of an RF deflector operating at 2.856 GHz for the rapid steering of 150 MeV proton beams. The design utilizes as TE11-like mode supported by two posts protruding into a pillbox geometry to form an RF dipole. This configuration provides a significant enhancement to the efficiency of the structure, characterized by a transverse shunt impedance of 68 MΩ/m, as compared to a conventional TM11 deflector. We discuss simulations of the structure performance for several operating configurations including the addition of a permanent magnet quadrupole to amplify the RF-driven deflection. In addition to simulation studies, we will present preliminary results from a 3-cell prototype fabricated using four copper slabs to accommodate the non-axially symmetric cell geometry.

INTRODUCTION

Proton beams are a critical tool in the arsenal of radiation therapy used for the treatment of cancer. The peak in localized dose deposition at a depth determined by the proton Bragg peak allows for enhanced conformal dose shaping to target the tumor while minimizing damage to surrounding tissue. Because they are charged particles, protons also allow for improvements to the flexibility and efficiency of transverse shaping through pencil beam scanning, as opposed to conventional collimators which shape the beam by blocking portions of it. Pencil beam scanning for proton therapy has been in clinical use for over a decade, relying on scanning magnets to steer the beam over a tumor cross-section [1]. RF-based techniques for modulating the proton beam energy have been proposed as a means of increasing the speed of layer switching, changing the depth of dose deposition by changing the beam energy with a linac rather than a passive energy absorber. We investigate an RF-based technique for transverse steering as well, in order to further improve the speed of pencil beam scanning. The push for high speed scanning is driven by the demand for high dose rates, which will be necessary for techniques like FLASH therapy [2], as well as overcoming the motion management challenges during prolonged treatment sessions.

The proton beams used in a clinical setting are primarily provided by cyclotrons, with beam energies ranging from 70-250 MeV [3]. The scope of our research on RF-based rapid proton beam scanning covers both an energy modulator and deflector targeted for 150 MeV protons, corresponding to a baseline depth of 15 cm in water [4, 5]. Here, we focus on the design of the deflector, including a discussion of simulated beam steering and prototype testing.

DEFLECTOR DESIGN

Our choice of deflector cavity design utilizes a TE_{11}-like mode produced by adding two posts protruding into a pillbox geometry. Figure 1 shows the electric field in the cross-section of the cavity, looking along the beam axis, with the profile of the opposing posts delineated in white. This configuration produces an RF dipole, with the deflection resulting from the strong electric field localized between the posts [6]. Conventional deflector cavities, like those used as a beamline diagnostic for longitudinal bunch profile characterization [7], rely on a TM_{11} mode in a plain pillbox geometry to provide an efficient kick for relativistic particles. The protons used for radiation therapy are non-relativistic, and therefore undergo far less efficient deflection in a conventional structure. The efficiency of the deflection is characterized by the transverse shunt impedance, R_T, defined in terms of the deflecting voltage per meter, $V_\perp$, and dissipated power per meter, P_{disp}, as $R_T = {V_\perp}^2/P_{disp}$. For a 150 MeV proton beam in a conventional TM_{11} cavity operating at 2.856 GHz, the optimized transverse shunt impedance is 4.6 MΩ/m. For our TE_{11}-like structure, the optimized transverse shunt impedance is 68 MΩ/m.

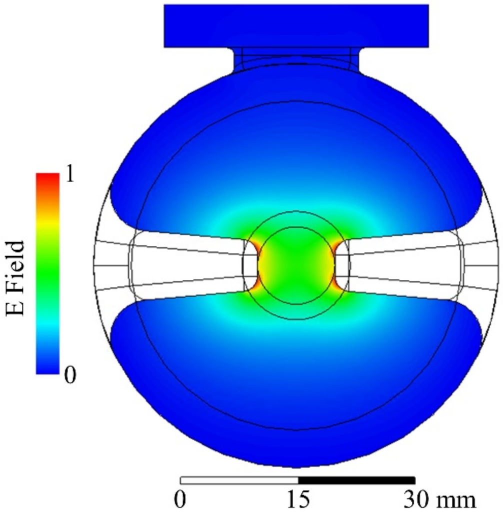

Figure 1: Electric field profile of the TE_{11}-like mode shown in a cross-section of the deflector cell, with beam axis oriented into the page. The opposing posts (profiles shown in white) produce an RF dipole, with the electric field pointing between the tips. Power is coupled in through the port at the top of the model simulated in ANSYS-HFSS.

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Because the geometry is not axially symmetric, there are non-zero higher order multipolar components of the deflecting mode. We don't expect the aberrations in the beam profile introduced by this asymmetry to impede the utility of the beam for treatment planning. The orientation of the posts determines the direction of the deflection, requiring cells of each polarization in order to achieve deflection in both transverse directions. The efficiency of the transverse deflection improves as the post tips are brought closer to the beam axis. This topology is limited by the same considerations as the irises between cells, with clipping becoming a problem as the deflected beam drifts farther off-axis. Design parameters for the deflecting cavity are shown in Table 1.

Table 1: Deflector Design Parameters (@ 300 K)

Name	**Unit**	**Prototype**
Frequency, *f*	GHz	2.856
Iris Aperture Radius, *a*	mm	5
Cell Period, *d*	mm	37.5
Iris Thickness, *t*	mm	4
Cell Quality Factor, Q_0		7295
Power Per Cell, $P_{\text{dissipated}}$	kW	400
Kick per meter in one cell, E_{kick}	MeV/m	27
$E_{\text{peak}}/E_{\text{kick}}$		9.3
$H_{\text{peak}}Z_0/E_{\text{kick}}$		3.2

In order to provide transverse coverage that is comparable to current scanning magnet systems, we need to achieve a 100 mrad deflection. We have explored several configurations to enhance the operation of our deflector in order to meet this goal, starting with extending the structure. Beyond six cells, the iris aperture between cells, and the distance between post tips, was increased in order to accommodate the off-axis drift of the deflected beam. This approach is limited by the decreasing efficiency of the deflection. For deflection purely along one polarization, the beam will drift closer to the post tip, maintaining an efficient kick with additional cells, but because the design goal includes deflection in both transverse directions, the combined orthogonal kicks will take the beam farther from the posts, leading to diminished overall efficiency.

By cooling the structure to 45 K, we expect to improve our transverse shunt impedance by roughly a factor of 4 [8]. This will be a key operating feature in our simulations and prototype testing. However, the deflection produced through a combination of cooling the structure and adding cells is still limited to around 48 mrad.

To push our deflection beyond this range, we now consider adding permanent magnet quadrupoles (PMQ) after the RF deflector in order to magnify the kick, as shown in Fig. 2. The effect of the PMQ will be to boost the deflection on one axis and correct the deflection on the other. In our case we do not want to correct the deflection, but we can effectively over-correct the deflection so that we still cover a large area. Examples of these beam trajectories are shown in Figs. 3 (a) and (b) for the case of maximum deflection. The deflector configuration utilized for these simulations has four cells polarized for deflection in y, followed by one cell for deflection in x, and a final cell for deflection in y, as seen in Fig. 2. The PMQ's are composed of 16 sections in a Halbach orientation, each 12 cm long, providing a field gradient of around 202 T/m [9]. Because the PMQ's are oriented for magnifying the kick in x, only a single RF deflecting cavity is needed for that polarization. The rastered beam distribution for 121 cumulative shots is shown in Fig. 3 (c). For the simulations shown in Fig. 3, the beam energy is 180 MeV, the highest energy provided by our upstream energy modulator and the stiffest case in terms of maximum achievable beam deflection.

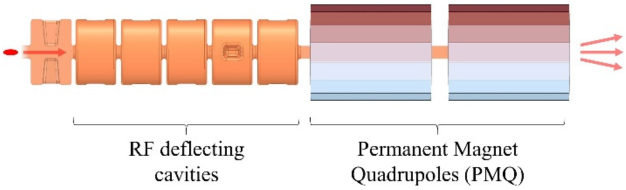

Figure 2: Schematic of a 6 cell RF deflecting structure followed by two permanent magnet quadrupoles to enhance the kick.

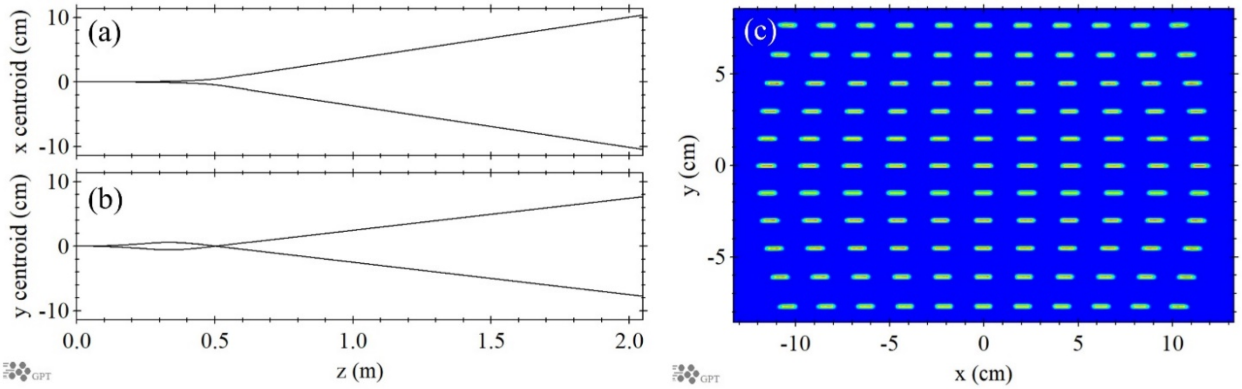

Figure 3. Beam centroid trajectories for maximum positive and negative deflection (a) in x and (b) in y. Note the over-correction in the PMQs of the y trajectories. (c) Rastered beam distribution showing 121 cumulative shots covering an area of roughly 23 cm x 16 cm. Simulations performed using General Particle Tracer (GPT) for a 6-cell structure operating at 45 K with 400 kW per cell and a proton beam energy of 180 MeV.

PROTOTYPE FABRICATION

In addition to simulations of the beam deflection achieved with a 6 cell deflector structure and PMQ pair operating at cryogenic temperatures, we have designed and fabricated a 3 cell prototype of the deflector. Figure 4 (a) and (b) shows the mechanical design of the structure with alternating polarization of the 3 cells. Because of the complexity introduced by the opposing posts in alternating locations, we fabricated the structure from 4 slabs of milled copper, as shown in Fig. 4. (c) prior to brazing. This technique required precision alignment over a sequence of more than 3 braze cycles. The results of the first cold test after brazing is shown in Fig. 5. The 3 cavity resonances are all within 2 MHz of the design frequency of 2.856 GHz. Each cavity will be tuned using a threaded post located on the outside of the cavity opposing the coupling port. Preliminary measurements of coupling between cells showed an S21 of around -75 dB. We expect coupling between cells to be negligible due to the alternating mode polarization and narrow iris aperture. Cross coupling will be re-measured once the cells are tuned to verify it remains low even with matched resonances, before proceeding with high power testing of the structure.

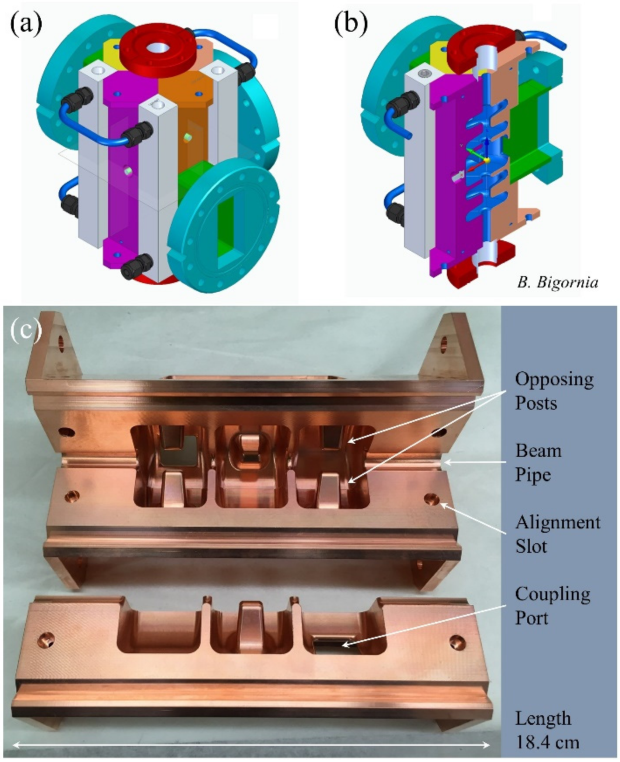

Figure 4: (a) Mechanical design for 3-cell deflector prototype. (b) Cross-sectional view of mechanical design showing alternating cell polarization. (c) View of the four slabs prior to brazing, with one slab removed to show the internal structure.

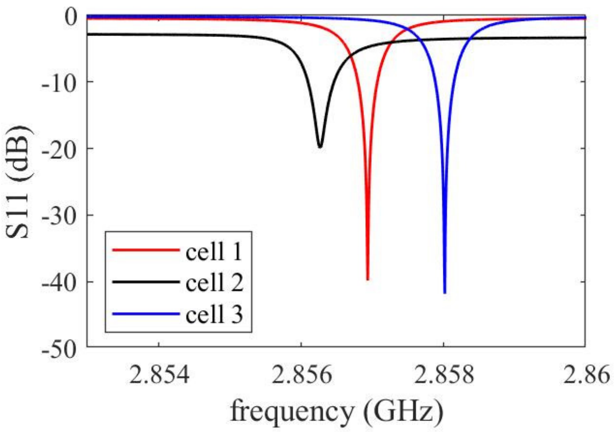

Figure 5: Cold test results for the 3 cells of the deflector prototype. The inferior coupling in cell 2 is attributed to poor alignment and RF contact of the adapter used for network analyzer measurements.

CONCLUSION

We have investigated utilizing an RF-based deflection scheme for pencil beam scanning of a proton beam for radiation therapy. Through a combination of a 6 cell RF structure operating at 2.856 GHz under cryogenic temperatures and a pair of permanent magnet quadrupoles, we are able to achieve maximum deflections exceeding 13 cm, given a distance of 2 m from the start of the deflector structure to the patient isocenter. This range is comparable with today's proton therapy facilities and can be accommodated within the footprint of existing gantry infrastructure. The increased treatment dose rate that could be enabled by this RF-based high speed pencil scanning system offers an attractive path towards achieving FLASH therapy and advancing a new generation of medical accelerator equipment.

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