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RAPID RADIO-FREQUENCY BEAM ENERGY MODULATOR FOR PROTON THERAPY*

X. Lu†, G.B. Bowden, V.A. Dolgashev, Z. Li, E.A. Nanni, A.V. Sy, S.G. Tantawi
SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

Abstract

We present the design for a rapid proton energy modulator with radio-frequency (RF) accelerator cavities. The energy modulator is designed as a multi-cell one-meter long accelerator working at 2.856 GHz. We envision that each individual accelerator cavity is powered by a 400 kW low-voltage klystron to provide an accelerating / decelerating gradient of 30 MV/m. We have performed beam dynamics simulations showing that the modulator can provide ± 30 MeV of beam energy change, with an energy spread of 3 MeV for a 7 mm long (full length) proton bunch. A prototype experiment of a single cell is in preparation at the Next Linear Collider Test Accelerator (NLCTA) at SLAC. The energy modulator is optimized for 150 MeV cyclotron proton beam, while this approach can work with different energies.

INTRODUCTION

Proton therapy has the advantage of a narrow range of proton energy deposition over other types of radiotherapy methods. The radiation dose of a proton beam can be precisely deposited at the tumor location, so healthy organs nearby can receive much less dosage. To deliver the radiation dose to varied depths in human bodies, a beam energy modulation system is needed. In current proton therapy machines, beam energy modulation is performed by a mechanical energy degrader; as a result, the modulation process is slow, reduces beam current and degrades emittance. Use of the mechanical degrader limits the capabilities of the proton source and beam delivery system and increases the treatment time so that the treatment results are more susceptible to organ motion [1]. Here we present a new approach for rapid energy modulation and scanning by radiofrequency (RF) cavities.

A schematic of the rapid proton beam delivery system using RF cavities is shown in Fig. 1. The proton beam is generated by a source such as a cyclotron, and then gets transported to the gantry comprised of permanent or superconducting magnets to bend the beam. The gantry is designed to have an energy acceptance of ±3 MeV, but the actual energy spread of the initial proton beam is an order of magnitude smaller. After the gantry, the beam enters the RF energy modulator to change the beam energy, and the RF deflector to scan the beam transversely. The goal of such a system is to deliver a proton beam which covers a scanning area of 25 cm × 25 cm with a depth variation of 12 cm within 1 second for a dose of 50 Gy/L/s.

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† xylu@slac.stanford.edu

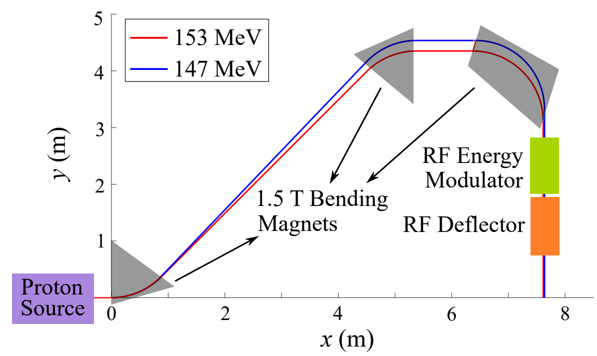

Figure 1: Schematic of the rapid proton beam delivery system, including a proton source, a gantry with three 1.5 T permanent magnets to transport the beam, an RF energy modulator and an RF beam deflector. The beam trajectories are shown for 153 MeV and 147 MeV.

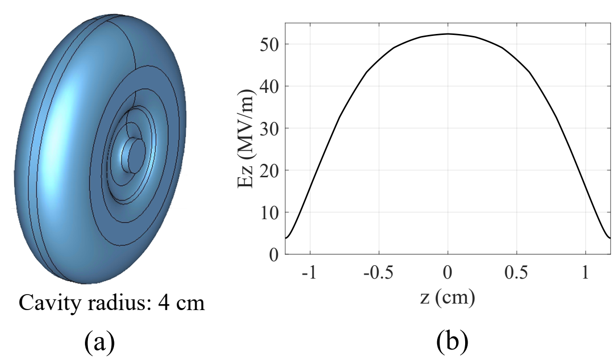

Figure 2: Single cavity of the energy modulator. (a) Vacuum space of a single cell. (b) Longitudinal electric field E_z on axis with 160° phase advance per cell. The field amplitude is normalized for an accelerating gradient of 30 MV/m for a 150 MeV proton beam.

This paper is focused on the design and fabrication of the proton beam energy modulator at 2.856 GHz. The design is optimized for a 150 MeV beam from a cyclotron provided by the Varian Medical Systems, Inc, but the general approach can be adapted to other proton beam sources.

ENERGY MODULATOR DESIGN

Cavity RF Design

The energy modulator is built from multiple accelerator cavities at 2.856 GHz. The geometry of a single cavity (vacuum space) is shown in Fig. 2 (a). The geometry is optimized to achieve a high shunt impedance while keeping

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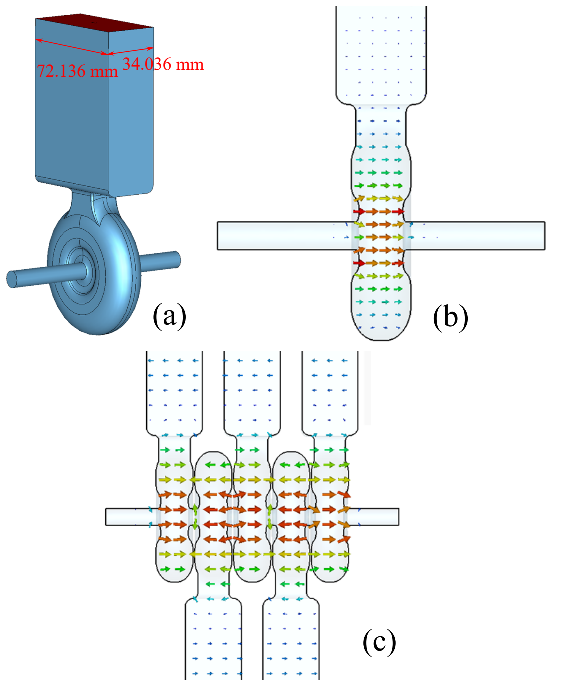

Figure 3: Energy modulator cavity with the power coupler. (a) Vacuum space of the single cavity model with its coupler to WR284 waveguide. Electric field amplitude mid-plane of a single cavity in (b), and of 5 cavities in (c). Each cavity is powered individually through its coupling waveguide, with a phase difference of 160° per cell. With 400 kW of input power, the accelerating gradient is 30 MV/m for a 150 MeV proton beam, and the peak surface E field is 68 MV/m.

a low peak surface electric field E and magnetic field H. The cavity length, 2.36 cm, corresponds to 160° of phase advance per cell for the 150 MeV proton beam. The longitudinal (z direction) electric field E_z in a single cavity is plotted on axis in Fig. 2 (b).

We plan to have a 1 meter long section of these cavities, where each cavity is fed individually by compact low-voltage klystrons. Figure 3 (a) shows a single cavity with its coupler to the WR284 waveguide. The method of feeding individual cells allows flexible phase control of each cavity to match the changing β value for the low-β proton beam ($\beta = v/c = 0.5067$ for the 150 MeV beam). It also allows for a small beam aperture of 1.05 cm to increase the shunt impedance [2]; as a result, the RF power required to drive these cavities at a certain gradient is lowered.

Figure 3 (b) and (c) present the electric field plots of the fundamental TM mode in a single cell and in five adjacent cells, respectively. In the 5-cell case, each cavity is driven individually with an equal RF power level and a phase difference of 160° between neighboring cells.

Table 1 lists the key parameters of the single cavity design with the coupler in the critical coupling regime. To provide an accelerating gradient of 30 MV/m, 400 kW of input power

Table 1: Design Parameters of the Energy Modulator Cavity With the Coupler, as in Fig. 3 (a)

Parameter	Value
Frequency	2.856 GHz
Beam aperture (diameter)	1.05 cm
Phase advance per cell	160°
Quality factor Q_0	11936
External quality factor Q_{ext}	11911
Shunt impedance r_s	54.8 MΩ/m
r_s/Q	4.6 kΩ/m
Acc. gradient E_a for $\beta = 0.5$	$15\ \text{MV/m} \cdot \sqrt{P/(100\ \text{kW})}$
E_{peak}/E_a	2.26
$H_{peak}Z_0/E_a$	1.25
Peak Poynting vector	$0.081\ \text{W}/\mu\text{m}^2 \cdot [P/(100\ \text{kW})]$
Pulsed heating temp.	$0.53°\text{C} \cdot [P/(100\ \text{kW})]\sqrt{t_p(\mu s)}$[1]

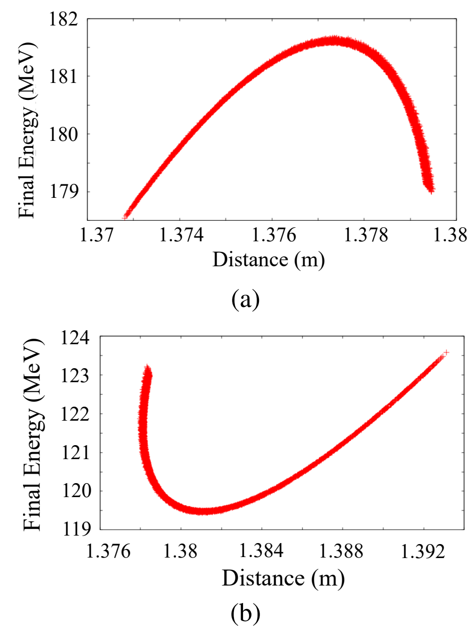

Figure 4: Beam dynamics simulations of the 150 MeV proton beam traversing a 50-cell energy modulator. The initial bunch length is 7 mm (full length). (a) Final beam energy showing 30 MeV acceleration. (b) Final beam energy showing 30 MeV deceleration.

is required to be fed into this cell. The peak surface E field in this case is 68 MV/m, and the peak H field is 99 kA/m.

Beam Dynamics Simulations

Beam dynamics simulations were performed in ACE3P and IMPACT [3] with 50 cavities of the S-band structures. The initial bunch length is 7 mm (full length), and the accelerating gradient is set to 30 MV/m. The beam can get accelerated or decelerated depending on its relative phase with the RF field. As the β value changes, the phase difference between cells is also changed accordingly in groups of 10 cells. In the acceleration case for example, the phase ad-

[1] $t_p(\mu s)$ is the RF pulse length in μs.

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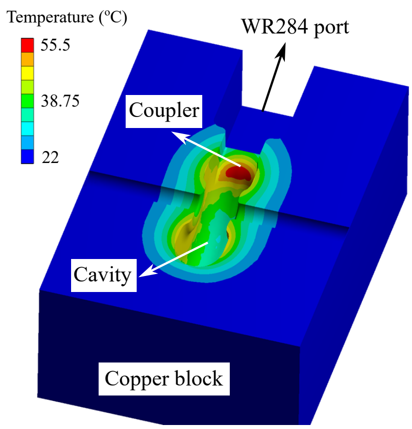

Figure 5: Temperature distribution at $t = 1$ s in a single cavity after being powered by a pulsed 400 kW RF power source with a duty factor of 2.5% for 1 s. No active cooling is present.

vance per cell is 160° for Cell #1-10, and then 158° for Cell #11-20, and so on. The final beam energy distributions in the acceleration case and in the deceleration case are shown in Fig. 4 (a) and (b), respectively. An energy modulation of ±30 MeV is shown in the simulations. The full energy spread is about 3 MeV in both cases, while it can be further reduced by using a shorter proton bunch to start with. A bunch compressor is also being developed to serve the purpose, so that rapid energy modulation with a precise step control can be achieved.

Thermal Simulation

To deliver the radiation dose at a rate of 50 Gy/L/s, we plan to run the energy modulator at a high repetition rate of 1-10 kHz for one second, and cool down afterwards. Thermal simulations were carried out to calculate the temperature rise in a single cell. Figure 5 shows the temperature distribution at $t = 1$ s. The cavity is fed by a pulsed 400 kW RF power source with a duty factor of 2.5% for 1 s, which is equivalent to an average power of 10 kW. The initial copper block temperature is 22°C (room temperature) without active cooling. After 1 s of high power operation, the peak temperature rises to 55.5°C. The structure cools back down to room temperature in about 10 s. The temperature rise is practical for the high repetition rate operation.

STRUCTURE FABRICATION

A single cell structure has been designed and is being fabricated. Figure 6 shows the two halves of the cavity, which will later be brazed together at the splitting surface. A high power S-band test stand will be commissioned for the structure test at the Next Linear Collider Test Area (NLCTA) at SLAC. The output microwave power from an S-band klystron will be fed into the WR284 waveguide, and coupled into the single-cell cavity. An RF probe will be mounted on the wall of a matching waveguide with about -60 dB of coupling coefficient, as shown in Fig. 6. The two ends of the beam pipe will be connected to two Faraday cups to measure the dark current and the breakdown current in case of an RF breakdown event. With this prototype, we will be able to demonstrate the high power operation of the energy modulator cavity.

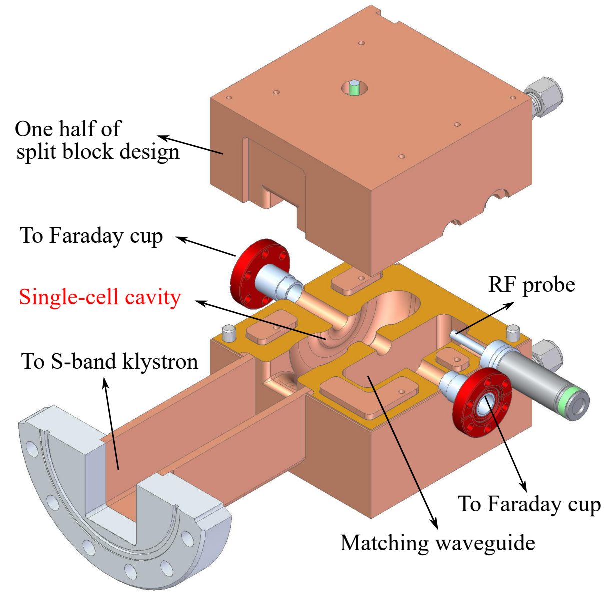

Figure 6: Drawing of the single cavity prototype structure to be tested at the NLCTA facility.

CONCLUSIONS

We have designed a rapid energy modulator with RF cavities at 2.856 GHz for proton therapy devices. The cavities can provide 30 MV/m of accelerating / decelerating gradient to a 150 MeV proton beam with 400 kW of microwave power fed into each individual cell. Beam simulations have demonstrated ± 30 MeV of energy modulation with a final energy spread of 3 MeV in a 50-cell energy modulator. Thermal simulations have shown that the high repetition rate operation with a duration of 1 s is practical. A single cell prototype is being fabricated and will be tested at the high power test stand at SLAC. The current design is optimized for the 150 MeV cyclotron beam, but it can be easily adapted to other proton sources with different beam parameters.

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