FAST SCANNING BEAMLINE DESIGN APPLIED TO PROTON THERAPY SYSTEM BASED ON SUPERCONDUCTING CYCLOTRONS*

B. Qin†, K.F. Liu, Z.K. Liang, X. Liu, W. Chen, Q.S. Chen, P. Tan, K.J. Fan, T.Q. Yu, M.W. Fan,
Institute of Applied Electromagnetic Engineering,
Huazhong University of Science and Technology (HUST), Wuhan 430074, China

Abstract

Proton therapy is recognized as one of the most effective radiation therapy method for cancers. The superconducting cyclotron becomes an optimum choice for delivering high quality CW proton beam with features including compactness, low power consuming and higher extraction efficiency. This paper introduces design considerations of the beamline with fast scanning features for proton therapy system based on superconducting cyclotrons. The beam optics, the energy selection system (ESS) and the gantry beamline will be described.

INTRODUCTION

HUST Proton Therapy Facility is a 5 years (2016-2020) Major State Research & Development Program supported by MOST (Ministry of Science and Technology, China). This is a collaborative project with teams from HUST, CIAE (China Institute of Atomic Energy), Tongji Hospital and Xiehe hospital affiliated to HUST. The main purposes of this project includes 1) R&D of a proton therapy facility based on isochronous superconducting cyclotron, with two 360 degrees gantry rooms and one fixed beam line treatment room; 2) Installation and commissioning in the International Medical Center of HUST; 3) Clinical experiments for CFDA. The main specifications are listed in Table.1.

Table 1: Main Specifications of HUST PT Facility

Parameter	Specification
Beam energy from the cyclotron	250 MeV
ESS energy range	70-250 MeV
Energy modulation time per step	⩽ 150ms
Gantry rotation range	±180 degree
Positioning precision at Iso-center	⩽0.5mm
Max. dose rate	3Gy/L/min
Field size	30cm×30cm

This paper mainly introduces design and considerations of the beamline. Since the cyclotron is designed to provide 250MeV fixed energy proton beam, ESS must be used to modulate beam energy in range of 70-250 MeV. Pencil beam scanning will be employed for fast and accurate treatment, with the main mode of spot scanning.

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† bin.qin@mail.hust.edu.cn

OVERALL CONSIDERATIONS OF BEAMLINE

Figure 1 shows the layout of the beamline. The degrader is placed at the downstream of the cyclotron, for better radiation control of neutrons. A DBA (double bend achromatic section) is followed with the degrader, with an energy select slit. For the gantry beamline, a downstream scanning scheme is chosen to avoid construction of large aperture 90 degrees dipole which is required in upstream scanning. Another cons is the linear dependency between the beam position and the scanning magnet current relieves difficulty of the therapy planning. To avoid the dose accumulation on skins due to un-parallel beam, the SAD (source-axis distance) is designed to around 2.8 m.

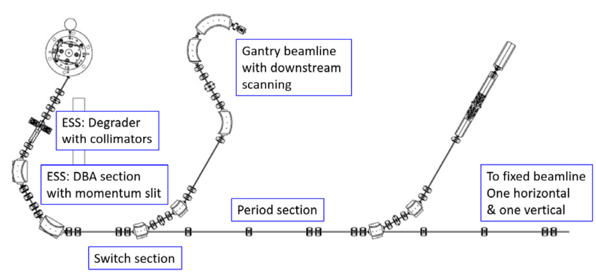

Figure 1: Layout of the beamline (correction magnets and beam diagnostics are hidden).

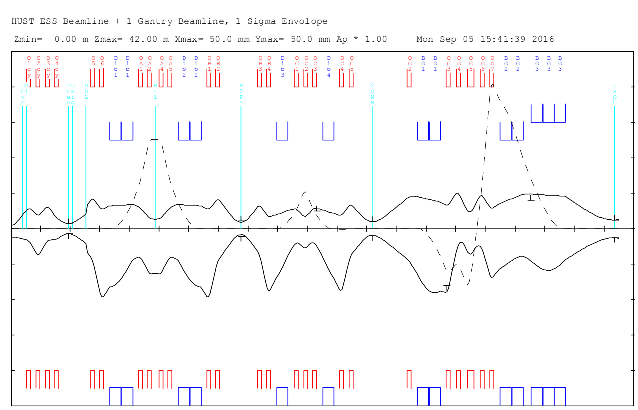

Figure 2: 1 sigma beam envelope for the main beamline including ESS and gantry beamline.

Figure 2 shows the 1 sigma beam envelope of the beamline using Transport code [1]. Main optics consideration about the beamline are:

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- A multi-wedge style degrader is positioned just after a four quadrupole set from the exit of the superconducting cyclotron, to limit the neutron radiation far from the treatment room. Beam waist at the degrader center for both planes is designed to minimum the scattering effect in the degrader.
- A DBA section is followed after the degrader, with an size-changeable energy slit for limiting energy spread from 0.3% to 0.5%.
- At the connection point (CP) between the fixed beamline and the rotation gantry beamline, mirror beam x=y, x'=y' is designed to make the gantry optics identical for different rotation angle. Beam waist is necessary condition, however it will maintain a better transmission at CP.
- For effective spot scanning, at the iso-center, the double beam waist is designed, with $\sigma_x = \sigma_y =$ 2.5 mm at 250 MeV and rms emittance $\epsilon_x = \epsilon_y =$ $7\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$.

At first stage, spot scanning method with pencil beam will be used. When repainting is required, the energy modulation time T_e corresponding to one depth step (5 mm water equivalent) becomes important for overall treatment time. For example, for 1 Litre water radiation with 5 mm depth step, one painting for energy modulation time is 2s for $T_e = 100$ ms and 20s for $T_e = 1$s. For HUST PT facility, $T_e = 150$ ms is expected to control the treatment within 5 minutes for 1 Litre volume with multi-repainting. Although as reported by PSI [2], $T_e = 80$ ms has been achieved, this value is still challenging, not from the beamline magnet hardware, but from the possible disturbance of the beam quality during fast magnetic field transition.

ENERGY SELECTION SYSTEM

ESS is an essential part for proton therapy facility based on fixed energy cyclotrons. Main considerations of HUST ESS are: 1) ability for fast energy modulation in range of 70 MeV to 250 MeV, for a normalized step corresponding to 5mm water equivalent depth, the change time should be controlled within 100 ms, with a repeatable accuracy of 0.1mm water equivalent; 2) careful design of collimators and energy slit after the degrader, to shape the beam after significant growth of emittance and energy spread during energy degrading process; 3) adequate local radiation protection around the degrader; 4) redundancy for control system and beam diagnostic for treatment safety..

Figure 3 shows the schematic configuration of the degrader. A double multi-wedge scheme was chosen, due to its structure simplicity for easy maintenance and possibility for fast movement. During energy degrading in the material, the beam emittance growth is mainly caused by multiple Coulomb scattering and angle scattering is a dominated factor [3]:

$$\Delta\epsilon \approx \beta \cdot < \theta^2_{x/y} > \qquad (1)$$

Since the rms multiple scattering angle $< \theta^2_{x/y} >$ is mainly related to the material property and thickness, in order to minimize the emittance growth $\Delta\epsilon$, double beam waist should be designed at the centre of the degrader for a minimum β function.

High density graphite will be used for degrader material. Low Z element such as Beryllium has a longer radiation length that will supress the scattering angle, however, the material processing is more difficult.

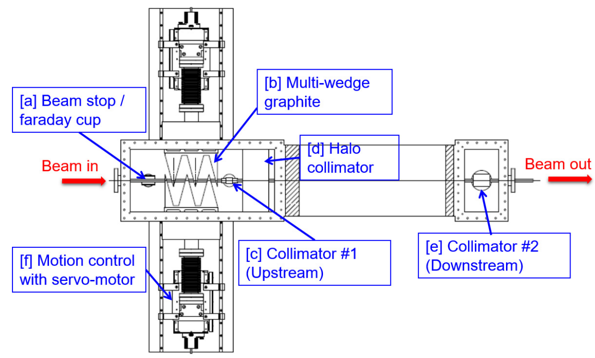

Figure 3: Schematic view of the multi-wedge degrader.

Geant4 code [4] based on Monte-Carlo algorithm was used for multi-particle simulation in the degrader [5]. For energy degrading to 70 MeV, the emittance is increased from initial $5\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$ to about $140\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$, and the spread in increased to higher than 3 MeV. By using a collimator set (Collimator #1 & Collimator #2) and an energy slit in DBA, the beam can be shaped to $5{\sim}10\pi \cdot \mathrm{mm} \cdot \mathrm{mrad}$ and $\pm 0.5\%$ spread. However, for this energy, even after optimization of the optics and drift space between the wedges, the transmission is quite small (about 0.2%) as shown in Fig. 4.

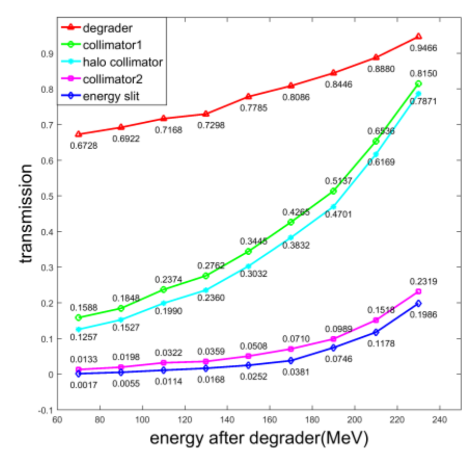

Figure 4: Transmission varies with the energy after degrader, simulated by Geant4 code.

From present study, the beam transmission in ESS varies significantly for lowest energy 70 MeV, is just 0.2%. Even for energy range 70 to 230 MeV, the transmission ratio is about 100, which leads to high intensity difference during treatment. To relieve this difference, we plan to perform intensity compensation in the beamline, to fur-

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ther supress beam intensity at higher energy and limit the intensity ration within 20, for example, 1-20 nA for treatment.

GANTRY BEAMLINE

Figure 5 shows the layout of the gantry beamline, which is design for a 360 degree gantry. B1 and B2 are two 60 degree dipoles, and B3 is a 90 degree dipole with a 20 degree exit angle for better control of vertical beam envelope. Two sets of BPMs and X/Y steering magnets are configured for beam alignment.

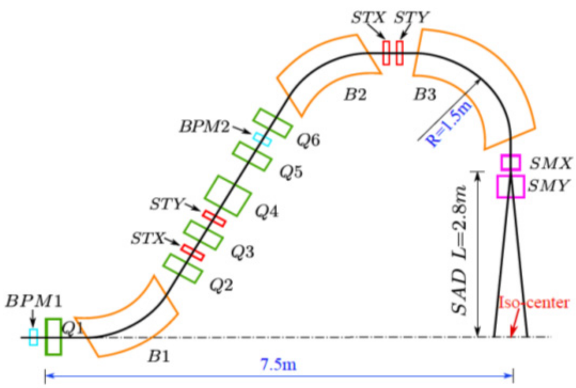

Figure 5: Schematic view of the downstream scanning gantry beamline.

Downstream Scanning and SAD

Compared to upstream scanning scheme, downstream scanning was chosen, with considerations: (1) to achieve a larger field size at the iso-center: 30 cm × 30 cm. When using upstream scanning, pitching has to be used for this size. (2) the dependency between the excitation current and the beam position is linear, which relieve the PBS (pencil beam scanning) system design. (3) to avoid the use of large aperture last 90 deg. dipole, as well as this type of dipole will further limit the energy modulation time.

The main disadvantage of downstream scanning comes from the un-parallel beam, which will bring higher dose on patient skin. To compensate this effect, a longer SAD L=2.8 m is adopted. A side-effect of long SAD is that the requirement for fast scanning magnet (SMX) is mitigated.

Scanning Magnet and Eddy Losses

Performance of scanning magnets is critical for pencil beam scanning. Careful design and optimization on two orthogonal scanning magnets SMX & SMY has been performed to find a compact solution with reasonable eddy losses [6]. For fast scanning magnet SMX, the upper limit of operating frequency is 100 Hz, corresponding to a scanning speed of 60 m/s. The magnetic field is 0.52 T for 250 MeV energy, which produce 55 mrad deflection angle. 0.1mm lamination steel will be used to reduce eddy current in poles.

Main eddy losses comes from the pole end due to fringe field. The cooling plate attached to the pole end is one solution, however this method will increase the magnet length. Slit cuts on the pole end is another method to cut off the eddy current efficiently, but dimensions and position of the slits are sensitive. To study these factors and optimize the eddy losses, OPERA3D with ELEKTRA / TEMPO modules is used to simulate the eddy current and temperature increase. Figure 6 shows an optimized configuration with 8 2 mm width slits. The maximum temperature is below 65℃, while the temperature without slits will beyond 175℃. Figure 7 is the assemble view of SMX.

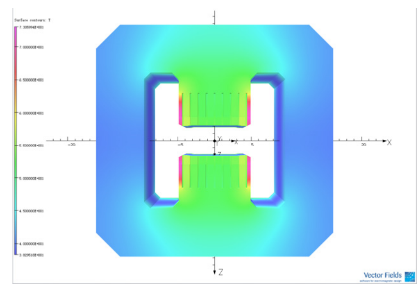

Figure 6: Eddy current and temperture analysis using ELEKTRA/TEMPO.

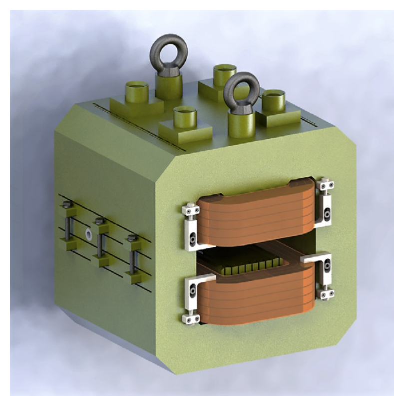

Figure 7: SMX magnet model.

CONCLUSION

Main considerations, optics design and scanning magnet design for HUST proton therapy beamline are introduced in this paper. Physical design of the ESS with help of Geant4 code has been performed, however, optimization of beam transmission and beam intensity compensation are required to achieve more stable beam delivery during treatment.

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