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Design of Prototype Magnets for HUST Proton Therapy Beam Line

Wei Chen, Bin Qin, XiaoYu Fang, QuShan Chen, Jun Yang, KaiFeng Liu*

State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, Wuhan 430074, Hubei, China

Abstract

HUST proton therapy facility (HUST-PTF) is a 5 years National Key Research and Development Program of China, which is based on an isochronous superconducting cyclotron with two gantry treatment rooms and one fixed beam line treatment room. In this paper we report the main design specifications of the beam line in HUST-PTF project, in which the main features are the intensity suppression scheme and point-point 1:1 image optics for the gantry beam line. As well as two prototype magnets (one quadrupole and one dipole) used in the beam line are studied and presented in the paper. Two-dimensional contour optimization and pole-end chamfer iteration are used to minimize the harmonic errors of the integral field. Finally, both the field homogeneity and multipole errors can achieve the precision requirement over the operating field range.

Layout and Specifications of the Beam Line

We have an isochronous superconducting cyclotron to deliver proton beams with fixed energy of 250 MeV at the origin of the beam line. Due to the fixed beam energy extracted from the cyclotron, an energy selection system (ESS) is placed behind the cyclotron to modulate the beam energy in range of 70-230 MeV for treatment of various depth tumors. The degraded beam is then transported to treatment rooms by the switch section and period matching section.

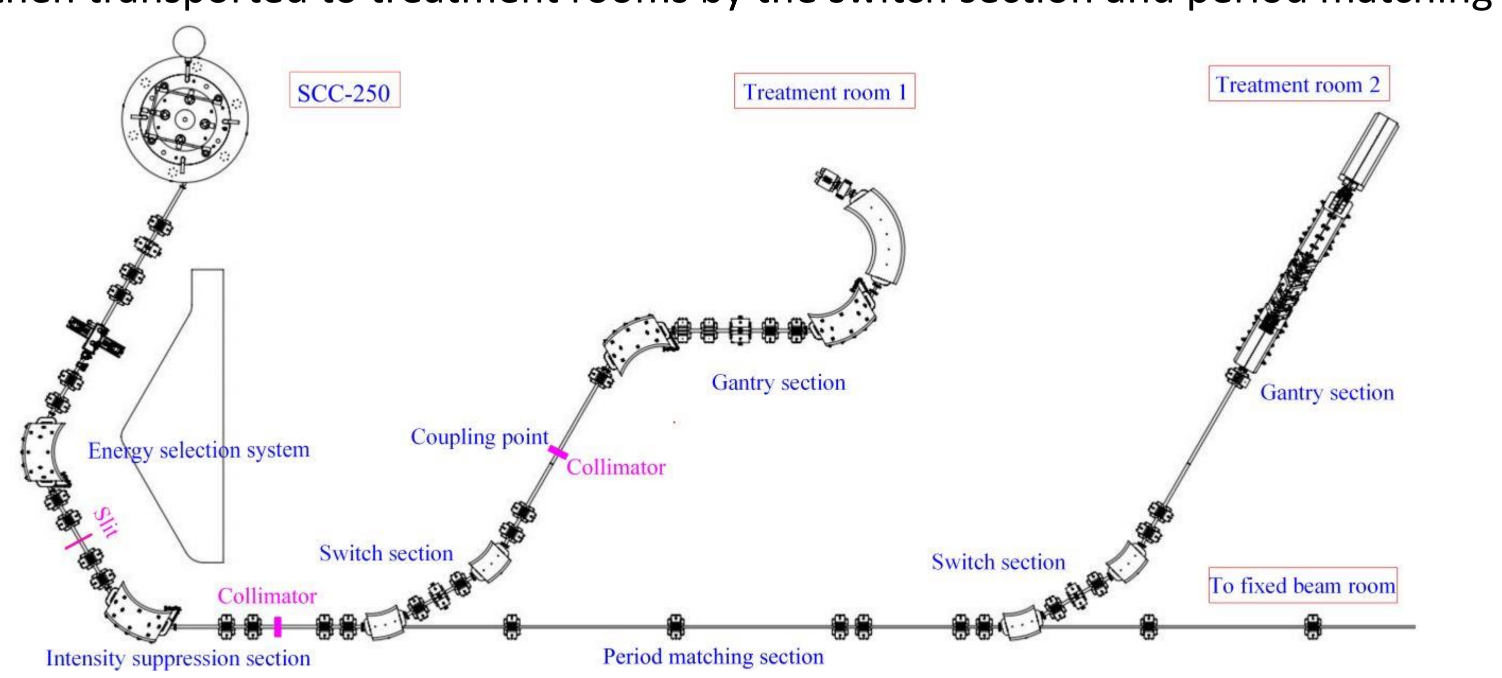

Fig.1 Layout of the HUST-PTF beam line, mainly consist of energy selection system (ESS), intensity suppression section, switch section, period matching section and gantry section.

TABLE I. Main Specifications of HUST-PTF beam line

Parameters	Specification
Accelerator type	Isochronous superconducting cyclotron (fixed 250 MeV)
ESS energy range	70-230 MeV
Energy step	2.5 MeV
Maximum transmission ratios	≤ 10
Energy modulation time per step	≤ 150 ms
Gantry type	± 180 degree, normal conducting
Max. dose rate	3 Gy/L/min
Pencil beam scanning field size	30cm × 30cm

Main design features of the beam line are:

(1) Due to the transmissions in the ESS are highly dependent on the beam energy, and the maximum transmission ratio between high energy (230 MeV) and low energy (70 MeV) is more than 200. If the extraction intensity of the cyclotron is fixed, the significant difference of transmissions will lead to high beam intensity difference during treatment, which is unacceptable for treatment safety. To reduce the difference, an intensity suppression section is placed behind the ESS in our case, which adopts a passive scheme by defocusing beam at high energies on the collimator and the transmission ratios can be controlled less than 10. For a fixed 500 nA initial beam extracted from the cyclotron, the intensity range for final treatment is about 0.4 nA-4 nA.

(2) At the coupling point (CP) between the fixed beam line and the rotation gantry beam line, rotational symmetric beam x=y, x'=y' is designed to make the gantry optics identical for different rotation angle. For safety concerns, a collimator is installed at the entrance of the gantry to guarantee the beam size and to remove uncertainties from beam misalignment.

(3) For the gantry beam line, a downstream scanning scheme is chosen to avoid construction of large aperture 90 degrees dipole, as well as with the consideration for the linear dependency between the beam position and the scanning magnet current. To obtain a stable beam at the iso-center, a point-to-point 1:1 image optics from the coupling point to iso-center is designed, which demands R11=R22=R33=R44=±1 and R12=R34=0 in the first-order R matrix. With the image optics design, even some parameters such as the beam divergence are changed at the entrance of the gantry; the beam size is still stable at the iso-center with a collimator installed at the entrance (CP).

L270 Quadrupole Prototype Design

A quadrupole magnet with length of 270 mm, radius of 40 mm and maximum gradient field of 17.5 T/m, is designed in this section. Two-dimensional contour optimization and pole-end chamfer iteration are used to minimize the multipole errors during design process. The multipole errors of the quadrupole are obtained by performing Fourier harmonics analysis of the integral field along the good field radius. To eliminate the high order harmonics errors, especially the dodecapole (n=6) error can up to 2.5e-3, a pole-end chamfer cut is necessary and highly effective. As shown in Fig.4, the high order harmonics errors can be well controlled less than 3e-4 with a proper pole-end chamfer after several iterations.

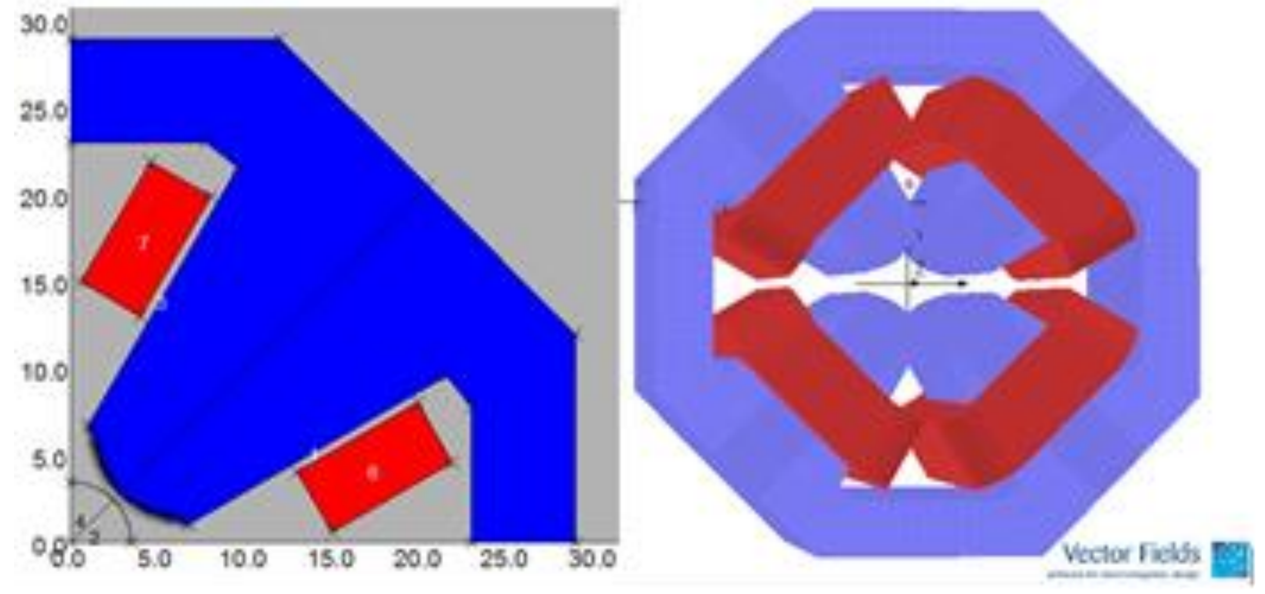

Fig. 2. TOSCA models of the quadrupole. Left: 2-D optimized transverse cross section; Right: 3-D model.

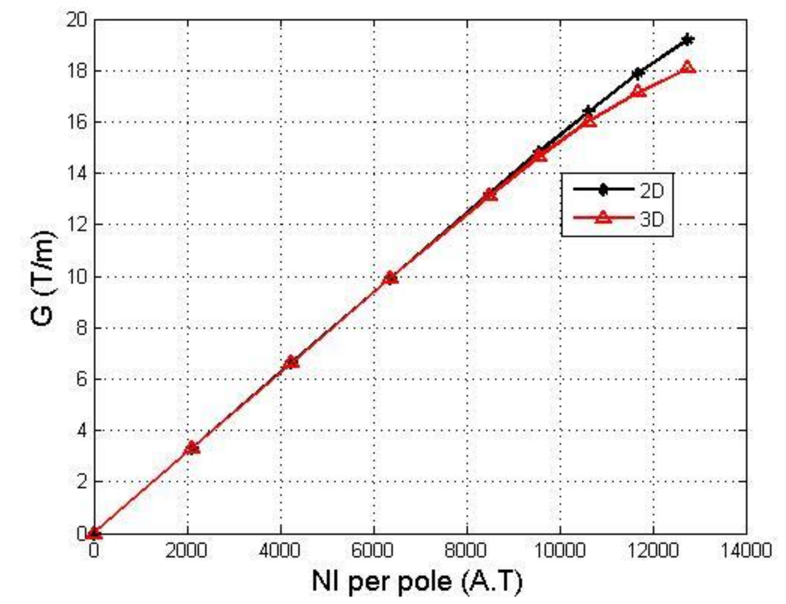

Fig. 3. The excitation curve (G-NI) of quadrupole magnet.

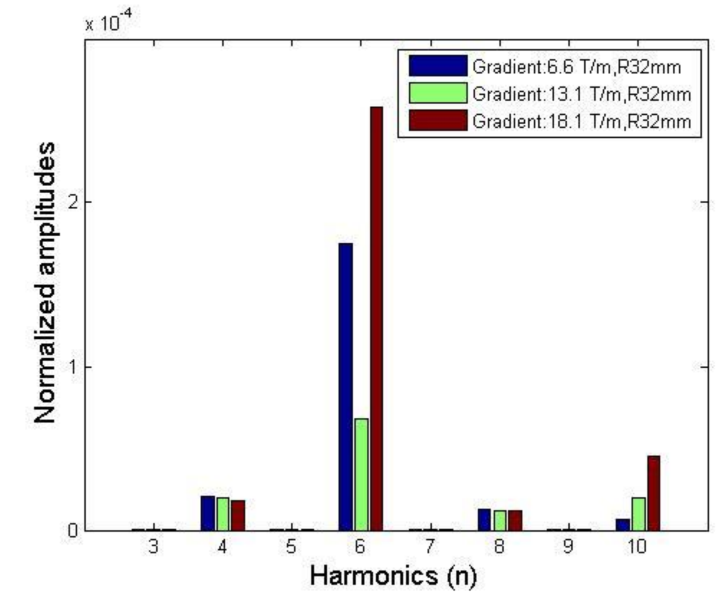

Fig. 4. Multipole errors of the quadrupole magnet after pole-end chamfered along the radius of 32 mm.

57 Degree Sector Dipole Prototype Design

H-type structure and racetrack coils were adopted in the dipole prototype magnet. The gap was designed to be 60 mm and bending radius was 1500 mm with the maximum field of 1.62 T corresponding to the maximum proton energy 250 MeV. The pole width was designed to be 250 mm to achieve a ±35 mm good field region.

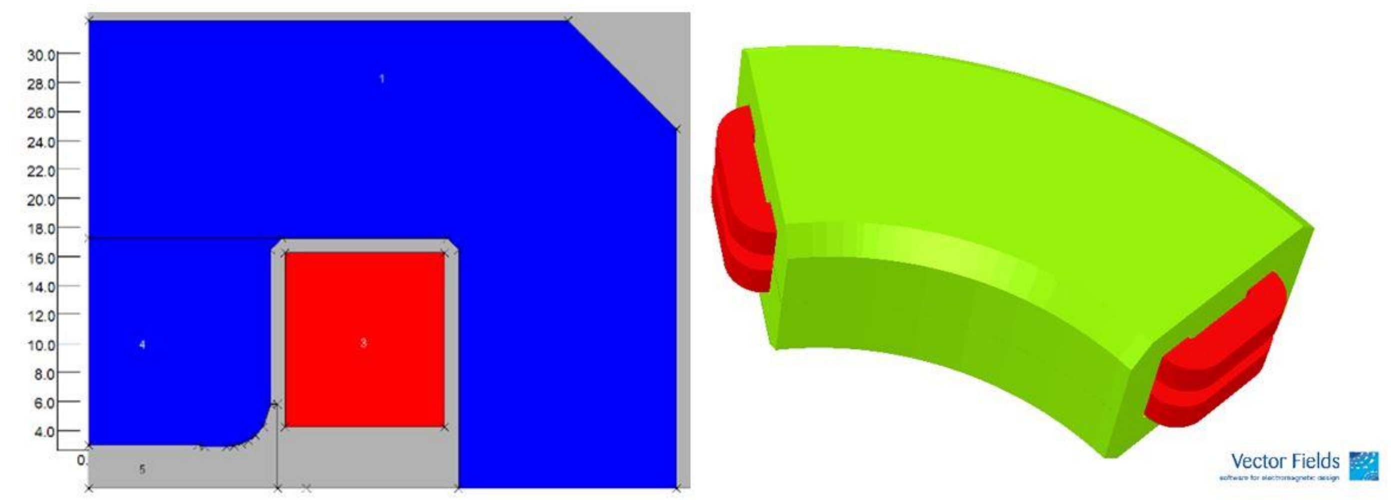

Fig. 5. TOSCA models of the dipole. Left: 2D optimized transverse cross section; Right: 3D model.

TABLE III. Main parameters of the Dipole

Parameters	Value
Yoke structure	H type
Bend angle	57 degree (sector)
Bend radius	1500 mm
pole gap height	60 mm
Pole width	250 mm
Good field width	±35 mm
Operating field range	0.8T - 1.62 T
Multipole field components	≤ ±0.08%
Overall weight	5.5 tons

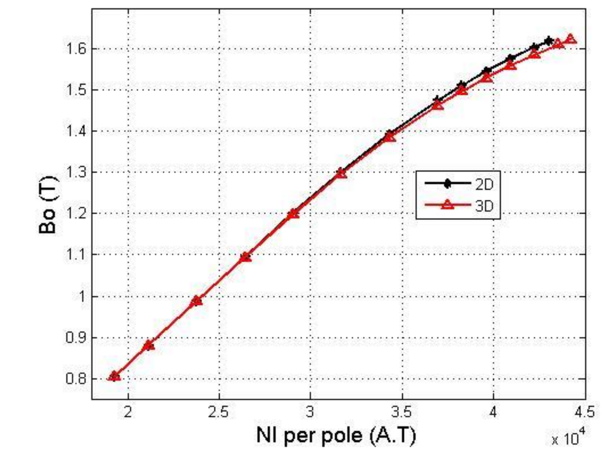

Fig. 6. The excitation curve (B-NI) of dipole.

Radial mapping trajectory is adopted for the integral field calculation of the sector dipole. For the pure sector, it intrinsically exists a quadrupole component (n=1) when performing the harmonic analysis, which respects to a thin lens focusing effect in the beam dynamics simulation. As shown in Fig.8, the high order multipole errors are reduced to less than ±0.08% over the operating field range of 0.8 T-1.62 T with a proper end chamfer. The normalized quadrupole component is 2.2% and not shown in Fig.8.

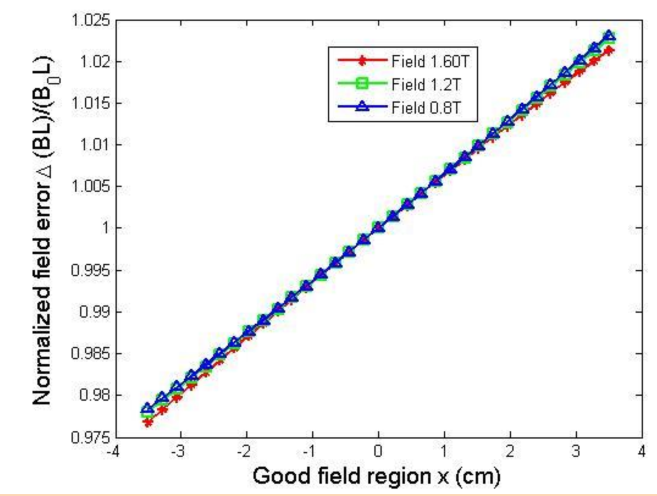

Fig. 7. Normalized field error $\Delta(BL)/B_0L$ of sector dipole after pole-end chamfered.

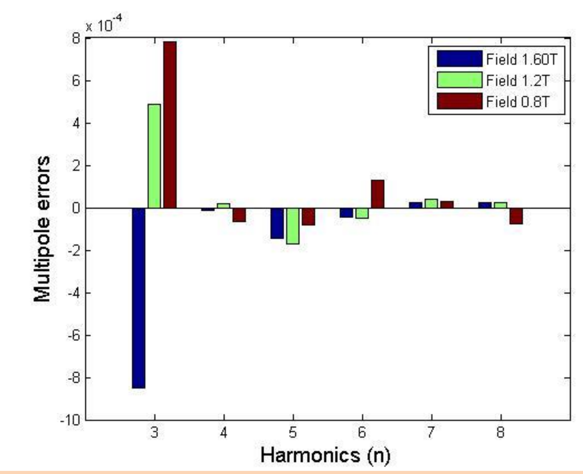

Fig. 8. Multipole errors of the sector dipole after pole-end chamfered. The normalized quadrupole component is 2.2% and is not shown in the Figure.

Conclusion: For the quadrupole, the high order harmonics errors of the integral field are less than 3e-4 with the gradient field range of 2-17.5 T/m. For the 57 degree sector dipole, the multipole errors (Sextupole and higher orders) are reduced to less than ± 0.08% over the operating field range of 0.8 T-1.62 T, with a normalized quadrupole component of 2.2%.