ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOPML039

COMPARISON OF TWO TYPES OF STEERERS APPLIED IN PROTON THERAPY GANTRY*

Z.F. Zhao†, W. Chen, X. Liu, Q.S. Chen, S.W. Hu, B. Qin
Institute of Applied Electromagnetic Engineering
Huazhong University of Science and Technology, Wuhan, China

Abstract

A proton therapy project HUST-PTF (HUST Proton Therapy Facility) based on a 250 MeV isochronous superconducting cyclotron is under development in Huazhong University of Science and Technology (HUST). Based on the optics design of the gantry, the steering magnets need to be placed in a compact structure, as well as meet the magnetic field requirement with a maximum deflection angle of ±5 mrad@250 MeV. In the paper, two types of steerers (O-shape and H-shape) were introduced and discussed in detail. The magnetic fringe field interference effects between quadrupoles and steerers were studied by using OPERA/TOSCA code. The result based on the contrastive analysis will give us a valuable reference to choose suitable steerers for proton therapy beamline.

INTRODUCTION

Proton therapy is recognized as one of the most effective radiation treatment method due to its ability of precisely localizing dose with the unique Bragg-peak dose distribution of proton beam [1]. A proton therapy facility with an isochronous superconducting cyclotron scheme is under development in HUST, which intents to include two 360° rotation gantry treatment rooms and one fixed beamline station with energy range of 70 MeV to 240 MeV [2].

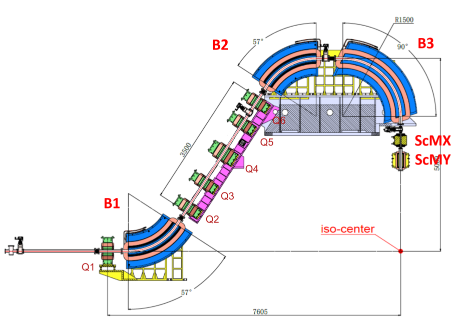

Figure 1: Layout of HUST-PTF gantry.

For the gantry beamline, a downstream scanning scheme is chosen to avoid construction of large aperture 90° dipole as well as with the consideration for the linear dependency between the beam position and the scanning magnet current. Figure 1 shows the layout of the gantry beamline. To correct the beam orbit, steerers designed to have ability to deflect proton particles up to ±5 mrad@250 MeV in both horizontal and vertical directions, will be placed between two quadrupoles (Q2-Q3, Q4-Q5), of which the minimum space (Q2-Q3) is 370 mm. It means integral magnetic field of magnets shall not be less than $1.215 \times 10^{-2}\ \mathrm{T \cdot m}$. In this context, we proposed two types of steerers. The analysis and comparasion of the two design schemes will be introduced in this paper.

DESIGN OF STEERER

The first design of steerer, based on compact layout, is the O-shape with double directions (as shown in Fig. 2). The key feature of this type of magnet is that two sets of coils can be wraped around the yoke to generate magnetic fields in both horizontal (X-) and vertical (Y-) directions, which saves space and is simple to manufacture. The cross-sectional area (CSA) of Y-coils (installed around the horizontal legs of yoke) can be appropriately enlarged to ensure the Y-deflection capacity is similar to X-deflection.

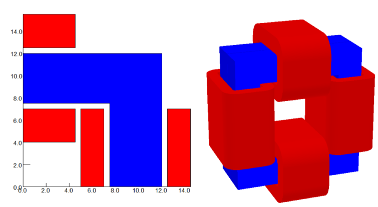

Figure 2: O-shape steerer with double directions.

The second design of steerer, based on high field intensity, is the H-shape with single direction (as shown in Fig. 3). This type of magnet has less pole gap than O-shape, but magnetic field can be generated in only one direction. Thus we designed a pair of 90° rotationally symmetric H-shape magnets with coil-to-coil distance of 90 mm, respectively for X- and Y- orbital corrections.

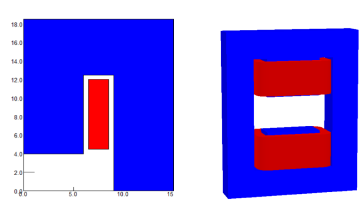

Figure 3: H-shape steerer with single direction.

Design parameters of two steerers are listed in Table 1. As can be seen, the H-shape magnets take up more space and are closer to quadrupoles. Suppose the maximum current density of coils is 2.5 A/mm^2 in the case of no water

* Work supported by The National Key Research and Development Program of China, with grant No.2016YFC0105305
† zfzhao@hust.edu.cn

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOPML039

Table 1: Design Parameters of Two Steerers

Parameters	O-Magnet	H-Magnets
Material	Dt4	Dt4
Pole Gap	160 mm	80 mm
Yoke Length	100 mm	2×60 mm
Y-Coil CSA	30×90 mm^2	20×75 mm^2
Y-Coil Volume	1122 cm^3	681 cm^3
X-Coil CSA	20×140 mm^2	20×75 mm^2
X-Coil Volume	1075 cm^3	681 cm^3
Total Length	170 mm	$2 \times 110 + 90$ mm

cooling. The magnetic field of the two types of steerers can be calculated by the finite element simulation software OPERA/TOSCA [3] as shown in Fig. 4. We changed coil current density of steerers and obtained a set of integral field values. Relationship between the two is linear (as shown in Fig. 5), which indicates the yokes are not saturated at this maximum current density. The result suggests that the integral magnetic field of O-shape on central orbit in both directions is 1.509×10^{-2} T · m (X-) and 1.440×10^{-2} T · m (Y-), while 1.374×10^{-2} T · m (X- & Y-) for H-shape magnets. It means that both O-shape and H-shape steerers could meet the requirement in the case without quadrupole.

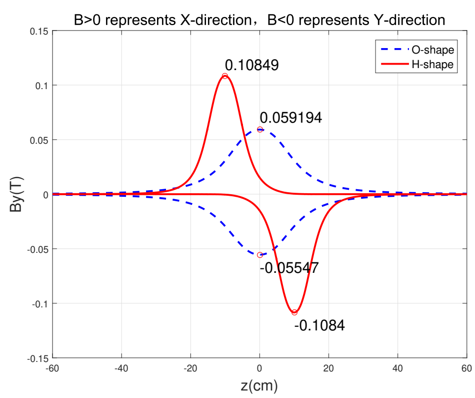

Figure 4: Magnetic field distribution at central orbit of two types of steerers.

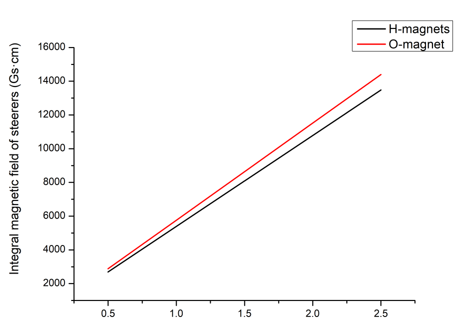

Figure 5: Relationship between coil current density of steerers and integral field.

MAGNETIC INTERFERENCE WITH QUADRUPOLES

Magnetic fringe field and field interference often play an important role in beam dynamics [4]. The field cross talk between quadrupole and steerer should be studied accurately for providing a key criterion to choose a suitable magnet design. Figure 6 shows the layout of the quadrupoles and two types of steerers in the gantry. The pole length (Z-) of quadrupole is 240 mm and total length including coils (Z-) is 400 mm. Details about the quadrupole are introduced in article [5].

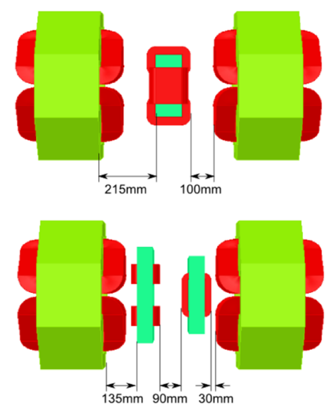

Figure 6: Sketch of the layout of O-shape magnet (Up) and H-shape magnets (Down) with quadrupoles.

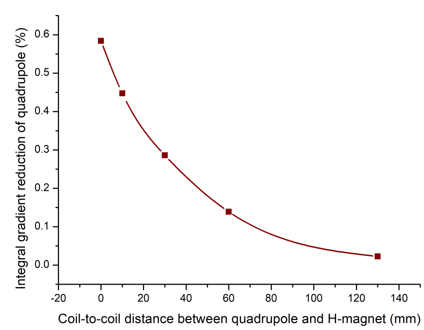

Figure 7: Relationship between integral gradient reduction of quadrupole and coil-to-coil distance.

The models were established in OPERA 3D. Two sets of simulation experiments were carried out. The first one focused on the change of integral gradient of quadrupole due to the nearby steerer's core. A direct current with density of 3 A/mm^2 was applied to the quadrupole coils while the steerer coil current was 0. Calculational results show that the integral gradient reduction of quadrupole due to O-shape magnet is about 0.040 %, while the reduction due to H-shape magnets is about 0.286 %. The latter is more than 7 times the former, but would still be acceptable. In fact, even we put H-magnet closer to the quadrupole (coil-to-coil distance≈0), the reduction is less than 0.6 % (as shown in Fig. 7). Thus,

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOPML039

quadrupole's integral gradient reduction caused by either kind of steerer is within a reasonable range.

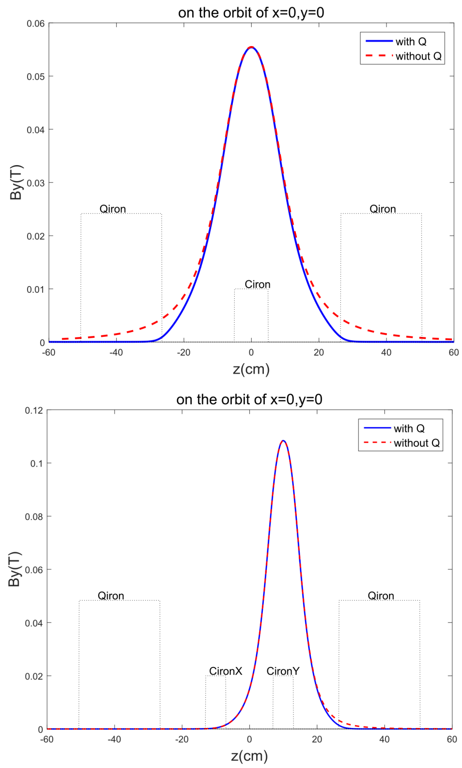

Figure 8: Field distribution of O-magnet (Up) and H-magnets (Down) with/without quadrupoles iron in Y- direction on central orbit.

The second simulation focused on the change of integral field of steerers due to quadrupole iron. Suppose current density of quadrapole coils is 0 and steerers coils is 2.5 A/mm^2. Figure 8 shows field distribution of steerers with/without quadrupoles iron in Y- direction on central orbit. The quantitative results are given in Table 2. As can be seen, both O-shape and H-shape steerers located between quadrupoles could meet the requirement of deflection, but integral field reduction of O-magnet is obviously larger than of H-magnets.

Table 2: Integral Field Change of Steerers

Magnet Type	**Direction**	**Integral Field without Q** ($T \cdot cm$)	**Integral Field with Q** ($T \cdot cm$)	**Integral Field Reduction**
O-Shape Magnet	B_x	1.440	1.269	11.9 %
	B_y	1.509	1.338	11.3 %
H-Shape Magnet	B_x=B_y	1.374	1.348	1.92 %

EFFICIENCY OF STEERER

In order to compare the working efficiency of the two types of magnets, it is necessary to analyze the power loss of coils under the same capacity of deflection. According to linear relationship between magnetic field amplitude and coil current density in the case of undersaturated yokes, current density can be normalized by dividing by integral field. Using the coil volume from Table 1 and normalized coil current density through calculated data from Table 2, coil power loss of two types of steerers located between quadrupoles can be figured out. The result suggests that under the same capacity of deflection, coil power loss of H-shape magnets in X- and Y- direction is 59.79 % and 56.14 % respectively of O-shape magnet, which means the efficiency of H-shape steerers is much higher than that of O-shape.

CONCLUSION

Based on the above analysis and comparison, both types of steerers can meet the requirement of ±5 mrad deflection capability. H-shape magnets with single direction have larger total length and less fringe field than O-shape magnet with double directions. Simulation results indicate that integral gradient reduction of quadrupoles due to both types of magnets is small enough to be accepted, while the integral field reduction of H-magnets due to quadrupoles is obviously smaller than of O-magnet. Calculation results suggest that the coil power loss of H-magnets is just abuot 57 % of O-magnet at the same deflection capacity. Actually, H-magnets are also easy to improve the magnetic field uniformity by shimming and are flexible to be settled in gantry beamline. After comprehensive consideration, the design of H-shape steerers will be adopted in HUST-PTF gantry.

REFERENCES

[1] R. Foote *et al.*, "The clinical case for proton beam therapy", Radiation Oncology, vol. 7, no. 1, p. 174, Oct, 2012, doi:10.1186/1748-717X-7-174

[2] B. Qin *et al.*, "Design of Gantry Beamline for HUST Proton Therapy Facility", IEEE Transactions on Applied Superconductivity, vol. 28, no. 3, pp. 1-5, April 2018, doi:10.1109/TASC.2017.2772868

[3] Opera User Guide, Vector Field Limited, Oxford, UK, 2013.

[4] M. Yang *et al.*, "Magnetic fringe field interference between the quadrupole and corrector magnets in the CSNS/RCS", Nucl. Instrum. Methods Phys. Res. A, Accel. Spectrom. Detect. Assoc. Equip., vol. 847, pp. 29-33, 2017, doi:10.1016/j.nima.2016.11.013

[5] W. Chen, B. Qin, X. Fang, Q. Chen, J. Yang and K. Liu, "Design of Prototype Magnets for HUST Proton Therapy Beamline", IEEE Transactions on Applied Superconductivity, vol. 28, no. 3, pp. 1-4, April 2018, doi:10.1109/TASC.2017.2775579