DESIGN OF THE FAST SCANNING MAGNETS FOR HUST PROTON THERAPY FACILITY*

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Abstract

For implementation of proton therapy, Huazhong University of Science and Technology has planned to construct a 250 MeV/500 nA superconducting cyclotron for proton therapy. In the beam-line, the scanning system spreads out the proton beam on the target according to the complex tumor shape by two magnets for horizontal and vertical scanning independently. As dipole magnets are excited by alternating currents and the maximum repetition rate is up to 100 Hz, the eddy currents are expected to be large. This paper introduces the design of these two scanning magnets and analyzes the eddy current effect. Slits in the end pole are proven to be an effective way to reduce the eddy current. Different directions, distributions and width sizes of slits are simulated and compared to determine the slits arrangement. At last, the maximum temperature of the optimized scanning magnets reaches the temperature requirements.

INTRODUCTION

Nowadays, particle therapy becomes a more effective method for radiation cancer treatment than traditional X-rays or gamma rays treatment. Huazhong University of Science and Technology(HUST) has proposed to construct a proton therapy facility based on a superconducting cyclotron in 2014 and this project is founded in 2016 [1]. In this project, we plan to build two rotating gantries and one fixed beam treatment room [2]. The energy of the proton beam ranges from 70 MeV to 250 MeV, corresponding to the range in water from 4 cm to 38 cm, and it can be modulated via the energy selection system(ESS) in the beam-line [3]. For active scanning method, a scanning magnet system is located at the end of beam line and precisely controls the beam position to spread out the proton beam on the tumor target. The scanning range at the iso-center is 30 cm×30 cm.

This paper mainly describes the design of two scanning magnets and analyzes the eddy current effect of AC dipole magnets.

SCANNING MAGNETS

The scanning magnet system is a core component of the active scanning system, which consists of two orthogonal H-type dipole magnets (SMX and SMY). The layout of the rotating gantry is shown in Fig. 1 and the main parameters of these two scanning magnets are list in Table 1 . To achieve the fast beam scanning at the iso-center and decrease the radius and cost of the gantry, the length of SAD(Source to Axis Distance) is 2.8 m. The distances from SMX and SMY to the iso-center are chosen as 2.85 m and 2.37 m. The maximum deflection angle is determined by the maximum magnetic rigidity 2.43 T·m, corresponding to 250 MeV proton beam. In the gantry, SMY is located after SMX, indicating that SMY should have a larger gap and pole width than SMX. According to the simulation of beam trajectory, the gap and pole width of SMX and SMY are determined. As for the power supply, these two dipole magnets are excited by alternating currents and the repetition frequencies are 100 Hz and 40 Hz, determined by the target scanning speed 60 m/s in x direction and 24 m/s in y direction. This requires the maximum current ramping speed to be up to 228 kA/s and the maximum magnetic field gradient to be 208 T/s.

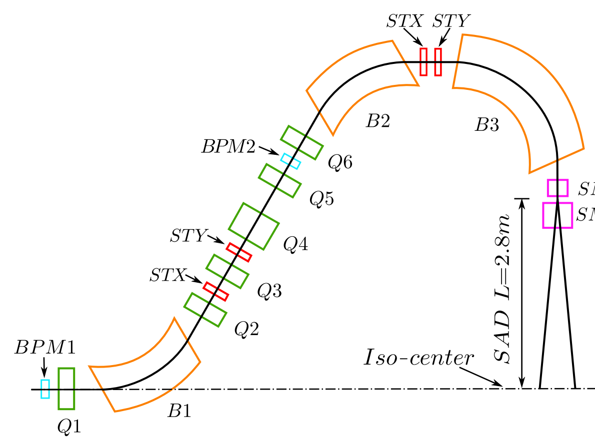

Figure 1: The layout of the rotating gantry and the illustration of the SAD length.

Table 1: Main Parameters of Scanning Magnets

Parameter	Units	SMX	SMY
Max Deflection Angle	mrad	55	65
Magnet Gap	mm	40	90
Magnet Pole Width	mm	90	160
Max Field Strength	T	0.52	0.39
Number of coil turn	Turns/pole	15	18
Coil Inductance	mH/coil	0.3325	0.605
Coil Resistance	mOhm/coil	2.21	2.74
Repetition Frequency	Hz	100	40

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EDDY CURRENT EFFECT

Origin of Eddy Currents

Eddy current is the major design concern of these AC magnets. Generally, laminated silicon steel sheets for iron core and aluminum stranded wires for the coil conductor are used to reduce the amount of eddy currents and the heat loss. However, the laminated magnets are still not free from the eddy current effect and the temperature rise will destroy the insulation of laminated steel sheets. This requires us do some specific designs for the pole edge.

Simulation Methods and Parameters Setting

To study the eddy current effect in the laminated magnets, we perform the transient electromagnetic simulation in the ELEKTRA Transient program of Opera Vector [4]. By calculating the root mean square value of the loss at different time, the average heat density in a period can be obtained and then imported into the TEMPO Steady State program. The thermal analysis can be carried out and the temperature distribution of the magnet is presented clearly.

In the electromagnetic simulation, the model of dipole magnet consists of the laminated iron core, two stainless steel(SS) end plates and two excitation coils. Coils are excited by sinusoidal alternating current. The laminated iron core is defined as a nonlinear BH curve and the packing factor is 0.98. The SS end plates are set as non-magnetic but conductive.

Simulation Results

The eddy currents are induced in the end laminations of iron core and stainless steel plates, and concentrated in the few centimeters above the magnet gap. Slits in these areas are proven to be an effective method to reduce the eddy current [6]. Due to the higher frequency and magnetic field strength of SMX magnet, the eddy current density will be bigger. That is why the SMX magnet is selected as the research object. To study the effect of slits on the eddy current and temperature rise of the magnet, some different simulations are carried out and compared with each other. To demonstrate the effect of slits, the maximum temperature of the model without sits is 176.8°C and distributed at the corner, as shown in Fig. 2.

Slits direction As we know, the eddy currents in the end plates are formed into circles. The horizontal and vertical slits also can cut the currents into small pieces to reduce the eddy current. Firstly, these two types of slits are simulated individually to determine the optimum direction of slits, as shown in Fig. 3. The solution results show that the vertical slits can reduce the temperature rise of 100°C when compared to the model without slits. However, the horizontal slits cannot reduce the eddy current density, but cause the more concentrated currents at the corner of the magnet. The temperature will be up to 247°C which is higher than the condition without slits. Therefore, the vertical slits are selected.

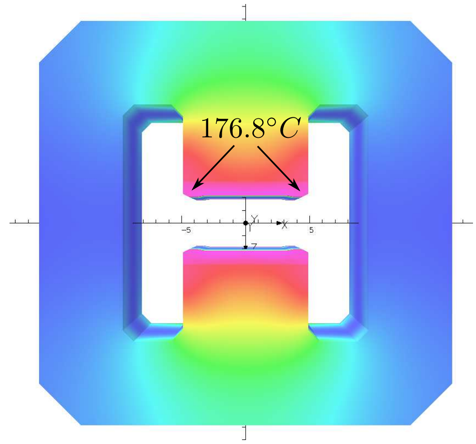

Figure 2: The temperature distribution of the unoptimized SMX magnet. The maximum value concentrates on the pole edge.

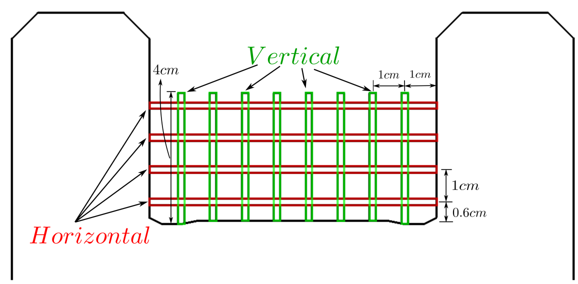

Figure 3: The illustration of slits direction in the pole. The green blocks show the horizontal slits and the red blocks are the vertical slits.

Slits distribution Secondly, three different numbers of vertical slits are compared. All slits are 2 mm wide and symmetrical distributed at intervals of 10 mm. The number of slits is 7, 8, 9, corresponding to the distance between the outermost slit and the pole edge is 15 mm, 10 mm and 5 mm, respectively. The distribution of slits is shown in Fig. 4 and the maximum temperature of the dipole magnet is listed in Table 2. Clearly, the model with eight slits is the better choice than the others. The wide distance can not cut apart the eddy current effectively in the pole edge and the tight distance will concentrate the current and increase the current density.

Table 2: The Relations between Maximum Temperature and Slits Distribution

num_slits	a/mm	b/mm	Max T/°C
7	15	10	72.29
8	10	10	64.16
9	5	10	73.06

Slit width As we know, the slit width determines the processing difficulty of silicon steel sheets. Figure 5 plots the dependence of the magnet's maximum temperature on

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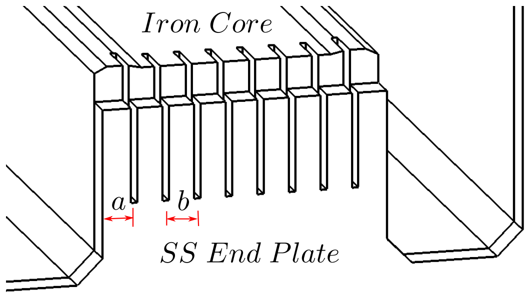

Figure 4: The distribution of slits in the SMX magnet.

the slit width. the temperature rise are not sensitive to the slit width. In order to facilitate the processing, the slit width is designed as 2 mm.

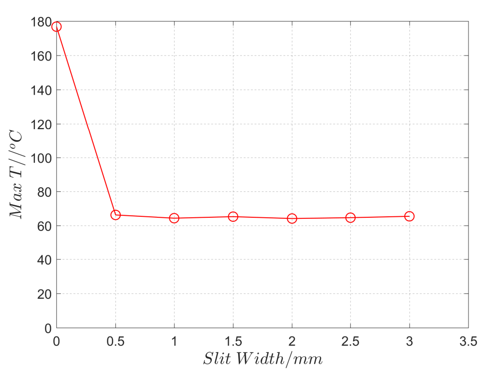

Figure 5: Maximum temperature of the SMX magnet vs. slit width.

From above discussions, the temperature of the SMX model which includes eight slits with 2 mm wide can be reduced to 64.2°C. The temperature distribution of the SMX magnet is shown as Fig. 6.

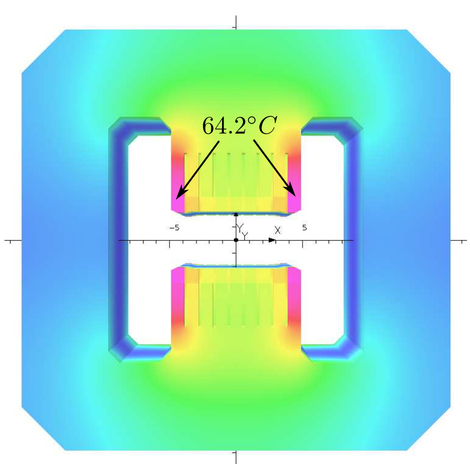

Figure 6: The temperature distribution of the optimized SMX magnet.

SMY Magnet

Eddy currents in the SMY magnet is smaller than the SMX magnet, but the maximum temperature is still up to 123.9°C. This temperature will also destroy the insulation of stainless steel sheet. So eight slits should be added in the end laminations of iron core and SS plates. As a result, the maximum temperature of the optimized SMY magnet is reduced to 43.7°C, lowering the allowance temperature rise.

CONCLUSION

This paper shows the layout of the scanning magnet in the rotating gantry and describes the magnet design of two alternating current dipole magnets. The eddy current effect and the heat loss are serious in the end laminations of iron core and the end stainless steel plates. Slits in these areas are an effective way to reduce the eddy current. Three comparisons are made to determine the arrangement of slits. The temperature of the optimized magnets can reach the allowance temperature rise of the silicon steel sheet. Besides,instead of slits, several water-cooling circuits can also be added in the SS end plates to reduce the temperature rise of the magnet, which requires the thick plates and increases the processing difficulty. The feasibility of this method needs to be validated by later simulations. The proton therapy project is now under design, and more design details will be considered.

REFERENCES

[1] B. Qin, K.F. Liu, D. Li, *et al.*, "Design Study of a 250MeV Superconducting Isochronous Cyclotron for Proton Therapy", in Proc. 12th Symposium on Accelerator Physics (SAP'14), Lanzhou, China, August 2015, paper WEPMH3.

[2] Bin Qin, Kuanjun Fan, Mingwu Fan, *et al.*, "Fast Scanning Beamline Design Applied to Proton Therapy System Based on Superconducting Cyclotrons", presented at the 21th Int. Conf. on Cyclotrons and their Applications (Cyclotrons'16), Zurich, Switzerland, Sep 2016, paper MOP12, this conference.

[3] Zhikai Liang, Wei Chen, Xu Liu, *et al.*, "Fast Energy Selection System Design for Proton Therapy Based on GEANT4 Toolkit", presented at the 21th Int. Conf. on Cyclotrons and their Applications (Cyclotrons'16), Zurich, Switzerland, Sep 2016, paper MOD01, this conference.

[4] Opera-3D reference, `http://www.vectorfields.com`

[5] S. Xian-Jing, D. Chang-Dong, K. Wen, "Transient electromagnetic simulation and thermal analysis of the DC-biased AC quadrupole magnet for CSNS/RCS", *Chinese physics C*, vol. 36, no. 5, p. 443-446, May 2012.

[6] M. Negrazus, D. George, V. Vrankovic, *et al.*, "Eddy current reduction in fast ramped bending magnets", *IEEE Transactions on Applied Superconductivity*, vol. 16, no. 2, p. 228-230, June 2006.