Design of Lightweight Superconducting Magnets for a Rotating Gantry With Active Shielding

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Design of lightweight superconducting magnets for a rotating gantry with active shielding

T. Obana, T. Ogitsu

Abstract—**In order to reduce the weight of superconducting magnets used in a rotating gantry for heavy particle radiotherapy, the design study of a cosine-theta superconducting magnet with active shielding was conducted. The superconducting magnet with active shielding was composed of a dipole coil and an active shield coil. The cross-section of each coil was designed, based on a cosine-theta current distribution made by the arrangement of a superconducting wire with NbTi filaments. The result of the design study indicated that the designed coil cross-sections can meet the requirements regarding the magnetic field distribution and the load factor for the magnet operation. Additionally, the weight of the superconducting magnet with active shielding was evaluated while comparing that of the superconducting magnet with an iron yoke. As a result, the superconducting magnet with the active shielding has a possibility to reduce the weight significantly.**

Index Terms— **Heavy particle radiotherapy, rotating gantry, cosine-theta current distribution, design study, active shielding.**

I. Introduction

IN heavy particle radiotherapy, a rotating gantry enables charged particles to be delivered to a tumor with great accuracy. Therefore, cancer therapy that minimizes unnecessary damage a patient can be realized by using the rotating gantry. In 2015, the world's first rotating gantry composed of superconducting magnets was developed in the National Institutes for Quantum and Radiological Science and Technology [1-3]. Using superconducting magnets instead of conventional magnets, it became possible to make a smaller, lighter gantry.

A superconducting magnet for the rotating gantry is composed of a cosine-theta superconducting coil surrounded with an iron yoke which is the heaviest part of the magnet's weight. The weight of one superconducting magnet reaches several tons, and the rotating gantry is equipped with ten superconducting magnets. Precise rotation control is required under the condition that several ten tons are mounted on the frame of the rotating gantry. In this study, a superconducting magnet composed of an active shield coil for the gantry has been proposed in order to simplify the control system and the frame structure of the rotating gantry by reducing its weight. Using an active shield coil instead of an iron yoke to shield the stray magnetic field, the magnet's weight can be reduced. In this paper, the design study of a superconducting magnet with active shielding for a rotating gantry is described.

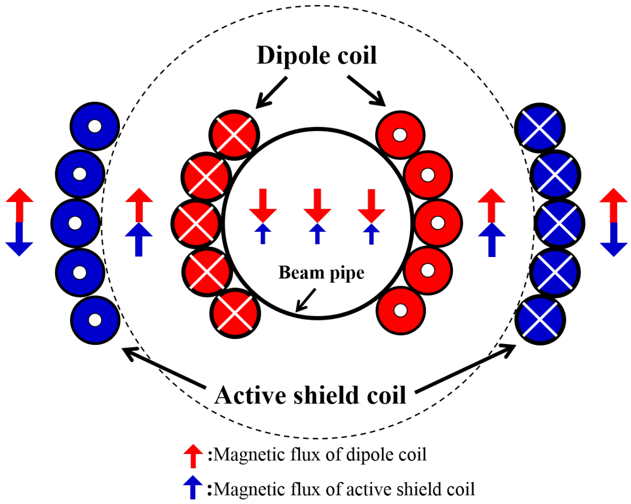

Fig. 1. Concept diagram of a dipole coil with an active shield coil.

II. Design Concept

In this study, an active shield coil was used to shield the stray fields instead of an iron yoke. Fig. 1 shows the concept diagram of a superconducting dipole magnet using an active shield coil. The superconducting magnet is composed of two types of superconducting coils. These are a dipole coil and an active shield coil, respectively. As illustrated in Fig. 1, the magnetic field of the dipole coil and that of the active shield coil cancel each other out on the outside of the magnet. As a result, the stray field generated by the magnet can be shielded. On the inside of a beam pipe, the dipole field is weakened by the field contributed from the active shield coil. Compared to superconducting magnets using an iron yoke, superconducting magnets using an active shield coil need to increase the magnetomotive force of the dipole coil.

III. Design Requirements

Taking into account the parameters of the superconducting magnet with an iron yoke [1-3], the design requirements of the superconducting magnet with the active shielding were determined as follows:

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(1) The inner radius of the dipole coil is fixed at 0.09 m.

(2) The dipole field is 2.37 T in the reference radius of 0.06 m.

(3) Higher multi-pole components normalized by the dipole component are less than 1.0×10^{-3}.

(4) The stray field is less than 5 G ($=5.0\times10^{-4}$ T) at a distance 0.5 m radially from the magnet center.

(5) The load factor (= operating current /critical current) of the magnet is less than 70% at 5 K.

(6) A superconducting wire with NbTi filaments is used for the coil winding based on the surface winding technology [4, 5]. The diameter of the wire is 0.9 mm. The critical current of the wire is 450 A at 5 K under the field of 2 T.

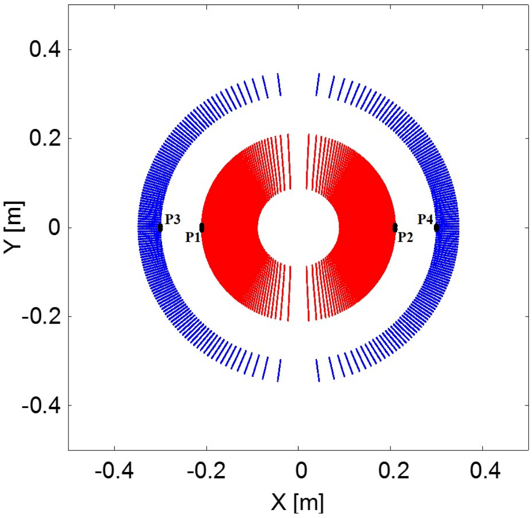

Fig. 2. Cross-section of the dipole and the active shield coils. The inner coil and the outer coil are the dipole coil and the active shield coil, respectively. The plots P1 and P2 show the position of the peak field in the dipole coil. And the plots P3 and P4 show the position of the peak field in the active shield coil.

IV. Design of Coil cross-section

To begin with, the design parameters of dipole and active shield coils were set while taking into account design requirements. Based on the parameters, cross-sections of a dipole coil and an active shield coil were designed using the developed design code [6, 7] which can make cosine-theta current distributions with a wire arrangement. Fig. 2 shows the cross-section of the dipole and the active shield coils. The inner and the outer radii of the dipole coil are 90 mm and 210 mm, and those of the shield coil are 300 mm and 350 mm, respectively. There are 60 layers of the dipole coil, and 25 layers of the shielding coil. The gap between layers is 1.1 mm. There are 6954 turns of the dipole coil, and 3000 turns of the shielding coil. The minimum gap between turns is approximately 1.5 mm. Regarding the coil winding, the surface winding technology [4, 5] is utilized.

After the design, the magnetic fields of the designed dipole and the active coils were calculated at the same coil current, and each magnetic field was combined. Finally, in order to fulfill the required dipole field at the magnet center and the stray field outside the magnet, operating currents of the dipole coil and the active shield coil were adjusted respectively. The operating currents were determined as follows: 217 A for the dipole coil and 249 A for the active shield coil.

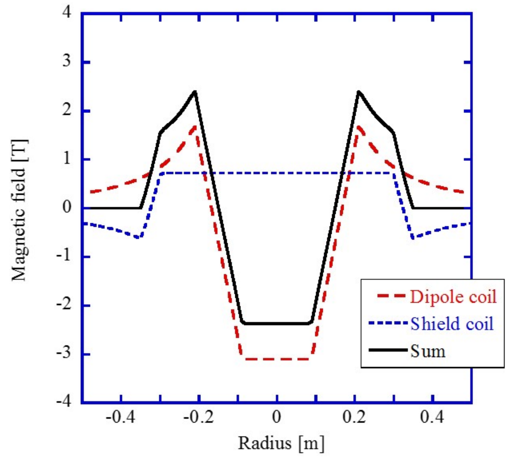

Fig. 3. Magnetic field distributions on the midplane.

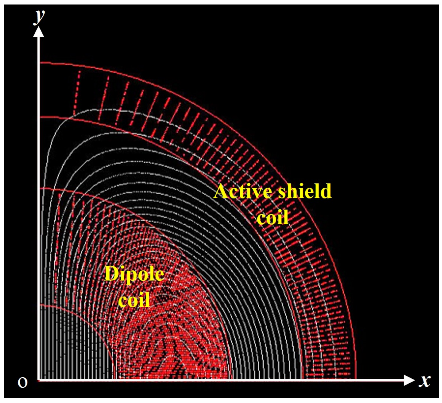

Fig. 4. Flux lines in a quadrant of the coil cross-section.

Table 1. Normal multipole coefficients *bn* in the coil cross-section at the reference radius of 60 mm.

b_n	Units	b_n	Units
b_1	10000.0	b_6	0.0
b_2	0.0	b_7	-0.1
b_3	-1.0	b_8	0.0
b_4	0.0	b_9	0.1
b_5	0.3	b_{10}	0.0

V. Magnetic field

Two-dimensional magnetic fields of the magnet were calculated based on the coil cross-section shown in Fig. 2. Fig. 3 shows the calculated magnetic fields of the magnet on the mid-plane. In the reference radius of 0.06 m, the magnetic flux density of 2.37 T was realized. On the outside of the active shield coil, the magnetic fields generated by the dipole and the active shield coils are compensated. On the other hand, the magnetic fields are strengthened in the region between the dipole and the active shield coils. The magnetic flux lines in the coil cross-section are shown in Fig. 4. The flux line is confined in the coil cross-section by the active shield coil. The density of the flux lines becomes higher around the midplane in the bore of the dipole coil and in the region between the dipole and the active shield coils.

To evaluate the field quality of the coil cross-section, the normal multipole coefficients b_n of the magnetic field were investigated. The multipole coefficients b_n are listed in Table 1. The results of the multipole coefficients fulfill the design requirements that higher multipole-pole components normalized by the dipole component are less than 1.0×10^{-3}.

The stray field of the magnet was evaluated when the dipole field was 2.37 T at the magnet center. The stray field could be reduced up to 5 G at a distance 0.5 m radially from the magnet center, which is the outside of the active shield coil. Fig. 5 shows the stray field distributions in x and y axes.

For the cross-sections of the dipole and the active shield coils, the peak fields were evaluated. The peak fields of the dipole and the active shield coils are 2.40 T and 1.55 T, respectively. The peak field of the dipole coil is close to the dipole field at the magnet center. The position of the peak field in the dipole coil is the outmost layer near the mid-plane, and that in the active shield coil is the innermost layer near the mid-plane, as shown in Fig. 2.

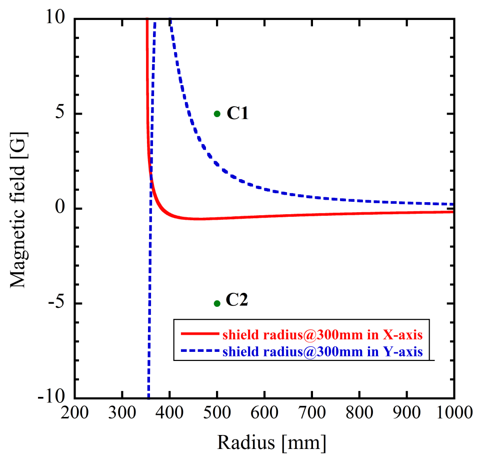

Fig. 5. The stray field distributions on x axis and y axis. The plots C1 and C2 indicate the criterion which is ± 5 G at a distance 0.5 m radially from the magnet center.

VI. Load Line

Fig. 6 shows the load lines of the dipole and the active shield coils. In Fig. 6, the plots indicate the operating condition at each coil. For the critical current line of a NbTi strand whose copper ratio is 4: 1 at 5 K, the load factors of each coil are as follows: 51% in the dipole coil and 52% in the active shield coil. As described in the section V, the peak field of the dipole coil is larger than that of the active shield coil. On the other hand, the operating current of the dipole coil is smaller than that of the active shield. As a result, the load factor of the dipole coil is comparable to that of the active shield coil. These results indicate that the designed magnet fulfills the requirement that the load factor of the magnet is less than 70% at 5 K.

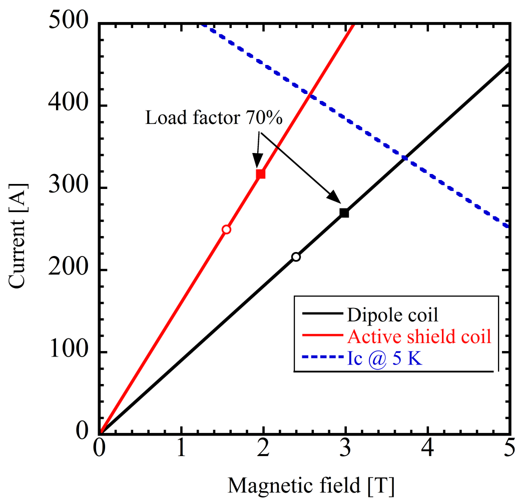

Fig. 6. Load lines of the dipole and the active shield coils. The plots indicate the operating condition at each coil.

VII. Electromagnetic Force

Electromagnetic (EM) force per unit length occurring in the coil cross-section was calculated when the magnetic field was 2.37 T at the magnet center. Figs. 7 and 8 show EM force in the dipole and the active shield coils, respectively. Regarding the dipole coil, EM force is generated outward at the coil inner side. On the other hand, at the coil outer side, EM force is generated inward. Therefore, compressive stress generates in the coil winding. Regarding the active shield coil, EM force is generated outward. Hence, tensile stress generates in the coil winding.

Additionally, total EM forces in the dipole and the active shield coils were evaluated by adding EM force in each wire. In the evaluation, the total EM force was divided into two forces, the EM force in the horizontal (x) direction and the EM force in the vertical (y) direction. Table 2 shows the horizontal and the vertical EM forces in one coil quadrant. The horizontal force of the dipole coil is comparable to that of the active shield coil. On the other hand, the vertical force of the dipole coil is much larger than that of the active shield coil. And the direction of the horizontal forces is different at each coil. The negative vertical force on the dipole coil means the compressive force in the vertical direction on the coil.

Regarding the coil support structure, the following concepts are being considered. Since the dipole coil has a large compressive force in the vertical direction, the support is installed on the inner layer side of the coil. In the case of the shield coil, the support is installed outside the coil since a tensile force is generated in the coil radial direction.

Table 2. Electromagnetic (EM) forces generated in a quadrant of the coil cross-section when the dipole field is 2.37 T at the magnet center.

	EM force in horizontal direction	EM force in vertical direction
Dipole coil	196 kN/m	-538 kN/m
Shield coil	182 kN/m	98 kN/m

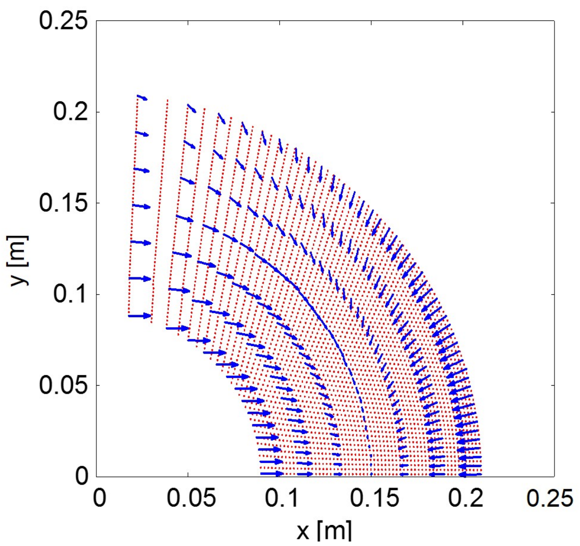

Fig. 7. EM forces in a quadrant of the dipole coil. Arrows show EM force at each wire position.

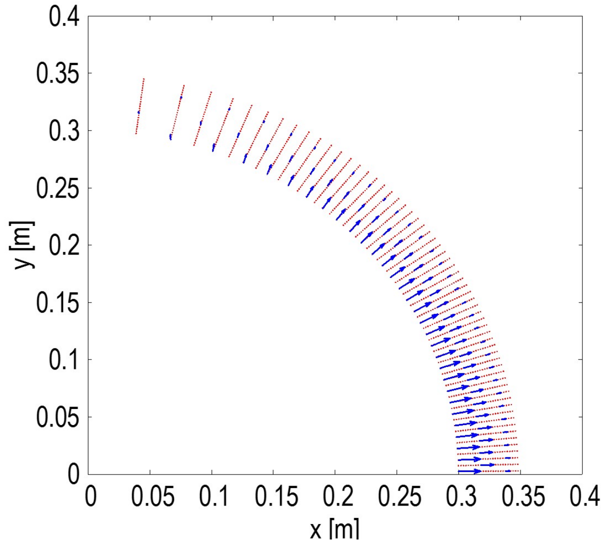

Fig. 8. EM forces in a quadrant of the active shield coil. Arrows show EM force at each wire position.

VIII. Evaluation of Magnet Weight

Regarding the weight of magnets for the rotating gantry, a superconducting magnet with active shielding was compared to a superconducting magnet with an iron yoke which is being used in QST [3]. In this comparison, both magnets have the same specifications regarding the dipole field, the stray field, and the diameter of a NbTi wire. To evaluate the magnet weight per unit length, the density of each component was used as follows: 8880 kg/m^3 for NbTi wire, 1850 kg/m^3 for epoxy, and 7870 kg/m^3 for the iron yoke. In the coil winding, the gap between NbTi wires is infilled with an epoxy because of the surface winding technology [4, 5]. Hence, the weight of epoxy was calculated by subtracting the cross-sectional area of a NbTi wire in the coil winding from that of the coil winding. Table 3 shows the results of the comparison for each magnet. In the magnet with the iron yoke, the iron yoke has the dominant weight. In the magnet with active shielding, the weight of the epoxy is larger than that of the coil windings. Regarding the coil weight including the epoxy, the magnet with active shielding is approximately nine times larger than the magnet with the iron yoke. However, the total weight of the magnet with active shielding is approximately one-fifth that of the magnet with the iron yoke, provided that the weight of support materials for EM force is not taken into account for the magnet with active shielding. The result of this design study implies that the superconducting magnet with the active shield coil has a possibility to reduce the weight significantly. Detailed design study on the support structure which strongly affects the total weight has to be demonstrated.

Table 3. Weight comparison between the magnet with active shielding and the magnet with an iron yoke.

	Magnet with active shielding	Magnet with iron yoke
Dipole coil winding	79 kg/m	28 kg/m
Shield coil winding	34 kg/m	—
Iron yoke	—	2472 kg/m
Epoxy	380 kg/m	25 kg/m
Total weight	493 kg/m	2520 kg/m

IX. Conclusion and Further Plans

The design study of a superconducting magnet with active shielding for a rotating gantry was conducted in order to realize the weight reduction of the magnet. As a result, it was successful to develop the coil design method of the superconducting magnet with active shielding. The results of the design study indicate that the superconducting magnet with the active shield coil can significantly reduce the magnet weight compared to the superconducting magnet with an iron yoke.

As for further plans, in the superconducting magnet with the active shielding, a support structure for an electromagnetic force is to be designed while conducting a structural analysis of the magnet. To enable the weight reduction of the support structure, aluminum alloy and FRP are considered as candidates of structural materials at present.

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