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Design of conduction-cooled HTS coils for a rotating gantry

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Abstract

Carbon ion cancer therapy is becoming more widespread due to its high curative effects and low burden on patients. Carbon ions are delivered to patients through electromagnets on a rotating gantry. A rotating gantry is attractive because it allows carbon ions to irradiate a tumor from any direction without changing the posture of the patient. On the other hand, because of the high magnetic rigidity of carbon ions, the weight of a rotating gantry for carbon cancer therapy is about three times higher than one for proton cancer therapy, according to our estimation. The use of high-temperature superconducting (HTS) magnets has been considered for reducing the size of the rotating gantry for carbon cancer therapy. The target weight is 200 t or less, which is equivalent to the weight of a typical rotating gantry for proton cancer therapy. In this study, the magnet layout of the rotating gantry and the superconducting magnets were designed from the viewpoint of beam optics. When applying high-temperature superconductors to accelerator magnets, there are some issues that should be considered, for example, the influence of tape magnetization and manufacturing accuracy on the field quality, the thermal stability of the conduction-cooled HTS coils under an alternating magnetic field, and methods to protect the coils from thermal runaway caused by an anomalous thermal input such as that due to beam loss. First, the thermal stability of the conduction-cooled HTS coils was simulated numerically, and the thermal runaway current was calculated in a static situation.

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Keywords: Carbon ion cancer therapy; rotating gantry; high temperature superconductor; conduction-cooled; thermal runaway

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1. Introduction

Carbon ion beam cancer therapy is becoming more widespread due to its high curative effects and low burden on patients. In particle cancer therapy, it is desirable that the treatment beam irradiate the tumor from different directions in order to reduce the dose on normal cells. A rotating gantry is a suitable apparatus to meet this requirement. Since the irradiation device orbits a patient inside the gantry, the beam can irradiate the tumor from any direction without changing the posture of the patient. Rotating gantries are already commonly used for proton beam cancer therapy. On the other hand, those designed for carbon ion beam cancer therapy have not yet been adopted because they are too large and heavy for installation in general hospitals. There are only two carbon ion gantries in the world; one is operated at HIT [1] and is constructed with normal conducting magnets, the other was manufactured at NIRS [2] and is constructed with low-temperature superconducting (LTS) magnets. The reason for the small number of practical installations is that the weight of the rotating gantry for carbon ion beam cancer therapy is about three-times higher than one designed for proton beam cancer therapy, according to our estimation.

An R&D project to reduce the size of a rotating gantry for carbon ion beam cancer therapy by applying high-temperature superconducting (HTS) magnets started in Japan in 2013. The target weight of this gantry is 200 t or less, which is equivalent to the weight of typical rotating gantries for proton beam cancer therapy. When applying high-temperature superconductors to the magnets of a rotating gantry, there are some issues that should be considered, for example, the influence of tape magnetization and manufacturing accuracy on the field quality, the thermal stability of the conduction-cooled HTS coils under an alternating magnetic field, and methods to protect the coils from thermal runaway caused by an anomalous thermal input such as that due to beam loss. The aim of this project is to develop fundamental technology for an HTS gantry. The final goal is to manufacture and test one of the magnets of the rotating gantry in 2017. In this study, the thermal stability of conduction-cooled HTS coils is discussed.

2. Beam optics and magnet layout

The rotating gantry is constructed from a number of electromagnets, and the carbon ions are bent, focused and defocused by these magnets and finally delivered to the patient. The magnet specifications are decided by considering the beam transport line and beam size. First, beam optics calculations were performed to determine the requirements for the magnets of the rotating gantry.

A schematic view of the electromagnet layout of the rotating gantry is shown in Fig. 1. The HTS rotating gantry has a length of approximately 9 m and a radius of 4 m. The magnet layout of the HTS rotating gantry was decided with reference to placement of the magnets in a previously constructed LTS rotating gantry. The HTS rotating gantry has ten HTS magnets, two pairs of steering magnets (STR1, STR2), and a pair of scanning magnets (SCM). The HTS magnets can provide both dipole and quadrupole fields, and this layout was considered so that the HTS magnets can generate a dipole field of about 6 T, which is two-times higher than the magnetic field generated by the LTS rotating gantry. To determine the field gradients of the quadrupole fields for each HTS magnet, the following matching conditions of the Twiss parameters at the entrance and the isocenter were used. The beam emittance was assumed to be $\varepsilon = 2\pi$ mm mrad:

Entrance: $\beta_H = \beta_V = 12$ m, $\alpha_H = \alpha_V = 0, D_H = D_V = 0, D'_H = D'_V = 0$
Isocenter: $\beta_H = \beta_V = 5$ m, $\alpha_H = \alpha_V = 0, D_H = D_V = 0, D'_H = D'_V = 0.$

The optimized beta function, dispersion function, and beam envelope for the gantry beam line are shown in Fig. 2. Calculated HTS magnet specifications are shown in Table 1. The magnets upstream of the scanning magnet (HTS magnets, types A and B) are required to produce a high quadrupole field, and from the calculated beam envelope, the reference radius was set to ± 20 mm. In the following, we focus on the design of magnet type A in Table 1.

3. Design of superconducting coils

The HTS coils composing the magnets of the rotating gantry were designed based on the required intensity, quality, and spatial size of the magnetic field.

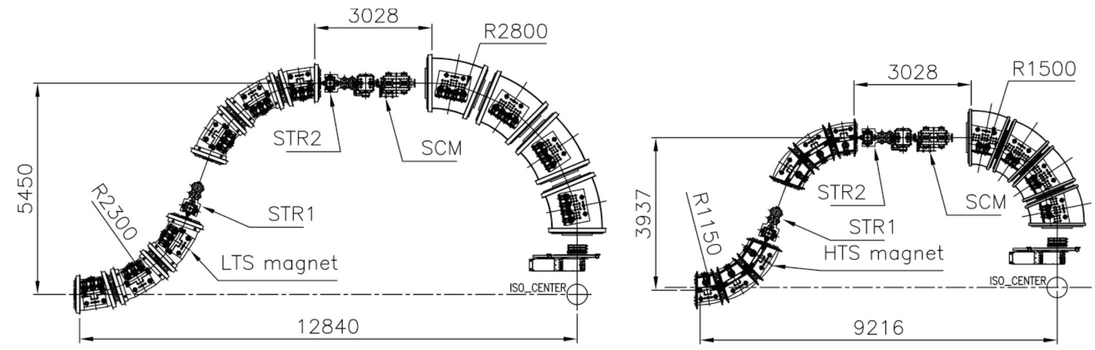

Fig. 1. Layout of rotating gantries (left: LTS, right: HTS).

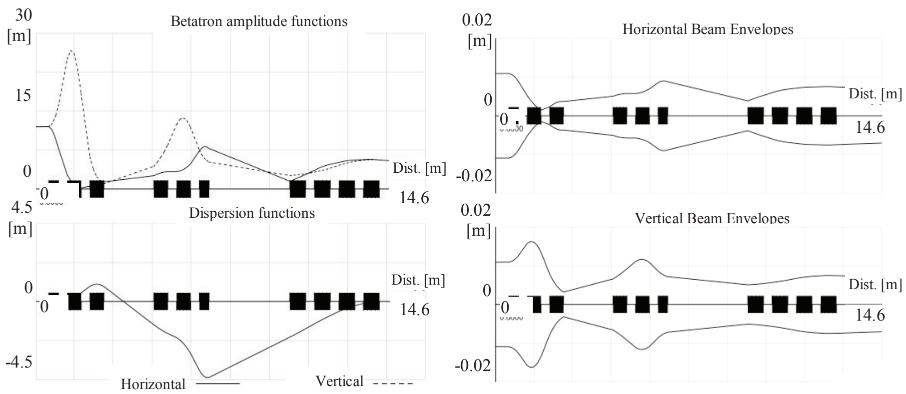

Fig. 2. Beta and dispersion function (left), and beam envelope (right) for the gantry beam line.

Table 1. Specifications of the HTS magnets of the rotating gantry.

Magnet type	A	B	C	D
Bending radius [m]	1.15	1.15	1.5	1.5
Bending angle [deg.]	18	26	22.5	22.5
Dipole field [T]	5.8	5.8	4.5	4.5
Quadrupole field [T/m]	15.5	33	-	1.7
Reference radius [mm]		± 20		
Bore radius [mm]		30		
Inner radius of the HTS coils [mm]		60		
Field quality		$\leq 1 \times 10^{-3}$		

From the requirements for the dipole and quadrupole fields of the type-A HTS magnet, namely, 5.8 T and 15.5 T/m, the magneto-motive force and the core size were calculated by two-dimensional non-linear magnetic analysis. To generate the dipole and quadrupole fields in the same space, the HTS coils has a layered structure in which the quadrupole coils are placed at the inner side and the dipole coils at the outer side. These coils can be excited independently. From the analysis, it was revealed that a dipole magneto-motive force of 823 kA and a quadrupole magneto-motive force of 21 kA can generate the required magnetic field, and a core thickness of more than 400 mm is needed to avoid saturation. These magnets of the rotating gantry are required to produce a high field quality of 1.0×10^{-3} in the reference radius of 30 mm because of the demand for high irradiation accuracy. The two-dimensional positions of the superconducting tapes of the dipole coils were optimized to generate a pure dipole magnetic field [3]. The optimized placement of the tapes for the first layer is shown in Fig. 3. The superconducting dipole coils had four blocks per pole with 50 turns per block, and these blocks were placed at angles of 7.33°, 21.58°, 36.71°, and 60.11°.

From the two-dimensional positions of the superconductors, three-dimensional coil forms were considered. When designing the coil with a three-dimensional shape wound with HTS conductors, we designed its shape in such a way that the two edges of the tape follow curves of equal length, forming a constant-perimeter condition, without applying edgewise bending. This coil shape was calculated by using Frenet-Serret's equations, as in [4]. To estimate the effects of the three-dimensional coil shape, three-dimensional magnetic analysis was performed. The calculated field quality in the mid plane position at the coil center is shown in Fig. 4. It is shown that the field quality within the reference radius of 20 mm is 2.75×10^{-4}, which satisfies the quality requirement above. It is difficult to use coolant for the magnets mounted on the rotating gantry because they are rotating. Therefore, conduction cooling should be employed. On the other hand, the magnetic field generated by the magnets of the rotating gantry should be changed depending on the energy of the carbon ion beam in raster-scanning irradiation. There is some possibility that the carbon ion beam will collide with the coils. This causes anomalous thermal inputs such as those due to ramp loss and beam loss, resulting in the problem of poor thermal stability of the conduction-cooled HTS coils heated by such thermal inputs. As a first step, the thermal stability of the conduction-cooled HTS coils under a static situation is considered.

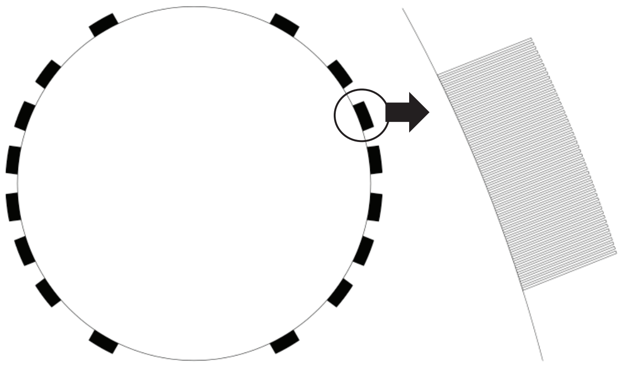

Fig. 3. Two-dimensional positions of the superconducting conductors (right: expanded view).

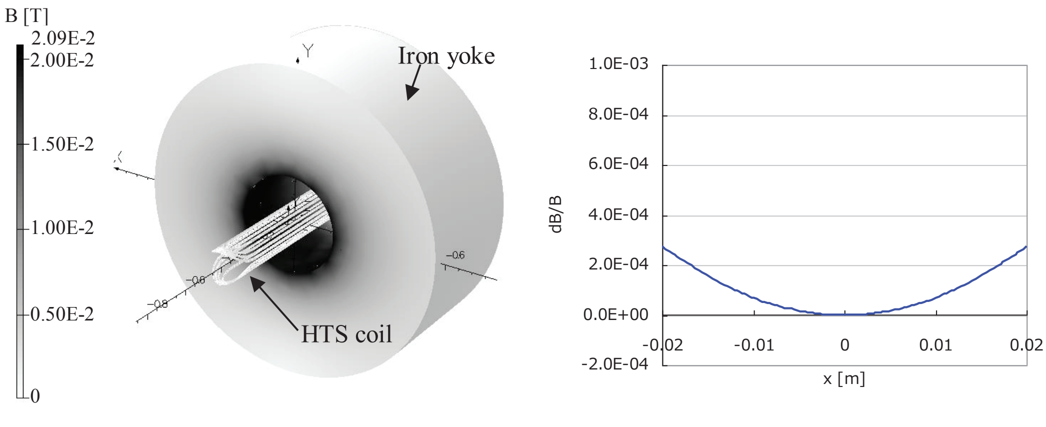

Fig. 4. Result of three-dimensional magnetic analysis (left), and the calculated field quality in the midplane position at the coil center (right).

4. Thermal runaway properties

In the case of a conduction-cooled HTS coil, the risk of thermal runway is higher when compared to immersion cooling using a coolant such as liquid helium or liquid nitrogen, when an excess current flows or local heating occurs in the HTS coil. It is important to understand the conditions under which thermal runaway occurs and the coil should be protected before the occurrence of thermal runaway. Therefore, a thermal runaway analysis for the conduction-cooled HTS coil was conducted.

The analysis model is shown in Fig. 5. The coils were impregnated with an epoxy resin because the coil is not sufficiently cooled without it, and a conduction plate made of aluminum with a thickness of 0.25 mm was fixed on the entire upper side of the coil. Since the coil has a symmetric shape, a 1/4 cut model was used in the analysis. In performing the analysis, the coil end part was divided into 49 mesh elements in the longitudinal direction, 5 mesh elements in the thickness direction, and 4 mesh elements in the width direction. The physical properties are shown in Fig. 6. For the epoxy and aluminum, the actual physical values were used, and for the coil equivalent property values were used. The thermal input of the coil was considered to be Joule heating loss by flux-flow resistances generated in the superconductor or in the stabilized copper part (Eq. (1)–(4) [5]):

$$V_{sc} = 10^{-4}\left(\frac{I_{op}}{I_c(B,T,\theta)}\right)^n d\ , \tag{1}$$

$$V_{cu} = R_{cu}\frac{d}{S_{cu}} I_{op}\ , \tag{2}$$

$$\mathrm{V} = \begin{cases} V_{sc} & (V_{sc} < V_{cu}) \\ V_{cu} & (V_{sc} \geq V_{cu}) \end{cases}, \tag{3}$$

$$\mathrm{q} = \frac{V I_{op}}{Sd}\ . \tag{4}$$

Here, V_{sc} and V_{cu} represent the voltages of the HTS conductor and the stabilized copper part, I_{op} and I_c are the operating and critical currents, and n, d, R_{cu}, S_{cu}, S, and q are the n-value, the length of the HTS conductor, the resistivity of the stabilized copper part, the cross-sectional areas of the stabilized copper part and the HTS conductor, and generated heat, respectively.

The thermal boundary conditions are that the temperature in the aluminum plate of the coil end be uniform and remains constant at 40 K, and that the other surfaces of the coil be thermally insulated.

The calculated result is shown in Fig. 7. When the operating current is 300 A, the temperature rapidly increases from the coil end, and the current is approximately the same as the critical current of the coil. It is considered that the result is due to the high n-value of the HTS conductor. A high n-value causes the generation of a sudden resistance, and this results in rapid heat generation.

Fig. 5. Thermal runaway analysis model.

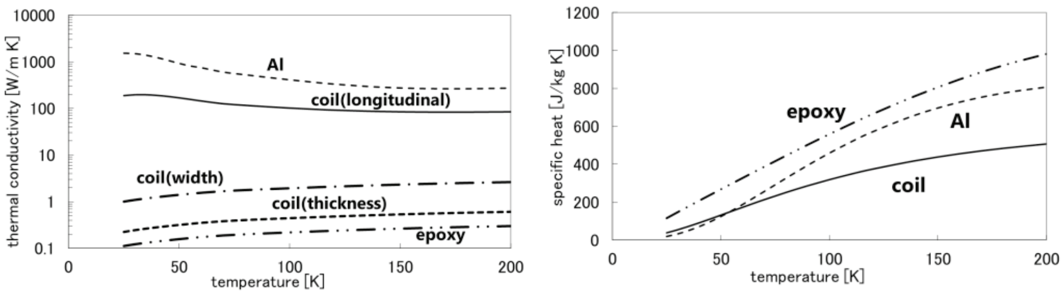

Fig. 6. Physical properties for the analysis (left: thermal conductivity, right: specific heat) functional temperature.

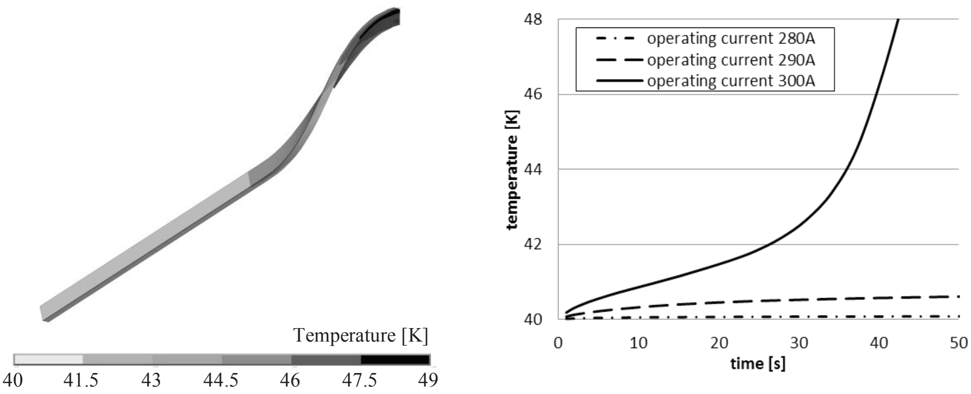

Fig. 7. Result of the thermal runaway analysis (left: the temperature distribution of the coil 40 s after causing a current of 300 A to flow; right: time dependence of the coil peak temperature).

5. Conclusion

The use of high-temperature superconducting (HTS) magnets was considered for reducing the size of the rotating gantry for carbon ion beam cancer therapy. The layout of the HTS rotating gantry for carbon ion beam therapy was designed from the viewpoint of beam optics, and the requirements for the magnets of the rotating gantry were determined. The three-dimensional HTS coil shape was calculated, and a coil shape that generates high field quality was obtained. It is difficult to use coolant for the magnets mounted on the rotating gantry because they are rotated. Conduction cooling should be used instead. On the other hand, there is a problem with the thermal stability of the conduction-cooled HTS coils heated by anomalous thermal inputs such as those due to ramp loss and beam loss. As a first step, thermal runaway analysis for the conduction-cooled HTS coils under a static situation was carried out. When the operating current is 300 A, the temperature of the coil rapidly increases from the coil end, and the current is approximately the same as the critical current of the coil. It is considered that this result is due to the high n-value of the HTS conductor. The high n-value causes the generation of a sudden resistance, and this results in rapid heat generation.

Acknowledgements

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