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Development of HTS Magnet for Rotating Gantry

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Abstract

The effectiveness of heavy-ion radiotherapy for cancer treatment has been recognized by medical experts and the public. However, due to the large size of the equipment, this therapy has not been widely adopted. In particular, the rotating gantries used to irradiate patients with the heavy-ion beams from any direction may be as heavy as 600 tons in our estimation. By employing high-temperature superconducting (HTS) wires in these rotating gantries and increasing the magnetic field generated by the deflecting coils, the total weight of the rotating gantry can be reduced to around the weight of those used for proton radiotherapy. A project for developing an HTS deflecting magnet for heavy-ion radiotherapy has been underway since 2013, supported by the Japanese Ministry of Economy, Trade and Industry (METI) and the Japan Agency for Medical Research and Development (AMED). The aim of this project is to develop fundamental technologies for designing and fabricating HTS deflecting magnets, such as irregular magnetic field estimating techniques, design technology for HTS magnets, high-precision HTS coil winding technology, AC loss estimating techniques, and thermal runaway estimating techniques and to fabricate a small model of an HTS deflecting magnet and evaluate its performance. In this paper, the project's progress will be described.

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Keywords: heavy-ion radiotherapy; rotating gantry; REBCO; deflecting magnet; magnetic field inhomogeneity; saddle-shaped coil; winding macine

1. Introduction

The effectiveness of heavy-ion radiotherapy for cancer treatment has been recognized by medical experts and the public. In heavy-ion radiotherapy, it is desirable to irradiate a tumor with a heavy-ion beam from different directions in order to reduce the dose on normal cells. A rotating gantry is suitable for meeting this requirement. Since the irradiation device rotates around the patient, the beam can irradiate the tumor from any direction without having to change the posture of the patient. Rotating gantries are already commonly used in proton radiotherapy. However, rotating gantries have not yet been installed for heavy-ion radiotherapy because they are too large and heavy. The weight can be as high as 600 ton or higher in our estimation.

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The National Institute of Radiological Sciences (NIRS) has proposed that low-temperature superconducting (LTS) magnets should be applied to these rotating gantries to reduce the weight and has been constructing a superconducting rotating gantry for HIMAC [1]. A project to further reduce the weight of the rotating gantry for heavy-ion radiotherapy by employing HTS magnets started in 2013. The target weight of the rotating gantry is less than 200 ton, which is equivalent to that of the typical rotating gantry used for proton radiotherapy.

In order to clarify the specifications required for the deflecting magnet in a rotating gantry with a total weight of 200 ton, conceptual design of the rotating gantry was carried out. The dipole magnetic field of the magnet should be approximately 6 T, and the length of the saddle-shaped coil for the magnet should be approximately 1.1 m. The magnetic field inhomogeneity should be less than 0.1 % because of the demand for high positional irradiation accuracy of less than 0.5 mm. The rate of change of magnetic field for the deflecting magnet should be more than 0.36 T/s because of the demand for a short treatment time of less than 20 minutes per patient. To meet the requirements for the deflecting magnet, methods for estimating and reducing irregular magnetic fields, design technology for REBCO coils operated in time-varying magnetic fields, high-precision winding technology for fabricating large, high-magnetic-field three-dimensional REBCO coils, AC loss estimating techniques, and thermal runaway estimating techniques have been developed in the project. This paper describes some of the results obtained so far.

2. Magnet design

The deflecting magnet for the rotating gantry should be designed by taking into consideration the effect of the irregular magnetic field induced in the REBCO-coated conductor when charging and discharging the deflecting magnet. However, since the method for estimating irregular magnetic fields described above is still being developed [2][3], as a first step the deflecting magnet was designed without considering the irregular magnetic field [4]. In the design, the magnetic field of the deflecting magnet is calculated by taking into account the coil-end structure of the three-dimensional coil.

The designed HTS rotating gantry is shown in Fig. 2. The rotating gantry has ten HTS deflecting magnets, two pairs of steering magnets (STR1 and STR2), and a pair of scanning magnets (SCM). Dipole magnetic field coils and the quadrupole magnetic field coils are arranged coaxially in each HTS deflecting magnets. The cross-sectional view of the deflecting magnet is shown in Fig.3. The specifications of the HTS deflecting magnets are shown in Table 1. In the design, a magnetic field inhomogeneity of 0.0024% is obtained. In this case the total weight of the rotating gantry is estimated to be 177 ton.

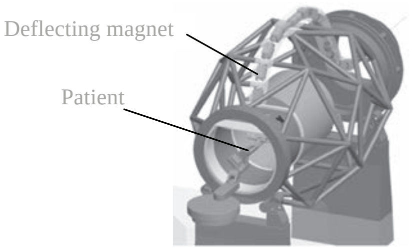

Fig. 1 External view of the rotating gantry.

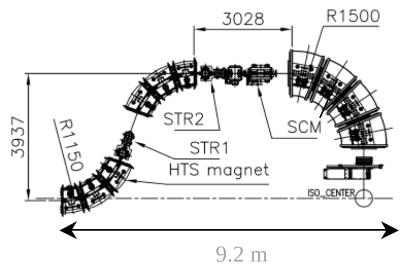

Fig. 2 Layout of HTS deflecting magnets for the rotating gantry.

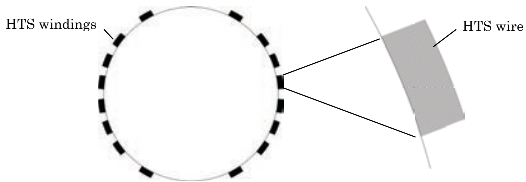

Fig. 3 Two-dimensional positions of the HTS wires.

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

Magnet type	A-type	B-type	C-type	D-type
Bending radius [m]	1.15	1.15	1.5	1.5
Bending angle [deg.]	18	26	22.5	22.5
Dipole magnetic field [T]	5.8	5.8	4.5	4.5
Quadrupole magnetic field [T]	15.5	33	-	1.7
Valid magnetic field region [mm]	±20			
Inner radius of beam duct [mm]	30			
Inner radius of HTS coils [mm]	60			
Magnetic field inhomogeneity [%]	0.0024			

3. REBCO coil winding

Since the coated conductor has a tape shape, it is difficult to wind it into a three-dimensional shape, such as a saddle-shaped coil. In view of the restrictions of the mechanical properties and the windability of the tape-shaped coated conductor, it is necessary to determine the conductor placement needed to meet the field distribution required by the deflecting magnet. Three-dimensional shaped REBCO coils of approximately 1.1 m in length are needed for the magnet. In order to obtain a magnetic field inhomogeneity of less than 0.1%, the coated conductor should be placed in the winding with a positional accuracy of less than 0.1 mm, in our first rough estimation. Detailed study results for the impact of manufacturing errors on the magnetic field inhomogeneity have been shown in another paper [5]. Fig. 4 shows a winding machine fabricated to meet the requirements. The multi-axis configuration of the winding machine is shown in Table 2. From the results of measuring the positional accuracy of the winding machine, an accuracy of less than 0.1 mm for each axis was obtained.

Using this winding machine, several kinds of saddle-shaped REBCO coils were fabricated, as shown in Fig. 5. From the results of measuring the superconducting performance of the coils in L.N_2, all of the coils showed a high n-value of more than 20, as shown in Fig. 6. The analysis results of superconducting performance, such as the critical current and the thermal runaway current for the saddle-shaped REBCO coils in conduction cooling, have been shown in another paper [6].

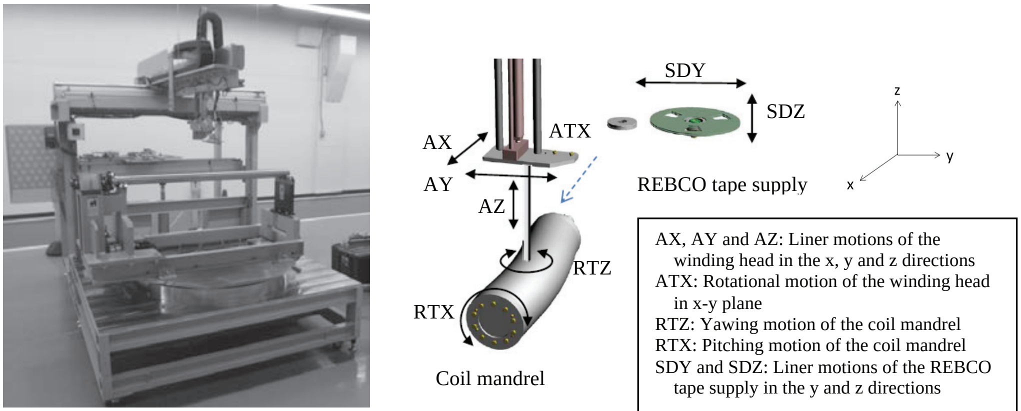

Fig.4 Photograph and schematic diagram of the windin

Table 2 Multi-axis configuration of the winding m

axis	ra
x-axis / head (AX)	500 mm
y-axis / head (AY)	1,250 mm
z-axis / head (AZ)	300 mm
Attitude control (ATX)	90 deg.
Yawing (RTZ)	360 deg.
Pitching (RTX)	360 deg.
y-axis / tape supply (SDY)	1,250 mm
z-axis / tape supply (SDZ)	300 mm

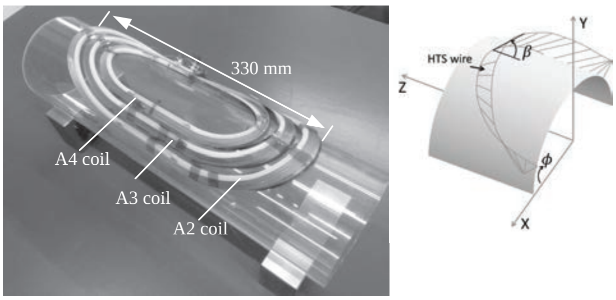

Fig.5 Three types of saddle-shaped REBCO coils and schematic view of HTS wire placement.

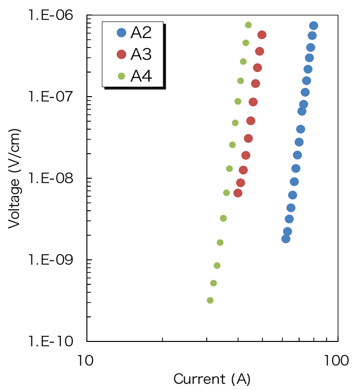

Fig. 6 *V–I* characteristics of saddle-shaped REBCO coils.

4. Fabrication of 1/3-scale model magnet

Before designing the full-scale deflecting magnet, we plan to fabricate a 1/3-scale model magnet. A schematic diagram and the specifications of the model magnet are shown in Fig. 7 and Table 3, respectively. The model magnet is composed of 24 saddle-shaped REBCO coils and iron yokes. The REBCO coils are cooled to approximately 20 K by a Gifford-McMahon (GM) cryocooler and generate a magnetic field of 3 T when the rated current of 366 A is applied to the magnet. After the rated current test, the magnetic field distribution in the inner duct of the magnet will be measured during charging and discharging of the magnet. The tests will be carried out in February 2016.

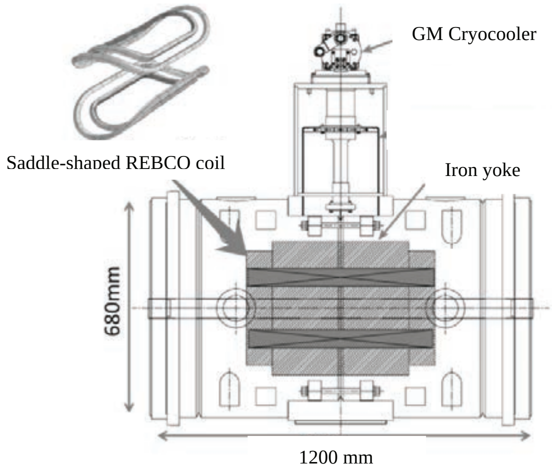

Fig. 7 Schematic view of the 1/3-scale model magnet

Table 3 Specifications of 1/3-scale model magnet.

Outer dimension	680 mm × 1200 mm
Magnetic field at the center of inner duct	3 T
Rated current	366 A
Diameter of inner duct	60 mm
Inner diameter of REBCO coils	120 mm
Outer radius of REBCO coils	160 mm
Coil length	330 mm
Number of REBCO coils	32
Total length of REBCO conductor	1 km

5. Conclusions

In order to reduce the total weight of a rotating gantry for heavy-ion radiotherapy for cancer treatment to less than 200 ton, methods for estimating and reducing irregular magnetic fields, design technology for REBCO coils operated in time-varying magnetic fields, high-precision winding technology for fabricating large, high-magnetic-field three-dimensional REBCO coils, AC loss prediction estimating techniques, and thermal runaway estimating techniques have been developed in this project. We fabricated a winding machine for the REBCO saddle-shaped coils and showed that it had a positional accuracy of less than 0.1 mm. REBCO saddle-shaped coils wound with this winding machine showed good superconducting characteristics, with high n-values of more than 20. Therefore it was confirmed that the winding machine was constructed without a problem. We have been fabricating a 1/3-scale model magnet composed of 24 saddle-shaped REBCO coils and iron yokes. The magnet will be tested in February 2016.

Acknowledgements

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