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Design and Test Results of Superconducting Magnet for Heavy-Ion Rotating Gantry

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Abstract. Heavy-ion radiotherapy has a high curative effect in cancer treatment and also can reduce the burden on patients. These advantages have been generally recognized. Furthermore, a rotating gantry can irradiate a tumor with ions from any direction without changing the position of the patient. This can reduce the physical dose on normal cells, and is thus commonly used in proton radiotherapy. However, because of the high magnetic rigidity of carbon ions, the weight of the rotating gantry for heavy-ion therapy is about three-times heavier than those used for proton cancer therapy, according to our estimation. To overcome this issue, we developed a small and lightweight rotating gantry in collaboration with the National Institute of Radiological Sciences (NIRS). The compact rotating gantry was composed of ten low-temperature superconducting (LTS) magnets that were designed from the viewpoint of beam optics. These LTS magnets have a surface-winding coil-structure and provide both dipole and quadrupole fields. The maximum dipole and quadrupole magnetic field of the magnets were 2.88 T and 9.3 T/m, respectively. The rotating gantry was installed at NIRS, and beam commissioning is in progress to achieve the required beam quality. In the three years since 2013, in a project supported by the Ministry of Economy, Trade and Industry (METI) and the Japan Agency for Medical Research and Development (AMED), we have been developing high-temperature superconducting (HTS) magnets with the aim of a further size reduction of the rotating gantry. To develop fundamental technologies for designing and fabricating HTS magnets, a model magnet was manufactured. The model magnet was composed of 24 saddle-shaped HTS coils and generated a magnetic field of 1.2 T. In the presentation, recent progress in this research will be reported.

1. Introduction

Because of its high curative effects and low burden on patients, heavy-ion radiotherapy is becoming more widespread, and the total number of patients treated with heavy-ion radiotherapy has been increasing. In order to reduce the physical dose on normal cells, it is preferable to irradiate the tumor with the heavy-ion beam from various directions. A rotating gantry is a suitable apparatus for meeting this requirement. Rotating gantries are already used in proton radiotherapy; however, the rotating gantries required for heavy-ion radiotherapy will be much larger because the magnetic rigidity of the heavy ions is about three-times larger than that of protons. There is only one heavy-ion gantry in the world, located in Heidelberg, which had been operating until 2014. The total weight of the gantry was reported to be 600 tons [1], whereas the typical weight of existing proton gantries is between 100 and 200 tons. To reduce the size of the heavy-ion gantry, we developed LTS magnets in collaboration with NIRS [2], and their installation in a superconducting rotating gantry was completed successfully in 2015. Beam commissioning is in progress to achieve the required beam quality [3]. In this paper, manufacturing and test result of the LTS magnets are reported.

For the purpose of further size reduction of the rotating gantry, we have been developing fundamental technologies for an HTS gantry in the three years since 2013, in a project supported by METI and AMED. In this project, a model magnet composed of 24 saddle-shaped HTS coils was fabricated and generated a magnetic field of 1.2 T [4]. In this paper, the fabrication and test result of the HTS magnet are reported.

2. LTS rotating gantry

2.1. Layout of LTS gantry

The layout of the LTS rotating gantry which was developed in collaboration with NIRS is shown in Figure 1. It is an isocentric gantry with an axial length of 5.5 m and a radius of 13 m. Ten LTS magnets of five different types were mounted on it. A pair of scanning magnets was arranged on the top of the gantry, and three pairs of steering magnets and beam monitors were placed in the straight section. A dose monitor, a beam position monitor, and a ridge filter were arranged downstream of the beam line. These devices were mounted on a cylindrical structure, allowing the gantry to irradiate patients with ions at angles of over ±180 degree by rotating this structure.

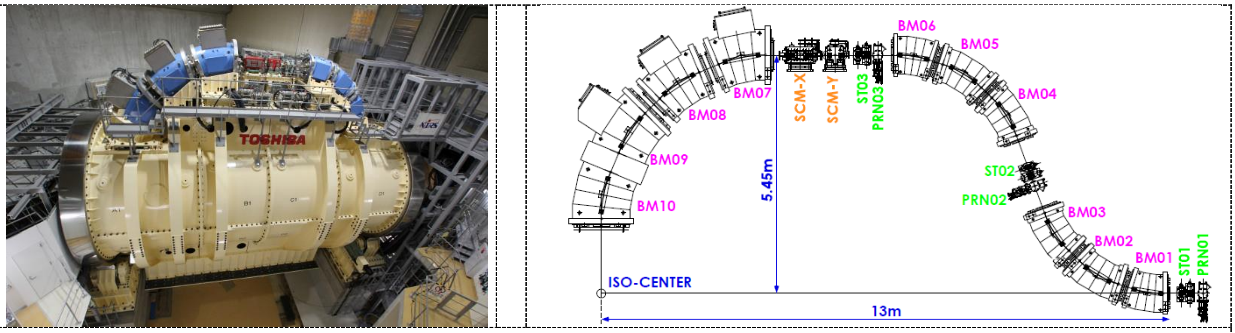

Figure 1. Left: Photograph of the rotating gantry at NIRS. Right: Layout of the gantry. The gantry consists of ten superconducting magnets (BM01-10), a pair of scanning magnets (SCM-X and SCM-Y), and three pairs of steering magnets and beam profile-monitors (ST01-03 and PRN01-03).

2.2. Design and test result of LTS magnets

The specifications of the LTS magnets are shown in Table 1. The maximum dipole field was 2.88 T, and the maximum quadrupole field was 9.3 T/m, and these values were determined by the beam optics [2]. Photographs of one of the LTS magnets and a coil are shown in Figure 2. The coils were saddle-shaped, and the positions of the superconductors followed a cos-theta distribution. The LTS magnets, except BM7 and BM8, have a dipole coil and quadrupole coil in a coaxial arrangement for shortening the gantry. The arrangement of the superconductors was determined by three-dimensional magnetic field analysis so that the integral dipole and quadrupole field were uniform [2]. Using an NC winding machine, conductors having diameters of 0.9 mm for BM1-6 and 1.3 mm for BM7-10 were wound so as to adhere to the outer surface of a bent cylinder with an accuracy of 0.1 mm. To reduce AC losses, NbTi wire with a filament diameter of 10 μm and CuNi barriers were employed. Each coil can be excited independently, and the LTS magnets were connected to power supplies placed on the non-rotating area with power cables through a cable spool located at the end of the gantry. The return yoke was arranged on the outside of the coil. It enhanced the magnetic field intensity and supported the magnetic force. To suppress eddy currents, the return yoke was constructed from laminated electromagnetic steel sheets. The magnetic field at the mid-plane of the return yoke was set to be less than 2 T in order to reduce the influence of saturation. Moreover, the vacuum vessel was made of iron for reducing magnetic field leakage. The magnetic field distributions of all manufactured LTS magnets were measured and their performance was checked [5]. The alignment reference point was determined from the measurement results, and the magnets were installed with an accuracy of ±0.3 mm.

Table 1. The specifications of the LTS magnets.

parameter	BM1 and BM6	BM2-BM5	BM7	BM8	BM9-10
Bending angle (deg.)	18	26	22.5	22.5	22.5
Bending radius (m)	2.3	2.3	2.8	2.8	2.8
Bore radius (mm)	30	30	85	120	145
Reference area (mm)	ϕ40	ϕ40	60×60	80×80	100×100
Maximum dipole field (T)	2.88	2.88	2.37	2.37	2.37
Maximum quadrupole field (T/m)	9.3	9.3	-	-	1.3
Field uniformity (dipole)	$\leq 1\times10^{-3}$			$\leq 1\times10^{-4}$	
Field uniformity (quadrupole)			$\leq 1\times10^{-3}$		

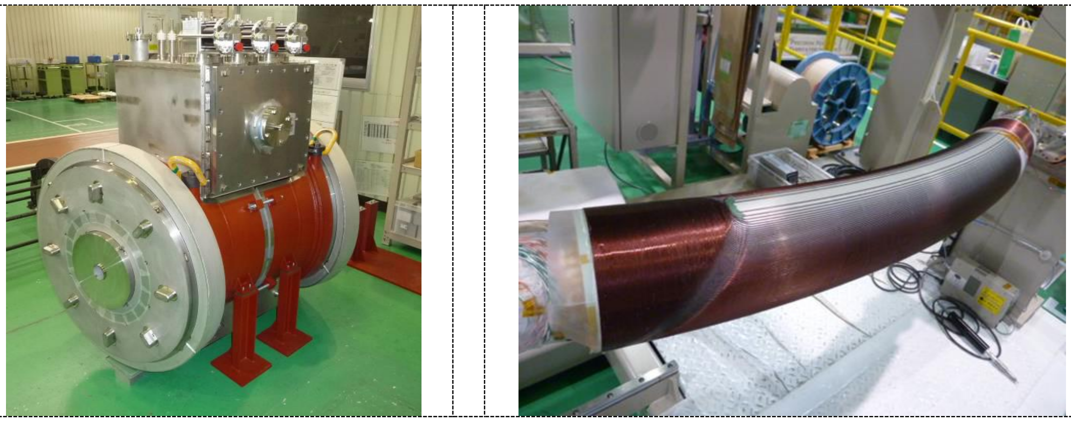

Figure 2. Photographs of the LTS magnet (left:BM4) and the saddle-shaped LTS coil (right).

A conduction cooling system with no coolant was adopted because the magnets were rotated. Small Gifford-McMahon (GM) cryocoolers having a cooling capacity of 1.5 W at 4.2 K were used, and the LTS coils and yokes were cooled by the cryocoolers through pure aluminum plates with a thickness of 1 mm. Three sets of cryocoolers were mounted on each of BM1-6, and four sets of cryocoolers were mounted on each of BM7-10, giving a total of 34 small cryocoolers in the LTS gantry. The compressors were arranged in the non-rotating area and were connected to the cryocooler with flexible helium gas lines with a length of 30 m via the cable spool. When cooling the magnets with only the cryocoolers, it took about 8 days for the initial cooling at BM4. To evaluate the influence of rotation on the cooling capacity, a continuous rotation test was carried out. The prototype LTS magnet was fabricated, and the coil temperature was measured while rotating the magnet repeatedly from –180 degree to +180 degree. The rotating speed was 1.5 rpm, so that the acceleration acting on the cryocooler mounted on the prototype magnet was the same value (0.002G) as the acceleration that acts on the cryocooler mounted on the gantry. As a result of the test, there was no change in the coil temperature even after changing the position 33,000 times. This number of position changes is equivalent to 1.5 years of operation. Moreover, it was checked that there were no faults, such as leaks or bad insulation, in the flexible helium gas line and power cables at the time of rotation. In order to control the irradiation depth by the beam energy, the operating currents of the LTS magnets were also changed in a short time according to the energy. At the time of the magnetic field change, the coils generated heat due to AC loss. Then, the coil temperature was measured using an operating pattern in which the coil was excited from 430 MeV/u to 80 MeV/u in 200 steps. The test results are shown in Figure 3. The average coil temperature was initially 3.7 K, and with the excitation pattern, the average coil temperature was stabilized at about 4 K, and a transient temperature rise of 0.5 K was observed [6,7]. On the other hand, there was no quenching. To reduce the treatment time, the magnets were rotated in the excited state. Even in such a case, there was no remarkable coil temperature rise or quenching. The cooling curve when training quench occurred in BM6 is shown in Figure 4. Re-cooling was completed in about 2 hour.

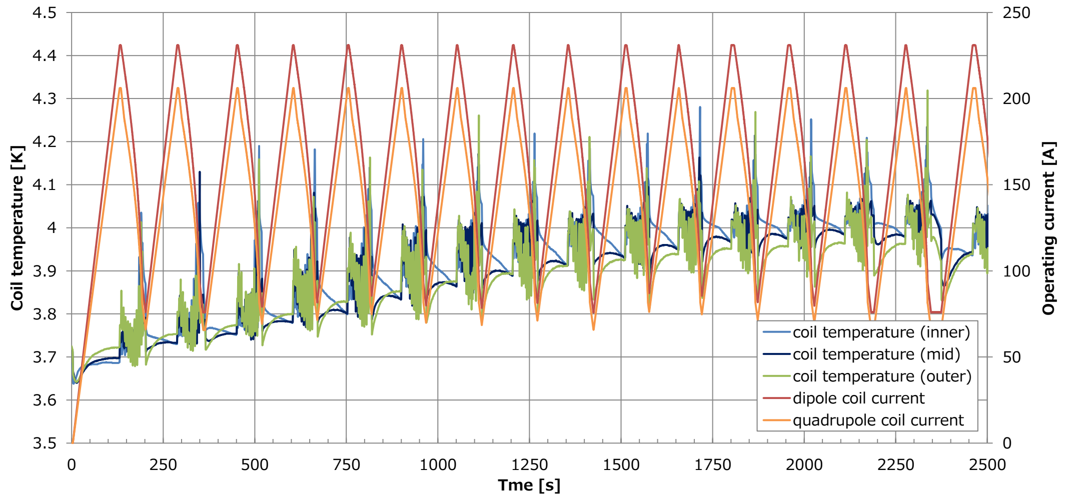

Figure 3. Test results of operating pattern in which coil was excited from 430 MeV/u to 80 MeV/u in 200 steps (BM10).

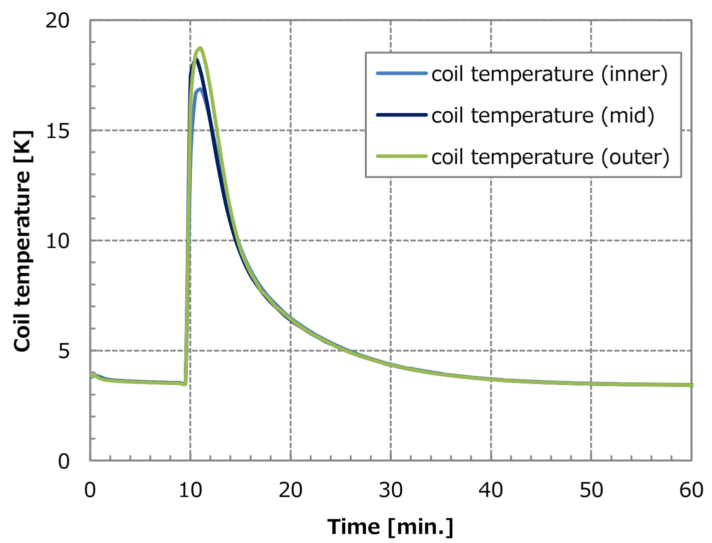

Figure 4. The re-cooling curve after quenching was occurred (BM6).

3. HTS rotating gantry

3.1. Layout of HTS gantry

For the purpose of further reducing the size of the rotating gantry, an R&D project to develop fundamental technologies for HTS gantries started in 2013, supported by METI and AMED. An HTS magnet can generate a high magnetic field and can be cooled efficiently because of the high operating temperature. On the other hand, there are some issues that should be considered, for example: the influence of tape magnetization and manufacturing accuracy on the field quality [8], the thermal stability of the conduction-cooled HTS coils under an alternating magnetic field [9], and methods to protect the coils from thermal runaway caused by an anomalous thermal input such as that due to beam loss. In order to clarify the required specifications, conceptual design of an HTS gantry was carried out. The layout of this HTS gantry is shown in Figure 5 [10]. This design was based on the LTS gantry, and it has an axial length of 9.2 m, a radius of 3.9 m, and a total weight of 177 tons. Ten HTS magnets of four different types were mounted on the HTS gantry.

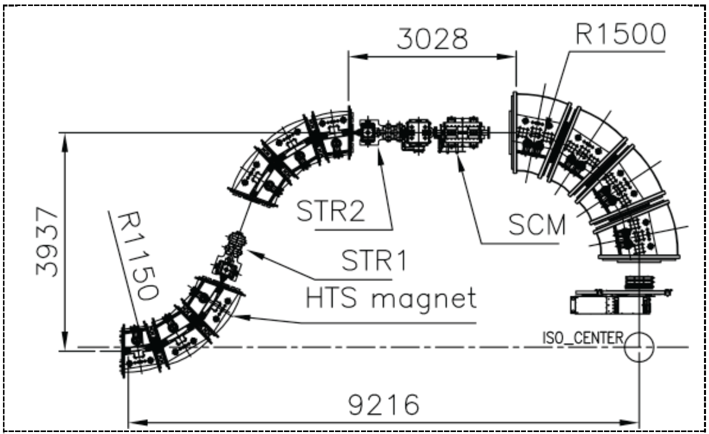

Figure 5. Layout of HTS rotating gantry.

3.2. Design and test result of HTS magnets

The specifications of the HTS magnets are shown in Table 2. The maximum dipole field of the HTS magnet should be approximately 6 T, and the maximum quadrupole field should be 33 T/m. These values were estimated from the beam optics [11]. 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. Also, in this study, REBCO conductor having a width of 4 mm and a thickness of 0.1 mm was considered because of its performance advantages in high magnetic fields and at high temperatures. To generate the magnetic field efficiently, the HTS coils were formed in a saddle shape. The return yoke was arranged on the outside of the coil for enhancement of the magnetic field and supporting the magnetic force. Conduction cooling was adopted because the magnets were rotated. To evaluate this design, a model magnet was fabricated.

Table 2. The specifications of the HTS magnets.

parameter	A type	B type	C type	D type
Bending angle (deg.)	18	26	22.5	22.5
Bending radius (m)	1.15	1.15	1.5	1.5
Maximum dipole field (T)	5.8	5.8	4.5	4.5
Maximum quadrupole field (T/m)	15.5	33	-	1.7
Field uniformity (dipole)	$\leq 1\times10^{-3}$		$\leq 1\times10^{-4}$	
Field uniformity (quadrupole)	$\leq 1\times10^{-3}$			

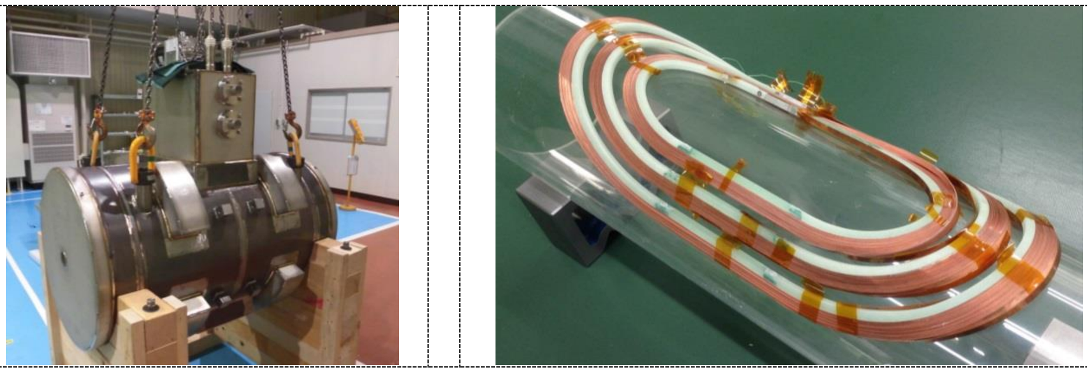

Figure 6. Photographs of the HTS model magnet (left) and the saddle-shaped HTS coil (right).

Photographs of the model magnet and the HTS coil are shown in Figure 6. This model magnet was a short model, and the specifications are shown in Table 3. Twenty-four saddle-shaped REBCO coils and iron yokes were applied, and these were cooled down to approximately 4 K by a GM cryocooler. To reduce stress in the windings, these saddle-shaped coils were fabricated by an automatic winding machine with an eight-axis synchronous control function [12]. To confirm the positional displacement of each turn in the HTS coils quantitatively, the roughness of the fabricated HTS coil surface was measured by a laser displacement meter, and the winding accuracy was measured to be 0.2 mm in the tape edge direction [8]. The superconducting properties of all saddle-shaped coils constructing the model magnet were confirmed under a liquid nitrogen environment, and the HTS coils were stacked in four layers and attached to the iron yoke. After assembly of the model magnet, initial cooling was carried out, which took about 13 days. The operating current was increased with a sweep rate of 5-10 A/minute, and the behaviors of the coil temperature and coil voltage generated in the saddle-shaped coils were measured. The temperature profiles of the operating current are shown in Figure 7. An anomalous temperature rise was observed at an operating current of 153 A, and the generated magnetic field at the center of the beam duct was 1.2 T at that time. Temperature rises also can be found at 1.14 hour, 1.34 hour, and 1.54 hour in Figure 7. This phenomenon was assumed to be explained by flux jump. In this event, the dipole field strength changed coincidentally less than 100 ppm level [4]. Since there was no anomalous temperature rise even after re-excitation under 153 A, field quality measurement was conducted with a harmonic coil system at an operating current of 120 A [4]. Large quadrupole and sextupole coefficients were observed compared with the values predicted in the simulation, and these were considered to be due to partial misalignment of the coils. Further investigation of the model magnet is on-going.

Table 3. The specifications of the model magnet.

parameter	value
Outer dimension (mm)	680×1200
Magnetic field at center of beam duct (T)	1.2
Rated current (A)	153
Radius of beam duct (mm)	30
Inner radius of REBCO coils (mm)	60
Outer radius of REBCO coils (mm)	80
Inner radius of iron yoke (mm)	95
Outer radius of iron yoke (mm)	205
Coil length (mm)	340
Number of REBCO coils	24
Number of turn for each coil	50
Total length of REBCO conductor (m)	820
Coil inductance (mH)	288.9

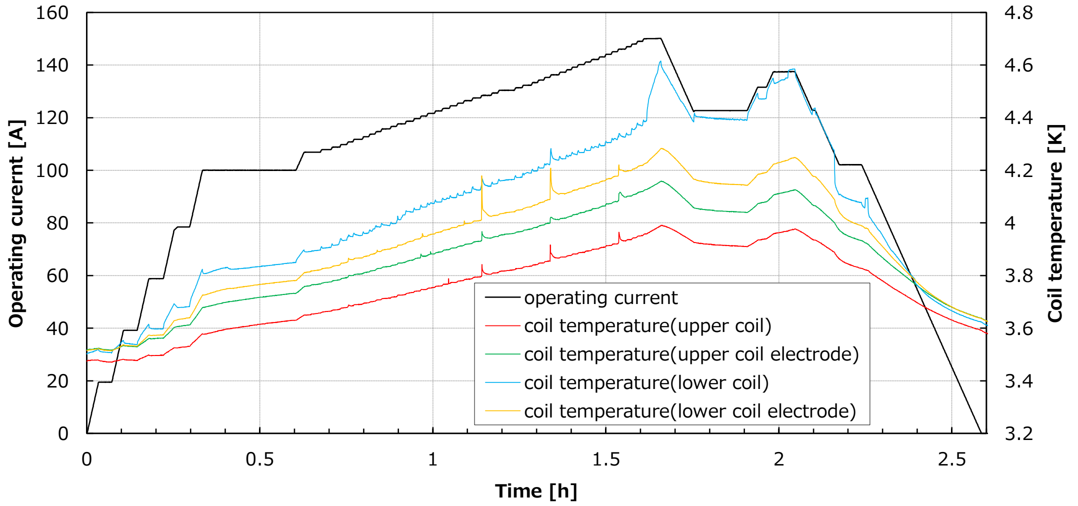

Figure 7. Excitation test result of model magnet.

4. Conclusion

To reduce the size of the rotating gantry for heavy-ion radiotherapy, we have been developing LTS magnets and HTS magnets. For the LTS magnets, the results of temperature and magnetic field measurements were positive, and manufacturing and installation of an LTS gantry were successfully completed. Beam commissioning to achieve the required beam quality is on-going. For the HTS magnets, we have been developing fundamental technologies for REBCO coils, and a model magnet composed of saddle-shaped REBCO coils was fabricated. The model magnet could generate a magnetic field of 1.2 T at the center of the beam duct. The field quality was measured using a harmonic coil system, and large multipole coefficients were observed. These were considered to be due to misalignment of the HTS coils. Further investigation of the model magnet is on-going.

Acknowledgments
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