ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUZGBF1

SUPERCONDUCTING GANTRY FOR CARBON-ION RADIOTHERAPY

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Abstract

A superconducting rotating-gantry for carbon-ion radiotherapy (CIRT) was developed. This isocentric rotating gantry can transport carbon ions having the maximum kinetic energy of E=430 MeV/u to an isocenter with irradiation angles of over ±180 degrees, and is further capable of performing fast three-dimensional raster-scanning irradiation. By using combined-function superconducting magnets, we could design a compact rotating gantry for CIRT. Construction of the gantry structure as well as the superconducting magnets began since 2013, and installation of the entire rotating-gantry system to the new treatment facility at the National Institute of Radiological Sciences (NIRS) was completed by the end of September, 2015. Beam commissioning subsequently began since October, 2015. After series of the beam commissioning, treatment using the rotating gantry was started since May 2017. We will present an overview of the development for the superconducting rotating-gantry.

INTRODUCTION

Cancer treatment using high energy carbon-ions, as obtained by the Heavy Ion Medical Accelerator in Chiba (HIMAC) has been carried out at NIRS since June 1994 [1], and more than 10,000 patients were treated by now. The successful results of cancer treatment have led us to construct a new treatment facility [2, 3]. As shown in Fig. 1, this new facility is equipped with three treatment rooms; two of them have both horizontal and vertical fixed-irradiation-ports (treatment room E and F), and the other is a rotating-gantry port (treatment room G). For all the ports, fast three-dimensional raster-scanning irradiation with a pencil beam is employed. The new facility was constructed in conjunction with the HIMAC complex, and the new beam-transport line to the three treatment rooms in the facility were connected to the existing beam line of the HIMAC, so as to provide carbon-ion beams from the upper synchrotron ring of the HIMAC.

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In the ion radiotherapy, a rotating gantry is a very attractive tool, because a treatment beam can be directed to a target from any of medically desirable directions, while a patient is kept in the best clinical position. This flexibility of the beam delivery for this type of the gantry, isocentric rotating gantry, is advantageous to treat tumors having wide range of tumor sites and sizes.

For proton cancer therapy, rotating gantries were commonly constructed around the world. However, it would be very difficult to construct a rotating gantry for CIRT, because the required magnetic rigidity for carbon-ion beams having the maximum energy of E=430 MeV/u is roughly three times higher than that for proton beams having the maximum energy of E=250 MeV/u, and hence the size and weight of the magnets, as well as the gantry structure including counterweights, would become considerably larger. To overcome this problem, a superconducting rotating-gantry for CIRT was developed [4]. In this paper, we will describe the overview of the gantry development.

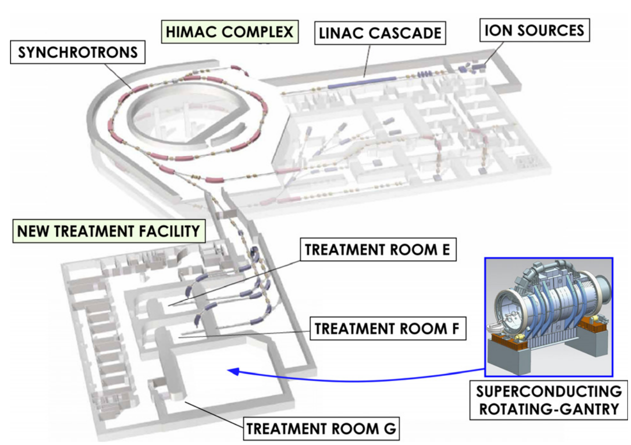

Figure 1: Bird's eye view of the HIMAC complex. The HIMAC complex consists of three ion sources, one linac cascade, two synchrotron rings, and three treatment rooms. The new treatment facility was constructed in conjunction with the HIMAC complex, and has the three treatment rooms.

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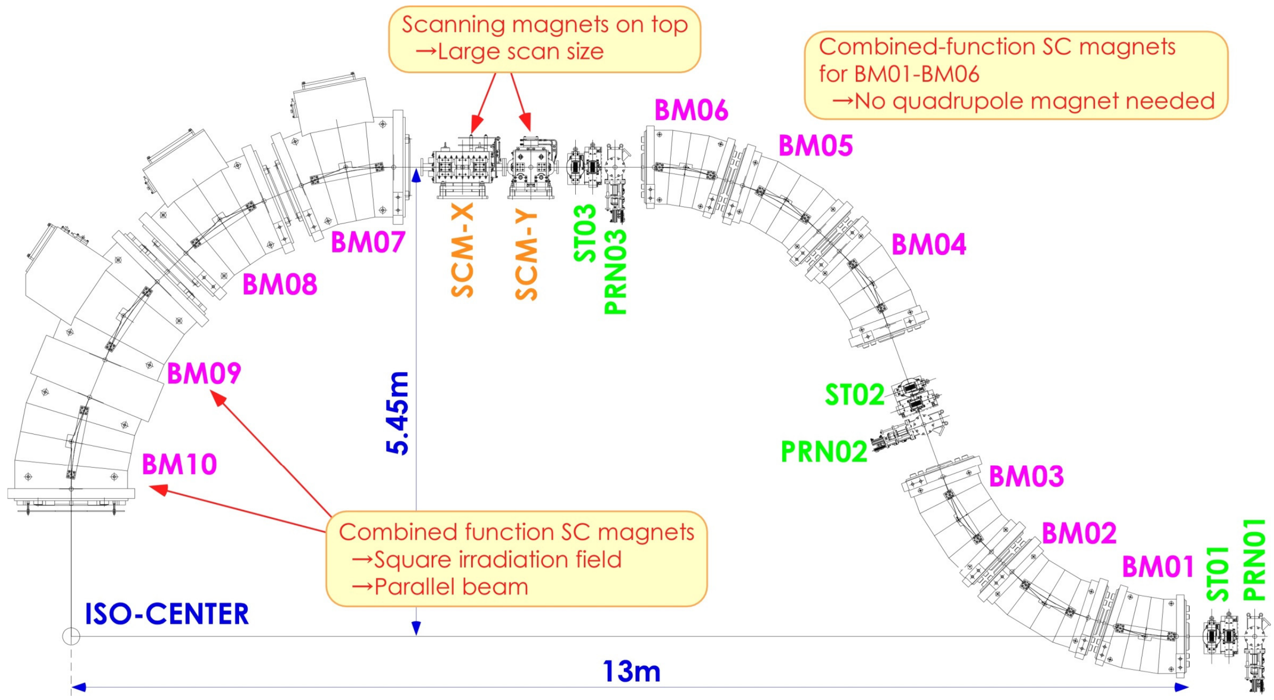

Figure 2: Layout of the superconducting rotating-gantry. The gantry consists of the ten superconducting magnets (BM01-BM10), the three pairs of the steering magnets (ST01-ST03) and profile monitors (PRN01-PRN03), and a pair of the scanning magnets (SCM-X and SCM-Y).

DESIGN

A three-dimensional image of the superconducting rotating gantry is presented on the right hand of Fig. 1. This rotating gantry has a cylindrical structure with two large rings having the outer diameter of 6.5 m at both ends. The distance between the two end rings is 14 m. The end rings support the total weight of the entire structure, and are placed on two pairs of turning rollers, so as to rotate the beam line on the rotating gantry along the central axis over ±180 degrees. Carbon-ion beams, provided by the HIMAC, are transported with ten superconducting magnets, mounted on the gantry structure through each of their supporting structures, and are directed to a target, located at the isocenter. The total weight of the rotating structure is estimated to be approximately order of 300 tons.

Figure 2 shows a schematic drawing of the beam line, mounted on the rotating part of the gantry. The beam line consists of ten superconducting magnets (BM01-BM10), a pair of scanning magnets (SCM-X and SCM-Y), and three pairs of steering magnets (ST01-ST03) and beam profile monitors (PRN01-PRN03). To design the compact rotating gantry, curved combined-function superconducting magnets was developed. These superconducting magnets have a surface-winding coil structure. Having wound dipole and quadrupole coils on a mandrel, the superconducting magnets can provide both dipole and quadrupole fields, while BM07 and BM08 only has a dipole coil. A maximum dipole field is 2.88 T for the small aperture group (BM01-BM06) and 2.37 T for large aperture group (BM07-BM10). Further, the maximum field gradients for BM01-BM06 and BM09-BM10 are 9 T/m and 1.3 T/m, respectively. By using the combined-function superconducting magnets, no quadrupole magnet is necessary for beam focusing, and hence we could design the compact rotating gantry. Further, by utilizing the quadrupole field of BM09 and BM10, we could provide square irradiation fields as well as parallel beams at the isocenter. Design details of the rotating gantry as well as the superconducting magnets can be found in Ref. [4].

CONSTRUCTION AND TESTS

The superconducting magnets as well as the gantry structure were constructed at the Toshiba Keihin Product Operations, located at Kanagawa, Japan. After the construction of the superconducting magnets, the superconducting coils were cooled down below 4K, and series of tests including magnetic field measurements were performed for all the magnets; some results of the tests can be found in Ref. [5]. The measured field map over the magnet aperture agreed with that calculated by a three-dimensional electromagnetic field solver, the Opera-3d code, although we observed a quadrupole field, originated from the dipole coil. However, since the magnets have the both dipole and quadrupole coils, this unexpected quadrupole field from the dipole coil can be corrected by tuning the coil current for the superconducting quadrupole coil.

Because of the construction and transportation issues, the cylindrical structure of the rotating gantry was divided into eight large parts. The eight parts as well as the two end rigs were made at the Toshiba Keihin Product Operations. At the Toshiba factory, the structure of the rotating gantry was once assembled with dummy weights, instead of the superconducting magnets, and rotation tests with up to the maximum rotation rate of 0.5 rpm were made. During the

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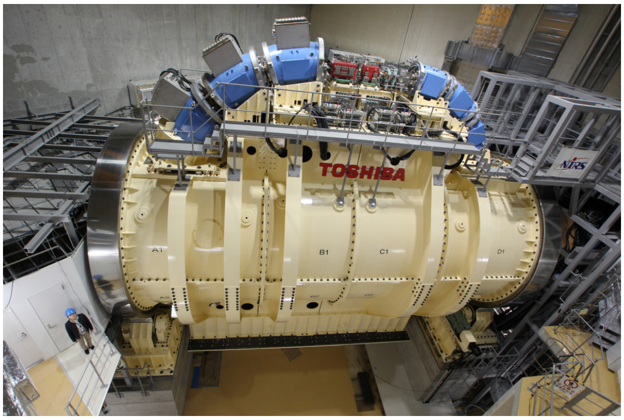

Figure 3: Picture of the superconducting rotating-gantry, as taken at the end of September 2015. The superconducting magnets and the scanning magnets are colored in blue and red, respectively.

rotation tests, targets of a laser tracker were attached over various places on the gantry structure including the isocenter, and absolute positions were precisely measured during the gantry rotation to monitor deformation of the gantry structure, as caused by rotations. As a result of the tests, we found that measured deformations agreed with those predicted by FEM calculations of the gantry structure.

Having made series of the tests at the Toshiba factory, the rotating gantry was disassembled into the parts, and transportation to the new treatment facility at NIRS initiated since early 2015. The parts were then installed and subsequently reassembled in the gantry room, and further the superconducting magnets as well as all the other beam transport devices were mounted on the gantry structure. All the construction of the superconducting rotating-gantry was completed by the end of September 2015. Pictures of the rotating gantry as well as the treatment room G are given in Fig. 3 and Fig. 4, respectively.

BEAM COMMISSIONING

Operations of the superconducting rotating-gantry as well as beam commissioning began since October 2015 [6]. Based on the central magnetic field as well as the effective


Figure 4: Picture of the gantry treatment room (Treatment room G). A patient is handed with the robotic couch.

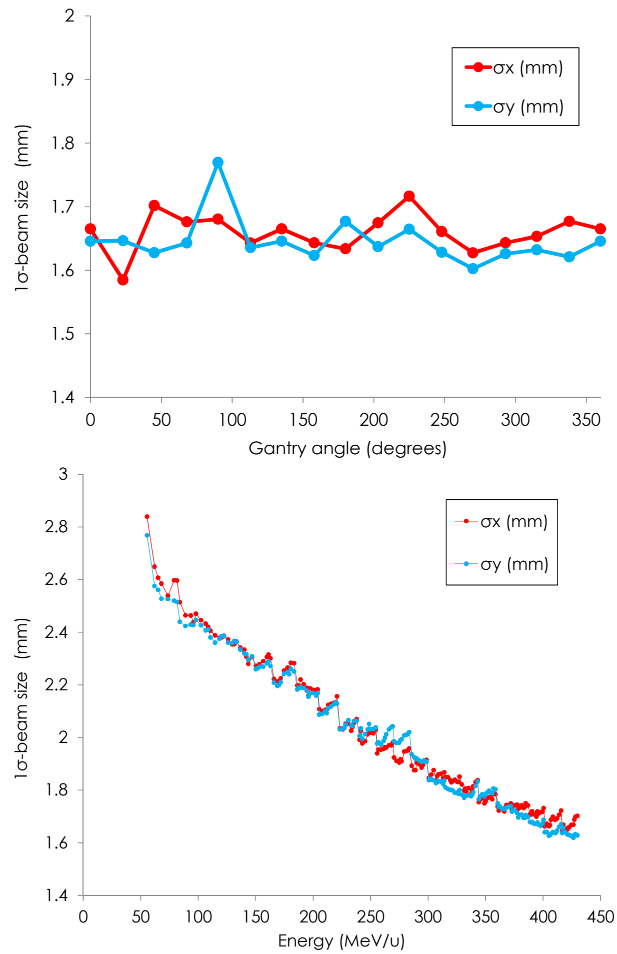

Figure 5: Measured 1σ beam sizes for the horizontal and vertical coordinates at the isocenter as functions of the gantry angle (upper) and beam energy (lower).

length of the magnetic field, as determined by the magnetic-field measurements, coil currents for the superconducting magnets were determined and used to generate parameter sets for their power supplies. Having used these parameter sets, carbon ions having the kinetic energies of between E=430–56 MeV/u, as accelerated by the upper synchrotron ring of the HIMAC, were successfully transported through the rotating gantry, and we observed expected beam spots at the isocenter without any beam losses. Further, the beam tuning for various combinations of beam energies and gantry angles was performed. Since it is important to obtain stable and circular beam spots with a Gaussian shape for scanning irradiation, careful beam tuning was made so as to obtain Gaussian beam spots at the isocenter over the various gantry angles and the beam energies. In the initial beam tuning, the gantry was rotated over ±180 degrees with an angular step of 22.5 degrees, and beam spots at the isocenter were measured. Having finely tuned the superconducting quadrupoles of BM05, we could obtain circular beam spots at the isocenter. Measured 1σ beam sizes for the horizontal and vertical coordinates at the isocenter for the beam energy of E=430 MeV/u as functions of the gantry angles is shown in Fig. 5 (upper).

9th International Particle Accelerator Conference IPAC2018, Vancouver, BC, Canada JACoW Publishing
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We see that the average beam size is approximately 1.65 mm as designed, while minimizing the angular dependence of the beam size to be within ±5%. Similarly, the beam spots for 201 kinds of beam energies of between *E*=430–56 MeV/*u* were tuned, and the representative result for the gantry angle of θ=43 degrees is given in Fig. 5 (lower). As a result of beam tuning over the various gantry angle angles and beam energies, we obtained Fig. 6, which shows the measured average beam-size at the isocenter as a function of the gantry angle and RID (range ID), where RID corresponds to the beam energy ID; RID=0 for *E*=430 MeV/*u* and RID=200 for *E*=56 MeV/*u*. The measured beam sizes smoothly increases as the beam energy decreases having small angular dependence, satisfying the requirements of scanning irradiation. By interpolating the parameter sets for the power supplies of the magnets, as obtained by the beam tuning, we finally determined the parameter sets for all the gantry angles with the angular step of $\Delta\theta$=1 degree.

The beam position was concurrently tuned by using the steering magnets of ST01-ST03 in the gantry beam-line, so as to center the beam spot at the profile monitors as well as the isocenter. As a result of the beam tuning, we obtained the 2D parameter maps for the coil current of the steering magnets, as shown in Fig. 7.

As a result of the beam commissioning, we finally started the cancer treatment using the superconducting rotating-gantry since May 2017.

FUTURE PLANS

Based on the design and experiences of the superconducting rotating-gantry, developed at NIRS, the 2nd-generation compact rotating gantry was developed by

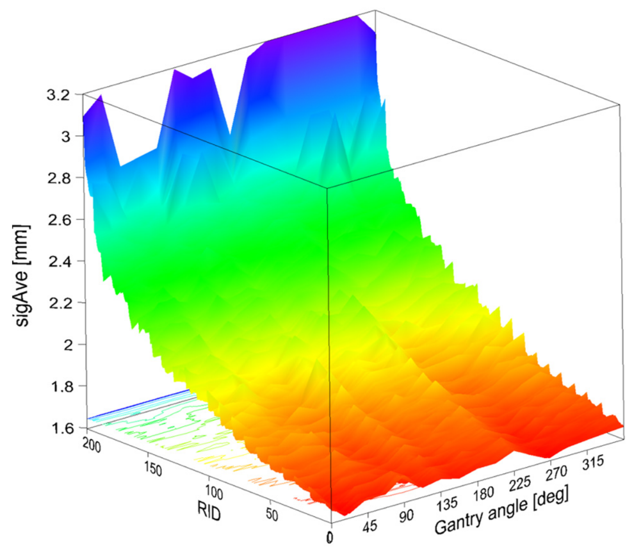

Figure 6: Measured 1σ beam size as a function of the gantry angle and RID. The RID corresponds to the beam energy ID; RID=0 for *E*=430 MeV/*u* and RID=200 for *E*=56 MeV/*u*. The beam size was obtained by averaging those for the horizontal and vertical coordinates.

Toshiba, and is being constructed at Yamagata University [7]. The compact rotating gantry employs the combined-function superconducting-magnets, of which the design is similar to that for our magnets of BM01-BM06, however the maximum dipole fields is increased up to B_{max}~3 T. Further, by using the newly developed scanning magnet and employing a layout of downstream scanning, a total length of the rotating gantry can be reduced.

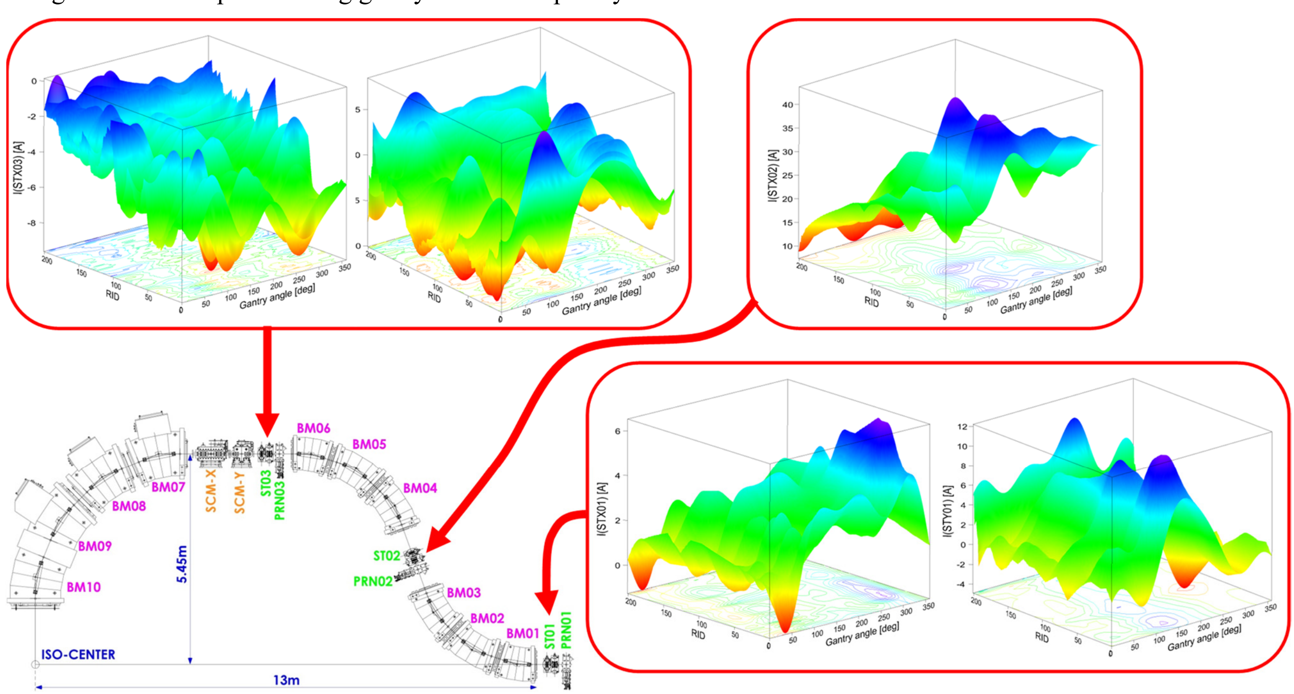

Figure 7: Coil currents for the horizontal steering magnets of STX01-STX03 and the vertical steering magnets of STY01-STY03 as functions of the gantry angle and RID. The steering magnets were turned so as to center the beam spot at the profile monitors as well as the isocenter.

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For further widespread use of carbon gantries, a 3rd-generation compact gantry was designed [8]. With three combined-function superconducting magnets, which can provide the maximum dipole field of B_{max}=5 T, the size of the rotating gantry would become very compact; the length and radius would be 5.1 m and 4.0 m, respectively. We will further perform R&D works for developing the superconducting magnets.

SUMMARY AND CONCLUSION

A superconducting rotating-gantry for CIRT was developed. The structure of the rotating gantry as well as the curved combined-function superconducting magnets were developed and constructed, and installation of the entire rotating-gantry system to NIRS was completed by the end of September 2015. Beam commissioning subsequently began since October 2015, and we could consequently obtain circular beam spots with a Gaussian shape at the isocenter over the various gantry angles and beam energies, while minimizing the angular dependence. After series of the beam commissioning, we finally started the cancer treatment using the superconducting rotating-gantry since May 2017. Further, we are now developing the next generation compact rotating-gantry for widespread use of carbon gantries.

ACKNOWLEDGEMENTS

We thank the members of Toshiba Corporation and Accelerator Engineering Corporation (AEC) for their helps in the gantry development. This work is supported by Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

REFERENCES

[1] Y. Hirao *et al*., "Annual Report", HIMAC, National Institute of Radiological Sciences, NIRS-M-89/HIMAC-001, 1992.

[2] K. Noda *et al*., Nucl. Instrum. and Meth. in Phys. Res. A, vol. 562, p. 1038, 2006.

[3] K. Noda *et al*., Nucl. Instrum. and Meth. in Phys. Res. B, vol. 266, p. 2182, 2008.

[4] Y. Iwata *et al.*, Phys, Rev. ST Accel. Beams, vol. 15, p. 044701, 2012.

[5] Y. Iwata *et al*., IEEE Transactions on Applied Superconductivity, vol. 24, no. 3, p. 4400505, 2014.

[6] Y. Iwata *et al*., Nucl. Instr. and Meth. in Phys. Res. A , vol. 834, pp.71-80, 2016.

[7] S. Takayama, T. Orikasa, Y. Nagamoto, T. Yoshiyuki, in *Proc. 14th Annual Meeting of Particle Accelerator Society of Japan*, 2017, paper WEP129, pp. 1235.

[8] Y. Iwata, T. Shirai, and K. Noda, IEEE Transactions on Applied Superconductivity, vol. 26, no. 4, p. 4400104, 2016.