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Recent progress of a superconducting rotating-gantry for carbon-ion radiotherapy

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ABSTRACT

A superconducting rotating-gantry for carbon-ion radiotherapy 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°, and is further capable of performing three-dimensional raster-scanning irradiation. By using combined-function superconducting magnets, we could design a compact rotating gantry for carbon-ion radiotherapy. Construction of the gantry structure began since early 2014, and the installation of the entire gantry system to the Heavy Ion Medical Accelerator in Chiba (HIMAC) complex was completed by the end of September, 2015. Beam tuning subsequently began since October, 2015, and carbon ions, as accelerated by the HIMAC upper synchrotron, having kinetic energies of between $E = 430$–48 MeV/u were successfully transported with the rotating gantry to the isocenter. The size and shape of the beam spots at the isocenter is being tuned over various combinations of the beam energies and the gantry angle. We will present the recent progress as well as the current status of the superconducting rotating-gantry.

1. Introduction

Carbon-ion radiotherapy (CIRT) using the Heavy-Ion Medical Accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS) has been carried out since June, 1994 [1]. The successful results of cancer treatments, made for more than 10000 patients, have led us to construct a new treatment facility, which equipped with three treatment rooms including a rotating gantry, as presented in Fig. 1 [2]. In particle radiotherapy, a rotating gantry is an attractive instrument, and is commonly used for proton radiotherapy, because treatment beams can be directed to a target from any of medically desirable directions, while a patient is kept in the best possible position. However, it is very difficult to construct a rotating gantry for CIRT, because the magnetic rigidity of carbon ions having an energy of 430 MeV/u is roughly three times higher than that for proton ions having an energy of 250 MeV/u, and therefore the size and weight of the entire gantry structure become considerably larger.

To downsize the rotating gantry for CIRT, we developed a compact superconducting rotating-gantry [3]. This rotating gantry can deliver carbon ions having kinetic energies of between $E = 430$–48 MeV/u to the isocenter over an irradiation angles of ±180°, having the capability of performing three-dimensional raster-scanning irradiation. By using combined-function superconducting magnets, we could design the compact rotating gantry. The construction of the rotating gantry was completed by the end of September 2015, and beam commissioning is in progress. In this report, a present status of the compact rotating-gantry is presented.

2. Construction and tests of the superconducting magnets

The beam-transport line of the rotating-gantry consists of 10 superconducting magnets (BM01-BM10), a pair of scanning magnets (SCM-X and SCM-Y), and three pairs of steering magnets (ST01-ST03) as well as beam-profile monitors (PRN01-PRN03) [3]. Combined-function superconducting magnets are employed for BM01-BM06 and BM09-BM10, and can provide both dipole and quadrupole fields; however, BM07 and BM08 are pure dipole magnets. A picture of the superconducting magnet assembly for BM01-BM03 and a schematic drawing of the superconducting coil are presented in Figs. 2 and 3, respectively. For the combined-

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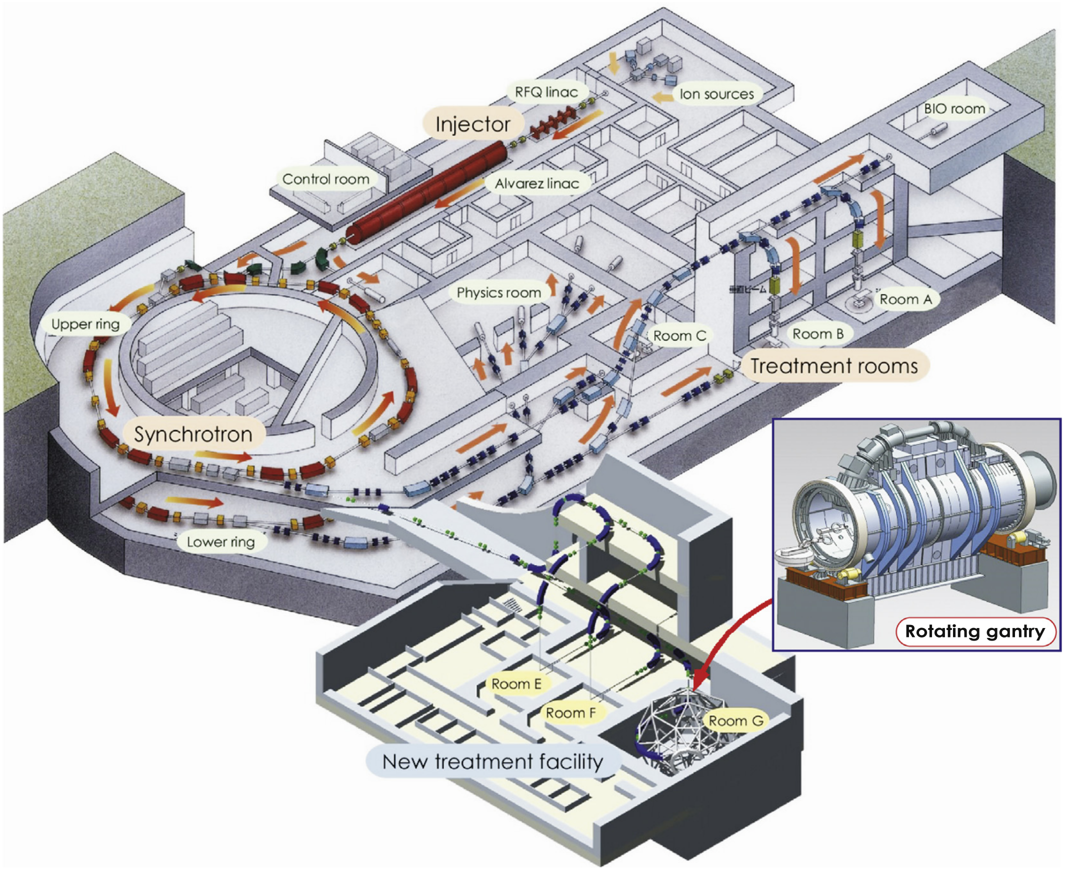

Fig. 1. Schematic drawing of the HIMAC complex as well as the new treatment facility.

Fig. 2. Picture of the superconducting-magnet assembly for BM01-BM03.

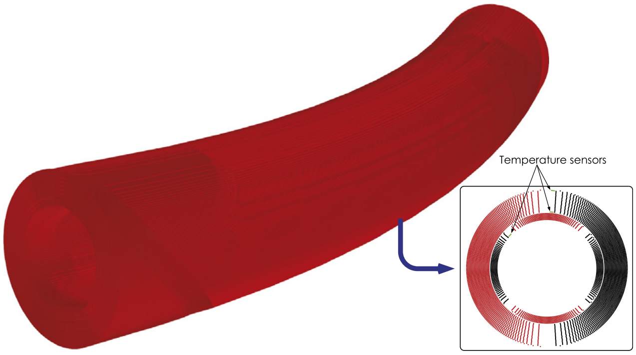

Fig. 3. Schematic drawing of the curved superconducting coil for BM02-BM05. Cross-sectional view of the coil is also presented.

function superconducting magnets, the dipole and quadrupole coils are electrically isolated in the magnet, and connected to independent power supplies, so that each field component can be independently excited. For cooling of the superconducting coils, compact 4 K Gifford–McMahon cryocoolers, RDK-415D, as produced by Sumitomo Heavy Industries, Ltd., are employed, so that no liquid helium is necessary; each of the superconducting magnet is equipped with three cryocoolers for BM01-BM06 and four cryocoolers for BM07-BM10.

After construction of the superconducting magnets, detailed magnetic-field measurements were performed for all of the 10 superconducting magnets. First, central magnetic field was precisely measured by using NMR probes. The NMR probe was installed and aligned in the middle of the magnet, and coil current of between $I = 0$–140 A for a small aperture group (BM01-BM06) and $I = 0$–240 A for a large aperture group (BM07-BM10) was applied for the dipole coil. The measured magnetic fields, B, for BM02 and BM10 are shown by the filled diamonds and triangles in Fig. 4, respectively. Further, the magnetic field as divided by the coil current, B/I, for BM10 is also presented by the filled circles in Fig. 4. We found that the magnetic field begins to saturate at $I \geqslant 180$ A; however, an effect of the saturation should be less than 0.3%. For comparison, a calculated result of B/I using the Opera-3d code is also plotted by the dashed line in the figure. The measured B/I curve around the maximum current appreciably differs with the calculated curve; this discrepancy might be attributed to a

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