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Beam commissioning 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 gantry can transport carbon ions having kinetic energies of between $E=430$ and 48 MeV/u to an isocenter over an angle of $\pm 180°$, and is further capable of performing three-dimensional raster-scanning irradiation. Construction of the entire rotating-gantry system was completed by the end of September 2015. Prior to beam commissioning, phase-space distributions of extracted carbon beams from the synchrotron were deduced by using an empirical method. In this method, phase-space distributions at the extraction channel of the synchrotron were modeled with 8 parameters, and the best parameters were determined so as to minimize a difference between the calculated and measured beam profiles by using a simplex method. Based on the phase-space distributions, beam optics through the beam-transport lines as well as the rotating gantry were designed. Since horizontal and vertical beam emittances, as extracted slowly from the synchrotron, generally differ with each other, a horizontal–vertical beam coupling would occur when the gantry rotates. Thus, the size and shape of beam spots at the isocenter should vary depending on the gantry angle. To compensate for the difference in the emittances, we employed a method to utilize multiple Coulomb scattering of the beam particles by a thin scatterer. Having compensated for the emittances and designed beam optics through the rotating gantry, beam commissioning over various combinations of gantry angles and beam energies was performed. By finely tuning the superconducting quadrupoles of the rotating gantry, we could successfully obtain the designed beam quality, which satisfies the requirements of scanning irradiation.

1. Introduction

In recent years, the application of high-energy particle accelerators to cancer therapy has attracted much attention, and a number of medical particle accelerators have been constructed around the world. In particle radiotherapy, proton or carbon ions are accelerated up to a few hundreds of MeV/u in order to obtain a maximum range of ~30 cm in water. Accelerated ions are then transported to treatment rooms through beam-transport lines as well as a rotating gantry, and are finally directed to a tumor in a patient.

A rotating gantry is a large rotatable structure, equipped beam-transport devices, such as magnets and beam diagnostic devices, and is a very attractive tool for particle 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. Since treatment can be made without tilting a patient, unexpected organ movement should be minimized, and the patient load must be reduced. Further, irradiations from multiple beam directions enable us to conform the dose distribution closely to the tumor shape while avoiding sensitive organs.

A rotating gantry was firstly employed for proton radiotherapy (PRT) at Loma Linda University [1,2]. Nowadays, rotating gantries for PRT are commercially available and are widely used; most modern proton facilities equip multiple rotating-gantry rooms. However, it is very difficult to construct a rotating gantry for carbon-ion radiotherapy (CIRT), because the magnetic rigidity of the treatment beams, as required for CIRT, is roughly three-times higher than that for PRT, and hence the size and weight of the magnets as well as a gantry structure would become considerably larger. The world's first rotating gantry for CIRT was constructed at

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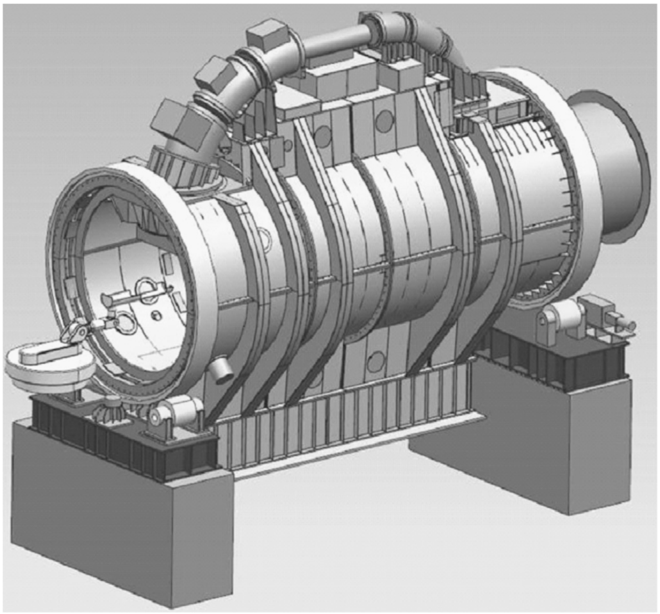

Fig. 1. Schematic drawing of the superconducting rotating-gantry for CIRT.

Heidelberg, Germany [3], and has been used in treatment operations since October, 2012; however, the total weight and length of their gantry are approximately 600 tons and 19 m, respectively.

To downsize a rotating gantry, we developed a superconducting rotating-gantry for CIRT at National Institute of Radiological Sciences (NIRS), Japan [4]. By using superconducting magnets, the total weight of the rotating structure is reduced to be approximately 300 tons. This rotating gantry can transport carbon ions having kinetic energies of between 430 and 48 MeV/u, and is further capable of performing three-dimensional raster-scanning irradiation. The construction as well as an installation of the superconducting rotating-gantry was completed by the end of September 2015, and beam commissioning has subsequently been carried out since October 2015. In this paper, the present status of beam commissioning for the superconducting rotation gantry is reported.

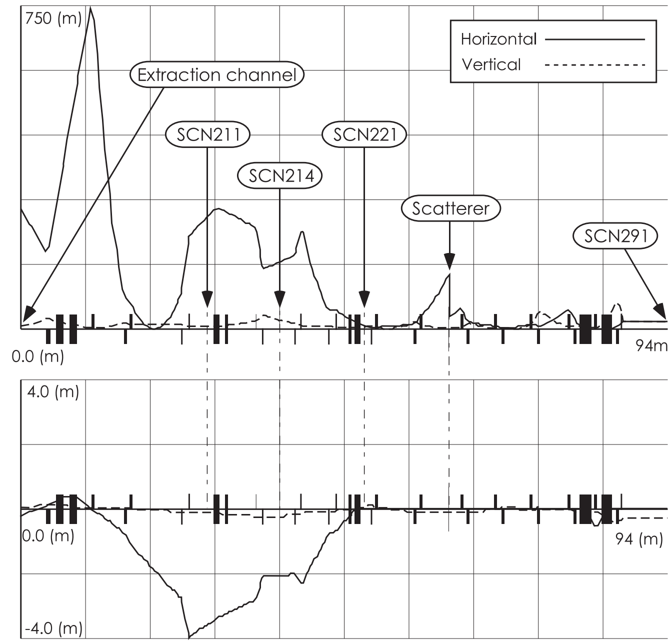

Fig. 3. Beta (upper) and dispersion (lower) functions between the extraction channel of the synchrotron and the entrance of the rotating gantry (SCN291). Locations of the three profile monitors (SCN211, SCN214 and SCN221) as well as the scatterer are indicated.

2. Design of a superconducting rotating-gantry

A schematic drawing of the superconducting rotating-gantry is presented in Fig. 1. This isocentric rotating gantry has a large cylindrical structure with two large rings having an outer diameter of 6.5 m at both ends; the entire structure is mounted on two pairs of turning rollers, so as to rotate all beam-transport devices on the rotating gantry along the central axis over an angle of $\pm 180°$. The length between the two end-rings is 14 m, and the beam orbit radius is 5.45 m. Fig. 2 shows the layout of the superconducting rotating-gantry. The beam-transport devices consist 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 (SCN291–SCN293).

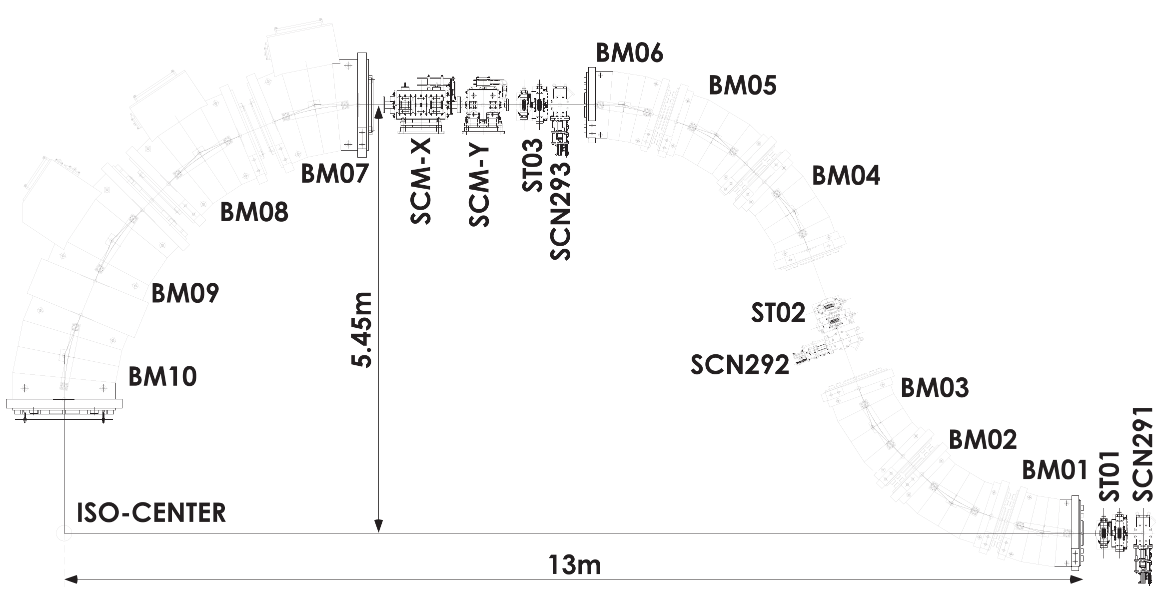

Fig. 2. Layout of the superconducting rotating-gantry. The gantry consists of 10 superconducting magnets (BM01–BM10), a pair of the scanning magnets (SCM-X and SCM-Y), and three pairs of beam profile-monitor (STR01–STR03) as well as steering magnets (SCN291–SCN293).