

## DESIGN OF SUPERCONDUCTING ROTATING-GANTRY FOR HEAVY-ION THERAPY

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### Abstract

An isocentric superconducting rotating-gantry for heavy-ion therapy is being designed. This rotating gantry can transport heavy ions having 430 MeV/u to an isocenter with irradiation angles over 0-360 degrees, and is further capable of performing the fast raster-scanning irradiation. For the magnets, combined-function superconducting-magnets were employed. The use of these superconducting magnets allowed us to design a compact gantry, while keeping a large scan size at the isocenter. The superconducting magnets were designed by using a 3D electromagnetic-field solver, the OPERA-3D code. To verify the design of the magnets, beam tracking simulations were performed. Consequently, we found that calculated beam profiles at the isocenter agreed well with those, designed by the beam optics, proving the validity of our design.

### INTRODUCTION

Tumor therapy using energetic carbon ions, as provided by the HIMAC, has been performed since June 1994, and approximately 7000 patients were treated until now. With the successful clinical results over more than 17 years, we constructed a new treatment facility[1]. This treatment

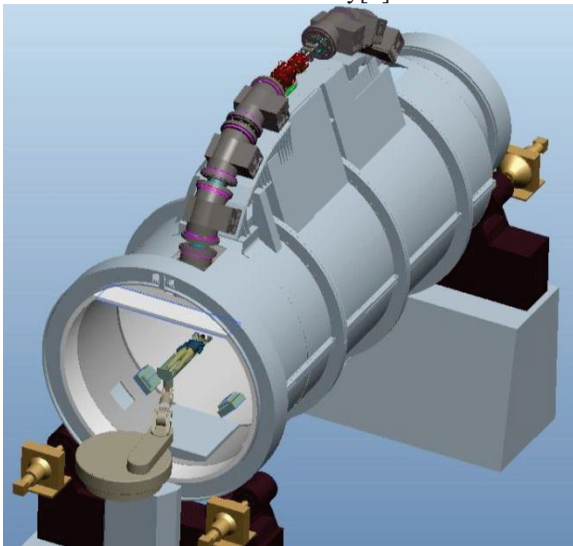


Figure 1: 3D image of the superconducting rotating gantry.

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facility has three treatment rooms. Two of them have both horizontal and vertical fixed-irradiation-ports, and they were constructed and commissioned. The other treatment room is reserved for a rotating-gantry-port.

The rotating gantry is an attractive tool in the ion radiotherapy, because a treatment beam can be directed to a target from any of medically desirable directions, while a patient is kept in the best 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, and hence the requirements of having the rotating gantry would increase for hospital-based therapy complexes, which will be constructed in near future.

We are designing the superconducting rotating-gantry for heavy-ion therapy. To make the structure compact, we employed combined-function superconducting-magnets for the gantry beam-line. In this paper, the design of the superconducting rotating-gantry, including details of their superconducting magnets, will be presented.

### LAYOUT OF ROTATING GANTRY

A 3D image of the isocentric superconducting rotating-gantry for the new treatment facility is presented in Figure 1. This rotating gantry has the cylindrical structure with the two large rings on the both ends. The end rings support the entire structure, and are placed on the turning roller to rotate along the central axis over 0-360 degrees. Figure 2 shows a layout of the beam line in the rotating gantry. The beam line consisted of ten superconducting combined-function sector-bending-magnets (BM1-10), a pair of scanning magnets (SCM-X and SCM-Y), and three pairs of steering magnets and profile monitors (STR1-3 and PRN1-3).

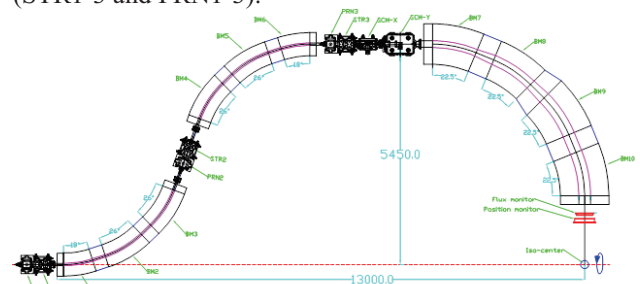


Figure 2: Layout of the superconducting rotating gantry.

Table 1: Summary of Major Parameters for Superconducting Magnets in the Gantry Beam-Line

Parameter	Symbol	BM1/BM6	BM2-5	BM7	BM8	BM9/BM10	Units
Bending angle	$\theta$	18	26	22.5	22.5	22.5	deg
Bending radius	$\rho$	2.3	2.3	2.8	2.8	2.8	m
Bore radius	$R_0$	30	30	85	120	145	mm
Reference radius or Effective area	$r_0$ or $A_0$	20	20	$\pm 60 \times 60$	$\pm 80 \times 80$	$\pm 100 \times 100$	mm or $\text{mm}^2$
Maximum field	$B_{\text{max}}$	2.88	2.88	2.37	2.37	2.37	T
Maximum field gradient	$G_{\text{max}}$	9.0	9.0	—	—	1.3	T/m
Uniformity (dipole)	$\Delta B_L / B_L$	$\pm 1 \times 10^{-4}$					—
Uniformity (quadrupole)	$\Delta G_L / G_L$	$\pm 1 \times 10^{-3}$					—

This isocentric rotating-gantry is capable of the fast raster-scanning irradiation[2]. According to the design of beam optics for the rotating gantry, the maximum scan size at the isocenter is calculated to be as large as 200 mm square. Further details of the beam optics can be found in ref. [3].

### SUPERCONDUCTING MAGNETS

Based on the design of the beam optics, specification of the superconducting magnets was determined. According to their apertures, the magnets are categorized into five kinds, as summarized in Table 1. The small-aperture magnets are BM1-6, which are located upstream of the

scanning magnets. The bore radius of the small-aperture magnets is 30 mm. However, the large aperture magnets are BM7-10; they are located downstream of the scanning magnets. Since scanned beams would traverse BM7-10, their bore radii range between 85 and 145 mm, depending of the magnet location.

All the magnets have the surface-winding coil structure. The superconducting coils were designed by using a 3D electromagnetic field-solver, the OPERA-3D code. In the code, the superconducting coils, having typically a few thousand turns per pole, were precisely modelled. A calculated magnetic field for BM9 or BM10 is given in Figure 3(a). To evaluate the field quality, mapping of the

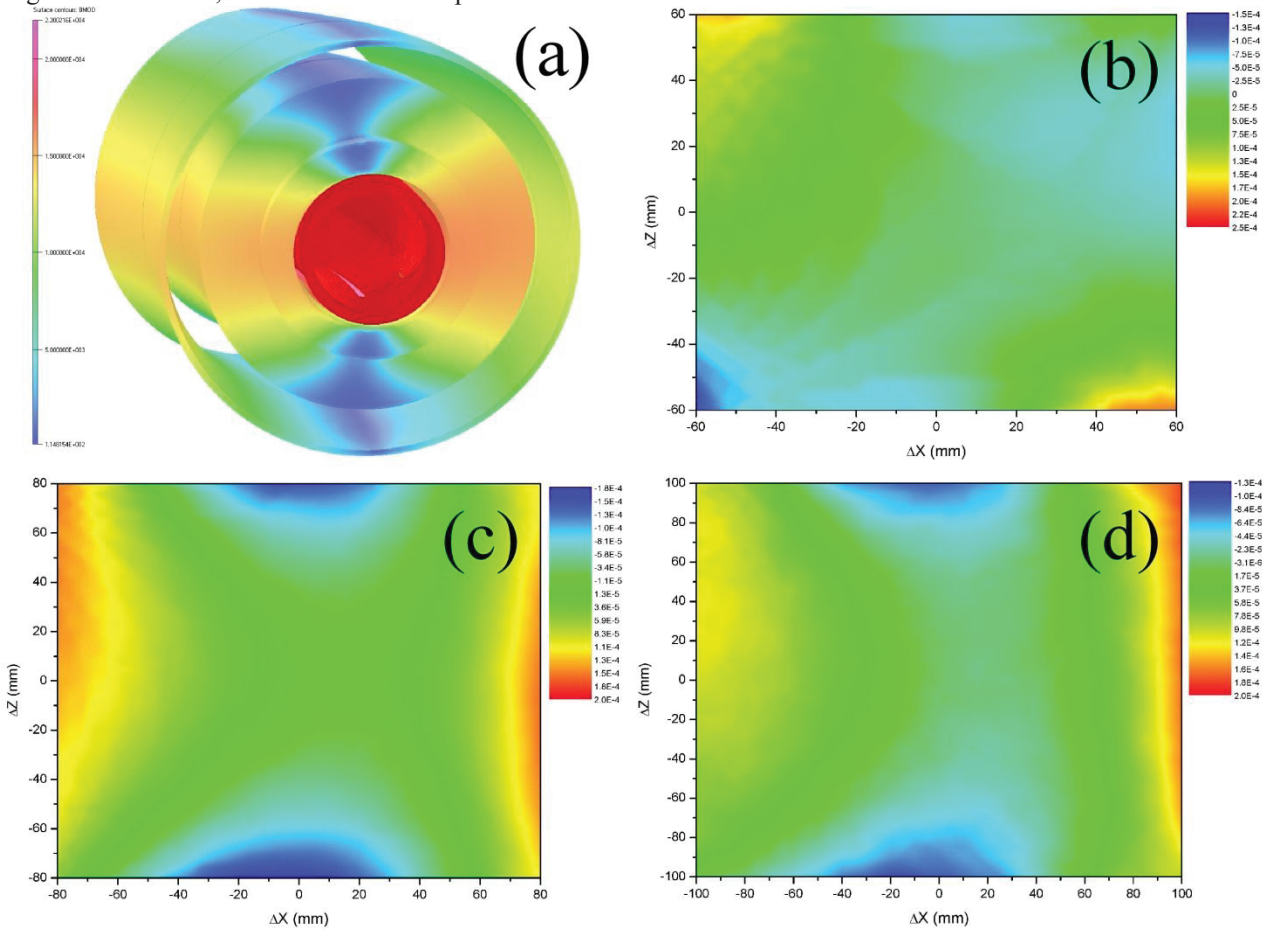


Figure 3: (a) 3D image of magnetic-flux density for the BM9 or BM10, as calculated by the 3D field-solver, OPERA-3D. Uniformity of the BL products,  $\Delta B_z L / B_z L$ , as shifted horizontally by  $\Delta X$  and vertically by  $\Delta Z$  from the central beam trajectory, for dipole field of (b) BM7, (c) BM8, and (d) BM9 or 10.

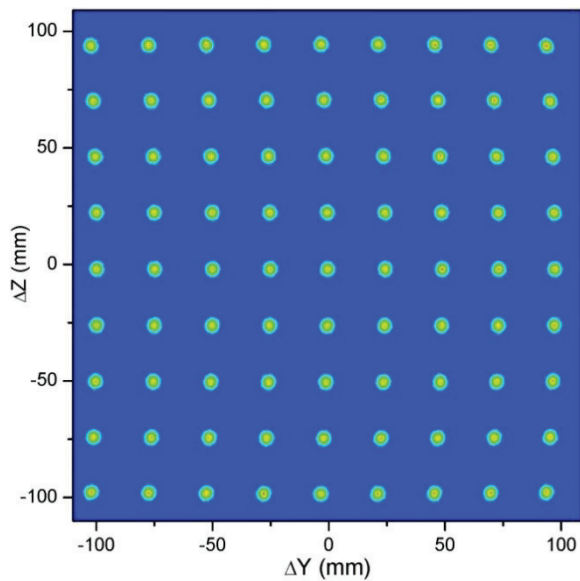


Figure 4: Beam profile at the isocenter, as calculated with tracking simulations. The beam energy is 430 MeV/u.

vertical magnetic-flux density, as integrated along a beam trajectory,  $B_z L$ , was performed. The uniformity of BL product,  $\Delta B_z L / B_z L$ , for various beam trajectories, as shifted horizontally by  $\Delta X$  and vertically by  $\Delta Z$  from the central beam trajectory, were calculated for BM7-10, as shown in Fig. 3 (b), (c), and (d). The corresponding beam energy for this field excitation is 430 MeV/u. We see that the observed uniformity would mostly satisfy the required specification, as prescribed in Table 1. Similar analyses were made for the dipole coils of BM1-6 as well as the quadrupole coils of BM1-6 and BM9/10.

### BEAM TRACKING SIMULATIONS

To evaluate the field quality, and concurrently to confirm the design of the superconducting magnets,

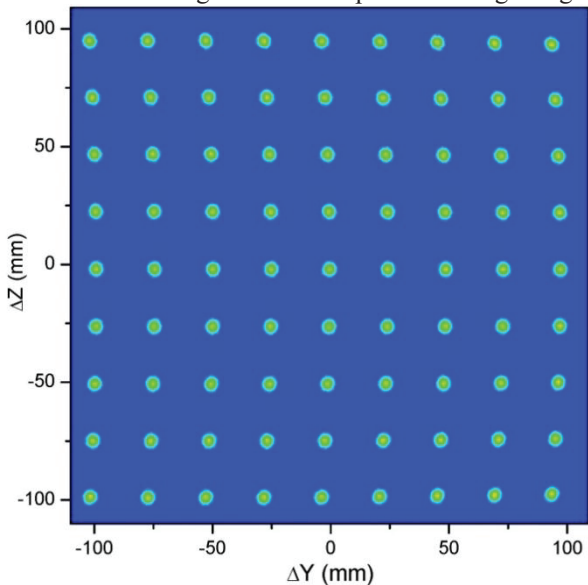


Figure 5: Beam profile at the isocenter, as calculated with tracking simulations. The beam energy is 80 MeV/u.

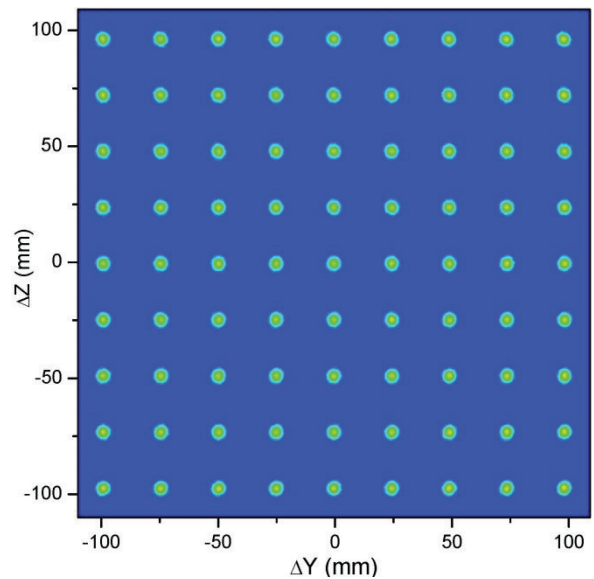


Figure 6: A similar plot as Figure 4, but position of each beam spots were corrected by adjusting kick angles of the scanning magnets.

beam-tracking simulations were performed. Since the quality of scanned beam is quite important, the simulations were made from the scanning magnets to the isocenter. In a simulation code, 3D maps of the magnetic field for BM7-10, as extracted by the OPERA-3D code, were used. Trajectories of beam particles were calculated by integrating an equation of motion with the 4th order Runge-Kutta method. The calculated beam profiles at the isocenter for the beam energies of 430 and 80 MeV/u are shown in Figure 4 and Figure 5, respectively. We found that the size and shape of the beam spot agreed well with the design of the beam optics, although we see displacement in spot positions. This displacement can be corrected by adjusting kick angles of the scanning magnets, as shown by Figure 6.

### SUMMARY AND FUTURE PLAN

The superconducting rotating-gantry for the heavy-ion therapy is being designed. Having employed the combined-function superconducting magnets, we could design a compact gantry. The 3D electromagnetic calculations for all the magnets were performed, and we obtained the satisfactory field uniformity. Furthermore, the design of the magnets was verified by performing the beam tracking simulations. Construction of the two superconducting magnets, BM2 and BM10, were completed, and they are being tested. We will construct the rest of the superconducting magnets within two years.

### REFERENCES

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