DESIGN STUDY OF SECTOR MAGNET FOR THE RIKEN SUPERCONDUCTING RING CYCLOTRON (I)

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Abstract

A 6-sector superconducting ring cyclotron is designed for the next project as the second of two booster cyclotrons following the existing ring cyclotron. Superconducting main coils as well as superconducting trim coils for rough fitting to isochronous fields are adopted for the sector magnet. Isochronous field distributions and betatron tunes are calculated.

1 INTRODUCTION

An "RI beam factory" has been proposed as the next facility-expanding project of the RIKEN Accelerator Research Facility (RARF)[1]. The "RI beam factory" aims at production and acceleration of radioactive isotope beams covering the whole mass region. It requires the energy of ion beam to be higher than 100 MeV/nucleon. To accomplish this requirement, a superconducting ring cyclotron was adopted as a post-accelerator of the existing RIKEN Ring Cyclotron (RRC). However, we have recently changed the design so that the superconducting ring cyclotron is divided into two stage: a 4-sector superconducting ring cyclotron (SRC-4) for the first stage and a 6-sector superconducting ring cyclotron (SRC-6) for the second stage[2].

The SRC-6 is expected to boost the energy of ion beam up to 400 MeV/nucleon for light heavy ions like carbon ions and 150 MeV/nucleon for very heavy ions like uranium ions. The sector magnet of the SRC-6 have to be flexible enough to generate isochronous fields in a wide range of energies and for various q/A's. In this paper we describe the feature of the sector magnet together with field calculation and orbit analysis.

2 GENERAL DESCRIPTION

The maximum acceleration energy of the SRC-6 was determined by experimental requirements. The maximum energies for typical ions are summarized in table 1. Beam currents are expected to be more than 100 pμA for 400 MeV/nucleon light heavy ions such as carbon and oxygen ions and about 0.2 pμA for 150 MeV/nucleon uranium ions.

Table 1. Required maximum energy of the SRC.

$^{238}U^{58+}$	150 MeV/nucleon
$^{84}Kr^{30+}$	300 MeV/nucleon
$^{16}O^{7+}$	400 MeV/nucleon

To accomplish this requirement, total velocity gain factor for the new cyclotrons becomes 2.26. The velocity gain factors of the SRC-4 and the SRC-6 are selected to be 1.50 and 1.506, respectively.

Figure 1 shows a schematic drawing of the SRC-6. Diameter and height of the SRC-6 is 18 m and 5.4 m, respectively. The sector angle is 25 deg. Weight of each sector magnet is about 680 tons. Three double-gap cavities are placed at valley regions. RF frequency range is from 18 MHz to 38 MHz. Radial injection is adopted. Main parameters of the SRC-6 are listed in table 2.

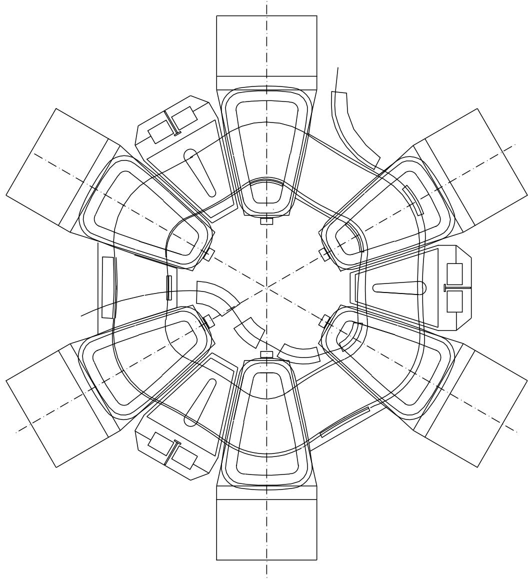

Figure 1. Schematic drawing of the SRC-6

Table 2 Main parameters of the SRC-6.

Number of sectors	6
Harmonics	6
Average radius: injection	3.56 m
extraction	5.36 m
Number of cavities	3
RF frequency	18-38 MHz

Isochronous field distributions for typical ions are shown in Fig.2. Difference of average magnetic fields between at the injection radius and at the extraction radius is 0.32 T for 400 MeV/nucleon ions and 0.07 T for 100 MeV/nucleon ions. According to the calculation of the magnetic field in the sector magnet, the difference on the sector axis becomes about 0.55 T. Therefore main coils as well as trim coils for coarse fitting have to be superconducting.

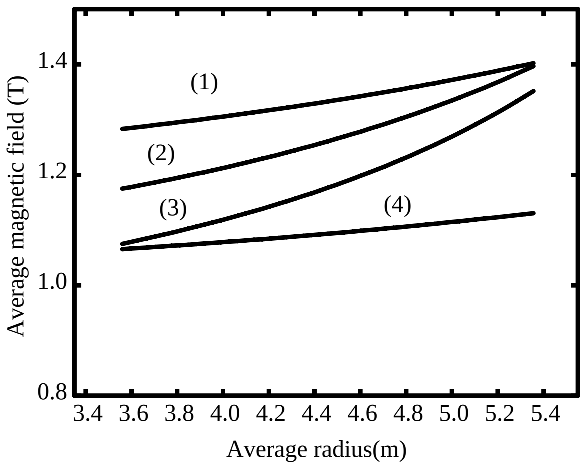

Figure 2. Isochronous fields for typical ions for
(1) 150 MeV/nucleon $^{238}U^{58+}$,
(2) 300 MeV/nucleon $^{84}Kr^{30+}$,
(3) 400 MeV/nucleon $^{16}O^{7+}$ and
(4) 100 MeV/nucleon $^{238}U^{58+}$.

3 STRUCTURE

3.1 General

The sector magnet is fundamentally of a C-type structure. It is advantageous to be equipped with a return yoke at the center side of the cyclotron, too. But complexity of the center region cannot afford to have a return yoke there.

In order to support strong magnetic force on the main coil, a cold-pole system is adopted. The coil vessel is tightly fixed to the pole; rigidity of the pole supports the force. Magnetic fields and related characteristics are calculated by the three-dimensional code TOSCA[3]. Figure 3 shows an example of the modeled magnet for TOSCA.

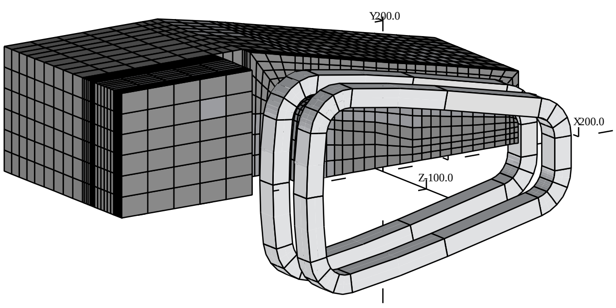

Figure 3. Example of modeled magnet for TOSCA.

3.2 Pole and Yoke

The pole shape is designed to have proper tune values for ions to be accelerated. Edge of the pole has a straight line from the injection side to the middle of the sector with the angle of 25 deg. Then the pole shape has a curvature of approximately 16-meters radius toward the extraction side.

Magnetic field in a valley region depends on the size and shape of the yoke. The maximum field in the valley is decided for 400 MeV/nucleon acceleration. The yoke is designed in order to have enough vertical focusing force in that case.

3.3 Superconducting Main Coil

Size of the superconducting main coil is 250 mm (width) x 300 mm (height). Maximum current density of the main coil is designed to be 40 A/mm^2. Thus the maximum excitation current is 6 MA for one sector magnet. The superconducting main coil is installed in the stainless steel Helium vessel which is fixed to the cold pole. Distance between the surface of the pole and that of the main coil is 80 mm.

3.3 Superconducting Trim Coil

Superconducting trim coils are placed on the inside surface of the cold pole. Conceptual sketch of the superconducting trim coils are shown in Fig. 3. The coils are not wound along beam orbits but just straight in the beam region. These coils are controlled by three independent currents. Each coil is placed with one layer whose thickness is 2 cm. Configuration will be optimized by detailed analysis.

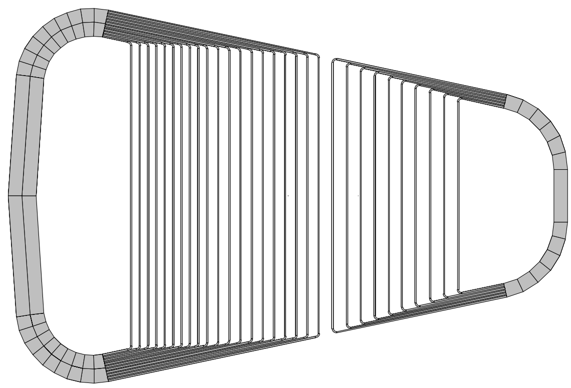

Figure 4. Conceptual sketch of superconducting trim coils. Three sets of trim coils are wound in three radial regions.

4 ISOCHRONOUS FIELD AND TUNE

Equilibrium orbits and betatron tunes were calculated by the computer program that had been originally developed for the RRC. Results of the field distributions by TOSCA were used in the orbit calculations.

Because of saturation of the iron pole, the field distribution is largely affected by coils' configuration. Examples of field distributions are shown in Fig.5 and Fig. 6. In the valley region, negative field is created. This field brings large flutter and sharp fringing field. Therefore, vertical focusing force is larger than that in a normal conducting ring cyclotron.

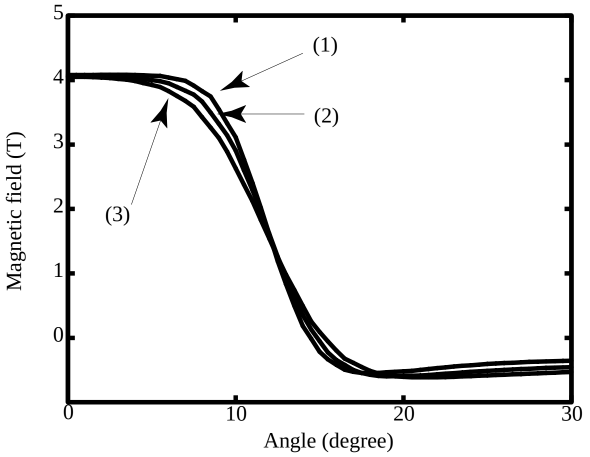

Figure 5. Field distribution along the azimuthal direction at (1) r = 3.58 m, (2) r = 4.3 m and (3) r = 5.1 m for 150 MeV/nucleon $^{238}U^{58+}$ ions.

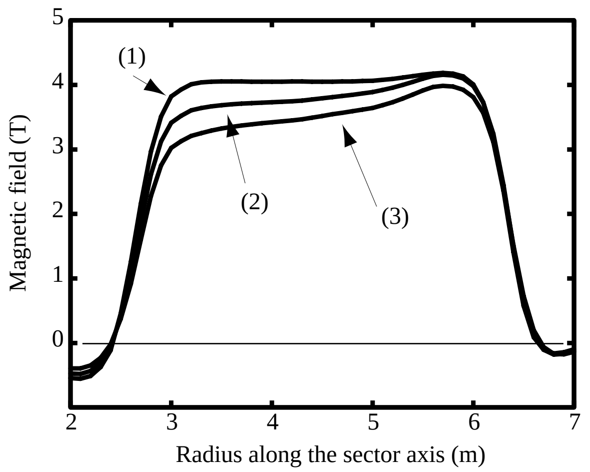

Figure 6. Field distribution along the sector axis for (1) 150 MeV/ nucleon $^{238}U^{58+}$ ions, (2) 300 MeV/nucleon $^{84}Kr^{30+}$ and (3) 400 MeV/nucleon $^{16}O^{7+}$.

Using three sets of superconducting trim coils, it is possible to adjust various distributions of isochronous fields within ±0.02 T. By the optimization of the configuration, it is expected to be less than ±0.01 T. Further fine adjustment will be done with trim coils of room temperature.

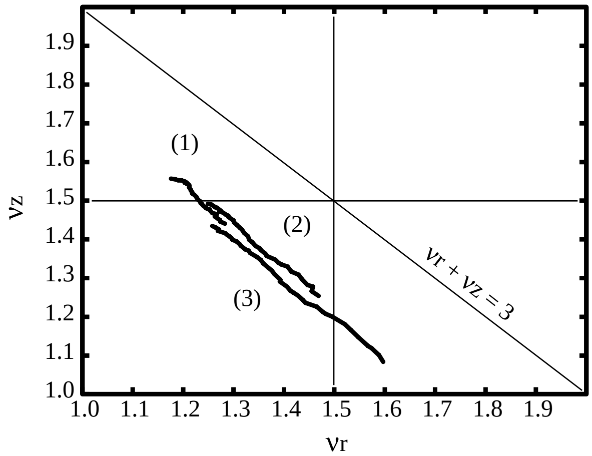

Figure 7. Tune values for typical ions for (1) 150 MeV/ nucleon $^{238}U^{58+}$, (2) 300 MeV/nucleon $^{84}Kr^{30+}$ and (3) 400 MeV/nucleon $^{16}O^{7+}$.

In the case of high energy acceleration, vertical tune ν_Z decreases as the energy increases. The sector angle was selected so that vertical tune values never across $\nu_Z = 1.0$. Smaller sector angle causes larger vertical focusing force. From the viewpoint of minimizing the maximum field, a large sector angle is preferable. Therefore, the sector shape has the curvature at the extraction side of it. This curvature increases ν_Z value by 0.1 at the extraction radius. Figure 7 shows typical tune values calculated for the sector magnet thus designed.

5 SUMMARY

Design study of the sector magnet for the 6-sector superconducting ring cyclotron for the proposed RIKEN RI beam factory has been carried out. Until now, it has turned out that isochronous fields for various ions can be generated by using superconducting main coils and superconducting trim coils within the accuracy of ±0.01 T. Detailed design studies and further optimization are under way.

REFERENCES

[1] Y.Yano et al.,"Present Status and Future Plan of RIKEN Accelerator Research Facility," Proc. EPAC 94, vol. 1, pp. 515-517

[2] Y.Yano et al.,"RIKEN RI Beam Factory Project," in this conference.

[3] Vector Fields Limited, Oxford, England