PA35

Design Study of Sector Magnet for
the RIKEN Superconducting Ring Cyclotron (I)

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Abstract

Design study of the sector magnets for a superconducting ring cyclotron, which is adopted as a post-accelerator of the existing ring cyclotron, is carried out. Superconducting main coils as well as super-conducting trim coils for rough fitting to isochronous fields are adopted for the sector magnets. Isochronous field distributions and betatron tunes are calculated.

1. Introduction

An "RI beam factory" has been proposed as a 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 meet this requirement, we have adopted a superconducting ring cyclotron (SRC) as a post-accelerator of the existing RIKEN Ring Cyclotron (RRC).

The SRC is expected to boost the energy of ion beam from the RRC 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 SRC have to be flexible enough to generate isochronous fields in a wide range of energies and for various q/A's. In this report 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 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. The minimum acceleration energy of the SRC is about 60 MeV/nucleon for very heavy ions.

Table 1 Required maximum energy of the SRC.

$^{84}Kr^{36+}$	300 MeV/nucleon
$^{12}C^{6+}$	400 MeV/nucleon
$^{238}U^{80+}$	150 MeV/nucleon

Figure 1 shows a schematic drawing of the SRC. The number of sectors for the SRC has been chosen to be 6. Diameter of the SRC is 20 m. The pole length is more than 3 m, the sector angle is around 23 deg., and the weight of one sector magnet is nearly 900 tons. From the matching condition with the RRC, the injection radius of the SRC was selected to be 2/3 of the extraction radius of the RRC; the SRC operates with a harmonics of 6, while the RRC with a harmonics of 9. Velocity gain factor is 2.26. RF frequency range is from 18 to 38 MHz. Main parameters of the SRC are listed in table 2.
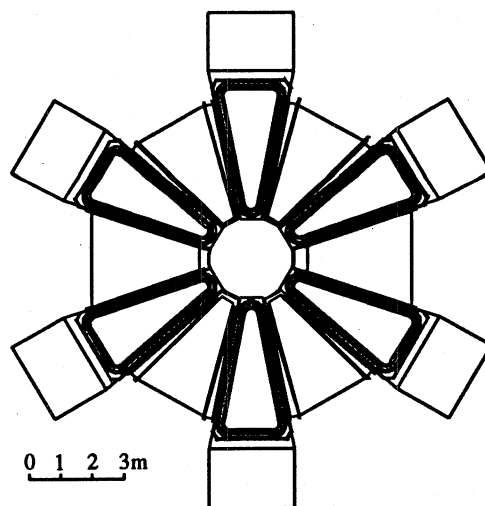

Fig.1 Schematic drawing of the SRC.

Table 2 Main parameters of the SRC.

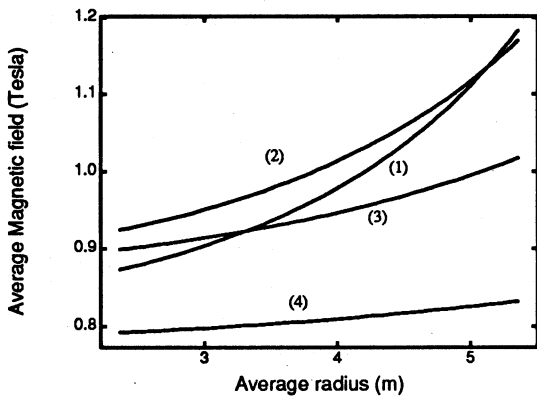| Number of sectors		6
Harmonics		6
Average radii	injection	2.37 m
	extraction	5.36 m
RF Frequency		18 - 38 MHz

Fig.2 Isochronous fields for typical ions for
(1) 400 MeV/nucleon $^{12}C^{6+}$,
(2) 300 MeV/nucleon $^{84}Kr^{36+}$,
(3) 150 MeV/nucleon $^{238}U^{80+}$ and
(4) 58 MeV/nucleon, $q/A = 0.25$.

Isochronous field distributions for typical ions are shown in Fig.2. The maximum required field in the sector magnet becomes nearly 4 T. Field difference between at the injection radius and at the extraction radius on the sector axis is 0.7 T for 400 MeV/nucleon ions and 0.1 T for below 100 MeV/nucleon ions. Therefore both main coils as well as trim coils for coarse fitting have to be superconducting.

3. Sector Magnet and Field Calculation

Magnetic fields were calculated by the three-dimensional code TOSCA[2]. For the sector magnet only a quarter of it was modeled because of its symmetry. For the coils a complete set of them in only one sector was taken into account in the calculation. An example of modeled magnet for TOSCA is shown in Fig.3. Strictly speaking, TOSCA requires all conductors of the system to be taken into account. But owing to appropriate selection of reduced potential region, good
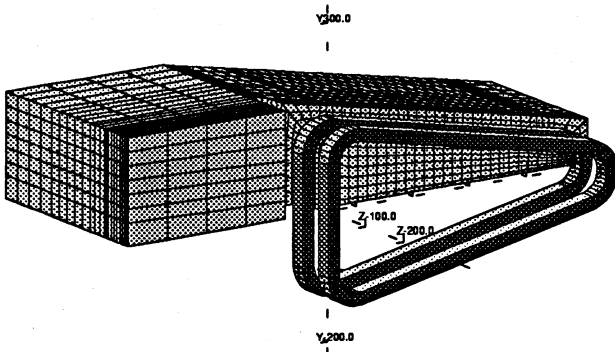

Fig.3 Example of modeled magnet for TOSCA.
Iron part and main coils are shown.

agreement of the magnetic field on the median plane can be obtained for both the six-symmetry system and the system with only one set. This method shortened the calculation time to be less than 25% of that of the six-symmetry system.

One important point in the design of the sector magnet is to optimize its geometry so that the magnetic forces acted on the main coil can be as small as possible. The expanding force acted on the radial part of the main coil reaches the oder of several hundreds tons. One way to support such a main coil is to put the pole in the cryostat and to fix the main coil directly to the pole (cold-pole method). Detailed study has been carried out in ref. 3. In the case of the cold-pole magnet with a sector angle of 23 deg., the excitation current is 2.9 MA/sector.

Conceptual sketch of the superconducting trim coils is shown in Fig.4. If the trim coils can be controlled by many independent currents, fields can be generated flexibly and precisely. But cryogenic system requires the minimum number of current leads to reduce heat load. Three sets of superconducting trim coils thus bring a realistic solution. Maximum excitation current of one set of trim coils is estimated to be 240 kA.
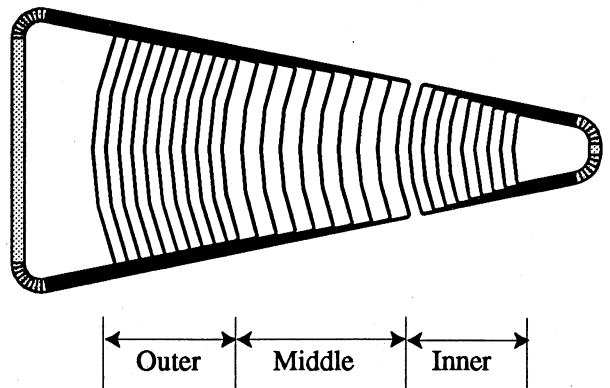

Fig.4 Conceptual sketch of superconducting trim coils.
Three sets of trim coils are wound in three radial regions.

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 region of the valley, negative field is
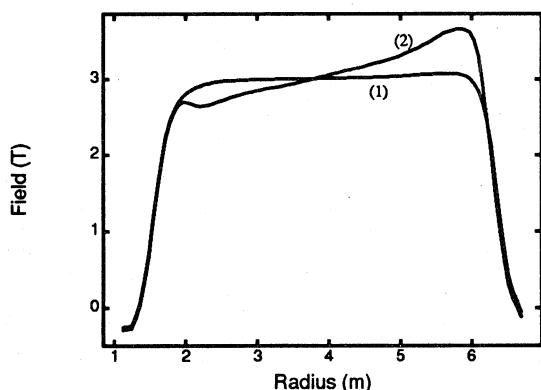
Fig. 5 Field distributions along the sector axis produced with (1) Main coil and (2) Main coil + Trim coil for 400 MeV/nucleon $^{12}C^{6+}$ ions.
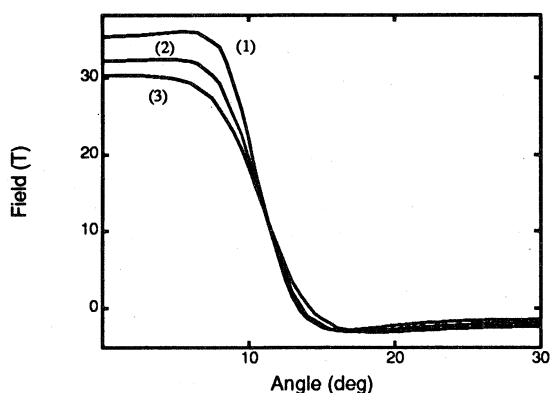

Fig. 6. Field distribution along the azimuthal direction at (1) r = 5.5 m , (2) r = 4.7 m and (3) r = 3.9 m.

created. This field brings large flutter and sharp fringing field. Therefore, vertical focusing force is larger than that in a normal conducting ring cyclotron.

Using three sets of superconducting trim coils, it was 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.

In the case of high energy acceleration, vertical tune v_z decreases as the energy increases. The sector angle was selected so that vertical tune value never across v_z = 1.0. Smaller sector angle causes larger vertical focusing force. But from the viewpoint of minimizing the maximum field, large sector angle is
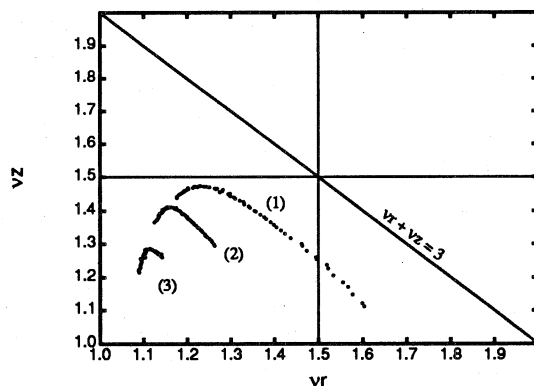

Fig.7 Tune values at a sector angle of 23.0 deg. for
(1) 400 MeV/nucleon $^{12}C^{6+}$,
(2) 150 MeV/nucleon $^{238}U^{80+}$ and
(3) 60 MeV/nucleon ions with q/A = 0.25.

preferable. Figure 7 shows typical tune values calculated for the sector angle of 23.0 deg. All the tune values are within the range from v_z=1.0 to v_z=1.5.

5. Summary

Design study of the sector magnet for the 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 ±0.01 T. Detailed design studies and further optimization are under way.

References

[1] Y.Yano et al.,"RIKEN RI Beam Factory Project," this symposium.
[2] Vector Fields Limited, Oxford, England.
[3] Kawaguchi et al., "Design Study of Superconducting Sector Magnet for the RIKEN Superconducting Ring Cyclotron (II)," this symposium.