DESIGN STUDY OF SECTOR MAGNETS OF SUPERCONDUCTING RING CYCLOTRON FOR THE RIKEN RI BEAM FACTORY

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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 superconducting trim coils for rough fitting to isochronous fields are used for the sector magnets. Isochronous field distributions and betatron tunes are calculated. Magnetic forces, coil support system, coil cooling method and cryogenic system are also described.

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, orbit analysis, structure of superconducting coils and cryogenic system.

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 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.

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 25 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 has been 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.

Table 1: Required maximum energy of the SRC.

$^{16}O^{8+}$	400 MeV/nucleon
$^{84}Kr^{30+}$	300 MeV/nucleon
$^{238}U^{58+}$	150 MeV/nucleon

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

Isochronous field distributions for typical ions are shown in Fig.1. 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 0.8 T for 400 MeV/nucleon ions and 0.1 T for below

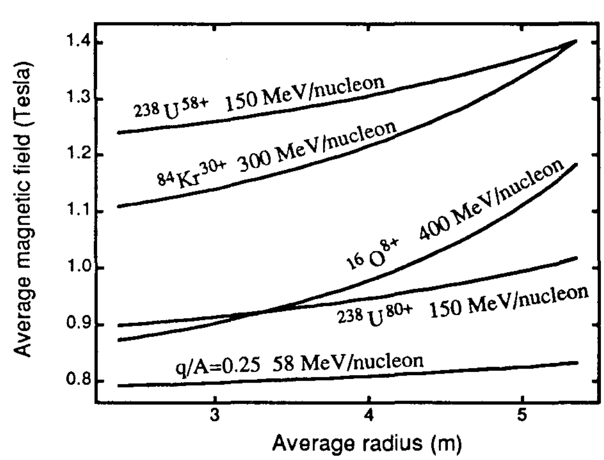

Fig. 1 Isochronous fields for typical ions.

100 MeV/nucleon ions. Therefore main coils as well as trim coils for coarse fitting have to be superconducting.

3 Isochronous Field and Orbit Analysis

3.1 Sector Magnet and Field Calculation

Magnetic fields and forces 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. Good agreements of the magnetic field on the median plane can be obtained for both the six-symmetry system and the system with only one set. An example of modeled magnet for TOSCA is shown in Fig.2. This example displays the whole magnet using reflection with respect to symmetric planes.

Conceptual sketch of the superconducting trim coils is shown in Fig.3. The superconducting trim coils are placed between the pole and the beam chamber. They are controlled by four independent currents. Two sets of the trim coils have current returns at the outer side of the pole, the other two sets have at the inner side. These trim coils are wound on two layers. Each layer contains the two sets of trim coils, one of which has the outer returns and the other has the inner returns.

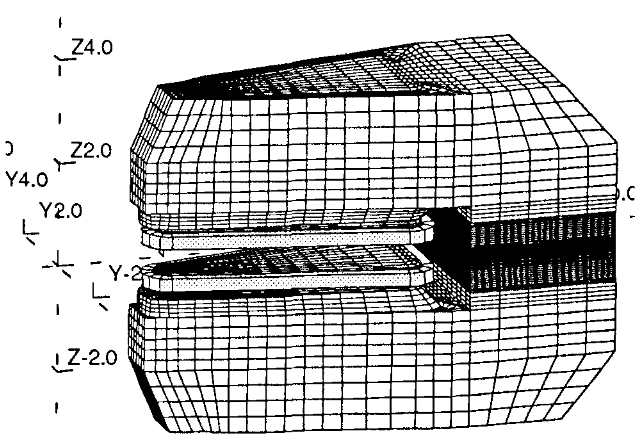

Fig. 2 An example of modeled sector magnet for TOSCA.

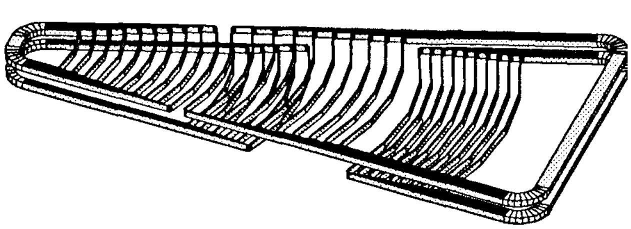

Fig. 3 Conceptual sketch of the superconducting trim coils.

3.2 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 and also structure of the pole and the yoke. Figure 4 shows an example of field distributions along the sector axis generated by the main coils, and both the main coils and the trim coils for $^{84}Kr^{30+}$ 300 MeV/nucleon. In this calculation, the sector angle is 25 deg. and height of the magnet is 6.4 m. In Fig. 5 field distributions along the azimuthal direction at r=5.5, 4.7 and 3.9 m are shown for the same model. In the region of the valley, negative field is created. Because this field brings large flutter and sharp fringing field, vertical focusing force is larger than that in a normal conducting ring cyclotron.

Using the four sets of superconducting trim coils, we expect that the field generated with both the main coil

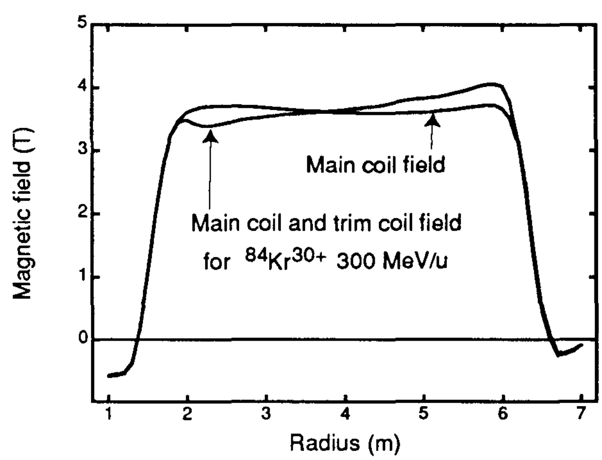

Fig. 4 Field distributions along the sector axis.

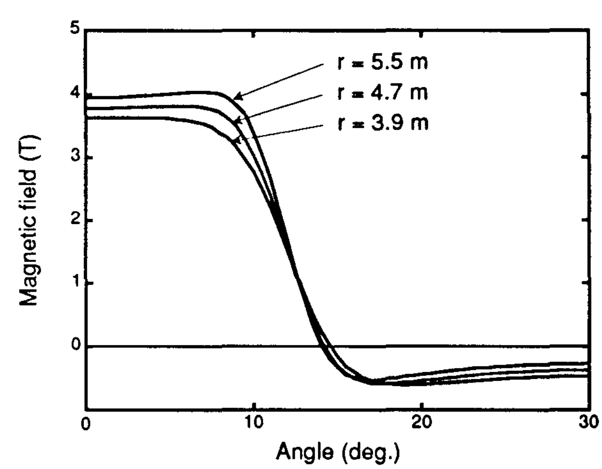

Fig. 5 Field distribution along the azimuthal direction.

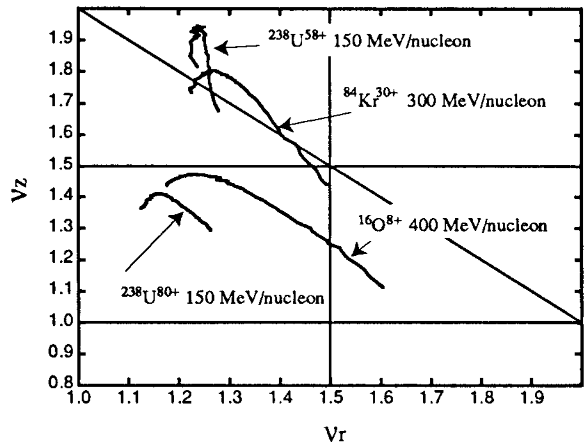

Fig. 6 Typical tune values in the case of 23-deg. sector angle.

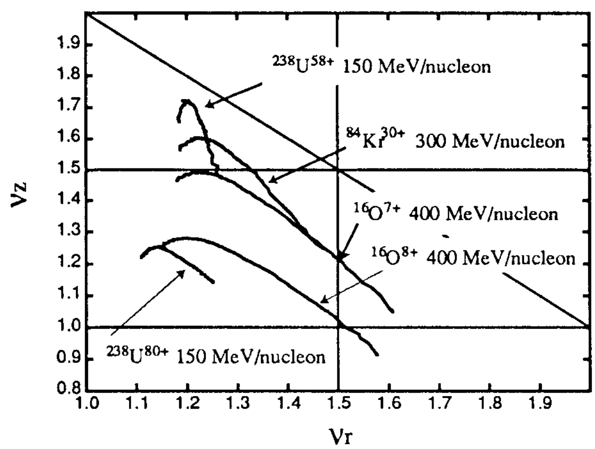

Fig. 7 Typical tune values in the case of 25-deg. sector angle

and the superconducting trim coils can be fitted to the isochronous field within ±0.01 T. Further fine adjustment will be done with trim coils of room temperature.

Figures 6 and 7 show typical tune values in the cases that the sector angle is 23 deg. and 25 deg., respectively. In the case of 23 deg., all tune values are above νz=1.0. But maximum magnetic field reaches 4.6 T. In the case of 25 deg., the tune values for $^{16}O^{8+}$ ions to 400 MeV/nucleon crosses νz=1.0. The maximum magnetic field, however, is reduced to be 4.1 T. In Fig. 7 is also shown the tune values for $^{16}O^{7+}$ ions. In this case the values are pushed above νz=1.0, but the beam intensity reduces by a factor of about 2 compared with that of $^{16}O^{8+}$ ions. The final selection of the sector angle will be made after the evaluation of difficulty in producing high field and risk of crossing the resonance line.

4 Structure of Sector Magnet

4.1 Superconducting Sector Magnet

The main components of the magnetic elements are superconducting coils, poles and a yoke. We use two kinds of superconducting coils: a pair of main coils and a group of trim coils. We have studied two ways of arrangements for the pole. One is a warm-pole system and the other a cold-pole one. Figure 8 shows the both systems with a cryostat. As for the warm-pole system, the poles are directly connected to the yoke in room temperature region, and thus the cold mass at 4.5 K consists of superconducting coils and coil vessels. As for the cold-pole system, the main superconducting coil is wound around the pole directly, so the cold mass consists of superconducting coils, poles and coil vessels. From the viewpoints of the mechanical rigidity and magnetic force, we have decided to use the cold-pole system. However, a serious problem on the cold-pole system is the difference of thermal contraction between the pole and the coil vessel during the cooldown of the cold mass from 300 K to 4.5 K. We are currently investigating this problem.

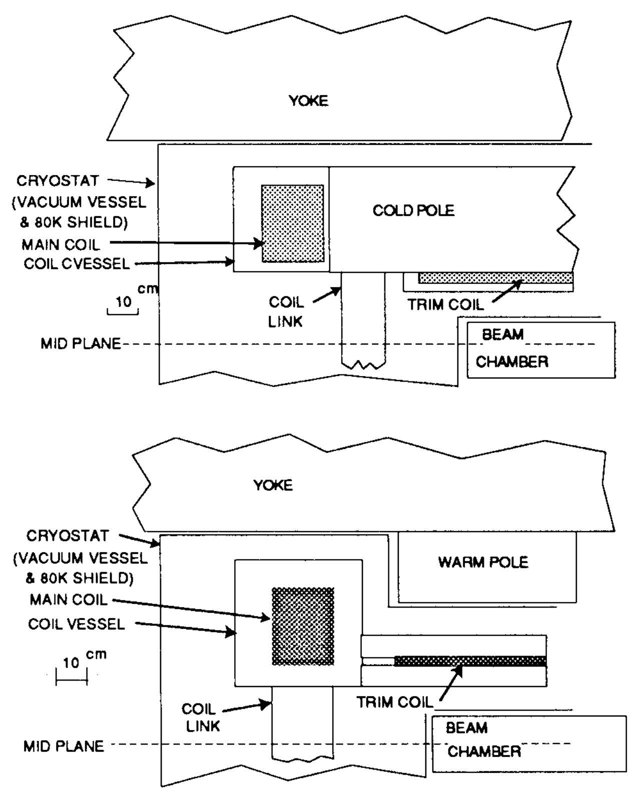

Fig. 8 Arrangements of cold-pole (top) and warm-pole (bottom).

4.2 Magnetic Field and Forces

Figure 9 shows the comparison of expanding forces on the straight section of the main coil between for the warm-pole system and for the cold-pole one. It is clear that the force in the cold-pole system can be reduced to be one-third of

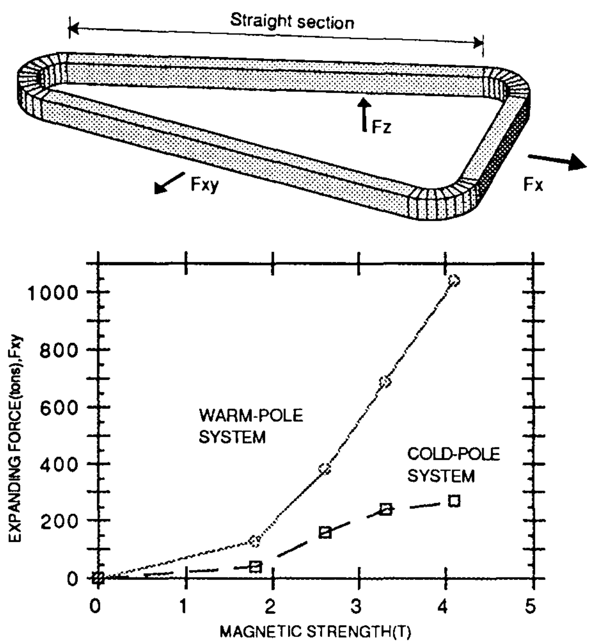

Fig.9 Comparison of expanding forces in straight section

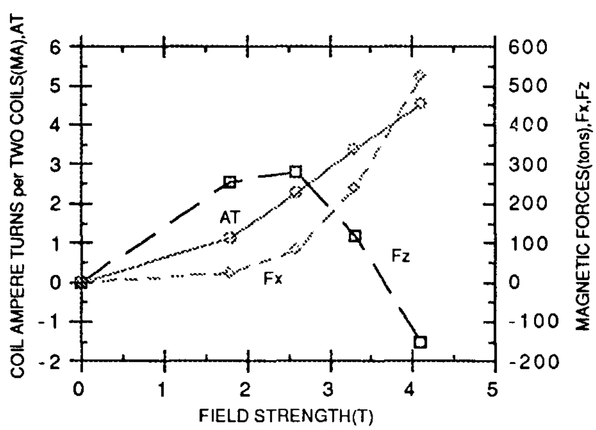

Fig. 10 Field strength and magnetic forces

that in the warm-pole system. This effect is due to the short distance between the main coil and the pole in the cold-pole system. Figure 10 shows magnetic forces Fx, Fz acted to the cold mass (consisting of the main coil and the cold pole) and the ampere turns of a pair of main coils, as a function of the magnetic field on the median plane. The magnetic force Fz in the vertical direction is supported with two coil links which are arranged between the upper cold mass and lower one. The force of 300 tons at the maximum causes a mechanical deflection of cold mass by about 4 mm. The magnetic force Fx in the radial direction is generated with a configuration of the six sector magnets . Each cold mass is pushed toward outer radius. The maximum force of Fx is estimated to reach about 500 tons per each magnet. It is very difficult to support this force by thermal insulating supports which locate in between the cold mass and the vacuum vessel. To support such a large Fx, we are investigating a cold ring of 2.6 m in diameter and 200 mm in thickness which connects the six cold masses in the central region of the ring cyclotron.

4.3 Superconducting Coils

The main superconducting coil has a triangle shape with two long straight sections of about 4 m length. This force is supported by the coil vessel and the cold pole. It is very difficult, particularly for the coil in non-circular shape, to prevent the coil's wire movement that causes a coil quench. However, quench-free is indispensable for such a system storing magnetic energy as much as 600 MJ and for maintaining a reliable long-time operation for the cyclotron. Taking the above matter into account, we apply fully cryogenic-stable cooling for both the main coil and the trim coils by adopting a method of conservative liquid-helium bath cooling. The operational currents of the main coil and trim coil are roughly set to be 5000 A and 500 A, respectively. In order to maintain the cryogenic stability, the average current densities of them should be less than 40 A/mm^2 and 50 A/mm^2, respectively.

4.4 Cryogenic System

The total heat leak of six magnets is roughly estimated to be 500 W at 4.5 K. A helium refrigerator having a capacity of 1 kW at 4.5 K stage will be used for the six sector magnets and beam injection and extraction channels. Weight of the total cold mass of the six magnets is about 360 tons. It will take almost one month for the cooldown of the cold mass from room temperature to 4.5 K by the helium refrigerator.

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 fitted roughly by using superconducting main coils and superconducting trim coils. The arrangement of the coils and the pole have been studied. The cold pole system is adopted in order to support and reduce the magnetic forces acted to the coils. Detailed design studies and further optimization are under way.

References

1. Y.Yano et al.,"RIKEN RI Beam Factory Project," this conference.
2. Vector Fields Limited, Oxford, England