TRIM COIL SYSTEM FOR THE RIKEN SUPERCONDUCTING RING CYCLOTRON

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Abstract

A superconducting ring cyclotron proposed as a booster of the existing RIKEN Ring Cyclotron (RRC), is composed of six superconducting sector magnets. In each sector magnet, the pole pieces are placed at 4 K to be used as a support structure of the coil vessel against large electromagnetic forces and also to enhance magnetic flux efficiently. The field trimming system suitable for such a cyclotron is thought to be a combination of superconducting and normal trim coils. Considering their differing properties, optimization of a trimming system has been carried out using numerical methods. The trimming system is required to isochronize the magnetic fields for various ions in a wide range of beam energy. Features of the trim coils and the results of optimization are described.

1 INTRODUCTION

A superconducting ring cyclotron with six sectors (SRC-6) is under design at RIKEN as the final booster of the primary beam in a cyclotron complex of the Radio Isotope (RI) Beam Factory [1]. Heavy ions such as $^{238}U^{58+}$ will be accelerated from 58 MeV/u to 150 MeV/u, and light ions such as $^{16}O^{7+}$ from 126 MeV/u to 400 MeV/u for efficient RI beam production using a projectile fragmentation method.

Variable energy cyclotrons need an efficient magnetic field trimming system, which requires optimization of its location, current, and so on. Regarding to the location, room temperature ring cyclotrons usually have their trim coils placed on the pole faces. However, in a superconducting ring cyclotron the location of resistive trim coils is restricted to either near the beam chamber or near the yoke due to the presence of a cryostat [2]. In both cases, the trimming capability solely by resistive trim coils is poor, partly also due to pole saturation. The SRC-6 will utilize both superconducting and normal trim coils. A major portion of field trimming is carried out with five sets of superconducting trim coils. Normal trim coils are then used for fine field tuning, keeping their power dissipation relatively low.

There have been design attempts to reduce the contribution from the trim coils by modifying the magnetic fields from the main sector magnet [3]. In our case, however, the superconducting trim coils easily make most of the correction, leaving the error fields less than ±15 gauss with a vertical space occupation of 2 cm.

2 DESIGN OF THE TRIM COIL SYSTEM

Figure 1 shows the isochronous fields and fields from the sector magnets of SRC-6, in which the fields are azimuthally averaged. Three representative cases have been used in designing the trim coil system, covering the major operation field region. The case of $^{16}O^{7+}$ accelerating to 400 MeV/u requires a maximum correction by the superconducting trim coils.

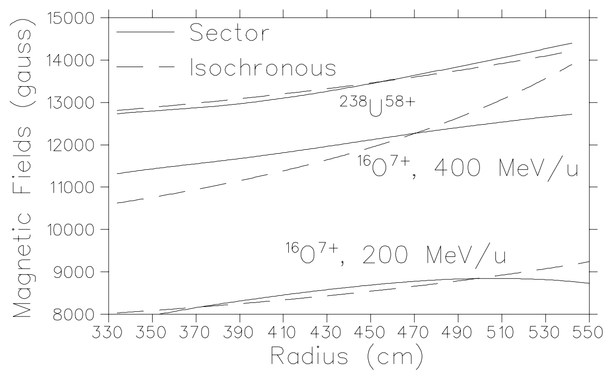

Figure 1: Isochronous fields and fields from the six sector magnets of SRC-6.

The locations of the trim coils are shown in Figure 2. The superconducting trim coils are enclosed with an independent liquid helium vessel from the main coil vessel [4]. The vacuum jacket of the resistive trim coils is separated from the beam chamber, and they comprise a room-temperature penetration through the midplane.

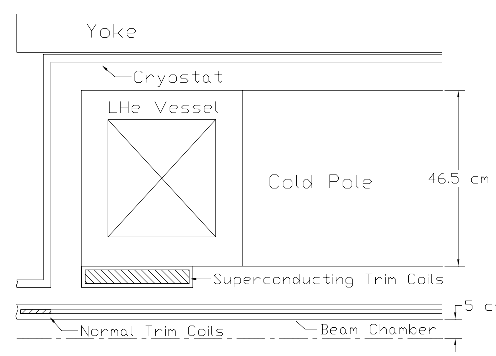

Figure 2: A schematic view of trim coil locations.

2.1 *Superconducting Trim Coils*

The superconducting trim coils are accommodated on the cold pole faces so that some vertical support is provided. However, fastening the trim coil vessel onto the pole will be limited to along the pole center line in order to reduce the thermal stress generated from thermal contraction difference between iron of the pole and stainless steel of the coil vessel.

Figure 3 shows a configuration of the superconducting trim coils. This is not the final shape, but it shows the main features such as no negative curvature. The number of independent excitation is five in the present design, and further details on this number are given in section 2.3.

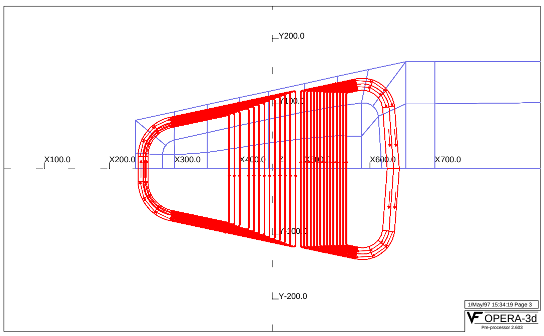

Figure 3: Configuration of the superconducting trim coils.

Among five sets three sets are wound around the nose of the sector, and two around the back of the sector. This configuration appears to be effective in field trimming in view of the shape of pure sector and isochronous fields as shown in Figure 1; the separation point of coil winding direction roughly matches with the intersection of the sector and isochronous fields of $^{16}O^{7+}$. The field distributions of the five-set trim coil system are given in the lower graph of Figure 4 when the sector field is 4.5 T.

Depending on the maximum current required on each set, the total number or the size of each coil has to be varied. Figure 3 shows the case of using a large number of coils in each set. The size of each coil is 1.3×2.3 cm, in which 24 turns can be wound. The coil will be cryogenically stabilized, and high-T_c material current leads will be used.

Superconductor is manufactured by Furukawa wire company with the maximum operation current of 500 A. Some parameters of the wire are listed in Table 1. Performance of the trim coils will be tested with the model sector magnet under construction [5].

Table 1: Parameters of the superconducting trim coil

J_{ave}	4100 A/cm^2
I_{op}	500 A
Superconducting Wire	2.9 × 3.6 mm Al/(Cu/NbTi)> 10 RRR > 400 I_c=1200 A at 6 T, 4.3 K

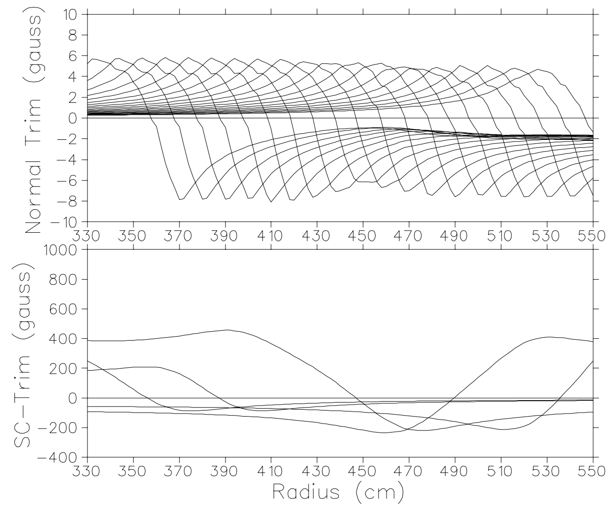

Figure 4: Upper Graph: field distributions of twenty normal trim coils at 500 A when the sector field is 3.8 T, and Lower Graph: field distributions of five superconducting trim coils when the sector field is 4.5 T

2.2 *Normal Trim Coils*

The structure of the normal trim coils will be similar to that of the present RRC [6]. Figure 5 shows a layout. Arcs of copper plates insulated with aluminum oxide coating are enclosed with an auxiliary vacuum jacket. At the ends of arcs the copper tubes are welded as both leads and cooling channel.

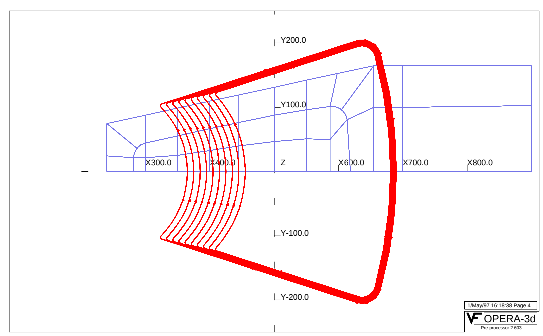

Figure 5: Configuration of the normal trim coils. Trim coils of only inner radii are plotted here.

The upper graph of Figure 4 shows the azimuthal average fields of the normal trim coils at the current of 500 A when the sector field is 3.8 T. Since the normal trim coils are located distant from the pole, the field shapes are not much different from those of the air core fields.

2.3 *Optimization of the Trim Coil system*

The criterion of optimization is not well defined as two different kinds of trim coils are involved. The condition of minimum power dissipation which is often adopted for the resistive trim coil optimization is not equally applicable to the superconducting trim coil. Figure 4 in fact implies that it may be advantageous to use a large number of superconducting trim coils since the field profile of the normal trim coil is not so optimal as a correction coil due to the cancelation effect on adjacent coils. However, the number of the superconducting trim coils is limited by available space for the current leads with a vertical space of 2 cm.

The program used in optimization is the same as used for the design of previous RIKEN cyclotrons [7], utilizing a least square fitting routine. The design ion first used is $^{16}O^{7+}$ in the energy range of 58-400 MeV/u because of the maximum correction field required. As a function of the superconducting trim coil number, the error fields are calculated and shown in Figure 6. With use of 5 sets, the error field reduced within $\pm$ 15 gauss, or ± 0.13 % of the isochronous field. The case of 6 trim coils didn't improve the fitting so much in the present calculation.

Twenty sets of normal coils were then tested with uniform spacing of 10 cm at radii between 365 cm and 555 cm. Figure 7 shows the leftover error fields after fitting. The orbital frequency error calculated with the EO code is less than ± 0.02 %. This error will produce the phase excursion of about 10°, allowing a low beam energy spread. Fitting was also performed for the case of $^{16}O^{7+}$ accelerating to 200 MeV/u. The orbital frequency error could be kept within ± 0.025 %, with which the phase excursion is also about 10° because of smaller number of turns.

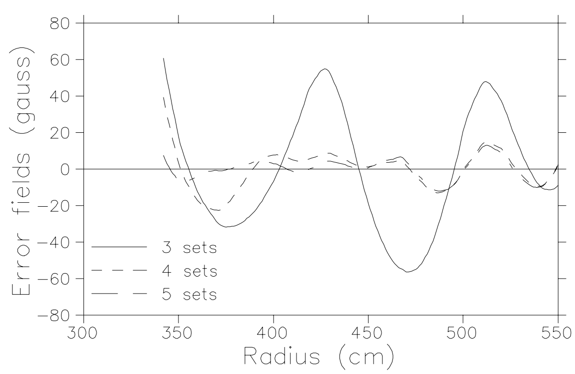

Figure 6: The error fields remained after fitting with different number of sets of the superconducting trim coils for $^{16}O^{7+}$.

In the present design the normal coils which are uniformly spaced can tune the fields well with even distribution of currents as a function of radius. The maximum current needed is about 500 A. The power dissipation is estimated to be 100 kW for 400 MeV/u $^{16}O^{7+}$, which is obtained by scaling the power loss of the present RRC trim coils.

2.4 Harmonic Field Effects

A major field perturbation in the SRC-6 is the first harmonic component coming from the stray fields of injection and extraction elements. The magnitude of the first harmonic is expected to be about 100 gauss on the first turn

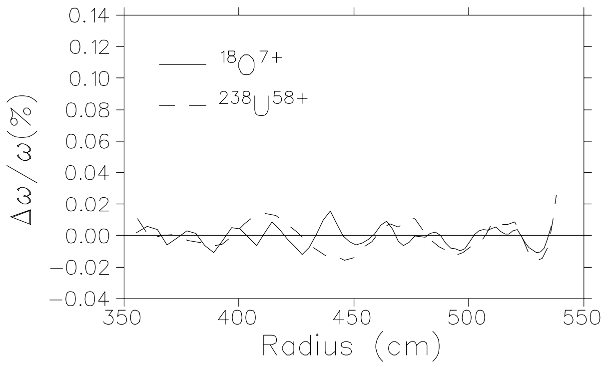

Figure 7: Orbital frequency error after fitting with normal trim coils

with active shielding employed. To compensate for this rather strong stray field, it seems that the innermost and the outermost radius sets of the superconducting trim coils need to be harmonic coils.

The first harmonic field is often used for orbit centering and for off-centering acceleration to increase the extraction efficiency. The estimated off-centering is 0.2 mm/gauss for $^{16}O^{7+}$, which means the first harmonic of about 10 gauss may be needed to move the orbit center. Resistive harmonic coils can handle this magnitude.

3 CONCLUSION

For the SRC-6 five sets of superconducting trim coils can effectively correct most of the error fields. The leftover fields can be easily corrected with twenty normal trim coils in the present calculation. The power loss on the normal trim coils is estimated to be around 100 kW for 400 MeV/u $^{16}O^{7+}$. The cryo-stability of the superconducting trim coils will be tested with the model sector magnet under construction.

4 REFERENCES

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