TRIM COIL DESIGN FOR RIKEN SUPERCONDUCTING RING CYCLOTRON

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The trim coil system of the RIKEN superconducting ring cyclotron was designed, and further details have been considered. With a combined use of room temperature and superconducting trim coils, quality isochronous fields can be obtained in the entire operation range. The design optimization was performed with a least-square fitting technique. A numerical procedure was developed to attain current settings on the main and trim coils using a series of existing and newly developed programs. Some trim coils will be independently excited on each sector to correct harmonic error fields. Because of traversing a half integer resonance it is essential to use such harmonic excitations for the SRC to remove the gradient of a third harmonic fourier component. Moreover, as a design study we have investigated the option of using superconducting trim coils alone, which can eliminate the usage of the normal trim coils.

1 Introduction

A superconducting ring cyclotron (SRC) will be constructed as the final booster of the primary beams in the radio-isotope (RI) beam factory project which is in progress at RIKEN. [1] The RI beams will be produced by the projectile fragmentation method, and utilized in various fields of the nuclear science.

The SRC will accelerate heavy nuclei to a wide range of final energies using variable rf frequencies ranging from 18 to 38 MHz in a harmonic number of six. For the SRC to generate isochronous magnetic fields in the entire operation range, an efficient field trimming system is required.

Configuration of the SRC sector magnet was primarily determined to avoid major vertical resonances and to have a simple mechanical structure. [2] The resulting field profiles without a trim coil correction turn out to match better with the isochronous fields for low energy accelerations. Correction fields are large for high energy nuclei, so that superconducting trim coils have been chosen as a major trimming device, normal trim coils being used for fine field adjustments. This scheme was chosen in the early design stage, and numerical optimization works have been done. [3]

A part of the trim coils will be independently excited on each sector to produce harmonic fields. The harmonic excitations are to compensate for a first harmonic and to remove a third harmonic. The control of the first harmonic is needed in the process of inducing precession at injection, while the gradient of the third harmonic should be eliminated for nuclei traversing the ν_r=1.5 resonance. The magnitudes and profiles of error harmonics have been estimated, further investigations being needed.

Since each set of the superconducting trim coils is composed of several sub-coils, it is feasible to discard the normal trim coils and to use the superconducting coils alone if sub-coils are independently excited. A notable advantage of this scheme stems from the fact that the superconducting trim coils have many turns, compared to a single turn of the normal trim coils. A maximum of about ±100 A is needed between neighboring sub-coils, and less than 50 A on some sub-coils for harmonic excitations. The increase in heat loads to 4 K is about 50 W at 4.5 K, which is not overwhelmingly large. More serious concern lies on the reliability of the protection system at magnet quenches. Detailed evaluations have not been done yet, but complicated quench protection circuits could be fragile, unless coils are self-protected.

2 Numerical Generation of Isochronous Fields

The SRC requires an efficient trim coil system. An optimal design of such system is intimately associated with the design of the main coil and sector geometry. For the SRC the design was stressed on keeping a simple mechanical structure of the main coil and avoiding the vertical resonances of ν_z=1 and 1.5. As shown in Fig. 1 the field profile prior to correction matches closer with the isochronous fields for low velocity ions. A large magnitude of correction fields is needed for light ions accelerating to the high end of the design energy. Normal trim coils are not suitable, especially considering the limited space allocated due to 4 K environment of the main coils. The superconducting trim coils were added.

For optimization of the trim coil system and also for beam optics study it is necessary to generate accurate self-consistent isochronous magnetic fields for given configurations of the trim coils. Different procedures could be followed, but the code equilibrium orbit (EO) [4] is commonly used to obtain orbital frequency errors needed

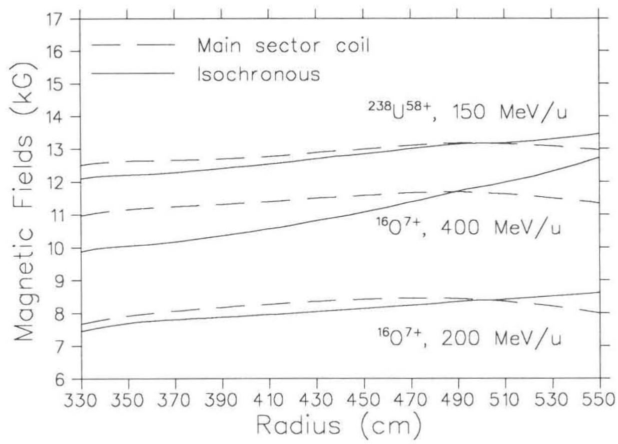

Figure 1: Field profiles of the main sector coils and isochronous magnetic fields for three design nuclei. Differences between two fields are to be corrected with the trim coils.

for field correction. For instance one method used at RIKEN employs a direct iteration of TOSCA [5] together with EO. The TOSCA iteration can be done within a reasonable time when the number of trim coils involved is small, which is the case for the SRC superconducting trim coils, which is set to five. [3] A fine correction is then made by manipulating the fields, which corresponds to energizing the normal trim coils. The second step of isochronization smoothes out the field, and may introduce errors in computing focusing tunes, which is believed to be not significant.

Isochronism can be evaluated by the degree of phase excursion during acceleration. The phase excursion ϕ is related to the integrated frequency error, $F(E)$ calculated by EO and given by

$$F(E) = \int (\omega\tau(E) - 2\pi)dE, \tag{1}$$

$$sin\phi = \frac{Ah}{qV_g}F(E), \tag{2}$$

where h is harmonic number, A/q mass to charge ratio, and V is the energy gain per turn. The $F(E)$ and ϕ are minimized by reducing the frequency errors at selected energies.

By adding a third harmonic flat-topping cavity, phase excursion larger than 20° could be tolerable if the beam phase width is narrow, but for acceleration of high current beams a large phase width is preferred in order to lessen the space charge effect. The phase excursion less than ± 5° is aimed, which is routinely achieved at the RRC.

Another approach utilized for the results in the next section employs a least-square fitting method. The magnetic fields calculated with TOSCA at several excitations are stored in polar coordinates, and they are used as basis for the first fitting. The isochronous field for the first fitting is generated with "zero-flutter" defined by $B(r)=B_0/\sqrt{1-(\frac{r}{c}\omega_0)^2}$. After the first fitting basis functions are switched to the orbital frequency errors. The main and trim coil fields are then adjusted to minimize them. In the following fittings the base functions of the main and trim coils are accordingly replaced with new frequency errors near the fitted field. Self-consistent isochronous fields are usually attained within four to five iterations in total. To reduce the number of iteration a grouping of the trim coils was used in the beginning, which was very effective in achieving a rapid convergence. The final distribution of the trim coil currents is then determined within errors caused by field interpolation.

3 Present Design

The trim coils of the SRC consist of the superconducting and normal coils. A functional separation was made such that a major correction of error fields is performed by the superconducting trim coils, and fine tuning with the normal trim coils. The superconducting trim coils may easily produce a large total current, but the use of a large number of independent excitations is disadvantageous because of the increase in heat transfer between 4 K and ambient temperature. The structure of the normal coil system will be similar to the one adopted for the RRC.

3.1 Correction of Error Fields

In designing the trim coil system, attention has been paid to develop schemes to correct harmful harmonics. Major sources of the error fields have been analyzed, their effects being studied on beam optics.

The fringe fields of the injection and extraction elements affect orbit trajectories. The profiles of averaged fields and their harmonics which affect the beam most are plotted in Fig. 2, which are calculated with TOSCA assuming air core. In the injection region the first harmonic shifts the orbit center, but stability is not a concern, since the radial tune is away from integers. For the magnitude shown in Fig. 2, correction may not be necessary. However, in controlling precession to achieve a single-turn extraction it could be handy to be equipped with a couple of harmonic coils in the injection region. In the extraction region fringe fields shown in Fig. 2 come from the magnetic extraction elements. The third harmonic is harmful for nuclei traversing the ν_r=1.5 resonance. But the fringe field of Fig. 2 is not strong enough to cause notable beam blow-up according to optics calculations.

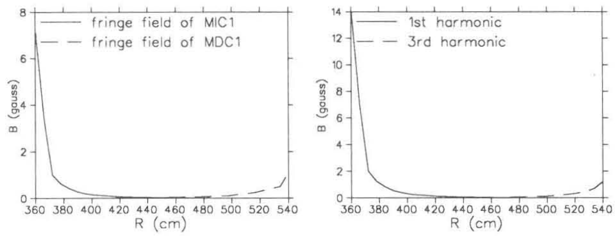

Figure 2: Fringe fields of the injection and extraction magnetic elements and their harmonic components which affect the beam most.

Three modes of alignment error shown in Fig. 3 were analyzed. The radial and angular misalignments produce harmonics of the main field, while the vertical displacement produces the horizontal fields. First the radial displacement generates relatively weak harmonic components, if the alignment is within tolerance. And the rotational error can be corrected with harmonic excitations of the main and trim coils as described in ref [6]. A present plan calls for using most of the trim coils and the main coils for harmonic excitations. The gradient of a third harmonic is the most difficult to be precisely corrected because of limited form factors of the trim coils. Further studies are going on to find out an optimum number of the trim coils for harmonic excitations.

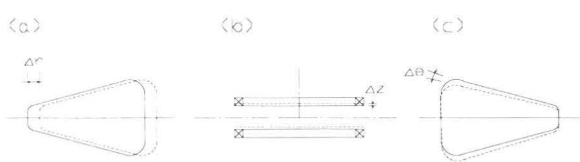

Figure 3: Three modes of alignment errors. The horizontal displacements introduce harmonic components of the main coil fields, and the vertical displacement induces horizontal field components.

The horizontal field components can not be compensated with the coils equipped in the SRC, and are also difficult to be measured. The present plan is simply to align the sector magnets along with beam measurements.

3.2 Mechanical and Electrical Features

The superconducting trim coils are cryogenically stabilized by contact with liquid helium. The superconductor and the coil structure were designed to meet the criterion of cryogenic stability, and tests have been carried out for evaluation. [7] The cross-sectional view of the superconducting trim coil is shown in Fig. 4. The depths of each coil are the same for all of the superconducting trim coils, the width being varied according to the total current required. An optimized design is thought to be that all five sets of the superconducting trim coils carry near equal current densities. The maximum operating current density is about 4000 A/cm^2 at the current of 500 A.

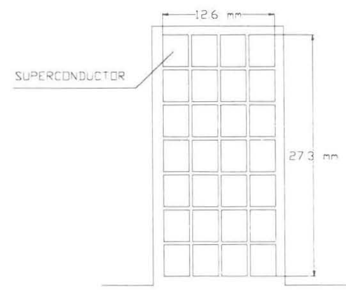

Figure 4: Cross-sectional view of a superconducting trim coil. The heights of the coils are the same, and their widths differ depending on locations.

The connection scheme of the superconducting trim coil system is schematically shown in the left hand side of Fig. 5. The circuit is drawn for two sets, and power connections for harmonic excitations are included. The harmonic current needed is not fully decided but should be less than 50 A. The circuit of the right hand side is for an option using superconducting trim coils alone, which is discussed in the next section.

The normal trim coils will basically have the same structure with those of the RRC. The coils are made of arcs of copper plates insulated with aluminum oxide coating, being enclosed with an auxiliary vacuum jacket. At the ends of the arcs the copper tubes are welded as both leads and cooling channel.

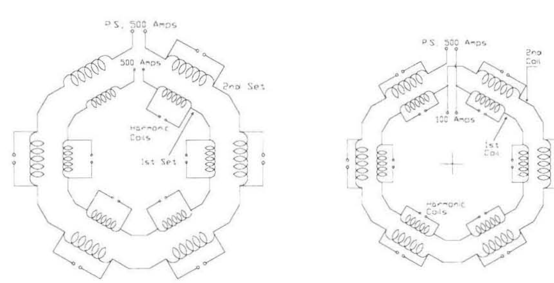

Figure 5: Left: A schematic circuit diagram of the superconducting trim coils drawn for two sets. Right: A diagram for an option using superconducting trim coils alone

4 An Option of Using All Superconducting Trim Coils

The normal trim coils can be replaced with the superconducting trim coils if each sub-coils in the five sets can be independently excited. This scheme was initially not considered seriously because it is not economical to use twenty sets of 500 A current leads and more leads for harmonic excitations. After further consideration it was found sufficient to use smaller power supplies of 100 A. And again the maximum current for harmonic excitations is less than 50 A for about sixty sub-coils. An increase in heat leak approximately amounts to 50 W at 4.5 K. On the other hand with use of twenty sets of the normal trim coils the maximum power loss is estimated to be around 120 kW which is scaled from the data on the RRC operation.

A new option requires a larger capacity of refrigerator, but removal of the normal trim coils and their cooling system seems quite attractive. More serious concern arise from the coil protection system in the situation of magnet quenches in which many coils and their current leads are to be protected. Since the trim coils are cryostabilized, a delay of quench after a main coil quenching may allow the transfer of a large amount energy to the trim coils before their own quenching, which is followed by a large current and voltage drop on the leads. A further study is needed for safe dumping of the stored energy. Actually this situation is the same even for the present five set case, probably with a reduced probability of the risk.

The selection of the five sets of the superconducting trim coil remains intact, because the field forms of each superconducting trim coil matches with those of the normal trim coils. Roughly speaking the superconducting trim coil can produce five times stronger fields per unit current than the normal coils in the present configuration. Current distribution in the sub-coils was carefully re-examined for different ions since they have different turn numbers from in the five-set design. Widths of the sub-coils were adjusted to make the maximum currents on all sub-coils about the same. Figure 6 shows the current distributions for O^{7+} 400 MeV/u and 200 MeV/u, which requires the largest current on each sub-coil and the largest current difference in neighboring coils, respectively. The total turn numbers of each sub-coil are also plotted, which indicates a larger total current in the extraction region.

5 Conclusion

The design of the trim coil system for the SRC has been detailed, working out the scheme of harmonic excitations against error harmonics. In the injection and extraction regions the first harmonic may be excited using the normal trim coils since the fringe fields from the magnetic elements will be low. To remove a third harmonic gradient, both the normal and superconducting trim coils as well as the main coils may be needed for harmonic excitations. Investigations of the third harmonic profiles are still needed for various conditions of misalignment and manufacturing errors to fully optimize the harmonic currents. For correction of the horizontal fields, beam diagnostics will the tool, alignment being adjusted.

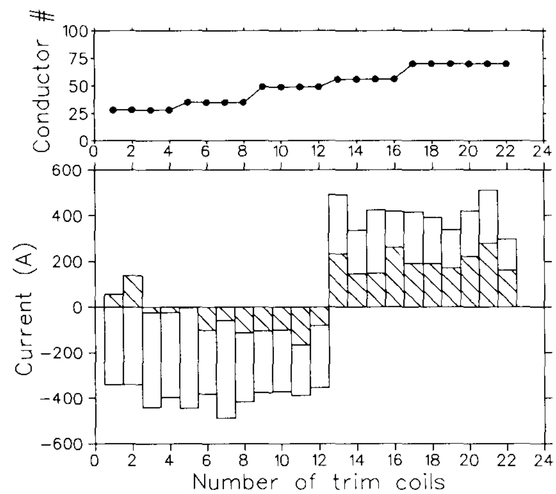

Figure 6: Current distribution in the superconducting trim coils for $^{16}O^{7+}$ accelerating to 400 MeV/u shown without hatch, and to 200 MeV/u with hatch. The number of superconductor in each set are given in the upper graph.

The trim coil design will be finalized after the testing of the prototype sector magnet. [7] The radial shifting forces due to the sector shape have to be measured and compared with calculations for different excitations of the trim coils. This will confirm proper locations of the trim coils. The option of using superconducting trim coils alone may not be adopted in favor of reliability.

References

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