ORBIT ANALYSIS OF THE RIKEN SUPERCONDUCTING RING CYCLOTRON

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The RI-beam factory has started at RIKEN Accelerator Research Facility (RARF). Superconducting Ring Cyclotron (SRC) is the main accelerator of this factory. Construction of the cyclotron has started. In this report we describe three issues related to the cyclotron from the viewpoint of orbit analysis; function and structure of two kinds of trim coils, influence of half integer resonances, and methods for cancellation of leakage magnetic field outside the cyclotron vault.

1 Introduction

Construction of the "RI beam factory" has started at RIKEN Accelerator Research Facility (RARF).[1] For production of radioactive isotope beams, two cyclotrons will be constructed; Intermediate Ring Cyclotron (IRC) and Superconducting Ring Cyclotron (SRC). [2] The IRC is a normal conducting 4 sector ring cyclotron. Fundamental structure of the IRC is similar to the existing RIKEN Ring Cyclotron. However, the SRC is a 6 sector ring cyclotron with sector shaped superconducting coils. Many problems should be solved for the construction of the SRC.

2 General description

The maximum acceleration energy of the SRC is 400 MeV/nucleon for light heavy ions and 150 MeV/nucleon for $^{238}U^{58+}$. Figure 1 shows the region of expected ions from the SRC (grey area) and typical ions (white circle). The maximum magnetic rigidity of the extraction beam is 7.56 Tm. The K value is approximately 2500. The mean injection and extraction radius are 3.56 m and 5.36 m, respectively. Figure 2 shows a layout of the SRC.

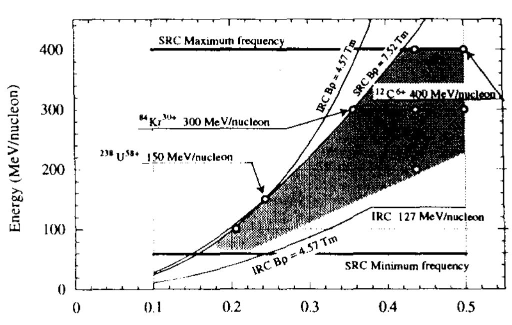

Figure 1: Performance expected for the SRC.

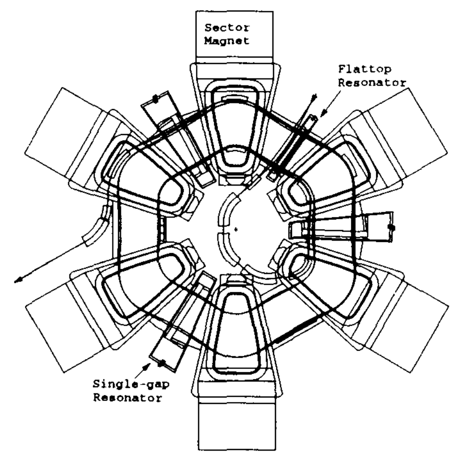

Figure 2: Layout of the SRC.

3 Trim coils for the SRC

The SRC equips two kinds of trim coils; superconducting and normal conducting. The superconducting trim coils work for rough fitting to various isochronous field. The normal conducting trim coils work for fine fitting. Figure 3 shows a schematic drawing of the cross-section of the sector magnet along the radial direction.

3.1 Superconducting trim coil

The superconducting trim coils are placed on the inner surface of the cold mass composed of a pole and a main coil vessel. Therefore, vertical position of the trim coils is 165 mm from the median plane. The trim coils are divided into five regions corresponding to different power supplies. Number of the independent power supply is limited by thermal heat loads, space for current leads and complexity of the structures. Figure 4 shows the configuration of the superconducting trim coils.

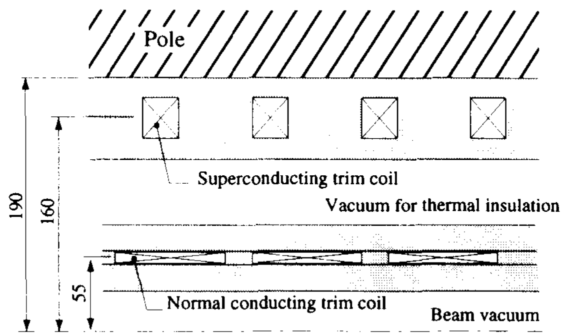

Figure 3: Cross sectional view.

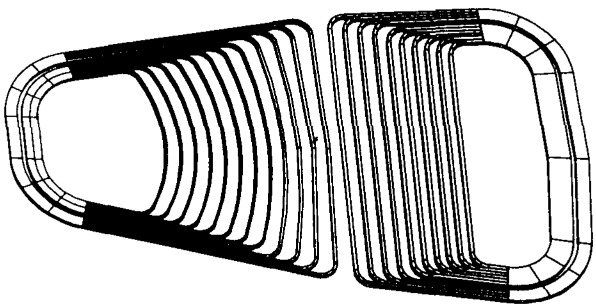

Figure 4: Configuration of the superconducting trim coils.

Using the five sets of the superconducting trim coils, it is possible to adjust to various distribution of isochronous field within frequency error of ± 0.1 %. This value correspond to ± 10 gauss of mean magnetic field error, which is given by multiplied $\gamma \overline{B}$. Figure 5 shows the frequency errors for typical ions. Local maximum or minimum is observed roughly in every 40 cm. Each local maximum or minimum is correspond to one region of the superconducting trim coil. The normal conducting trim coils work in order to cancel this errors.

3.2 Normal conducting trim coil

The normal conducting trim coil is placed inside the cryostat wall, so the vertical position is 55 mm from the median plane. The normal conducting trim coils works in magnetic field of more than 2 Tesla. And they are apart from the cold pole. Thus field distribution due to the normal conducting trim coil is similar to air core coil rather than usual trim coil used in the low magnetic field. The magnetic field decrease as the distance from conductor becomes longer. Figure 6 shows field distributions of normal trim coils. In this calculation, 20 trim coils with 500 Amps each are assumed as air core coils.

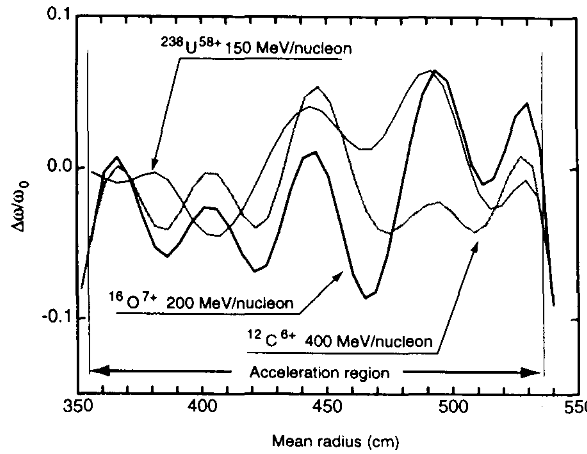

Figure 5: Frequency error to the isochronous condition.

The line (A) shows the case that current direction of the all the trim coils are the same. The line (B) shows the case that current direction changes every 2 conductors alternately. Field gradient of the case (B) is 4 or 5 times large than the case (A). The case (B) is the just the case that the normal conducting trim coils of the SRC will be used in order to reduce the error field of the superconducting trim coils. By using the normal conducting trim coils, errors to isochronous condition becomes less than ± 0.01 %. Figure 7 show an fitting example using normal conducting trim coils. Normal trim coil is designed so that four coils in the one superconducting trim coil region.

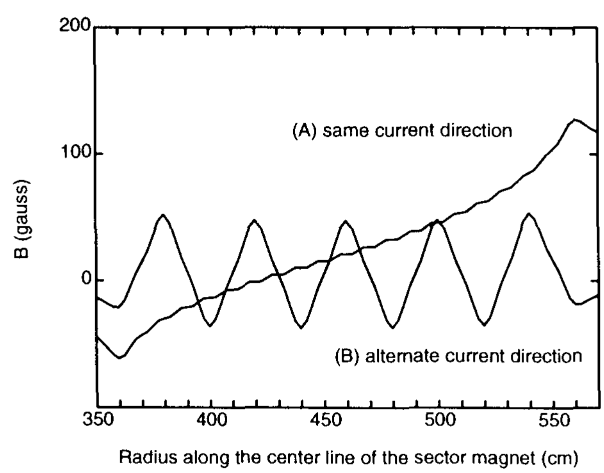

Figure 6: Effect of normal trim coil.

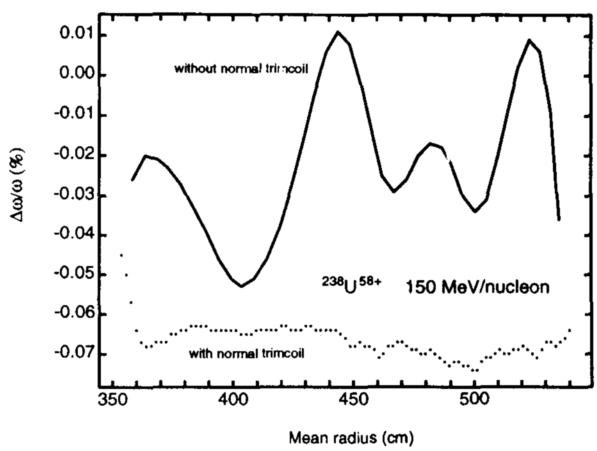

Figure 7: Effect of normal trim coil: frequency error to isochronous.

4 Half integer resonances

Working paths of radial and axial betatron frequencies for the SRC are spread in a wide region of the ν_r-ν_z diagram. Figure 8 shows working paths of typical ions. Three resonance lines should be studied for the SRC; $\nu_z = 1$, $\nu_z = 3/2$ and $\nu_r = 3/2$. For the resonance $\nu_z = 1$, we have the result that the minimum ν_z should be larger than 1.04.[3] Half integer resonance of cyclotron was studied at SIN (now PSI).[4] Here we use the same way in order to estimate the resonances.

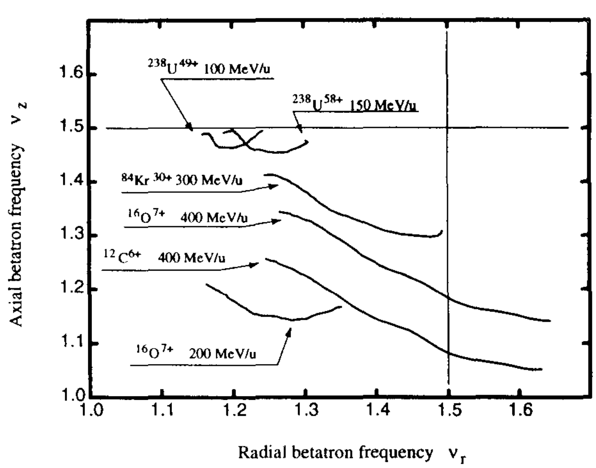

Figure 8: Working paths of typical ions.

4.1 Vertical resonance $\nu_z = 3/2$

In the case of low energy and high magnetic field acceleration such as $^{238}U^{49+}$ 100 MeV/nucleon, the working path lies near the $\nu_z = 3/2$. In order to consider the influence of the resonance, we introduce the Mathieu equation:

$$\frac{d^2z}{d\theta^2} + [\nu_z{}^2 + \varepsilon cos3(\theta - \theta_3)]z = 0.$$

Stop band $\Delta\nu_z$ is

$$|\nu_z - 3/2| \leq |\varepsilon/6| = \Delta\nu_z.$$

Inside the stop band, amplitude of beam increases as

$$z \simeq z_0 cos\frac{3}{2}(\theta - \theta_3)e^{\mu\theta},$$

where $\mu = Im(\nu_z)$. If we assume that amplitude increase should be less than 10 %, we get by using $\mathrm{Im}(\nu_z) \leq \Delta\nu_z$:

$$|\frac{\Delta z}{z}| \leq e^{2\pi n_s \Delta\nu_z} - 1 \leq 0.1;$$

so

$$n_s \Delta\nu_z \leq 0.015,$$

where n_s is number of turns inside the stop band. We consider that betatron shift per turn $d\nu_z/dn$ is constant. Then we get

$$n_s^2 \frac{d\nu_z}{dn} \leq 0.015.$$

In the case of $^{238}U^{49+}$ 100 MeV/nucleon, $d\nu_z/dn$ =0.00038 at the extraction region which is near the resonance. We get

$$\Delta\nu_z = 0.0024 \quad and \quad n_s = 6.3.$$

For the SRC, there is possibility that two manufacturer will supply three sector magnets each. In that case, sector magnets will placed alternately. Such layout may induce the $\nu_z = 3/2$ resonance. If two kinds of the sector magnets have different vertical focusing force ν_A and ν_B, tolerable difference is given by using Fourier expansion of focusing force.

$$|\nu_A - \nu_B| = \pi\Delta\nu_z = 0.0075$$

This value is large enough to construct two kinds of the sector magnets within the tolerance. For the present design, The maximum vertical betatron frequency is 1.495, so it does not cross the resonance.

4.2 Radial resonance $\nu_r = 3/2$

In the case of high energy acceleration over 300 MeV/ nucleon, working paths cross the resonance $\nu_r = 3/2$. We can handle the resonance as the same formula as $\nu_z = 3/2$. In the case of $^{16}O^{7+}$ 400 MeV/nucleon, radial betatron shift per tern is $d\nu_r/dn = 0.001$. Then we can get following results.

$$\Delta\nu_r = 0.0039, \quad n_s = 3.9 \quad and \quad \varepsilon = 0.024.$$

Here we assume that amplitude increase is 10 %. Tolerable magnetic field gradient g_3 is give by following

$$g_3 = \varepsilon \frac{\overline{B}}{\overline{R}} = 0.6\ gauss/cm$$

Resolution of one normal conducting trim is 0.0026 gauss /cm/Amps. Field gradient of 0.6 gauss/cm can be controlled by normal conducting trim coils.

Equilibrium orbit calculation shows the error to isochronous $\Delta\omega/\omega$ is less than ± 0.01 % by using two kinds of trim coils. But field gradient error $\Delta dB/dr$ is ± 0.3 gauss/cm. This error comes from the spacing of the normal conducting trim coils. If the normal trim coil is aligned within 1 mm error, gradient error among sector magnets is less than 0.02 gauss/cm. So the resonance $\nu_r = 3/2$ can be crossed.

5 Magnetic field shield

The SRC utilizes the leakage magnetic field in valleys in order to increase vertical focusing force. The leakage field is still large outside of the cyclotron vault. At the 50 meters point from the center of the SRC, more than 1 gauss is to be observed. In order to cancel the field outside the cyclotron vault, two methods are considered. One method is use of iron plate surrounding the vault. Width of the iron plate is required to be 15 cm. Total weight of the iron plate is approximately 3500 tons. The other method is use of shielding coils. The shielding coil is put on the wall of the vault. Radius of the coil is 14 meters. Required current is 260 kA.

Figure 9 shows estimation of the shielding methods. Both methods decrease the leakage field about 1/10 outside the vault. Inside the vault, iron plate reduce the leakage field. But shielding coil increase the field.

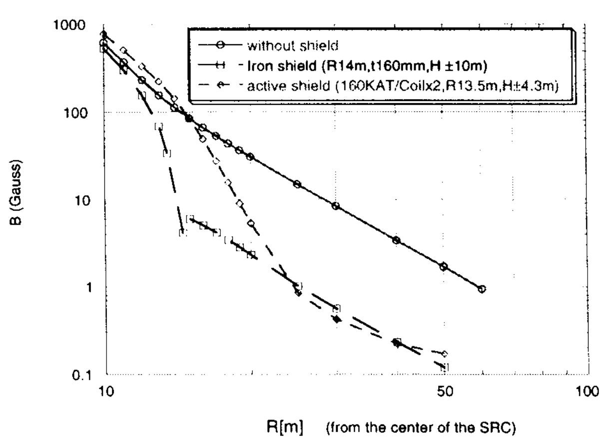

Figure 9: Leakage field distribution.

From the viewpoint of orbit analysis, both methods affect on field distributions. Figure 10 shows the effect to the betatron frequencies by two shielding methods. In the case of the iron plate method, vertical betatron frequency decrease by 0.01 because the plates work as return yoke. The shield coil method does not change the betatron frequency very much. We have not decided which method will be adopted. But the design of the SRC requires careful attention to the shielding method.

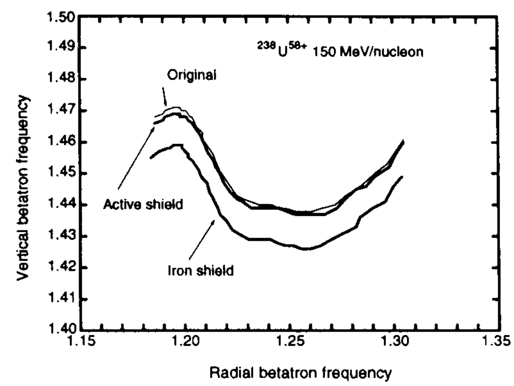

Figure 10: Effect of magnetic shield to betatron frequencies.

6 Summary

The SRC uses both the superconducting trim coils and normal conducting trim coils. From the orbit analysis, this system functions well. The half integer resonances $\nu_z = 3/2$ and $\nu_r = 3/2$ are studied. These resonances can be crossed. Magnetic field shielding for the leakage field is studied. Shielding method affects beam orbit. So shielding method should be carefully designed from the viewpoint of orbit analysis.

References

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[3] T. Mitsumoto et at.,"Orbit Analysis for the RIKEN Superconducting Ring Cyclotron" Proc. of Particle Accelerator Conference, Vancouver (1997).

[4] W. Joho, "Tolerances for the SIN ring-cyclotron", SIN report TM-11-4 (1968).