ORBIT ANALYSIS FOR THE RIKEN SUPERCONDUCTING RING CYCLOTRON

T. Mitsumoto, A. Goto, T. Kawaguchi, J.-W. Kim, Y. Tanaka, T. kubo, H. Okuno, T. Tominaka, S. Fujishima, K. Ikegami, N. Sakamoto, T. Morikawa, S. Yokouchi and Y. Yano
The Institute of Physical and Chemical Research (RIKEN), Wako, Saitama, 351-01, JAPAN

Abstract

An “RI beam factory” has started to be constracted as the next 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 accomplish this requirement, the following two ring cyclotrons have been adopted as post-accelerators of the existing RIKEN Ring Cyclotron (RRC): a 4-sector ring cyclotron for the first stage (IRC) and a 6-sector superconducting ring cyclotron for the second stage (SRC). The sector magnet of the SRC has to be flexible enough to generate isochronous fields in a wide range of energies and for various q/A values. In this report we describe the isochronous field generation and orbit analysis of the SRC.

1 INTRODUCTION

The maximum acceleration energy of the SRC was determined by experimental requirements. The SRC is expected to boost the energy of ion beam up to 400 MeV/nucleon for light heavy ions like carbon and 150 MeV/nucleon for very heavy ions like uranium. Beam current is expected to be more than 100 pμA for light heavy ions and about 0.2 pμA for 150 MeV/nucleon uranium ions. Figure 1 shows the region of expected ions from the SRC (grey area) and typical ions (white circle).

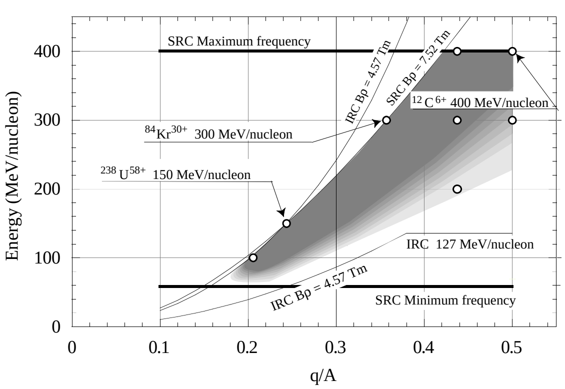

Figure 1: Performance expected for the SRC.

Main parameters of the SRC are listed in Table 1. Figure 2 shows a layout of the SRC. Six sector magnets, three RF cavities and injection and extraction devices together with injection and extraction orbits are displayed.

Table 1: Main parameters of the SRC.

Number of sectors		6
Harmonics		6
Mean radius	injection	3.56 m
	extraction	5.36 m
RF frequency		18 - 38 MHz

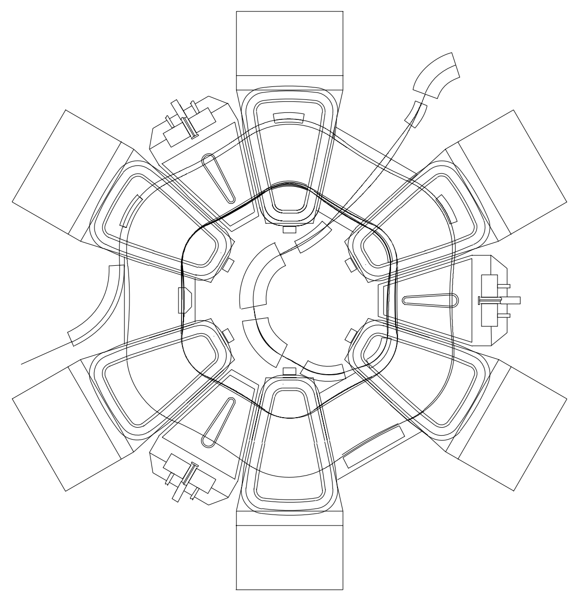

Figure 2: Layout of the SRC.

2 ISOCHRONOUS FIELD GENERATION

The maximum magnetic field is required for the acceleration of 150 MeV/nucleon $^{238}U^{58+}$. The magnetic field of the sector magnet is 4.0 T at the injection and 4.3 T at the extraction. In the case of 400 MeV/nucleon $^{16}O^{7+}$[1], the magnetic field is 3.3 T at the injection, and 4.1 T at extraction side. Field distribution for typical ions are shown in Fig. 3.

The sector magnet of the SRC has a set of superconducting main coils for base field generation, five sets of superconducting trim coils for coarse fitting to the isochronous field and about 20 sets of normal conducting trim coils for fine adjustment.

Magnetic field distribution is calculated by three dimentional code TOSCA[2]. Working path of the radial and axial betatron frequencies for typical ions are shown in Fig. 4.

0-7803-4376-X/98/$10.00 © 1998 IEEE

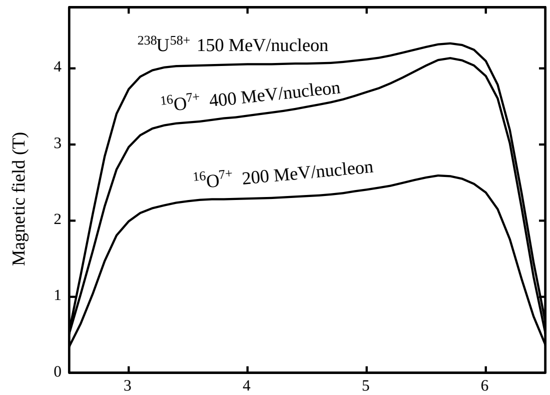

Figure 3: Magnetic field strengths along the center line of the sector magnet for typical ions.

2.1 *Pole and superconducting main coil*

Size of the superconducting main coil is 284 mm (width) x 310 mm (height). The maximum excitation current is 6 MA for one sector magnet (two coils). The superconducting main coil is installed inside a He vessel made of stainless steel which is tightly fixed to the cold pole. Pole gap is 380 mm. For details, see Refs. [3] and [4].

Smaller sector angle causes larger vertical focusing force. From the viewpoint of minimizing the maximum field and magnetic forces, however, a large sector angle is preferable. Therefore, edge of the pole has a straight line from the injection side to the middle of the sector with the wide angle of 25 deg. Then the pole shape has a curvature in order to increase the axial betatron frequency ν_z at the extraction side.

Figure 5 shows the radial and axial betatron frequencies of three different pole shapes for 400 MeV/nucleon $^{12}C^{6+}$. The radius of curvature of 8.0 m increases ν_z value by 0.12 at the extraction radius compared with the straight pole. Required excitation current of the main coil dose not increase but the currents of superconducting trim coils at the extraction side increase.

2.2 *Superconducting trim coil*

Five sets of superconducting trim coils are placed on the inner surface of the cold pole. Two sets at the extraction side have current returns at the extraction side, which are not wound along beam orbits but just straight in the beam region in order to avoid concave curveture of conductors. The other three sets have current returns at the injection side. The first coil on the injection orbit is wound along beam orbit, then it gradually becomes straight towards the extraction side.

Figure 6 shows the configuration of the superconducting trim coils.

Using the five sets of superconducting trim coils, it is possible to adjust various distributions of isochronous fields within $\pm$0.1%. Further fine adjustment will be done with the trim coils of room temperature.

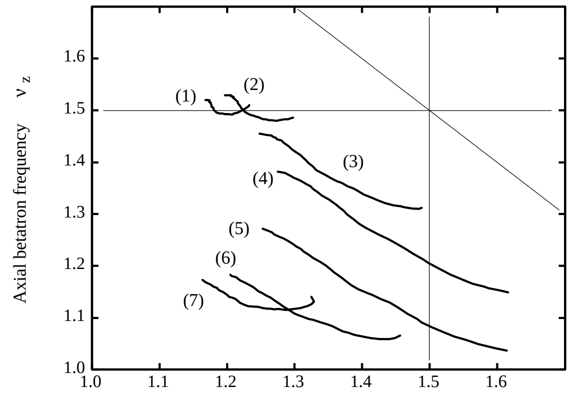

Figure 4: Working paths of the radial and axial betatron frequency of typical ions for the SRC are shown: (1) 100 MeV/nucleon $^{238}U^{49+}$, (2) 150 MeV/nucleon $^{238}U^{58+}$, (3) 300 MeV/nucleon $^{84}Kr^{30+}$, (4) 400 MeV/nucleon $^{16}O^{7+}$, (5) 400 MeV/nucleon $^{12}C^{6+}$, (6) 300 MeV/nucleon $^{12}C^{6+}$ and (7) 200 MeV/nucleon $^{16}O^{7+}$.

3 ORBIT ANALYSIS: RESONANCE

Working paths of radial and axial betatron frequencis for the SRC are spread in a wide region of the ν_r-ν_z diagram because various conditions of ions have to be accelerated. Some of the working paths lie near the resonance lines. We studied influences of the resonance, under the condition that the manufacture error or mis-alignment from the design values was 1 mm.

The reason for this assumption is the following:

- The pole and the superconducting coils in cryogenic vessels are supported by the thin rod from room temperature. They are affected by large force from room temperature yoke.
- Direct measurement of the pole position at low temperature is difficult, and moreover measurement of the main coil in He vessels is impossible.
- The pole gap (380 mm) is four or five times larger than normal conducting cyclotron. So larger error than a normal separate sector cyclotron should be tolerable.

3.1 *Integer resonance:ν_z = 1.0*

In the case of high energy acceleration, the axial betatron frequency ν_z goes down toward 1.0 as the energy increases. Influence of resonance line ν_z=1 was studied by the a computer simulation. Figure 7 shows an example of the calculation for 400 MeV/nucleon $^{12}C^{6+}$ in the case that the working path of the betatron frequency crosses ν_z=1 resonance.

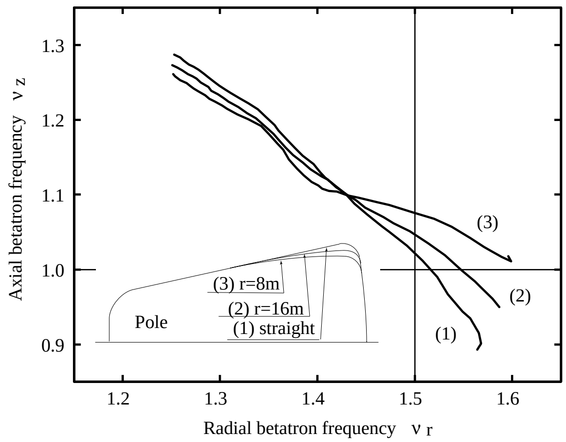

Figure 5: Effect of the curveture of the pole at the extraction side. The betatron frequencies in the case of (1) straight, (2) curveture of 16-meter radius and (3) curvature of 8-meter radius are shown.

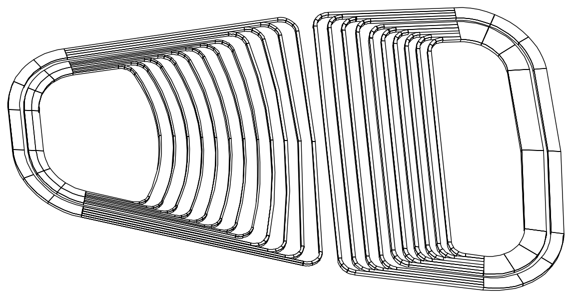

Figure 6: Configuration of the superconducting trim coils. Two of five sets have current returns at the extraction side and the others have current returns at the injection side.

In this calculation, magnetic field was perturbed to have the first-order harmonics simulated that one sector magnet and another sector magnet of opposite side were vertically displaced 1 mm and -1 mm, respectively. Amplitude of vertical oscillation increases fatally when the beam crosses the resonance. It is impossible to accelerate ions across the resonance line of ν_z=1. Minimum ν_z was found to be set 1.04 in order to avoid the influence of the resonance.

3.2 Half integer resonance ν_z=1.5 and ν_r=1.5

In the case that the extraction energy is higher than 300 MeV/nucleon, the working path crosses the ν_r=1.5 line. For ions of energy less than 150 MeV/nucleon with small q/A, the working path crosses the resonance line ν_z=1.5.

By a preliminary estimation, influence of half integer resonance ν_z=1.5 and ν_r=1.5 was found to be small.

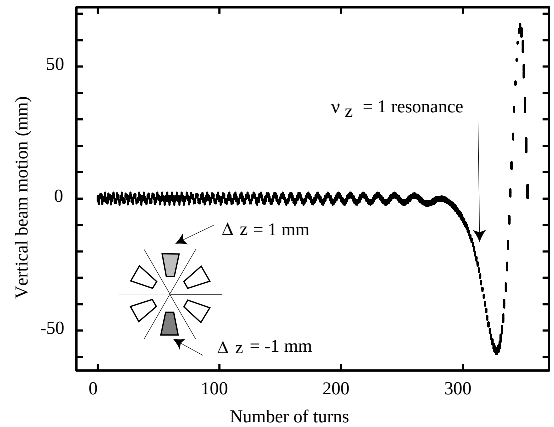

Figure 7: Effect of ν_z=1 resonance.

4 SUMMARY

Design study of the sector magnet for the SRC for the RIKEN RI beam factory has been carried out. Combination of the superconducting main coil, superconducting trim coils and normal conducting trim coils can generate isochronous field for various ions. The minimum axial betatron frequency is set to be 1.04 in order to avoid the ν_z=1 resonance.

5 REFERENCES

[1] Y. Yano *et al.*, 'RIKEN RI-Beam Factory project', this conference.

[2] Vector Field Limited, Oxford, England.

[3] T. Kawaguchi *et al.*, 'Design of the Sector Magnets for the RIKEN Superconducting Ring Cyclotron', this conference.

[4] T. Kubo *et al.*, 'Design of a Model Sector Magnet for the RIKEN Superconducting Ring Cyclotron', this conference.