Orbit Studies on Pre-extraction for the RIKEN Superconducting Ring Cyclotron

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Abstract

A six-sector superconducting ring cyclotron has been designed as a primary accelerator in the RIKEN RI beam factory project. As for the design of sector magnet and main cyclotron components, significant progress has been made and reported previously. With those results obtained we now undertake detailed study of beam optics to further optimize our design. In the orbit study a main issue is to reduce beam losses throughout injection, acceleration, and extraction processes. A method called off-centered injection would be used to enhance the turn separation in front of the extraction channel, which will allow a single turn extraction. A care has been taken in the injection region to avoid losses due to this off-centering. Since the SRC is designed not to cross any dangerous resonances, this method works well. The magnetic field map used in calculations includes the stray fields from injection and extraction magnets for a more realistic evaluation. Some preliminary results are given in this report.

1 Introduction

The six-sector superconducting ring cyclotron (SRC) which is under design at RIKEN as a booster of the existing ring cyclotron (RRC), will accelerate heavy ions to produce radioactive ion beams by the technique of the projectile fragmentation [1]. Since the primary beam is accelerated up to 400 MeV/u and the current is in the range of hundred particle micro amps for light ions, one major design issue is to avoid beam loss which leads to heating and activation of cyclotron components. A series of orbit computations is under way to simulate the beam dynamics in order to achieve zero beam loss.

The beam loss occurs predominantly during the injection and extraction processes. In addition, to reduce the extraction loss the beam quality should not be deteriorated during acceleration. The sector magnet of the SRC is designed not to cross serious resonances that can cause beam emittance growth [2].

The turn separation by acceleration is not large enough for single turn extraction especially for light ions, so that a mechanism to enhance turn separation is needed. As demonstrated in the RRC and other ring cyclotrons, the off-centered injection appears to be very effective [3][4]. We resort to this method to achieve sufficient turn separation even for light ions. On the other hand, injection loss can occur due to the off-centering of the beam in the first turns. Orbit tracking was carried out to ensure the clearing the injection elements by a finite emittance beam.

When a single-frequency rf system is employed, the phase acceptance is very narrow [5]. For instance, in our case the increase of beam size at extraction is unacceptable when the initial phase width is larger than 5 rf degrees. A use of flat-topping cavity is being considered to ease this requirement.

2 Single Turn Extraction

Since the SRC is a high-energy and high-current cyclotron, a single turn extraction should be achieved with 100 % efficiency in order to avoid beam loss on the extraction elements. The last turn needs to be well separated in front of the extraction septum. If the beam does not precess, the turn separation is determined by acceleration, which mainly depends on the energy gain per turn and the radial focusing frequency (ν_r) as the final beam energy and the extraction radius are fixed. For the SRC having six sectors, three cavities will be used with double gaps or a single gap. The properties of both kinds of cavities are currently under investigation. We assumed in the present calculation the voltage gain per turn to be 1.62 MV, considering the performance of the RRC cavities. The design particle is $^{16}O^{7+}$, accelerating from 126.6 MeV/u to 400 MeV/u, which imposes the most stringent condition on turn separation. The ν_r is 1.62 at 400 MeV/u, and the resulting turn separation by acceleration is only 2 mm.

The radial beam width at extraction is roughly determined by the transverse and the longitudinal emittances. The transverse emittance from the RRC is approximately known to be 10 mm·mrad. This value is used because the injection energies to the SRC for light ions are similar to the current extraction energies from the RRC. The beam energy spread used is ±0.05% ($\Delta E/E$). The radial beam width calculated with these conditions is about 5 mm at the entrance of the electrostatic deflection channel (EDC). A stronger restriction lies on the phase width of the beam bunch. In the case of using a single frequency rf, a small phase width is a requisite for the single turn extraction. The use of the third harmonic flat-topping is under consideration. Fig. 1 shows the radial beam spread at 400 MeV/u as a function of the initial rf phase for the single frequency and the flat-topping cases. As can be seen in the figure, a phase width less than 5 rf degrees is required to keep the additional radial beam spread within 2 mm for the single frequency case. With addition of a flat-topping cavity, the phase acceptance becomes larger than 30 rf degrees. In the present calculations the flat-topping is assumed.

Orbit calculations have been carried out to evaluate the beam behavior throughout the acceleration process. The code SPRGAP was used, which integrates orbits in

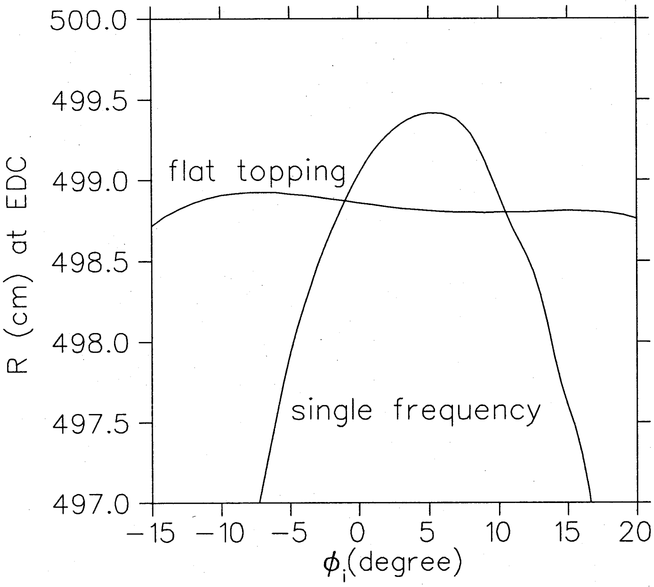

Fig. 1 Radial beam spread at the entrance of the EDC as a function of starting rf phase for single frequency and flat topping cases.

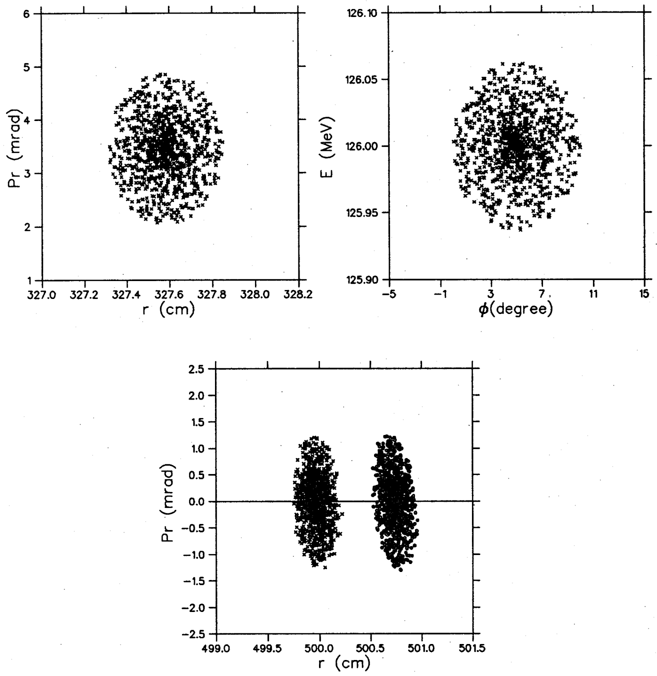

Fig. 2 Upper: the initial radial and longitudinal phase spaces which are coupled. Lower: the final radial phase spaces of the last two turns in front of the EDC.

the magnetic fields [6]. The magnetic field used allows the phase excursion of 20°. On the other hand, using a combination of superconducting and normal trim coils, the excursion can be reduced to about 10° [7]. This difference, however, does not yield different optics behavior since flat-topping is assumed.

The turn separation can be enhanced by accelerating ions with off-centered injection. As demonstrated at the RRC, one method to induce off-centering is by controlling the voltage of electrostatic inflector channel (EIC). Orbit calculations have been made to simulate this mechanism, first in a perfect six-fold symmetric field. A four-dimensional phase space is used as an initial phase space, which has a coupling between radial and longitudinal phase spaces. A coupling with axial phase space was not included because that coupling is not strong. The initial phase space at the center of EIC is shown in the upper part of Fig. 2. One thousand particles are randomly generated to fill the eigen-ellipse. In the lower part, the radial phase spaces are shown for the last two turns. A sufficient turn separation appears to be obtained.

The magnetic field of the real SRC does not have a perfect six-fold symmetry because of disturbance by the injection and extraction elements. Near the injection region harmonic trim coils are located to compensate for these stray fields. In fact, off-centering can be controlled with the harmonic coils, but this effect is not fully investigated yet.

To generate the field map of the sector magnet, the program TOSCA [8] has been used. Using this program, however, it is rather difficult to obtain sufficiently accurate results when all perturbing elements are included with no symmetry condition applied. On the other hand, there is an advantage in the field calculation of high field superconducting magnets with saturated iron poles: a perturbing field may be independently calculated assuming an air-core case, and added to the main field map. The actual current distribution of the injection and the extraction elements is rather complicated [9]. Instead of including all conductors, a single coil configuration is employed for each magnet. This approximation is thought to be reasonable since we use only the stray field of the magnets. Fig. 3 shows the Fourier components of the stray field as a function of radius, and the azimuthal distribution at two radii. The field amplitude by the injection element is 50 gauss at the radius of 370 cm, while the amplitude by the extraction element is 30 gauss near the last turn. As can be seen in the figure the amplitudes of the stray fields are assumed to be the same at given radii for each injection and extraction element, respectively. More realistic calculations will follow.

Orbit calculations are performed to ensure the turn separation at extraction when all perturbing fields are included. In Fig. 4, the radial phase spaces are plotted for the last turns. Again the last turn is clearly separated. This is also a case when the voltage of the EIC is adjusted to optimize the last turn separation.

3 Injection Loss Investigation

When the beam is well centered, the amplitude of coherent radial oscillation is minimized. However, since we use off-centered injection method, coherent oscillation is inevitably induced, and its amplitude depends on the perturbation strength. The initial turns were carefully observed to look into beam hitting on the injection

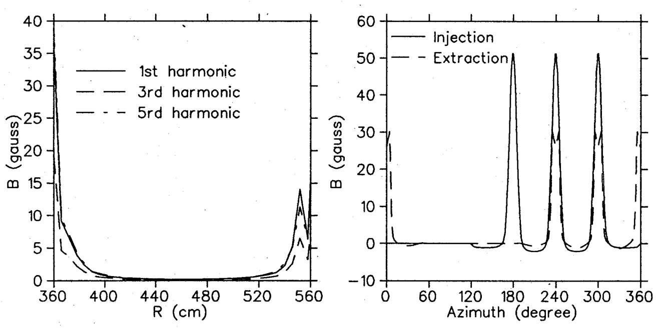

Fig. 3 Right: azimuthal distribution of the stray fields. The amplitude is 50 gauss at the radius of 370 cm, and 30 gauss at 550 cm. Left: Fourier components of the stray field as a function of radius.

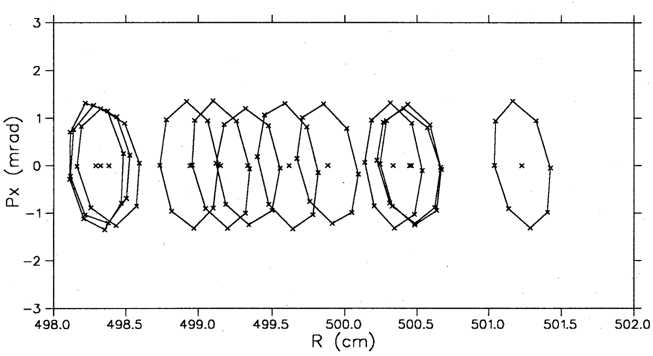

Fig. 4 Radial phase spaces for the last few turns. The last turn is well separated from the previous turn by controlling the voltage of the EIC.

elements, since the present magnet locations were determined assuming centered injection.

Fig. 5 shows the first five turns when the orbit is started at the middle of the EIC. The trajectory shown in the figure is the inner radius of the beam. Compared to the centered injection case, the radial clearance to the MIC 1 is actually increased by 5 mm for $^{16}O^{7+}$. Because the MIC 1 is not located at the azimuth where the peak oscillation amplitude appears, there seems to be no serious problem in avoiding the injection loss for all ions.

Although it is possible to analytically interpret this off-centering effect, different harmonic components of the stray field make such an analysis rather complicated. Numerical orbit computations have mainly been used. At present we have considered the case that the stray field is not corrected by the harmonic trim coils. Detailed analysis will be needed to optimize the harmonic coil design and the strength of the stray field.

4 Conclusion

In order to obtain a sufficient turn separation at extraction, ions will be accelerated with off-centering at

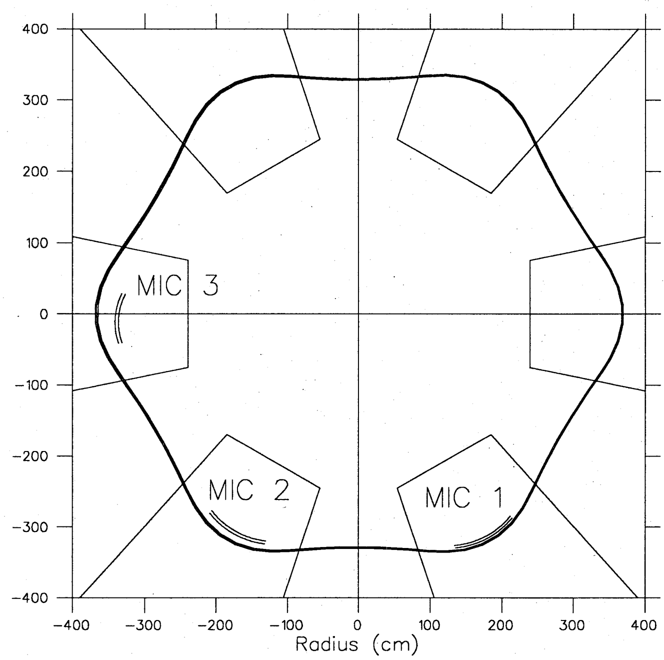

Fig. 5 Trajectory of inner radius of a finite emittance beam for the first five turns. The beam clears the MIC 1 which is located nearest to the beam.

injection. In the simulation, it is shown that the voltage of the EIC can be controlled to induce the proper separation of the last turn, even in the presence of uncorrected stray fields from injection and extraction elements. In addition, this off-centering seems not to cause interference with the injection elements by the first turn. The effect of the harmonic trim coils has not been considered yet. Further refinements on the simulation will be pursued.

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