A Single-turn Extraction Study for the RIKEN Superconducting Ring Cyclotron

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The superconducting ring cyclotron which will be built at RIKEN needs to accelerate high-current heavy ion beams for ample production of radio-isotope beams. Beam extraction out of such a cyclotron should be carried out with a low loss to avoid the heating and radiation problems by stray beams. To enhance the last-turn separation the beam will be injected off-centered. And to ensure well-defined turns, it is crucial to maintain the quality of the radial phase space, but difficulties arise for beams traversing the ν_r=3/2 resonance. After the resonance traversal, the beam phase space mismatches with a new eigen-ellipse when a third harmonic gradient exits. Correction of the error fields is planned to be made with harmonic excitations of the main and trim coils. In addition, space charge effect may hinder the high-current acceleration with disturbed turn structure. The linear component of its force could be compensated by tuning of a flat-topping cavity.

1 Introduction

The superconducting ring cyclotron (SRC) designed at RIKEN will accelerate high-current heavy ion beams to produce radio-isotope (RI) beams through the projectile fragmentation process.[1] The RI beams produced will be used in various branches of the nuclear science. Since only a fraction of the primary beam is converted to the aimed RI beams through the fragmentation process, high current beams are required. While the beam currents are often limited by the ion source performance, beam losses at the high-energy end can also limit the maximum operation current. The beam losses may occur by different processes in heavy ion cyclotrons, such as by poor vacuum, but a major loss may take place at extraction.

For a minimum beam loss the turn separation at the extraction should be larger than the beam width. But in the SRC when light ions are accelerated to the upper end of the design energy, the last-turn separation is not large enough by acceleration alone. To enlarge the last-turn separation different methods could be used. But the most effective method for the SRC is to use an off-centered injection. Precession induced at the injection leads to an enhanced last-turn separation. [2] This method is effective since ν_r is away from integers.

It is important to keep the phase space well-preserved throughout acceleration, but resonances can cause difficulties. The major resonances of the SRC are ν_r=3/2 for ions in the final energy range of 300–400 MeV/u, and ν_z=1/1 and 3/2. The vertical resonances are tried to be avoided with a yoke modification [3], but the radial resonance is unavoidable. Since the SRC is expected to accompany a third harmonic fourier component, elaborate calculations are underway to ensure the correction scheme. Most of the third harmonic could be removed by independent excitations of the main and trim coils, but the probable magnitudes and profiles of error fields need to be further investigated.

High current primary beams are required, especially at the injector mode for the accumulator ring. To evaluate the space charge effect, analytical models were used. And for more realistic evaluations, measurements are necessary using the existing RIKEN ring cyclotron (RRC).

2 Single Turn Extraction

Extraction from the SRC should be carried out with a minimum beam loss. The beam power is high at the high energy end; for instance 6.4 kW at 400 MeV, 1 pμA of ^{16}O. The loss of a few percents may not be acceptable on a localized spot considering the radiation and heating problems.

A main design ion for extraction studies is O^{7+} accelerating to 400 MeV/u because of its largest number of turns and smallest last-turn separation. For other design ions such as $^{238}Ur^{58+}$, 150 MeV/u and $^{84}Kr^{30+}$, 300 MeV/u, phase space motion was studied. Orbit tracking has been performed using SPRGAP [5], assuming that the beam phase space is well matched to an eigen-ellipse by adjusting the injection elements. A typical voltage gain is 1.6 MV per turn at the highest rf frequency of 38 MHz with three single-gap cavities and one third-harmonic flat-topping cavity employed. The initial transverse phase space is assumed to be 10 mm·mrad which is inferred from the measured value at the RRC.

In Fig. 1 is shown the phase space motion in the injection and extraction regions for O^{7+} beam, where momentum in y-axis is in cyclotron unit which has a length dimension by being divided by mc and multiplied by c/ω_0. The orbits are well-centered in this case. The plots are made at the azimuth of the front of the electrostatic deflector. It is clearly shown that extraction efficiency of the well-centered beam will be poor.

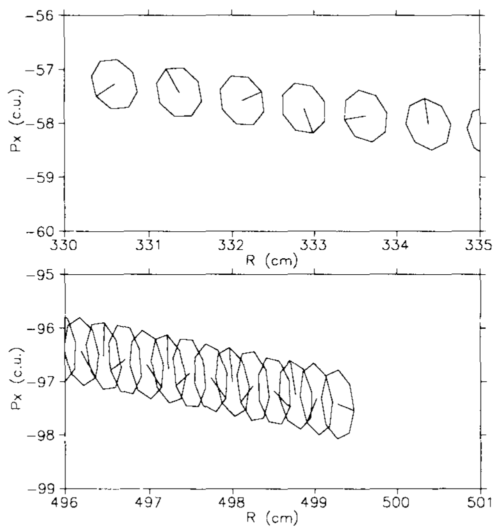

Figure 1: Upper: phase space motion of O^{7+}, 400 MeV/u in the injection region. The plots are made at the azimuth of the electrostatic deflector. The sticks drawn on the phase ellipses are the indicative of the radial focusing tunes. Lower: in the extraction region

As demonstrated at the RRC and other ring cyclotrons, one effective method to increase the last-turn separation is to induce precession at injection. Since the radial tune is not near integers, the first harmonic component is not concerned for the betatron amplitude growth. The first harmonic primarily shifts the beam centering. When the beam is injected on an equilibrium orbit (EO) in the presence of the first harmonic, orbital precession occurs with an amplitude proportional to the magnitude of the first harmonic. For O^{7+} beam, the first harmonic of 10 gauss induces precession with an amplitude of 5 mm.

At the injection main sources of the first harmonic are the fringe fields of the injection elements. The peak value of the fringe field on the first EO is designed to be less than 100 gauss, resulting in the first harmonic amplitude below 10 gauss. Correction of the fringe field may not be needed from the optics viewpoint, but it can be used to control precession. It may be preferable to adjust the first harmonic rather than to generate a beam displacement or momentum kick at the electrostatic inflector, considering the tight beam passage through the injection channels,

Figure 2 shows the phase space motion when the orbit is off-centered by 5 mm at the injection. The correct phase of the precession can be attained by adjusting the cavity voltage. It appears that clean last-turn separations can be achieved for all ions with orbital precession, if no harmonic field perturbations and beam current effects are assumed.

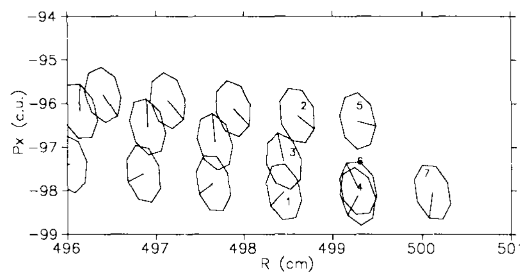

Figure 2: The phase space motion when the beam is injected off-centered by 5 mm. The cavity voltage is 540 kV. Numbering is made for the last seven turns. The last-turn is clearly separated.

The increase of cavity voltage is beneficial in reducing the space charge effect as well as in enhancing turn separation. Figure 3 shows the last-turn separation versus the rf voltage with and without precession. A larger amplitude of precession can be applied at higher rf voltages.

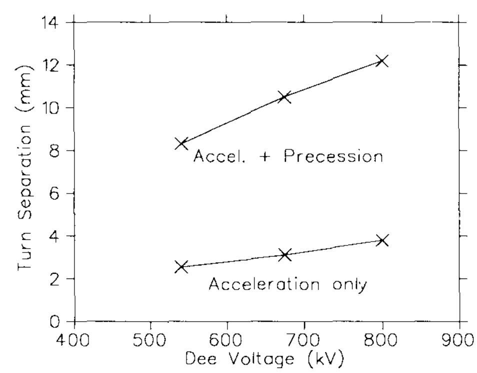

Figure 3: The turn separation at the extraction versus cavity voltage when the beam is injected centered (acceleration only) and off-centered.

3 Harmonic Error Fields and Their Correction

A part of the SRC trim coils will be independently excited on each sector to correct the harmonic error fields due to the stray fields, misalignments and manufacturing errors. As described previously, at the injection a couple of normal trim coils can be used in such a way to control the precession amplitude. In addition, harmonic excitations are needed to remove a third harmonic fourier component and its gradient which induce the ν_r=3/2 resonance. For cyclotrons such as the SRC to accelerate the beams to 300–400 MeV/u, it is unavoidable to traverse the ν_r=3/2 resonance. The gradient of the third harmonic causes the lowest order resonance, and a higher order for the third harmonic itself. The flat part of the third harmonic can be corrected, but correction may not be precise for the gradient.

At the ν_r=3/2 resonance, the relationship between the bump strength and the stop-band width was studied using static phase plots for O^{7+} beam. Figure 4 shows the phase space trajectories with a flat and gradient field bumps. The stable phase region becomes tilted as the beam approaches the resonance. The plots were made at 306 MeV/u with ν_r of 1.496. The flat bump is 37 gauss, the gradient being 0.3 gauss/cm. The gradient bump starts at the radius of 460 cm, while the average radius of the resonance is 480 cm. The amplitude of orbit scalloping of about 20 cm is taken into account. As a result the gradient bump practically contains a flat bump. At 308 MeV/u, ν_r becomes 1.5008, the radial stability being recovered for weak bumps. For instance if the flat bump is 5 gauss, most of the beam is within the stable region. But for the bump strengths used for Fig.4 the stable region is not yet returned. The stability becomes fully recovered at 310 MeV/u with ν_r of 1.506.

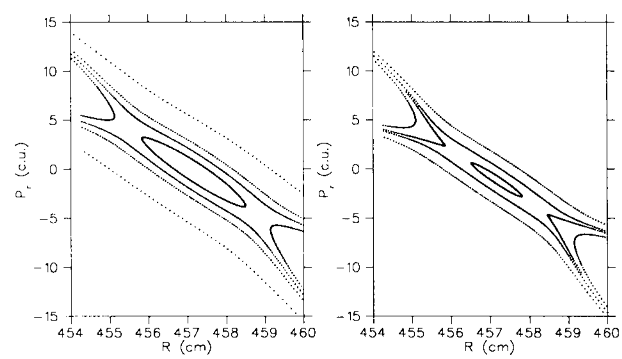

Figure 4: Left: A phase plot at 306 MeV/u with a third harmonic gradient of 0.3 gauss/cm. Right: with a flat third harmonic of 37 gauss.

It is expected that most of the flat component of the third harmonic can be removed by independent excitations of the main and some trim coils on each sector. The main coil current for harmonic excitation is set to be ±100 A in the present design, while the maximum is 5000 A. However, the gradient may not be accurately corrected due to the limited form factors of the trim coils. A further study is needed on that aspect.

To clearly see the effect of the resonance traversal on phase spaces, optics calculations have been made including the third harmonic errors prescribed. Figure 5 shows the case when the gradient is 0.3 gauss/cm starting at r=460 cm without off-centering. The phase space matched at injection oscillates after traversing the resonance because of mismatching with a new eigen-ellipse. Since the resonance can be traversed swiftly, the beam loss may not occur during acceleration, but the turn structure is disturbed. The last-turn separation is not clean even with an off-centering injection. The tolerable gradient is calculated to be about 0.1 gauss/cm. On the other hand the tolerance is higher for ions traversing the resonance at a larger radius such as for $^{84}Kr^{30+}$, 300 MeV/u.

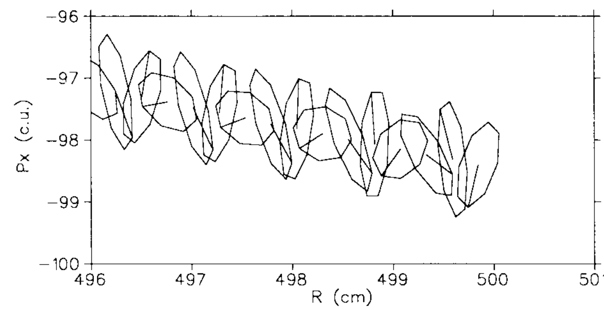

Figure 5: The phase space motion near extraction when the third harmonic gradient is 0.3 gauss/cm. Due to mismatch with a new eigen-ellipse, the phase ellipses are elongated and oscillate.

To estimate the probable harmonic error fields, three modes of misalignment are considered as shown in Fig. 6. First the effect of a radial displacement is relatively minor. With a displacement of even 1 cm by one sector, the third harmonic is about 10 gauss. Secondly when one sector is rotated by 0.05°, the profile of the third harmonic is shown in Fig. 7, along with the profiles when the main and trim coils are energized to produce the third harmonic. In this case correction can be mainly done with the main coils. The profile of the normal trim coils is the case that the largest gradient is produced with the current of 100 A, which shows the capability to correct the gradient errors. Thirdly the vertical displacement induces horizontal field components. The problem is that vertical alignment of the six sector magnets is not easy, considering difficulties in measuring the horizontal fields.

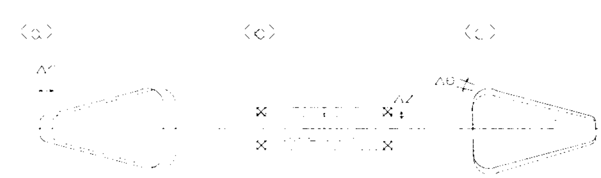

Figure 6: Three modes of misalignment.

A horizontal field component with a flat profile was included in orbit tracking to simulate the vertical off-centering errors. Assuming the $^{238}Ur^{58+}$ beam traverses the ν_z=1.5 resonance, the vertical motion was calculated as shown in Fig. 8 when the third harmonic of B_r is 1.5 gauss, which the case of a beam blow-up. The B_r error should be kept below 1 gauss if the resonance is tra-

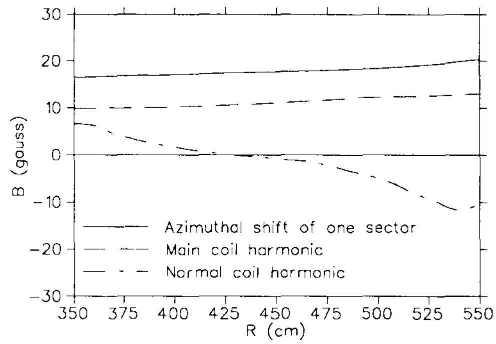

Figure 7: The third harmonic component when one sector is shifted by 0.05°, and the harmonic profiles when the main and normal trim coils are excited to produce the third harmonic.

versed. For q/A=0.5, ν_z is about 1.05 near 400 MeV/u. The beam blow-up is seen at about 40 gauss of the first harmonic of B_r.

Fortunately the magnitude of the horizontal component may be small if misalignment and manufacturing errors are maintained within tolerance. For instance with a displacement of 1 mm by one sector, the first and third harmonic of B_r are less than 1 gauss. In the SRC design, the main fourier component of the fields has been changed with a yoke modification to avoid the vertical resonances.

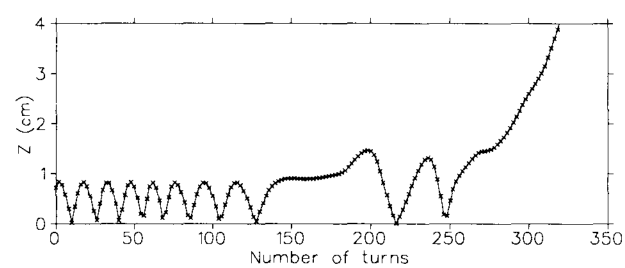

Figure 8: The vertical beam envelope for $^{238}Ur^{58+}$ accelerating to 150 MeV/u when the flat third harmonic of B_r is 1.5 gauss.

4 Space Charge Effect

The space charge effect will be serious on a high-current beam acceleration. In the RI beam factory, the first two accelerators are RFQ and linear accelerator which can provide both the transverse and longitudinal focusings. The space-charge limited beam current is higher than that of isochronous cyclotrons.

Following the linear accelerators the RRC is the first-stage in a chain of three cyclotrons. While the IRC and SRC which are the booster of the RRC will be equipped with a flat-topping cavity, the RRC is not. The phase width of the RRC beam is measured to be about 5 rf degrees with a momentum spread of $\pm 5\times10^{-4}$ in usual operation. But the phase width will become larger at high currents. Since the last-turn separation at the RRC is much larger than that at the SRC (for instance 2 cm by acceleration compared to 3.5 mm at the SRC for O^{7+} 400 MeV/u), a larger energy spread may be acceptable, but the beam quality deteriorates. The space charge effect at the RRC needs to be studied.

On the other hand, at the SRC the phase width can be larger than 20 rf degrees without increasing the momentum spread. However, in this case the total of the beam phase width and the phase excursion should not exceed the flat-topping width of an rf wave.

A sector model of charge distribution [6] was used to estimate the electric fields on the edges of the beam bunch. The space-charge limited current determined by the maximum allowable phase increase is calculated to be around 5 pμA for O^{7+}.

According to recent measurements using Ti beam, the charge distribution versus rf phase is quite symmetric. If the symmetry is kept at high currents, correction of the linear part of the space charge force can be effectively done by tuning the relative phase of the flat-topping cavity to the main cavity.

5 Conclusion

The last-turn separation at the SRC can be greatly increased with an off-centering injection. The traversal of the ν_r=3/2 resonance is a concern. Harmonic excitations of the main and trim coils may not accurately correct the third harmonic gradient in some cases. Investigations of the error fields and their correction schemes are underway in relation to the trim coil design. The vertical resonances of ν_z=1 and 1.5 have been tried to be avoided with a yoke modification. The space charge effect has been roughly estimated, and measurements would be needed for high current beams at the RRC.

References

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