NUMERICAL ANALYSES OF THE INJECTION AND EXTRACTION TRAJECTORIES FOR THE RIKEN SUPERCONDUCTING RING CYCLOTRON

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Abstract

Current status of numerical analyses of the injection and extraction trajectories for the RIKEN superconducting ring cyclotron is described. With numerical analyses, the difference of trajectories in the elements and required fields of the elements are minimized. As a result, layouts and specifications of the elements are optimized.

1 INTRODUCTION

For the RIKEN RI Beam Factory project[1], a six-sector superconducting ring cyclotron (SRC) is designed[2][3]. The SRC has strong stray fields from the sector magnets, and these fields strongly depend on the condition of acceleration. Thus, the trajectories of various beams differ very much from each other. And besides, the injection and extraction elements must be placed in small space limited with the sector magnets, the RF-cavities, and the beam chambers. These difficulties make the design of the injection and extracion systems challenging. The injection system consists of four bending magnets (BM1, BM2, BM3, and BM4), three magnetic inflection channels (MIC1, MIC2, and MIC3), and an electrostatic inflection channel (EIC). The extracion system consists of a bending magnet (EBM), three magnetic deflection channels (MDC1, MDC2, and MDC3), and an electrostatic deflection channel (EDC)[4].

To analyze the injection and extraction trajectories of the SRC, we modified a computer program originally developed to analyze injection beam trajectories of the existing four-sector normal-conducting RIKEN Ring Cyclotron (RRC). In this computer program, a Lorentz equation concerning the time is solved with Runge-Kutta-Gill method. Magnetic fields of sector magnets used in these analyses were calculated with a 3D-code 'TOSCA'. Magnetic field of each element was approximated to be constant in the element, and was added on the field of sector magnets. Voltage of double-gap cavity was assumed to be 230 kV at injection and 276 kV at extraction.

Table 1 shows energies and magnetic rigidities of typical beams.

In the case of 200 MeV/u(ext.) $^{16}O^{7+}$ and 150 MeV/u(ext.) $^{238}U^{58+}$, the difference of Bρ between the two beams becomes maximum, so that the difference of trajectories between the beams also becomes maximum. To minimize the bore of the elements, the difference of trajectories must be suppressed as small as possible.

Table 1: Energies and magnetic rigidities of typical beams.

	Energy Inj. [MeV/u]	Energy Ext. [MeV/u]	Bρ Inj. [Tm]	Bρ Ext. [Tm]
$^{16}O^{7+}$	74.2	200	2.89	4.90
$^{16}O^{7+}$	126.7	400	3.83	7.25
$^{238}U^{58+}$	58.0	150	4.57	7.52

2 INJECTION

Figure 1 shows schematic layout of the injection elements and the injection trajectories of typical beams.

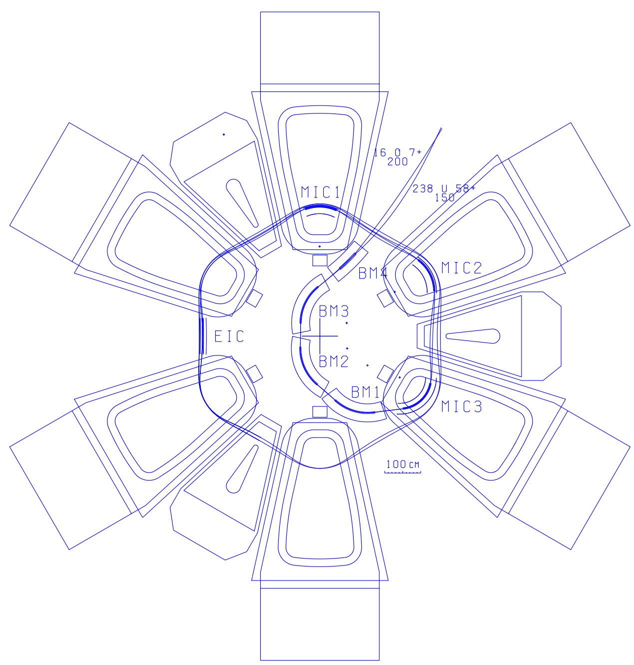

Figure 1: Schematic layout of the injection elements and the injection trajectories of typical beams.

Table 2 shows characteristics of the injection elements. For the acceleration of 400 MeV/u(ext.) $^{16}O^{7+}$, the EIC and MIC1 should generate the maximum fields. For the injection of 150 MeV/u(ext.) $^{238}U^{58+}$, the MIC2, MIC3, BM1, BM2, and BM3 should generate the maximum fields. The length of each element was determined in consideration of balance between the difference of trajectories in the element and required field of the element. Table 3 shows the differences of trajectories in the injection elements.

Table 2: Characteristics of the injection elements.

	Radius [cm]	Angle [deg]	Length [cm]	B or E maximum
EIC	variable	variable	100	95 kV/cm
MIC1	111	46.5	90	0.18 T
MIC2	110	52.5	101	0.27 T
MIC3	87	73.9	112	1.5 T
BM1	132	52.0	120	4.02 T
BM2	130	52.0	118	3.92 T
BM3	128	52.0	116	3.96 T
BM4	492.5	7.0	60	-0.8,+0.7 T

Table 3: Differences of trajectories in the injection elements.

	Difference [cm]
EIC (movable)	10
MIC1	1.0
MIC2	1.2
MIC3	1.2
BM1	0.9
BM2	0.7
BM3	0.5
BM4	2.3

2.1 EIC

Figure 2 shows the difference of trajectories in the EIC. The maximum change in the radius of the orbit is about 10 cm. Accordingly, the EIC must be movable in the radial direction by 10 cm, and the radius of curvature of the EIC should be adjustable in the range from about 10 m to almost infinity.

Performance of the EIC determines the turn separation between the first equilibrium orbits and the injection trajectories at the MIC1. The turn separation at the MIC1 is required about 5 cm to place the MIC1. To give this turn separation, the EIC is required to generate the maximum electric field of 95 kV/cm and to have the length of 1 m.

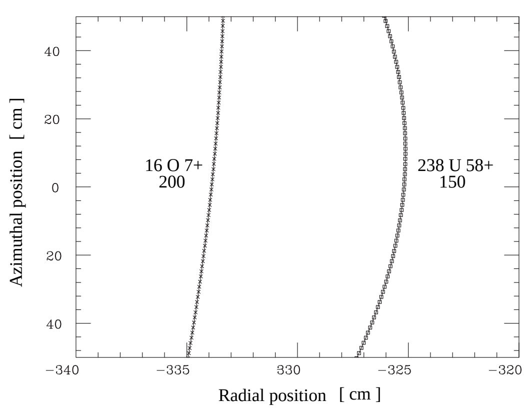

Figure 2: Difference of trajectories in the EIC.

2.2 MIC1

The MIC1 is required to generate the magnetic field of 0.18 T at the maximum with normal-conducting coils. Figure 3 shows the turn separation at the MIC1.

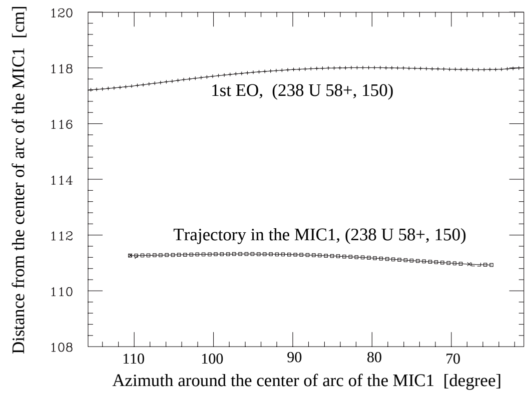

Figure 3: Turn separation at the MIC1.

2.3 MIC2

The MIC2 is required to give appropriate turn separation about 25 cm for the MIC3. To give this turn separation, the MIC2 generates the magnetic field of 0.27 T at the maximum with normal-conducting coils. The turn separation at the MIC2 is about 10 cm, so that the MIC2 has more space for coils than the case of the MIC1. Thus, the MIC2 can accomplish the maximum magnetic field of 0.27 T with almost the same current density as that of the MIC1.

2.4 MIC3

The MIC3 is required to generate the magnetic field of 1.5 T at the maximum with superconducting coils. The position of the MIC3 was determined in consideration of effective use of background magnetic field by the sector magnet.

2.5 BM1

The BM1 is required to generate the magnetic field of 4 T at the maximum with superconducting coils. The edge size and width of the BM1 are required as small as possible. Because the space to place the BM1 is extremely restricted by a yoke-link and a cryostat of the sector magnet. Because of high field and small space, design of the BM1 is most challenging[5].

2.6 BM2 and BM3

The BM2 and BM3 are required to generate magnetic field of 4 T at the maximum with superconducting coils.

2.7 BM4

The BM4 must accept various beams coming from a pre-accelerator. The beams come through a long valley with stray fields from sector magnets, so that the increment of the difference of trajectories in the BM4 is inevitable. To minimize the difference of trajectories, the BM4 generates magnetic field not only positive but also negative. The range of the field is from -0.8 T to +0.7 T, and the field is generated with superconducting coils. Therefore, the difference of trajectories in the BM4 can be less than 2.3 cm.

Figure 4 shows the difference of trajectories in the BM4.

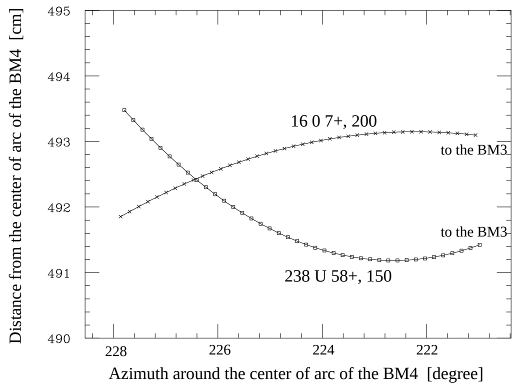

Figure 4: Difference of trajectories in the BM4.

3 EXTRACTION

The extracion system is similar to the injection system, so that the extraction trajectories were analyzed in almost the same way as for the injection trajectories. Analysis of the extraction trajectories has just been started.

Figure 5 shows schematic layout of the extraction elements and the extraction trajectories of typical beams.

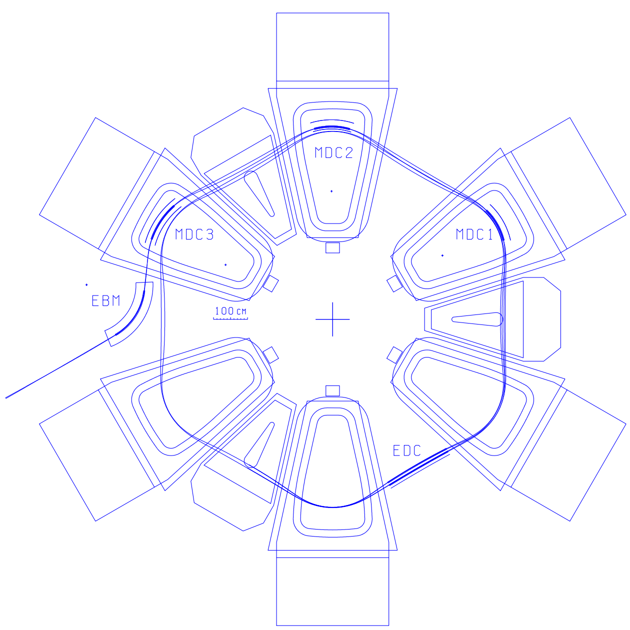

Figure 5: Schematic layout of the extraction elements and the extraction trajectories of typical beams.

Table 4 shows characteristics of the extraction elements. For the extraction of 400 MeV/u(ext.) ^{16} O $^{7+}$, the EDC, MDC1, and MDC2 should generate the maximum fields. For the extraction of 150 MeV/u(ext.) ^{238} U $^{58+}$, the MDC3 and EBM should generate the maximum fields.

Table 4: Characteristics of the extraction elements.

	Radius [cm]	Angle [deg]	Length [cm]	B or E maximum
EDC	variable	variable	200	100 kV/cm
MDC1	185	32.0	103	0.2 T
MDC2	190	32.0	106	0.3 T
MDC3	230	30.0	120	1.12 T
EBM	170	54.0	160	3.9 T

4 CONCLUSION

Layout and characteristics of the injection elements of the SRC have almost been determined. Preliminary layout and characteristics of the extraction elements have also been determined. Further optimization will be continued.

5 REFERENCES

[1] Y.Yano *et al.*, 'RIKEN RI-Beam Factory Project', in this proceedings.

[2] T.Mitsumoto *et al.*, 'Orbit Analysis for the RIKEN Superconducting Ring Cyclotron', in this proceedings.

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

[4] H.Okuno *et al.*, 'Design Study of the Injection and Extraction Systems for the RIKEN Superconducting Ring Cyclotron', in this proceedings.

[5] T.Tominaka *et al.*, 'Design Study of the Injection and Extraction Elements for the RIKEN Superconducting Ring Cyclotron', in this proceedings.