Analysis of the Injection and Extraction Trajectories in the RIKEN Superconducting Ring Cyclotron

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Abstract

Current status of the analysis of the injection and extraction trajectories in the RIKEN superconducting ring cyclotron is described. The purpose of this analysis is to optimize the layouts and specifications of the injection and extraction elements. For the optimization, differences of trajectories in the elements and required fields of the elements are minimized. Beam envelopes are also studied to adjust the beam width.

1 Introduction

For the RIKEN RI Beam Factory project, a six-sector superconducting ring cyclotron (SRC) is designed[1][2]. 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. 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 extraction 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 extraction system consists of a bending magnet (EBM), three magnetic deflection channels (MDC1, MDC2 and MDC3), and an electrostatic deflection channel (EDC)[3].

2 Method of the Analysis

To analyze the injection and extraction trajectories of the SRC, we modified a computer program originally developed to analyze injection and extraction 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 the sector magnets used in these analyses were calculated with a 3D-code "TOSCA". Magnetic field of each element was added on the field of the sector magnets. Voltage of one RF-cavity was assumed to be 460 kV at injection and 550 kV at extraction.

3 Property of the Beams

Table 1 shows energies and magnetic rigidities of typical beams. In the case of the oxygen beam of 200MeV/nucleon(Ext.) and the uranium beam of 150MeV/nucleon(Ext.), the difference of B ρ 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 [MeV/u] Inj.	Energy [MeV/u] Ext.	B ρ [Tm] Inj.	B ρ [Tm] Ext.
16 O 7+, (1)	74.2	200	2.89	4.90
16 O 7+, (2)	126.7	400	3.83	7.25
238 U 58+	58.0	150	4.57	7.52

4 Injection

Figure 1 shows schematic layout of the injection elements and the injection trajectories of typical beams. Table 2 shows specifications of the injection elements. The MIC3, BM1, BM2, BM3 and BM4 are superconducting. 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.

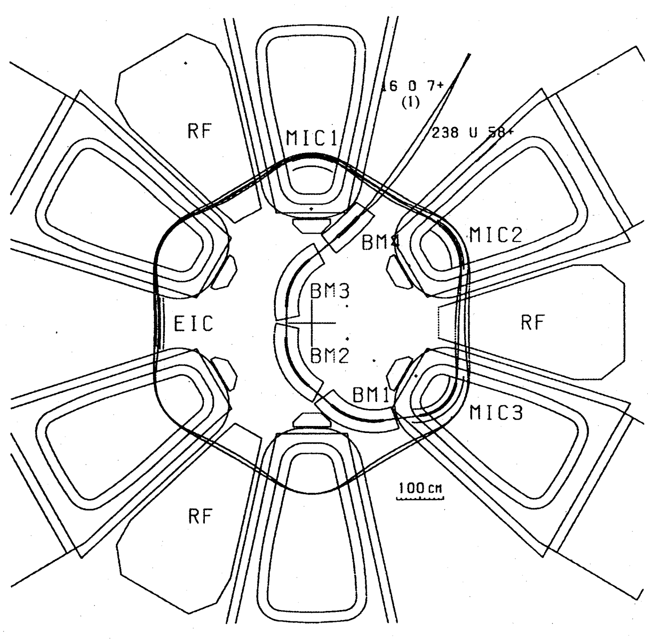

Fig.1 Schematic layout of the injection elements and the injection trajectories of typical beams.

Table 2
Specifications 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	130.5	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	1.3
BM1	0.9
BM2	0.6
BM3	0.7
BM4	2.5

4.1 Injection Elements

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. The turn separation between the first equilibrium orbits and the injection trajectories 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 electrostatic field of 95 kV/cm and to have the length of 1 m.

The MIC1 gives the turn separation about 10 cm for the MIC2. The MIC2 is required to give appropriate turn separation about 25 cm for the MIC3. The position of the MIC3 was determined in consideration of effective use of background magnetic field by the sector magnet.

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. The BM2 and BM3 have almost the same specification as that of the BM1. The BM4 must accept various beams coming from a pre-accelerator. The beams come through a long valley with stray fields from the 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 not only positive magnetic field but also negative one. Therefore, the difference of trajectories in the BM4 can be less than 2.5 cm. Figure 3 shows the difference of trajectories in the BM4.

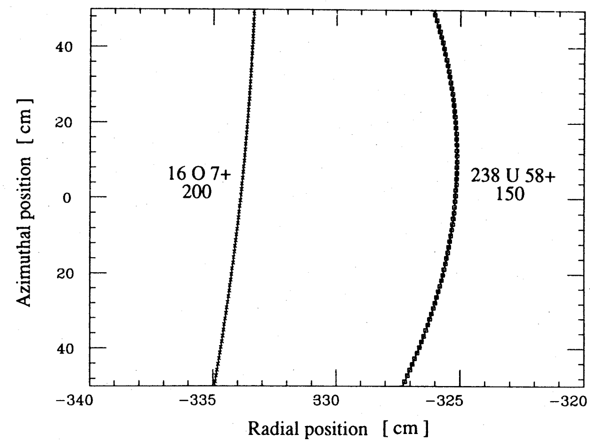

Fig.2 Difference of trajectories in the EIC.

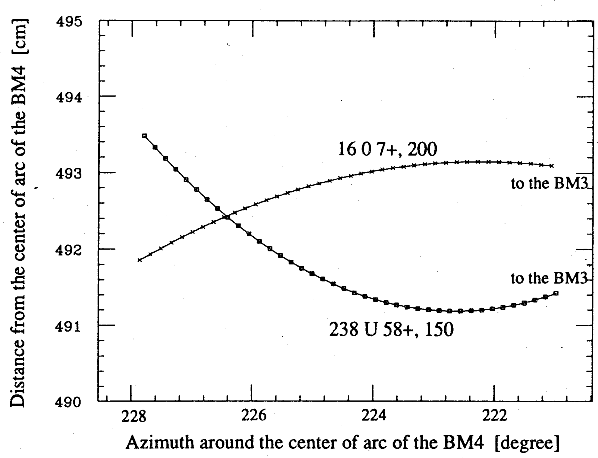

Fig.3 Difference of trajectories in the BM4.

4.2 Injected Beam Envelopes

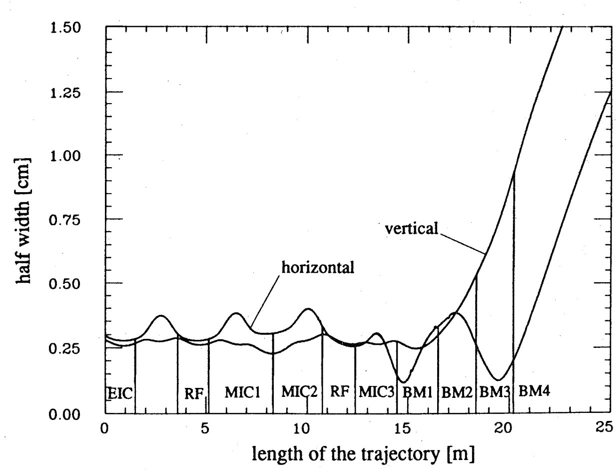

Fig.4 Envelopes of the injected beam of uranium, without gradient-field-coils.

Figure 4 shows the envelopes of the injected beam of uranium. Emittance at the injection point was assumed to be 10 μ m·rad. The beam widens around the BM2, BM3 and BM4. To suppress the beam spread, we added gradient-field-coils generating 200 gauss/cm at the maximum in the BM2 and in the BM3. Figure 5 shows the adjusted envelopes of the injected beam.

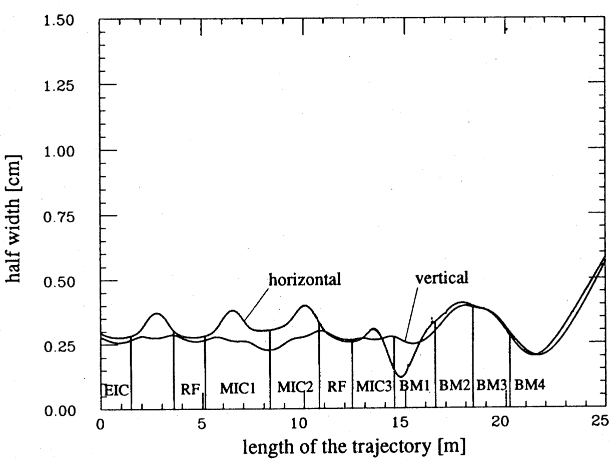

Fig.5 Envelopes of the injected beam of uranium, adjusted with gradient-field-coils.

5 Extraction

The extraction system is similar to the injection system, so that the extraction trajectories were analyzed in almost the same way as for the injection trajectories. Figure 6 shows schematic layout of the extraction elements and the extraction trajectories of typical beams. Table 4 shows specifications of the extraction elements. The MDC3 and EBM are superconducting. Table 5 shows the differences of trajectories in the extraction elements.

Figure 7 shows the envelopes of the extracted beam of uranium. In consideration of adiabatic damping, emittance at the extraction point was assumed to be 6.6 μm•rad. Width of the extracted beam is small enough. Thus, additional gradient-field-coil is not necessary.

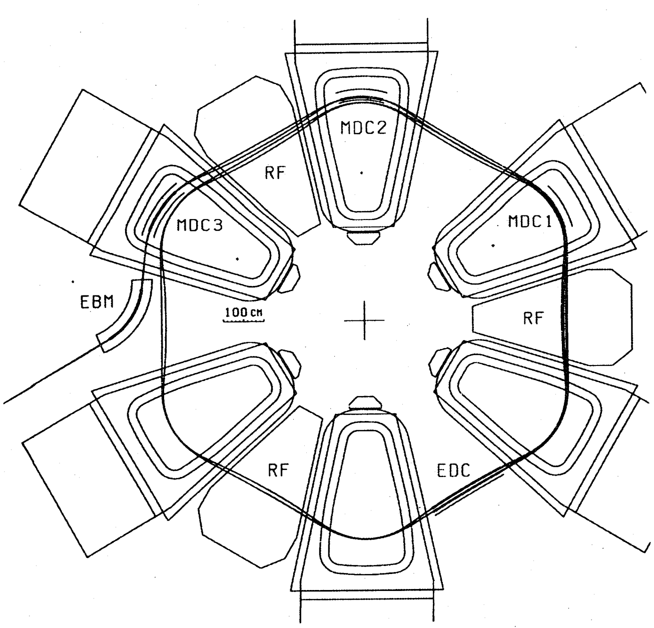

Fig.6 Schematic layout of the extraction elements and the extraction trajectories of typical beams.

Table 4
Specifications of the extraction elements.

	Radius [cm]	Angle [deg.]	Length [cm]	B or E maximum
EDC	variable	variable	199	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	175	52.0	159	3.9 T

Table 5
Differences of trajectories in the extraction elements.

	Difference [cm]
EDC(movable)	10
MDC1	0.6
MDC2	0.6
MDC3	1.2
EBM	1.1

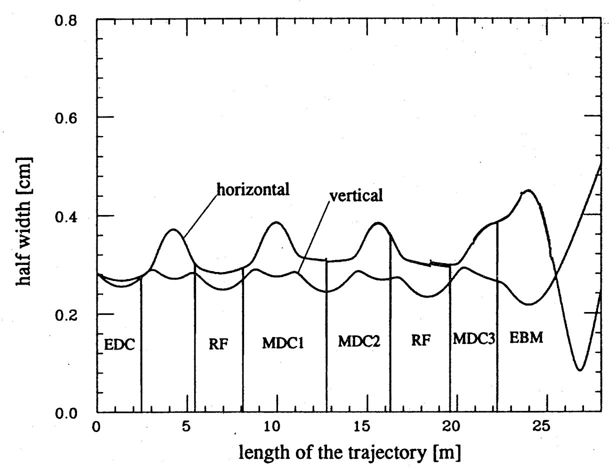

Fig.7 Envelopes of the extracted beam of uranium.

6 Conclusion

Layout and specifications of the injection and extraction elements of the SRC have almost been optimized. Further optimization is in progress.

References

[1] A.GOTO et al., "Superconducting Ring Cyclotron for the RIKEN RI Beam Factory", in this proceedings.
[2] T.MITSUMOTO et al., "Orbit Analysis for the RIKEN Superconducting Ring Cyclotron", in this proceedings.
[3] H.OKUNO et al., "Design Study of the Injection and Extraction systems for the RIKEN Superconducting Ring Cyclotron", in this proceedings.