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

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Design of a six-sector Superconducting Ring Cyclotron for the RIKEN RI Beam Factory project is in progress. Purpose of present analysis is to optimize the layouts and specifications of the injection and extraction elements in the SRC. For the optimization, the required fields of the elements and the differences of trajectories in the elements were minimized. Beam envelopes were also studied to adjust the beam width.

1 Introduction

The RIKEN Superconducting Ring Cyclotron (SRC)[1] has strong stray field from the sector magnets, and this field depends non-linearly on the magnetic rigidities of the beams. Thus, the trajectories of various beams differ considerably from each other. Besides, the injection and extraction elements should be installed in a small space limited with the sector magnets, RF-cavities, and beam chambers. These difficulties make the design of the injection and extraction systems challenging.

2 Property of the beams

Table 1 shows energies and magnetic rigidities of three typical beams. The beam of ^{16} O $^{7+}$ (1) has minimum magnetic rigidity. On the other hand, the beam of ^{238} U $^{58+}$ has maximum one. Between these two beams, the difference of trajectories becomes the maximum. The beam of ^{16} O $^{7+}$ (2) has maximum electric rigidity.

Table 1 : Energies and magnetic rigities of typical beams.

	Energy [MeV/u]		$B\rho$ [Tm]	
	Inj.	Ext.	Inj.	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

3 Composition of the injection and extraction systems

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). To minimize the bore of the elements, the difference of trajectories in the elements must be suppressed as small as possible. Length of each element was determined in consideration of the balance between the difference of trajectories in the element and the required field of the element.

4 Method of the analysis

For the analysis, an equation of motion was solved with Runge-Kutta-Gill method. Electric or magnetic field of each element was superimposed on the field of the sector magnet calculated with a three-dimensional computer code, "TOSCA".[2]. Trace direction of the injected beam is backward from the injection points, that is from the EIC to the BM4. On the other hand, trace direction of the extracted beam is forward from the extraction points, that is from the EDC to the EBM.

5 Layouts and Specifications

Figure 1 shows schematic layouts of the injection and extraction elements, and trajectories of two typical beams of ^{16} O $^{7+}$ (1) and ^{238} U $^{58+}$. Because of stray field in the valley, two trajectories differ considerably from each other. All MICs and MDCs are installed between upper and lower main coils of the sector magnets. Table 2 shows specifications of the injection elements. The MIC3 and all BMs are superconducting. Table 3 shows specifications of the extraction elements. The MDC3 and EBM are superconducting. Each magnetic element consists of main dipole coils and compensation coils. Table 4 shows difference of trajectories and gap in the elements.

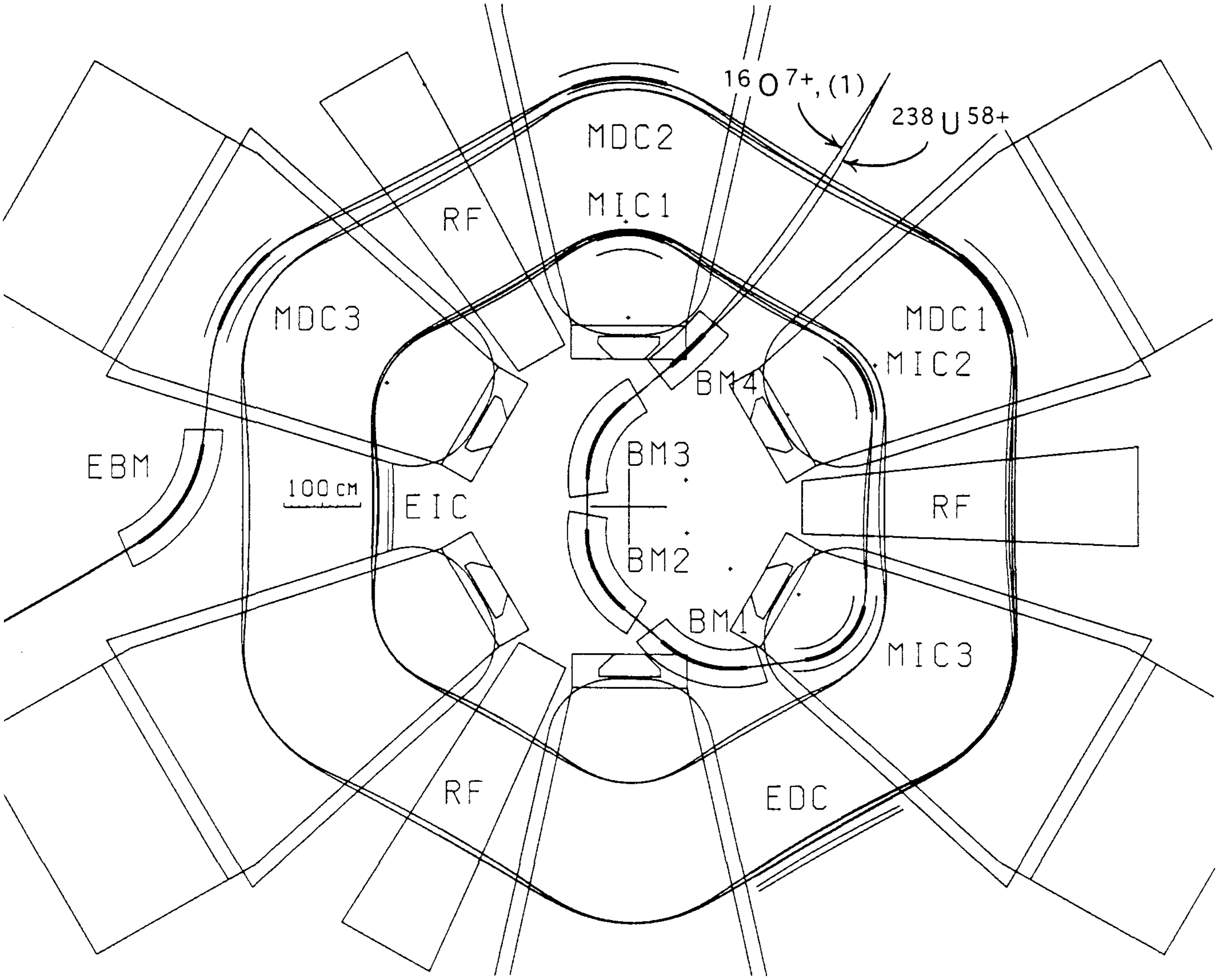

Figure 1: Schematic layouts of the injection and extraction elements and trajectories of two typical beams.

Table 2 : Specifications of the injection elements.

	Radius [cm]	Angle [deg.]	Length [cm]	Max. Field [kV/cm], [T]
EIC	variable	variable	100	110
MIC1	111.0	46.5	90	0.17
MIC2	110.0	52.5	101	0.28
MIC3	87.0	73.9	112	1.57
BM1	132.0	52.0	120	4.00
BM2	130.5	52.0	118	3.99
BM3	128.0	52.0	116	3.97
BM4	492.5	7.0	60	+0.69, -0.67

Table 3 : Specifications of the extraction elements.

	Radius [cm]	Angle [deg.]	Length [cm]	Max. Field [kV/cm], [T]
EDC	variable	variable	210	-110
MDC1	185.0	38.0	123	-0.19
MDC2	190.0	38.0	126	-0.28
MDC3	230.0	30.0	120	-1.01
EBM	175.0	52.0	159	-4.04

Table 4 : Difference of trajectories and gap in the elements.

	Difference [mm]	Gap H * V [mm]
EIC	70	12
MIC1-BM3	10	40*30
BM4	20	50*30
EDC	85	12
MDC1-EBM	10	40*30

6 Injection

6.1 EIC

Figure 2 shows trajectories in the EIC. Maximum difference of trajectories is 7 cm, therefore the EIC should be movable in the radial direction by 7 cm. Besides, radius of curvature should be changed from 10 m to 43 m. To adjust curvature, the EIC consists of three arcs conected with two hinges. For the injection of the beam of ^{16} O $^{7+}$(2), the EIC should generate maximum field of 110 kV/cm to make turn separation to install the MIC1. The gap between electrodes will be 12 mm. E*V value of 14520 $(\mathrm{kV})^2$/cm is considerably high. Therefore, R&D for the EIC is planed to establish its feasibility.

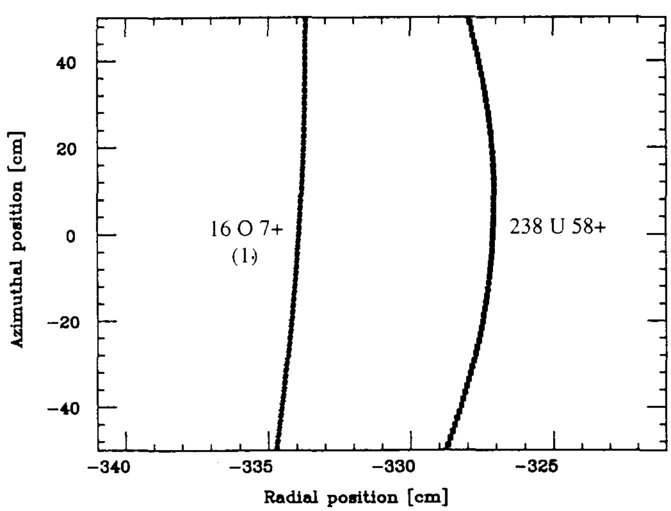

Figure 2 Trajectories in the EIC.

6.2 MIC1

Figure 3 shows turn separation between 1st equilibrium orbit (1st E.O.) and injection trajectories in the MIC1. Horizontal space for the MIC1 is limited with turn separation of 5 cm, and vertical space is limited with the gap of 60 mm in the beam chamber of the sector magnet. Besides, on the 1st E.O., fringe field from the MIC1 should be suppressed less than 100 gauss. Therefore, a normal-conducting dipole magnet with copmpensation coil was adopted as the MIC1. In consideration of power consumption and cooling, overall current density of the MIC1 is planed to be about 25 A/mm^2.

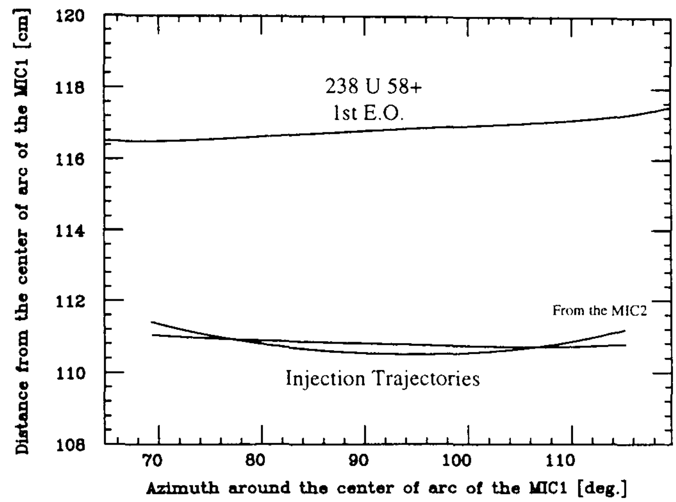

Figure 3: Turn separation at the MIC1.

6.3 MIC2

Turn separation at the MIC2 is about 12 cm and still insufficient to install superconducting magnetic channel, therefore, the MIC2 is normal-conducting. Basic structure of the MIC2 is similar to that of the MIC1, but space to place coil is larger, so that the MIC2 can generate stronger field than that of the MIC1 with almost the same current density.

6.4 MIC3

Turn separation at the MIC3 is about 25 cm. Position of the MIC3 was detemined especially in consideration of effective use of the background field by the sector magnet. The superconducting MIC3 is installed in a cryostat separated from the beam chamber of the sector magnet. Because of small bending radius of 87 cm, it may be difficult to support inner coils of the MIC3 perfectly. How to wind and support inner coils is the key of stability of superconducting state in the MIC3. Overall current density of the MIC3 is planed to be about 150 A/mm^2. Prototype of the MIC3 will be fabricated in this fiscal year.

6.5 BM1

Edge size of the BM1 is required as small as possible to minimize the distance between a cryostat of the sector magnet and coil of the BM1. Therefore, no-bend-up coil structure was adopted for the BM1[3]. Overall current density of the superconducting BM1 is planed to be about 200 A/mm^2.

6.6 BM2 and BM3

Basic structures of the BM2 and BM3 are similar to that of the BM1, but gradient-field-coils are built additionaly in the BM2 and BM3 to adjust beam envelopes.

6.7 BM4

Figure 4 shows trajectories in the BM4. The BM4 must accept various beams coming through a long valley filled with stray field, so that large difference of trajectories is inevitable. But, to suppress the difference of trajectories as small as possible, the BM4 generates not only positive field in the case of $^{238}U^{58+}$, but also negative field in the case of $^{16}O^{7+}$(1). Besides, length of the BM4 was shortened compared with other bending magnets. Consequently, the difference of trajectories in the BM4 was suppressed to be 20 mm. Because of still large difference of trajectories, only BM4 has wider horizontal gap of 50 mm. Overall current density of the superconducting BM4 is planed to be about 75 A/mm^2.

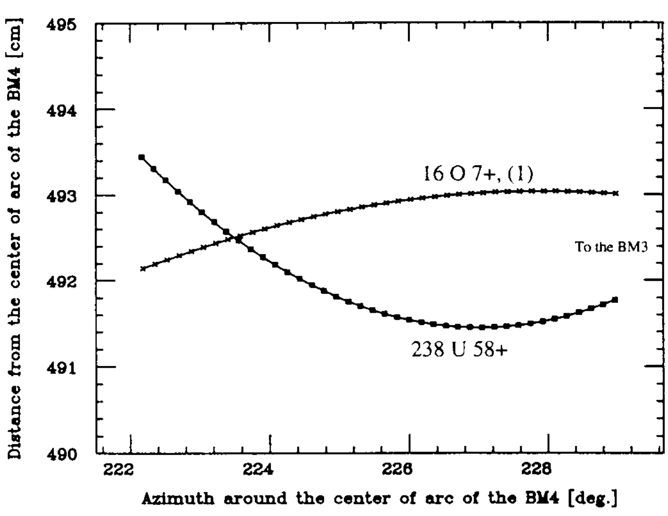

Figure 4: Trajectories in the BM4.

6.8 Envelope

Figure 5 shows envelopes of the injected beam of $^{238}U^{58+}$. Emittance was assumed to be 3π mm mrad. To suppress the beam spread, the envelopes were adjusted with field gradient of 350 gauss/cm generated by the gradient-field-coils built in the BM2 and BM3.

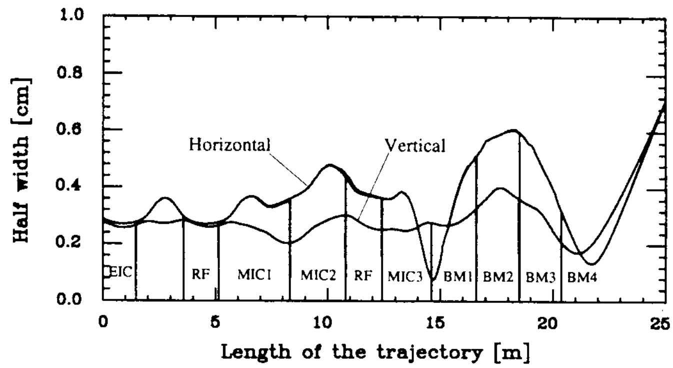

Figure 5: Envelopes of the injected beam, adjusted with gradient-field-coils.

7 Extraction

The extraction system is similar to the injection system. Layout and specifications of the extraction elements were optimized in the same way as the injection elements.

8 Conclusion

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

References

[1] A. Goto et. al., " The K2500 Superconducting Ring Cyclotron of the RIKEN RI Beam Factory -Overview and Status- ", 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 for the Injection and Extraction Systems for the RIKEN Superconducting Ring Cyclotron ", in this proceedings.