DESIGN OF NEW SUPERCONDUCTING RING CYCLOTRON FOR THE RIBF

J. Ohnishi, H. Okuno, M. Nakamura, RIKEN Nishina Center, Wako, Saitama, Japan

Abstract

In order to increase the current of uranium beams by more than five times at the RI-Beam Factory (RIBF), we conducted a design study for a new superconducting ring cyclotron (SRC2 in this paper). It is a replacement for the existing fixed-frequency ring cyclotron (fRC) for accelerating U^{64+}, and it will enable us to accelerate U^{35+} extracted from an ion source from a beam energy of 11 MeV/u to 48 MeV/u. The SRC2 consists of four superconducting sector magnets. The maximum magnetic field in the beam orbit area is 3.4 T. This paper discusses electromagnetic forces acting on the coils and their support structure. We also successfully designed the beam injection and extraction system. A superconducting magnetic channel used for the beam injection line has been also designed. We found no significant problems in these fundamental designs.

INTRODUCTION

One of the most important goals for accelerators is to increase the current of primary beams because experiments on nuclear physics using rare RI-beams with a small production cross section are the main types of experiments performed at the RIBF. Because uranium beams are particularly important in the production of these rare RI-beams, increasing the strength of uranium beams is strongly desirable for RIBF experiments. Uranium beams are accelerated by an RFQ, a DTL linac, and four ring cyclotrons (RRC, fRC [1], IRC, and SRC [2]), as shown in Fig. 1. U^{35+} ions extracted from the 28-GHz ECR ion source are converted to U^{64+} at the first charge stripper (CS) after the RRC and to U^{86+} at the second one after the fRC. The converting efficiencies of the two CSs are approximately 18% and 27%, respectively, and the total transmission efficiency from the ion source to the exit of the SRC is approximately 1/200, which is considerably low. Accordingly, we have investigated the design of a second superconducting ring cyclotron (SRC2 in this paper) to replace the fRC, which can accelerate U^{35+} without any need for the first CS. By introducing the SRC2, a more than five-fold increase of the transmission efficiency can be expected by omitting the first CS and a reduction of the beam dispersion caused by the CS. In order to reduce the construction cost, the design policies of the SRC2 are as follows: (1) use of a fixed acceleration frequency, (2) use of four sector magnets, (3) use of cryocoolers, and (4) use of normal-conducting-type trim coils.

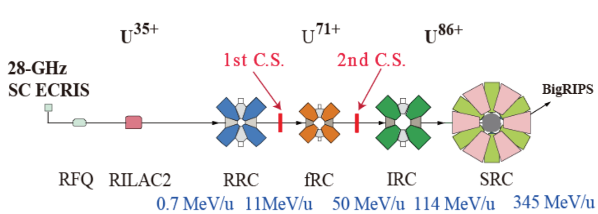

Figure 1: Existing acceleration system for U beam.

NEW SUPERCONDUCTING RING CYCLOTRON

The list of parameters and the plan view of the SRC2 are given in Table 1 and Fig. 2, respectively. The number of sector magnets is four and the K-value is 2200. Two accelerating RF cavities and a flattop cavity are used. The acceleration RF frequency is 36.5 MHz, which is the same as that of RILAC2, and the harmonic number is 9. Although the accelerating RF voltage needs more than 500 kV per cavity, the RF cavities have not yet been designed.

Table 1: SRC2 Parameters

K-value			2220
Energy	injection	MeV/u	10.8
	extraction	MeV/u	48
RF frequency		MHz	36.5
Harmonics			9
Average radii	injection	m	1.775
	extraction	m	3.65
Tune	ν_r		1.09-1.15
	ν_z		0.71-0.76

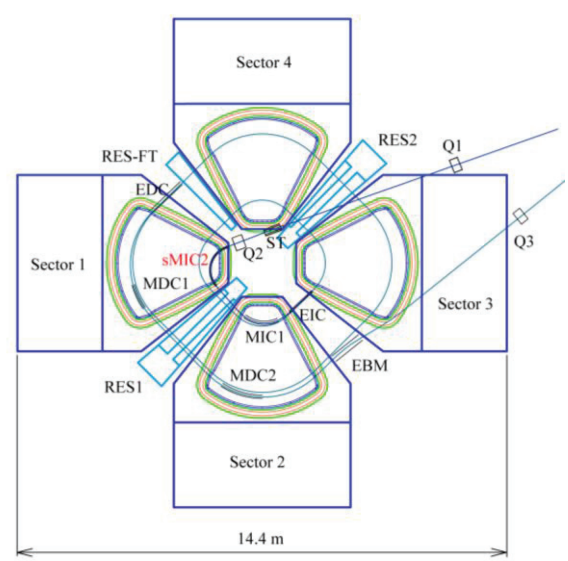

Figure 2: Plan view of new superconducting ring cyclotron.

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Table 2: Superconducting Sector Magnet Parameters

No. sector		4
Yoke weight	t	1200
Pole gap	mm	180 + 200
B_{max} on orbit	T	3.4
Magnetomotive force	MA/sector	1.9
Stored energy	MJ/sector	19.6
Main coil		
Cross section	mm	100 × 100
Perimeter	m	10.9
B_{max} on coil	T	4.5
Conductor		NbTi/Cu
Cu/NbTi ratio		5
Load rate		0.6
Temperature rise on quench	K	110

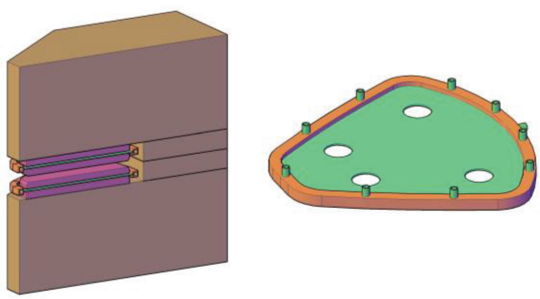

Figure 3: Half-cut model of sector magnet and support structure of main coil.

Sector Magnet

The list of parameters and an illustration of the half-cut model of the sector magnet are given in Table 2 and Fig. 3, respectively. The sector magnets use superconducting main coils and 20 normal-conducting trim coils, and the weight of the yokes of one sector is approximately 1200 t. The maximum magnetic field in the beam orbit region is 3.4 T. The magnetic poles have three gaps. The height of the central gap is 180 mm, which is determined by the height of the superconducting magnetic channel (sMIC2) installed into the gap. The two upper and lower gaps are 100 mm each, in which the cryostat to contain the main coil vessel and their support plate are installed. Because the beam energy is fixed, the isochronous magnetic field can be generated with the only 20 normal-conducting trim coils by optimizing the pole shape. The currents of the trim coils were calculated to be less than ~600 A (15 Gauss). We confirmed that the isochronous magnetic fields can be generated for not only U^{35+} but also the ions with M/Q = 2.

Superconducting Main Coil

The maximum magnetic field of the superconducting main coils is 4.5 T. Superconductors use NbTi/Cu monolith round wires with a diameter of 3 mm and a Cu/NbTi ratio of approximately 5. The size of a section is 100 mm × 100 mm and the perimeter of the main coils is and 10.9 m. The coils are epoxy-impregnated type and

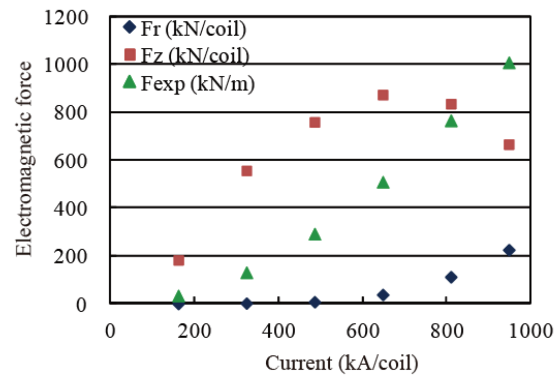

Figure 4: Electromagnetic force acting on the main coil as calculated by Opera-3d [3]. F_r indicates a radial force from the cyclotron center to the outside. The vertical force F_z works in the upward direction for the upper coil. F_{exp} indicates the expanding force of the coils per unit length.

bath-cooled in liquid helium. The total stored energy is 19.6 MJ per sector, and the load rate of the superconducting wires is 0.6. When a coil quench occurs, all stored energies are consumed as a temperature rise of the coils. The average temperature rise of the coils is estimated to be 110 K. Figure 4 shows the electromagnetic forces in the radial, vertical, and expansion directions as a function of the main coil current. The expansion force is supported by a stainless plate with a thickness of 20 mm. In the case that the thickness of the main coil vessel is 30 mm, the maximum deformation of the coil vessel was calculated to be approximately 1 mm by ANSYS [4], and the stress on the plate was approximately 230 MPa, which is a tolerable value. Glass-fiber reinforced plastic (GFRP) multi-cylinders are used for support in the radial and vertical directions in order to reduce the heat leak to liquid helium temperature. The use of these GFRP thermal insulation supports and high *Tc* current leads enables cooling with GM/GMJT cryocoolers in the same manner as the cooling of the superconducting dipole (33 MJ) of the SAMURAI spectrometer at the RIBF [5].

BEAM INJECTION AND EXTRACTION

The injection and extraction orbits for the SRC2 are shown in Fig. 2. For beam injection, superconducting and normal-conducting magnetic channels (sMIC2 and MIC1) and an electrostatic channel (EIC) are used. For beam extraction, an electrostatic channel (EDC), two normal magnetic channels (MDC1 and MDC2), and an extraction bending magnet (EBM) with the N-value are used. The ST in the injection line indicates a steering magnet, which also has the function of a magnetic shield. Table 3 lists the parameters of these devices for U^{35+} beams. The magnetic channels of a normal type other than sMIC2 have the almost same design as those of the SRC [6]. The beam envelopes for the injection and extraction are shown in Fig. 5. The beam emittances for the injection and extraction were supposed to be 3π and 1.5π mm mrad, respectively. The blue lines represent the envelopes for

Table 3: Injection and Extraction Device Parameters

	Length (m)	Magnetic/Electric field (T) (kV/cm)
sMIC2	1.47	1.74
MIC1	1.03	0.25
EIC	0.9	90
EDC	1.3	95
MDC1	0.76	−0.08
MDC2	1.26	−0.28
EBM	0.99	1.75 + (2 T/m)

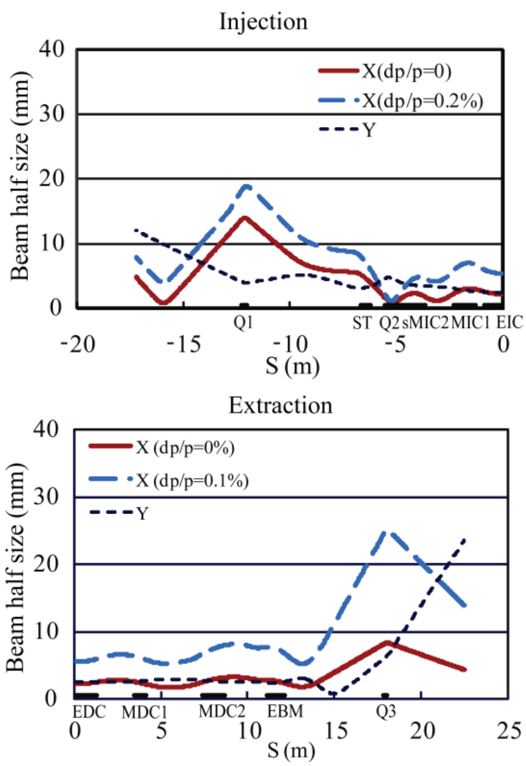

Figure 5: Beam envelope along the injection and extraction orbit. The blue line indicates the envelope for the beams with momentum dispersion.

the beams with momentum dispersion of 0.2% and 0.1% for injection and extraction, respectively. Although the injection beams are affected by a magnetic field gradient induced by the main coil around the outside of the sector 1 ($s = -10$ m) and the extraction beams are affected similarly around the outside of the sector 4 ($s = 13$ m), it is expected that the beams can be injected and extracted without any loss.

Superconducting Magnetic Channel (sMIC2)

The magnetic channel sMIC2 is the only superconducting channel of the injection and extraction devices. The sMIC2 is installed inside the pole gap of the sector magnet. The sMIC2 produces a magnetic field of 1.7 T in addition to the magnetic field of 3.2 T of the sector magnet. As shown in Fig. 6, the sMIC2 consists of two coils located on the upper and lower sides of the beam orbit (coil A), two coils located on both sides of the beam orbit (coil B), and upper and lower iron poles. Coils A and B are arranged so that the magnetic field leakage to the circulation orbit is reduced. The parameters of coils A and B are listed in Table 4. The coils use NbTi/Cu conductors and are impregnated with epoxy, and they are bath-cooled by liquid helium. The maximum magnetic fields on coils A and B are 6.1 T and 5.2 T, and the load rates of the conductor for both coils are 0.68 and 0.67, respectively.

Table 4: Superconducting Magnetic Channel sMIC2 Parameters

		Coil A	Coil B
No. coils		2	2
Section size	mm	28 × 20	14 × 52
Perimeter	m	1.7	1.7
Current	kA/coil	80	193
Stored energy	kJ	12.4	17.5
B_{max} on coils	T	6.1	5.2
Conductor		NbTi/Cu	NbTi/Cu
Averaged current	A/mm^2	143	265
Cu/NbTi ratio		1.3	1.3
Load rate		0.68	0.67
Temperature rise on quench	K	40	40

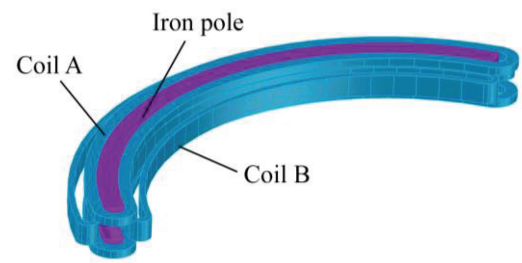

Figure 6: Superconducting magnetic channel sMIC2.

CONCLUSION

We performed a design study of the new superconducting ring cyclotron (SRC2), which has a K-value of 2200. It is a replacement for the existing fRC and will enable us to accelerate U^{35+} ions from 11 MeV/u up to 48 MeV/u. In this study, a fundamental design of the sector magnet and the beam injection and extraction system was conducted. Though there were no significant problems in the extent of our study, more detailed designs for the sector magnet, the sMIC2 and RF cavities are required to conclude the feasibility of the SRC2.

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