THE MAGNETIC FIELD OF THE SUPERCONDUCTING RING CYCLOTRON

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Abstract

The magnetic field mapping of the superconducting ring cyclotron (SRC) was made in the spring of 2006 before installing the RF resonators. The deviation of the magnetic field on the center lines of the sector magnets from the TOSCA calculations was smaller than 110 G (0.35%) at a maximum excitation, and their dispersion was within about 20 G, except that the one sector 'SM1' was smaller than the others by about 50 G. Not only the differences among the sectors but also the injection and extraction magnets generate large harmonic magnetic fields. These harmonic fields can be adjusted with the auxiliary power supplies connected with the main and the trim coils of three pairs of the sectors (SM6-SM1, SM2-SM3, SM4-SM5). The isochronous magnetic field with the harmonic field corrected was calculated from the mapping data, and the acceleration of the first beam 345 MeV/u Al^{10+} succeeded for a short time without adjusting the trim coil currents in December 2006.

INTRODUCTION

The superconducting ring cyclotron (SRC) [1] is the last-stage accelerator of the RIBF accelerator complex with a k-value of 2600 MeV and is able to accelerate all ions to energy of larger than 345 MeV/u [2]. The injection and extraction radii are 3.56 m and 5.36 m, respectively. The maximum magnetic field on the beam orbit is 3.8 T. Figure 1 shows a plan view of the SRC. The SRC is composed of six superconducting sector magnets (SM1~SM6) and five RF resonators (Res1~Res4, FT). The RF frequency can be changed from 18 MHz to 38 MHz. The harmonics is six. The acceleration of the first beam of 345 MeV/u Al^{10+} succeeded in December 2006 and 345 MeV/u U^{86+} beams in March of 2007 [3].

MAGNETIC FIELD PURTURBATION DUE TO THE INJECTION AND EXTRACTION ELEMENTS

As shown in Fig. 1, the beam injection and extraction system consists of a superconducting dipole (SBM), magnetic channels (MIC1,MIC2, MDC1, MDC2, MDC3), electrostatic deflectors (EIC, EDC), and the normal extraction dipole (EBM). Their operation parameters are listed in Table 1. As shown in Fig. 2, the MIC2 and the MDC3 use iron bars to generate a strong magnetic field and each has two coils excited by individual power supplies to reduce the stray magnetic field to the acceleration orbit. On the other hand, the Iron yokes of the EBM (17 tons) and the SBM (6 tons) absorb the

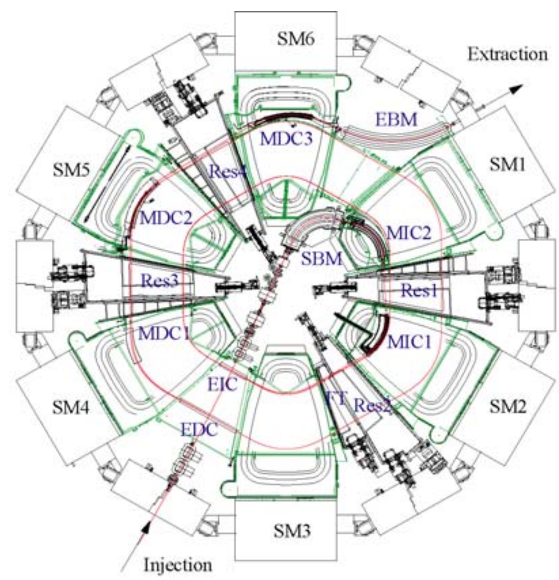


Figure 1: A plan view of the SRC

Table 1: Parameters of the injection and extraction elements in the acceleration of 345 MeV/u U^{86+} beam.

injection			extraction		
SBM	3.6	T	EDC	95	kV/cm
MIC2	0.9	T	MDC1	-0.075	T
MIC1	0.29	T	MDC2	-0.15	T
EIC	95	kV/cm	MDC3	-0.51	T
			EBM	-2.0	T

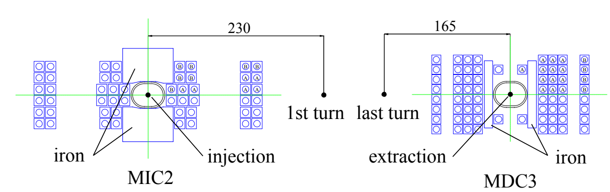


Figure 2: Cross-sections of the MIC2 and the MDC3.

magnetic field in inverse direction (-0.04T~-0.08T) in the valley region and make a large first harmonic field.

For example, if an error field of 100 G exists in the region of 30 degrees in the acceleration of the U^{86+} 345 MeV/u ions, the beam orbit distortion is calculated to be 6 mm in the injection side and 11 mm in the extraction side, where the betatron tunes are 1.18 and 1.49, respectively. If this error magnetic field exists in the radial range of

Table 2: The rated currents of the power supplies for the superconducting main and trim coils.

unit: A

	SM6	SM1	SM2	SM3	SM4	SM5
Main coil	5000					
aux. PS	-100	-100	-100	-100	-100	-100
Trim coil 1	3000					
aux. PS	-400		-400			
Trim coil 2-4	3000					
aux. PS	-100		-100			

200 mm, the beam phase changes by 28 degrees of the RF frequency (36.5 MHz), where the acceleration voltage is 2 MV/turn and the turn separations are 3.4 mm in the extraction region. From these estimations we need to reduce the error field to about a tenth of the above value.

TRIM COILS AND POWER SUPPLIES

The sector magnets have superconducting trim coils and normal trim coils. The superconducting trim coils have eleven blocks located at intervals of about 20 cm and are excited with four main power supplies. Table 2 shows a list of the rated currents of the power supplies for the superconducting main and trim coils. The main coils have six auxiliary power supplies and the currents can be adjusted by the sectors to correct the harmonic magnetic fields. Similarly, each superconducting trim coil has two auxiliary power supplies and the currents can be adjusted by three pairs of the sectors (SM6-SM1, SM2-SM3, SM4-SM5). Since the isochronous magnetic fields formed by the superconducting trim coils have a deviation of about 2 x 10^{-3}, they are corrected by the normal trim coils composed of 22 pairs of one-turn coils. The normal trim coils located in the mid region (5~18) are excited in series of the six sectors. Both four pairs at the injection and extraction sides (1~4, 19~22) are excited individually by the same three pairs of the sectors as the superconducting ones to correct the harmonic magnetic field generated by the injection and extraction elements.

MAGNETIC FIELD MEASUREMENTS

The magnetic field mapping was done with Hall probes in a whole orbit area. The intervals were about 50 mm. The magnetic fields generated by the superconducting main and trim coils were measured at ten levels of the main coil current from 1800 A to 5000 A. The total number of the measuring days, maps, and points were 50, 390 and 3,300,000, respectively.

THE MAGNETIC FIELD DISTRIBUTION ALONG THE SECTOR CENTER LINE

Figure 3 shows the deviation of the magnetic field distributions along the center lines of the six sectors from the TOSCA calculations at a main coil current of 5000 A. Except for the injection and extraction regions, the measured values are smaller than the calculated ones by 110~180 G (0.35%~0.58) for the SM1 and 40~110 G

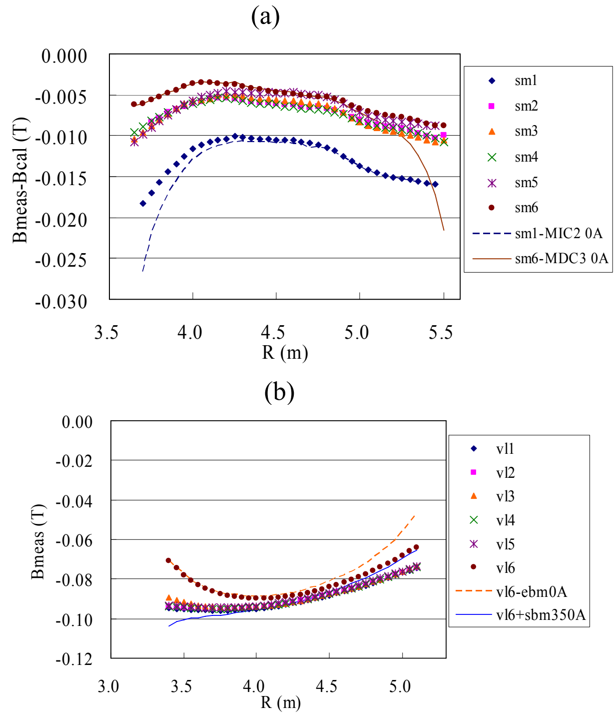


Figure 3: Magnetic field distributions along (a) the sector center lines and (b) the valley center lines.

(0.15%~0.35) for the others. The reason that the SM1 is smaller than the other sectors is because its yokes have been converted from the prototype, and the material and the dimensions differ slightly. In order to reduce the fluctuation of the magnetic field and horizontal magnetic field due to the asymmetry between upper and lower halves, the yokes use soft iron whose contents of carbon, manganese, and sulfur are smaller than 0.01 wt%, 0.2 wt%, and 0.01 wt%, respectively, including the SM1. The solid and dashed lines indicate the field distributions when the MIC2 and the MDC3 are not excited and the reduction due to the iron bars in the MIC2 and the MDC3 is seen. It is found that this reduction is corrected by their excitation.

On the other hand, the magnetic fields on the center lines of the valleys are 650G ~ 950G in the opposite direction of the sector fields. Only the magnetic fields on the center line of the valley VL1 between the SM1 and the SM6 is reduced due to the existence of the SBM and the EBM. While the dashed line indicates the magnetic fields when the EBM is not excited, the solid line when the SBM is excited.

ISOCHRONOUS MAGNETIC FIELD

Figure 4 shows the radial distributions of the average magnetic field calculated from the data of the magnetic field mapping. A current of the main coil is 5000 A and all the injection and extraction magnets are excited at the design currents for the 345 MeV/u U^{88+} beam. The average magnetic field of the SM6 is high because the magnetic field in the valley is decreased by the existence

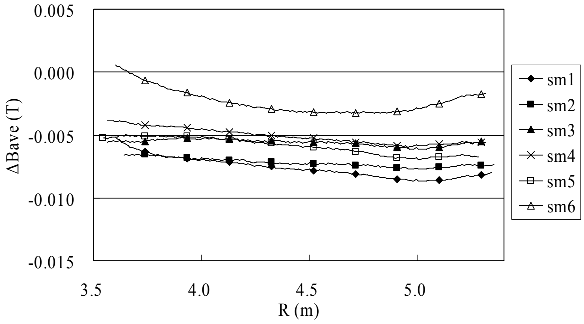
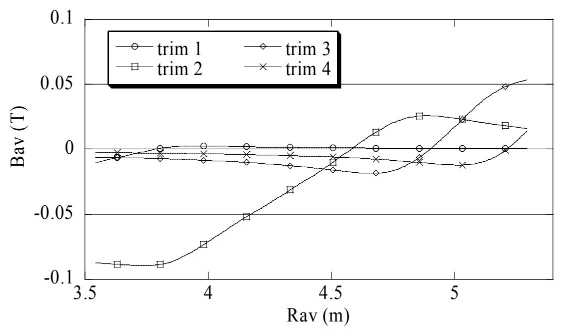


Figure 4: The average magnetic field of each sector magnet at a main coil current of 5000 A.

(a)



(b)

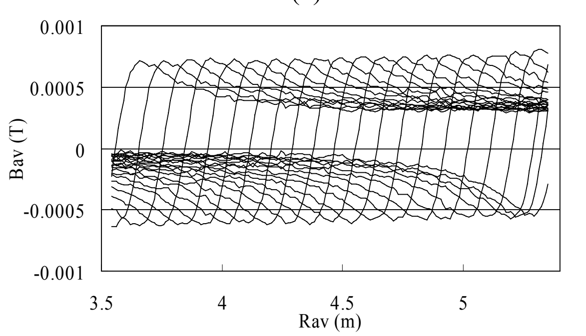


Figure 5: The average magnetic field for (a) the superconducting and (b) the normal trim coils.

of the EBM and the SBM. On the other hand, that of the SM1 is as small as the magnetic field of the sector .

Figures 5(a) and 5(b) show the average field of the superconducting trim coils at a main coil current of 5000 A and that of the normal trim coils at a main coil current of 4000 A. Since the magnetic field mappings were not made for all the normal trim coils, the average fields shown in Fig. 5(b) are converted from the distributions on the sector center lines measured for all the normal trim coils.

The main and trim coil currents generating the isochronous magnetic field with the harmonic field corrected are calculated with the least square fit from the average magnetic field in the three areas of the two-sectors (SM6-SM1, SM2-SM3, SM4-SM5). Figure 6 shows relative residuals in the fitting of the isochronous magnetic field for the 345 MeV/u U^{86+} beam. The lines

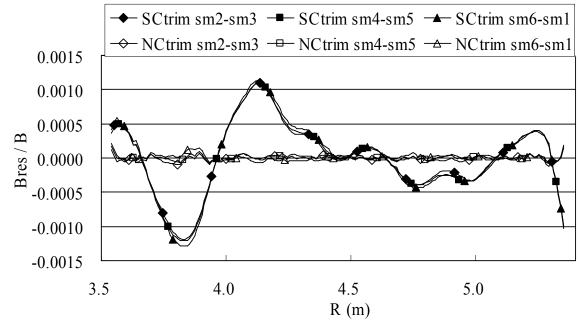


Figure 6: Relative residuals in the fitting of the isochronous magnetic field for the 345 MeV/u U^{86+} beam.

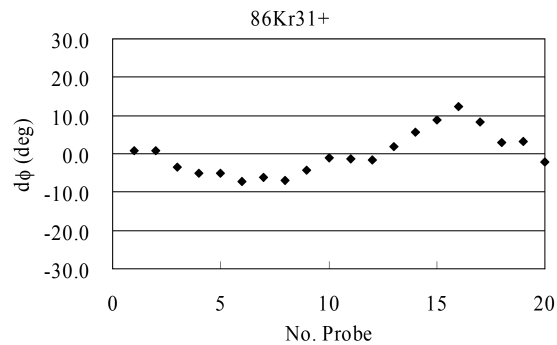


Figure 7: Measured phase excursion of the $^{86}Kr^{31+}$ beams accelerated in the magnetic field of the calculated trim coil currents.

with black markers indicate the fitting residuals by the superconducting main and trim coils. Besides, when the normal trim coils are used, the residuals can be reduced within ±0.02% (2.5G) as the lines with white markers indicate. However, the actual residuals are presumed larger because of the measurement errors.

Figure 7 shows the beam phase excursion measured in the beginning of the commissioning. The beam is $^{86}Kr^{31+}$ with the extraction energy of 345 MeV/u. The trim coil currents were as calculated while the main coil current was increased by 2.4 A. The deviations from the isochronous magnetic field is estimated to be smaller than 1×10^{-4} from these data.

CONCLUSION

It was found from the results of the magnetic field measurement that the magnetic fields in the SRC were as designed and the first beam was able to be accelerated easily in the preset isochronous magnetic field.

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