THE K2500 SUPERCONDUCTING RING CYCLOTRON OF RIKEN RI BEAM FACTORY - OVERVIEW AND STATUS -

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A cascade of ring cyclotrons for an energy booster of the existing K540-MeV ring cyclotron are being designed in detail to provide primary heavy ions, up to uranium ions, with energies exceeding 100 MeV/nucleon The one in the first-stage is a K930-MeV room-temperature ring cyclotron with four sectors and that in the second stage a K2500-MeV superconducting ring cyclotron with six sectors. Design of the superconducting ring cyclotron and status of the construction of its prototype is described.

1 Introduction

The RARF (RIKEN Accelerator Research Facility) houses a heavy-ion accelerator complex consisting of a K540-MeV ring cyclotron (RRC) as a main accelerator and two different types of injectors: a variable-frequency heavy-ion linac (RILAC) and a K70-MeV AVF cyclotron (AVF). One of the remarkable features of this facility is capability of supplying light-atomic mass RI (Radioactive Isotope) beams with the world-highest level of intensity produced by a projectile-fragment separator. In order to further promote research fields by utilizing RI beams, the RARF constructs "RIKEN RI Beam Factory" as a next facility-expanding project.[1] The factory is aimed at providing RI beams covering over the whole atomic-mass range with very high intensity in a wide range of energies up to several hundreds MeV/nucleon.

To meet this requirement, we plan to construct a cascade of ring cyclotrons after the RRC. The ring cyclotrons are a room-temperature ring cyclotron with four sectors and a superconducting ring cyclotron with six sectors. They are expected to boost the energy of ion beams from the RRC up to 400 MeV/nucleon for light heavy ions like carbon and over 100 MeV/nucleon for very heavy ions like uranium. In this paper we describe the design of the superconducting ring cyclotron and stauts of the construction of its prototype.

2 Heavy-ion Accelerator Complex for High-intensity RI Beam Production

We have proposed an accelerator complex as illustrated in Fig. 1. We build a cascade of ring cyclotrons as an enery booster of the existing RRC, and upgrade the RILAC by introducing a new pre-injector system and a charge-state multiplier (CSM). Some details of the pre-injector system and the CSM are described in Ref. 1.

In a previous design[2,3], a very large single superconducting ring cyclotron had been studied as a post-accelerator of the RRC. After a further study, we have modified the design in such a way that it is split into two stages: a 4-sector room-temperature ring cyclotron (IRC; Intermediate-stage Ring Cyclotron)) for the first stage and a 6-sector superconducting ring cyclotron (SRC) for the

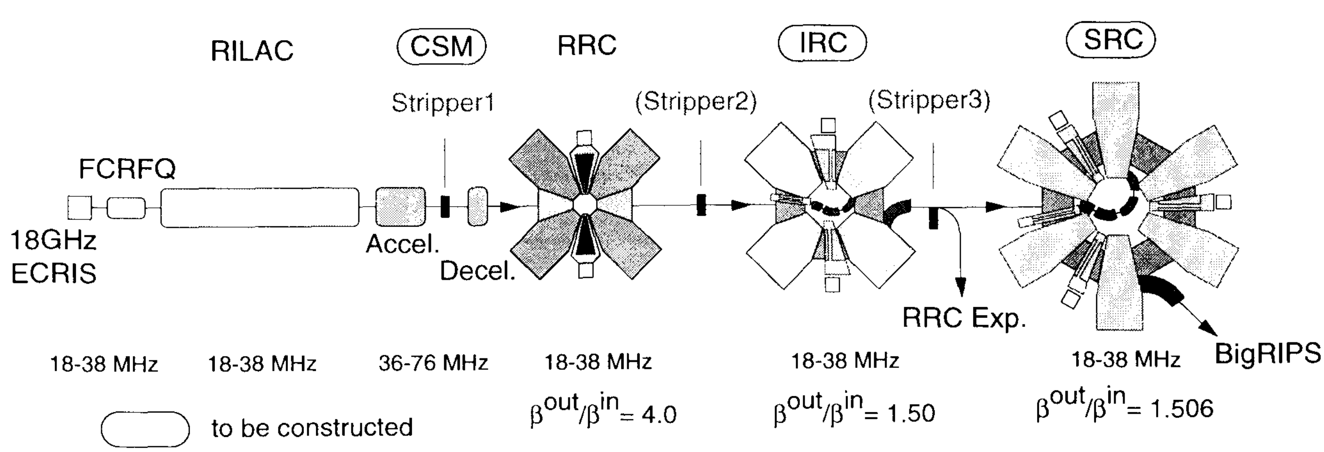
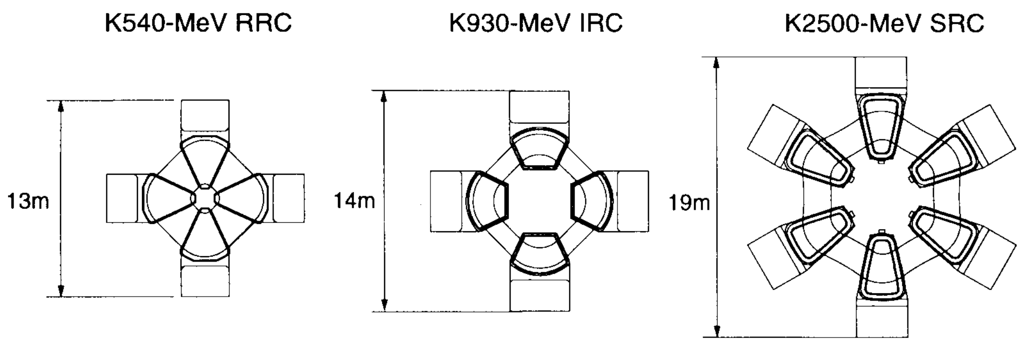


Figure 1: Concept of the heavy-ion acclerator complex for the RI beam factory.



Rinj (m)	0.89	2.77	3.56
Rext (m)	3.56	4.15	5.36
Velocity gain	4.0	1.50	1.51
h	9	7	6
B (T)	1.7	1.9	4.4
Weight (ton)	2,100	2,400	4,300

Figure 2: Comparison of geometries and characteristics of the RRC, the IRC and the SRC.

second. This two-stage scheme has two big advantages. Firstly, the simultaneous utilization of the IRC beam is possible in both the existing experimental facility and the new facility, when a part of the beam is charge-stripped and is transferred back to the existing facility. As an example, we give a 127 MeV/nucleon $^{16}O^{7+}$ beam from the IRC, while the main part of which is injected into the SRC, a part of which is charge-stripped to O^{8+} and delivered to the existing facility (where the magnetic rigidity of the O^{8+} beam can be accepted). Secondly, the difficulty of fabrication due to huge length of the cold mass and huge electromagnetic force on it is drastically eased compared to the single-stage scheme.

The maximum beam energy of the SRC is set to be 400 MeV/nucleon for light heavy ions, which should be achieved at 38 MHz, the maximum rf frequency stably operated in the RILAC. This means that the velocity of the RRC output beam has to be amplified by a factor of 2.26 by both the IRC and the SRC. Harmonic numbers of the IRC and the SRC are chosen to be 7 and 6, respectively, while that of the RRC is 9, considering the maximum magnetic field strengths and the injection and extraction radii. The mean injection radius of the IRC is taken to be 7/9 times the mean extraction radius of the RRC, and the velocity gain factor of the IRC to be 1.50. (For 400 MeV/nucleon light heavy ions, their beam energy from the IRC becomes 127 MeV/nucleon, which is almost the same as the maximum beam energy of the RRC now available.) From the above conditions, the mean injection and extraction radii of the IRC are 2.77 m and 4.15 m, respectively, and those of the SRC are 3.56 m and 5.36 m, respectively. The sector angles of the IRC and the SRC are 53 deg. and 25 deg., respectively. The radio-frequency of the IRC and the SRC ranges from 18 MHz to 38 MHz, which is the same as that of the RILAC and the RRC. The maximum magnetic fields required for the IRC and the SRC are to be 1.9 T and 4.4 T, respectively. This cascade of the ring cyclotrons boost energies of heavy ions, up to uranium, with energies exceeding 100 MeV/nucleon.

Geometries and characteristics of the IRC and the SRC thus designed are shown in Fig. 2 along with those of the RRC. The structure and size of the IRC are similar to those of the RRC. Details of all the components except for the rf resonators can be designed after the components of the RRC. Therefore, our effort has been concentrated mainly on the design of the SRC, in particular, on the design of its sector magnet and injection and extraction systems.

2 Despcription of the Superconducting Ring Cyclotron (SRC)

Figure 3 shows a schematic layout of the SRC. The SRC consists mainly of six sector magnets with an angle of 25 deg., three acceleration rf resonators, a flat-top resonator and injection and extraction systems. Figure 4 shows the performance of the SRC. The maximum energies are 400 MeV/nucleon for light heavy ions up to around Ar, 300 MeV/nucleon for Kr^{30+}, 150 MeV/nucleon for U^{58+} and 100 MeV/nucleon for U^{49+}. The minimum energy is 60 MeV/nucleon.

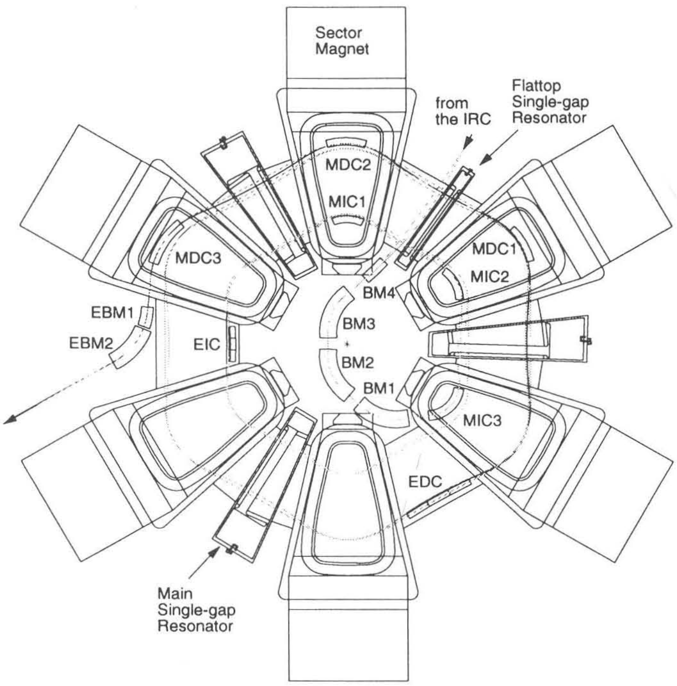


Figure 3: Layout of the SRC.

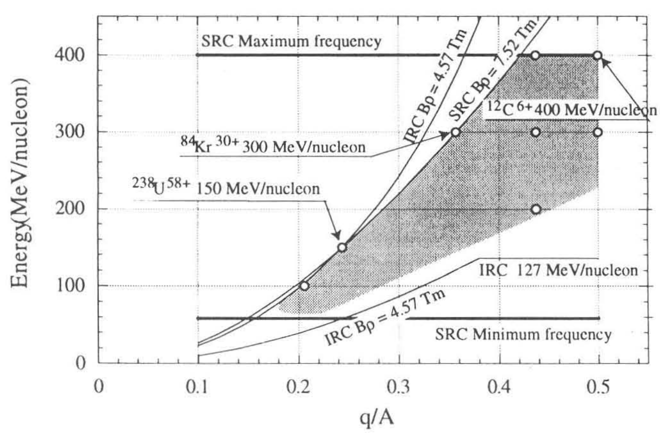


Figure 4: Performance of the SRC.

Magnetic fields and related characteristics were calculated with a three-dimensional computer program TOSCA.[4] Equilibrium orbits and betatron tunes were calculated with the computer program that had been originally developed for the RRC. Shape of the sector magnet has been optimized with those programs.[5] Figure 5 shows typical tune values calculated for the sector magnet thus optimized. The sector angle was determined so that vertical tune values never cross the $\nu_z = 1$ imprfection resonance. Smaller sector angle causes larger vertical focusing force. From the viewpoint of minimizing the maximum field, however, a large sector angle is preferable. Therefore, edge of the pole has a straight line from the

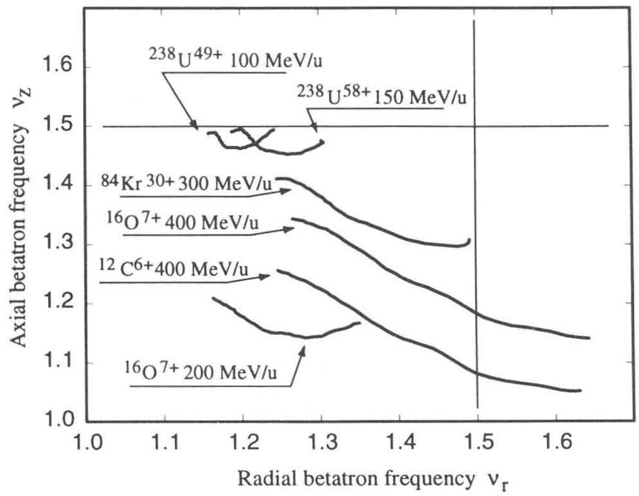
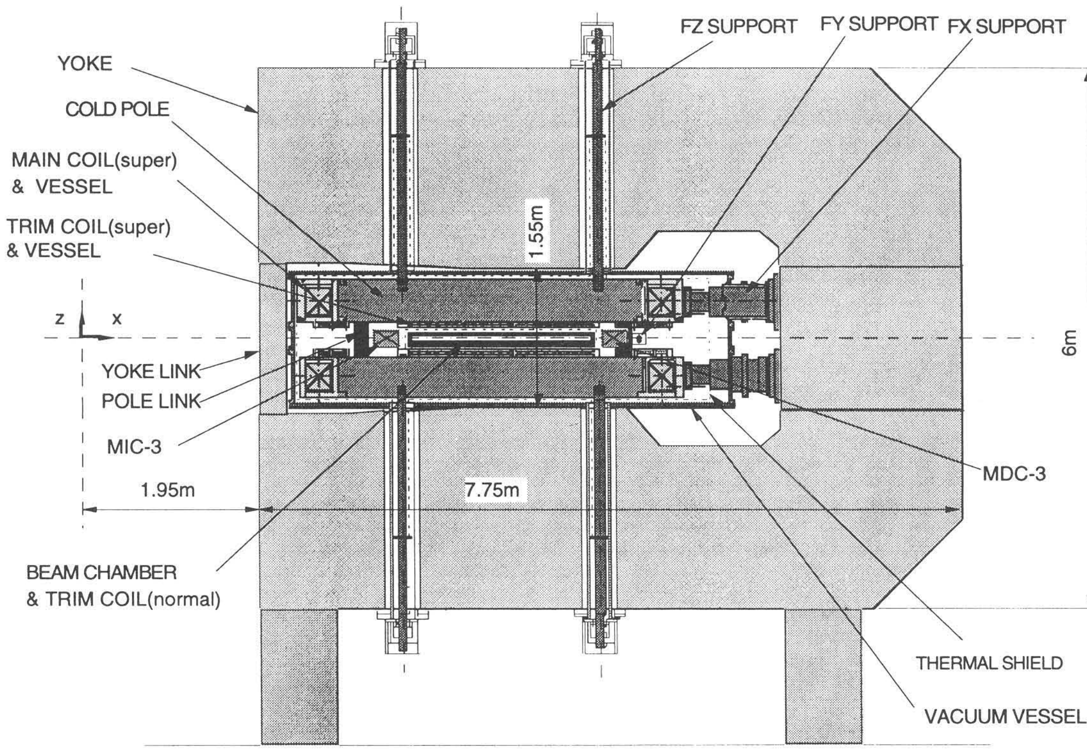


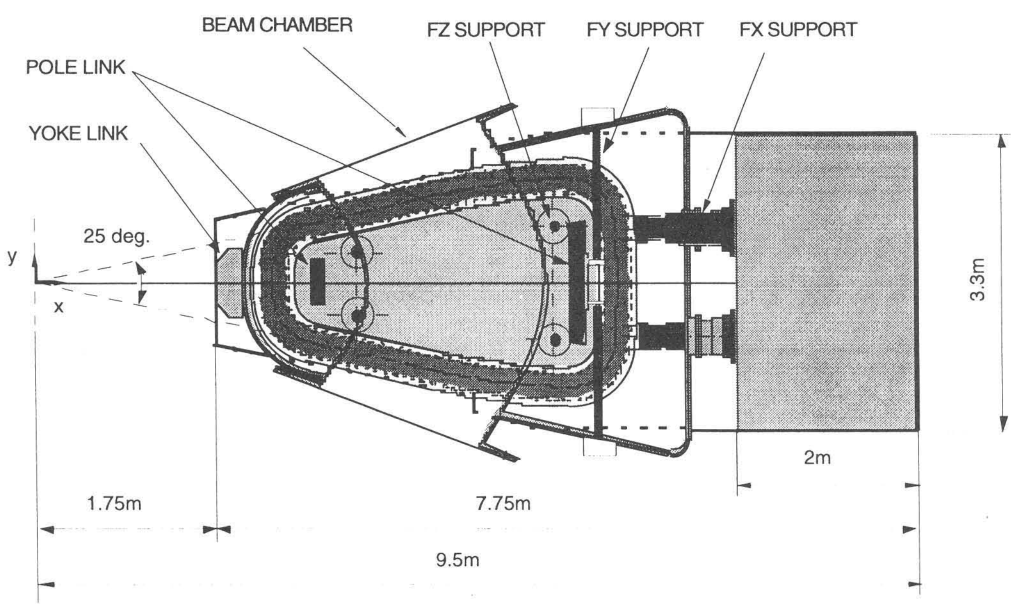
Figure 5: Tune values for typical ions in the SRC.

injection side to the middle of the sector with the wide angle of 25 deg, then the pole shape has a curvature in order to increase vertical tune ν_z at the extraction side. The radius of curvature of 8 m increases ν_z value up to 1.05 at the extraction radius.

Figure 6 shows cross-sectional and plan views of the sector magnet. The sector magnet is 7.8 m in length and 6.0 m in height. Main components of the sector magnet are superconducting and room-temperature coils, poles and a yoke. Two kinds of super-conducting coils are used: a pair of main coils and a group of trim coils. The maximum currents required for the main coil and the trim coils are 5,000 A and 500 A, respectively. The maximum ampere-turns of a pair of main coils is 6 MA, which is large enough to generate the designed field strength of the sector magnet. A group of room-temperature trim coils are also arranged on the upper and lower sides of the beam chamber. In general, in a superconducting ring cyclotron like the SRC, it is a big issue to support huge electromagnetic forces on the main coil, due to a large magnetic field and a large coil current. In order to figure out this problem, we have adopted a cold-pole arrangement.[6] This arrangement gives an easier mechanical support against the huge magnetic force on the main coils, and gives the reduction of ampere-turns and of magnetic forces, compared with a warm-pole arrangement. Figure 7 shows some details of the main coil and the cold-pole. The pole pieces are separated from the iron yoke and are cooled down to 4.5 K together with the main coils in the cryostat. Two coil vessels that accommodate the main coils are attached to the side of the upper and lower pole pieces that are linked to each other by pole links. The pole gap is designed to be 380 mm, considering sizes of the trim coils and of the magnets for injection and extraction to be installed in the gap space. The cold-mass weight is estimated to be about 50 tons. The coil vessels are made of stainless steel. The detailed design



a) Cross-sectional view



b) Plan view

Figure 6: Cross-sectional and plan views of the sector magnet of the SRC.

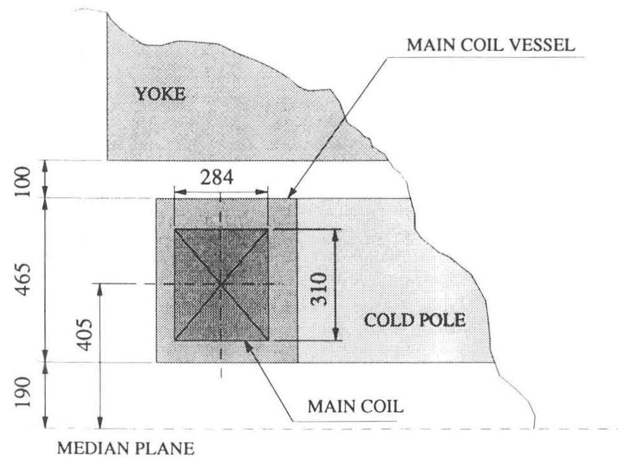


Figure 7: Some details of the main coil and cold pole.

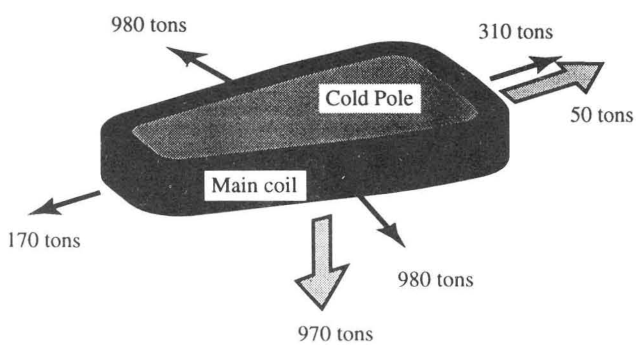


Figure 8: Magnetic forces exerted on the main coil and cold pole.

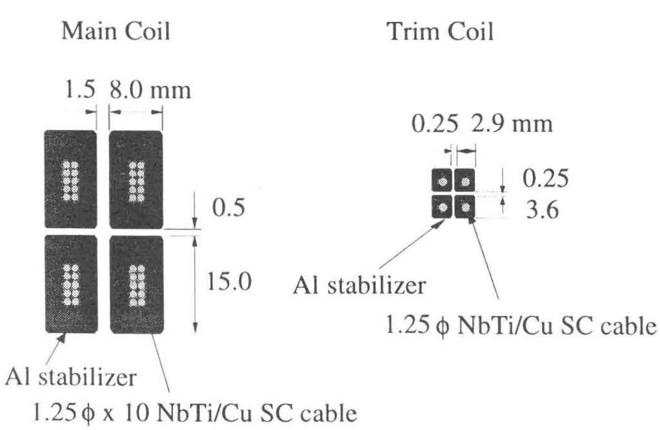


Figure 9: Cross sections of the superconductors for the main and trim coils.

study is in progress, considering the stresses due to the thermal contraction and electromagnetic force. Some details of how to fix will be described in sect. 3.

Figure 8 shows the calculated magnetic forces exerted on the main coil and cold-pole at an ampere-turns of 6 MA per magnet. The expansion force exerted on the main coil amounts to as strong as about 1,000 tons at the long staraight part. The vertical force F_z of about 1,000 tons that is exerted on the cold pole is supported with the pole links between the upper and lower cold-poles. It will make a bending deflection of 2 mm in the normal direction to the cold-pole of 465 mm in thickness. The radial force F_x of 100 tons exerted on both the upper and lower poles, which is generated by the arrangement of six sector coils and the asymmetric configuration of the coils and irons, is supported with large-size thermal-insulation supports between the cold-mass and the side yoke. The supports are made of stainless steel. The radial force will make the cold-mass position change by 1 mm in the radial direction. The vertical supports, which support the cold mass, are made of high-strength material like titanium alloy. These thermal-insulation supports as well as the F_y supports are designed to withstand not only the magnetic forces but also an acceleration of as large as 1 G in an earthquake.

Cross sections of the super-conductors for the main coil and trim coil designed are shown in Fig 9. A cryogenically-stabilized superconductor for the main coil was designed based on Maddock's partial stabilization criterion in order to prevent the main coil from quenching. The main coil has been designed to be stable up to a current of 6,000 A when the applied magnetic field is 6 T and the cooling efficiency is assumed to be 50 %. The conductor has a rectangular shape, consisting of a Rutherford-type NbTi cable located at the center of conductor and a stabilizer housing. The conductor's cross-sectional area measures 8 mm by 15 mm. The stabilizer material has been chosen to be pure aluminum with a residual resistivity ratio greater than 500. Cross-sectional area of the main coil measures 284 mm by 310 mm, as shown in Fig. 7. The number of turns is 600 for each coil. The main coil is wound by the solenoid winding method in such a way that it has 30 layers in the horizontal direction and 20 turns in the vertical direction. The horizontal and vertical cooling gaps are taken to be 0.5 mm and 1.5 mm, respectively. These gap widths are large enough to achieve the designed heat flux. The spacers of FRP (Fiber Reinforced Plastic) are placed in the gaps in such a way that 50 % of conductor surface is exposed to the liquid helium. The current density at 5,000 A is estimated to be 34 A/mm^2. Total length of the main coils for six sector magnets is 77 km. On the other hand, a cryogenically-stabilized superconductor for the trim coil was designed based on Stekly's full stabilization criterion. The trim coil has been designed to be stable up to a current of 550 A when the cooling efficiency is assumed to be 40 %. The conductor's cross-sectional area measures 2.9 mm by

3.6 mm. Critical current of the conductor at 4.5 K is greater than 1,000 A at 6 T. Pure aluminum is also used as a stabilizer. The horizontal and vertical cooling gaps are taken to be 0.25 mm. The current density at 500 A is estimated to be 39 A/mm^2. Total length of the trim coils for six sector magnets is 47 km.

In designing a superconducting ring cyclotron like the SRC, it is one of the main works to optimize a magnetic field trimming system for the field isochronization.[7] We have designed to use two kinds of trim coils. A major correction is made with superconducting trim coils, and the remnant error field is corrected with normal-conducting trim coils. A combination of five sets of superconducting trim coils and twenty sets of normal-conducting trim coils was found to satisfy our requirement. By use of five sets of superconducting trim coils, the error field reduced within ± 10 gauss, or ± 0.1 % of the isochronous field. The field error can be less than ± 0.05 % by further using twenty sets of normal-conducting trim coils.

The injection and extraction systems have also been designed.[8,9,10] The injection system consists of, from the upstream, four bending magnets (BM1, BM2 BM3 and BM4), three magnetic channels (MIC1, MIC2 and MIC3) and an electrostatic channel (EIC); the extraction system consists of an electrostatic channel (EDC), three magnetic channels (MDC1, MDC2 and MDC3) and two bending magnets (EBM1 and EBM2), as shown in Fig. 3. The MIC's and MDC's are inserted in the pole gaps. The problem in the SRC injection and extraction systems is that the beam trajectory changes depending on the kind of ion due to the difference of fringe field in the valley region. For example, the EIC (the EDC) is required to be radially movable by about 10 cm (8.5 cm) and its curvature should be changeable from 10 m (17 m) to 43 m (44 m). To adjust the curvature, each of the EIC and the EDC consists of three arcs connected with two hinges. Apertures of the other elements should also be wide enough to accept the difference of trajectories. The six bending magnets and both the MIC3 and the MDC3 are superconducting. These injection and extraction systems have been designed in a three-resonators configuration. The systems in a four-resonators configuration are also being studied.

Two refrigerators having a capacity of 500 W each at 4.5 K will be used for cooling of the six sector magnets plus the beam injection and extraction magnets. A total of cold-masses of the six sector magnets weigh 360 tons, and therefore it will take one and a half month for cooling them from room temperature to 4.5 K. By taking the two-refrigerators operation, the magnets can be kept at between 5 K and 6 K even when one of the two refrigerators breaks down. No liquid nitrogen in this cryogenic system is used for simplicity of the cooling system.

The rf resonators have been designed [11] using a three-dimensional computer program MAFIA.[12] The three acceleration resonators are of a single-gap type with a pair of rotatable tuning panels. Their resonant frequency is required to cover the range from 18 MHz to 38 MHz. The necessary maximum power is estimated to be 50 kW/resonator for a gap voltage of 600 kV (at 38 MHz), which is large enough to achieve a single-turn extraction for 400 MeV/nucleon light heavy ions.[13] The third-harmonic flat-top resonator is of a single-gap type with a pair of movable shorting plates. A 1/10-scaled model of the acceleration resonator was made with wood boards covered with an aluminum foil of 15 μm in thickness. The resonant frequencies agreed well with the MAFIA calculation within an accuracy of a few percent.

3 Prototype of the Sector Magnet

We are constructing a full-scaled prototype sector magnet of the SRC to verify particularly the mechanical design of magnet and the cryogenic design of the main and trim coils. Two kinds of schemes have been adopted in the model as shown in Fig. 10. In the scheme shown by the upper figure, a sort of "hook" is used to fix the coil vessel to the pole. The coil vessel and the "hook" are assembled by welding. The second scheme shown by the lower figure in

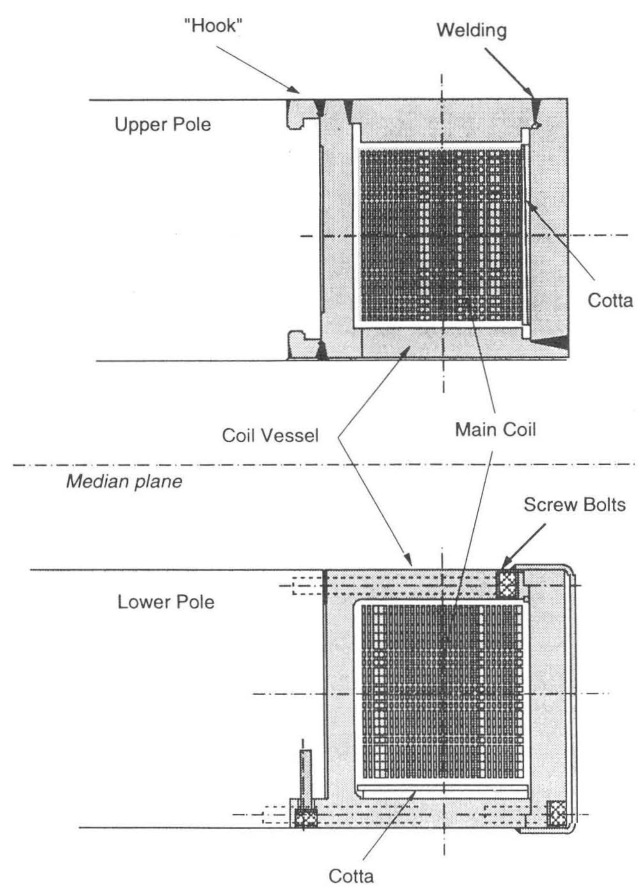


Figure 10: Cross-sectional view of the main coil, coil vessel and cold pole of the prototype sector magnet.

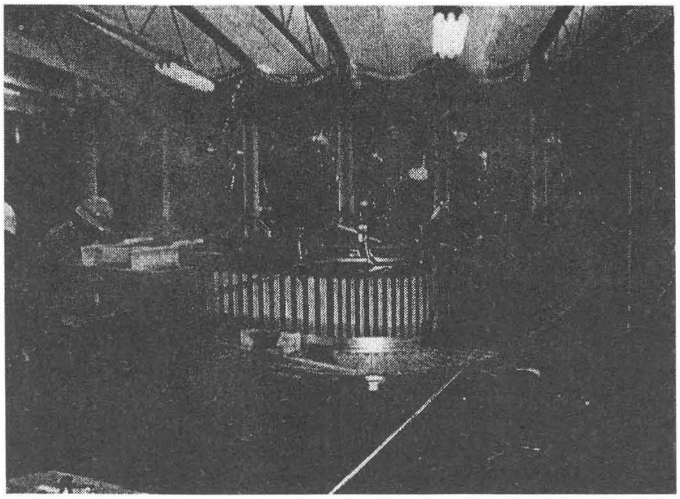


Figure 11: Photograph of the main coil vessel where several turns of main coils are wound.

Fig. 10 uses screws to fix the coil vessel to the pole as well as assemble the coil vessel. A photograph of the main coil vessel in the "hook" scheme where several turns of main coils are wound is shown in Fig. 11. We plan to examine through the test operation of prototype magnet which scheme is better.

The design of main coil vessel was made estimating the stress caused by the electromagnetic force and thermal contraction. The material of coil vessel was chosen to be a stainless steel (SUS316L) by considering its strength. The wall thickness of coil vessel was determined so that the estimated maximum stress does not exceed the allowable maximum stress of SUS316L. The size and interval of screws were determined in the same way. The material of screws was chosen to be a stainless steel (A286). The displacement of the main-coil vessel due to the electromagnetic force was simulated to be about 1.1 mm in the horizontal direction and 1.9 mm in the vertical direction at maximum. The fatigue limit was also checked for the coil vessel, welding spots of coil vessel and screws. It was found that no breaks are expected for the assumed cycles of 10,000 (1 cycle/day for 30 years). Model trim coils, which correspond to a part of real trim coils, are to be fabricated and installed in the pole gap space as shown in Fig. 6. The trim coil vessel is connected in series to the main coil vessel, so that the trim coil can be cooled by the liquid helium provided by a common refrigerator.

Fabrication of the superconductors for both the main coil and the trim coil finished in the spring of 1997. Heat transfer from the Al stabilizer to liquid helium was measured using a setup simulating their configurations. It was found that the measured heat transfer was large enough to acheive the design value of maximum stabilized current. Cryogenic-stability test was made in the magnetic field of 6 T for both the main and trim coils by making a small model in which the test coils were assembled into a bias superconducting coil. In this stability test, the partial stabilizing current of the main coil was found to be 5,700 A, and fully stabilizing current of the trim coil to be 630 A. These results verified the validity of the design on the cryogenic stabilization. The measurement of mechanical properties such as tensile strength, stress-strain hysteresis, fatigue and stress-creep characteristics were also made at room temperature and 77 K using sample pieces of the conductors. It was found that the conductors were strong enough against the electromagnetic force and thermal contraction.

Two sets of models of main coil assembly in the straight section were made to study the assemblying and mechanical stiffness in the two scheme. A photograph of the model in the scheme using screws is shown in Fig. 12. In a process of this test, the equivalent Young's modulas of stacks of main coils and insulators was measured. The measured equivalent Young's modulas was about 10 GPa, which is much smaller than the expected value of about 40 GPa.

Three sets of 1/6-scaled sector magnets with normal conducting coils operated in a pulse mode are being constructed to measure the unbalanced magnetic forces in x, y and z directions.

Construction of the whole system of the prototype is scheduled to be completed in the spring of 1999.

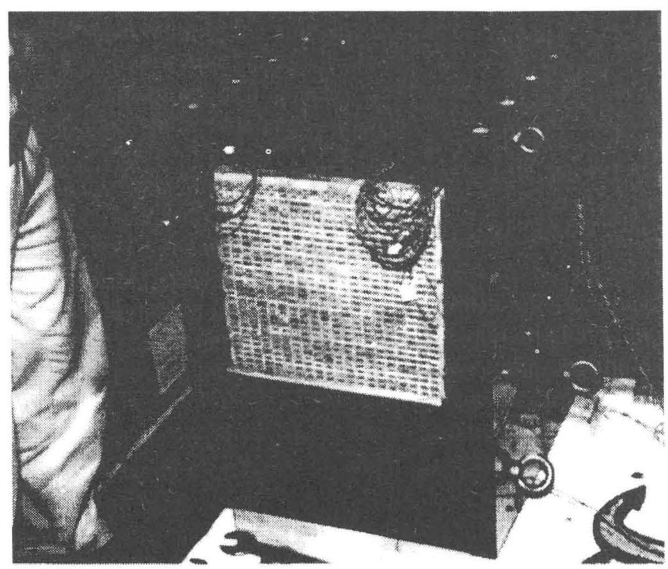


Figure 12: Photograph of a model of main coil assembly in the straight section.

4 Summary

Two ring cyclotrons with 4-sector and 6-sector magnets, respectively, are designed as an energy booster of the existing ring cyclotron for "RIKEN RI Beam Factory." A cascade of the two ring cyclotrons are aimed at accelerating heavy ions up to : e.g., 400 MeV/nucleon for light heavy ions like carbon, 300 MeV/nucleon for krypton ions, and over 100 MeV/nucleon for uranium ions. The 6-sector ring cyclotron SRC, which is a superconducting ring cyclotron, adopts a cold-pole arrangement and a cryogenically-stabilizing method for the main and superconducting trim coils. A full-scaled prototype of the sector magnet of the SRC is being made to verify the design. Construction of the two ring cyclotrons has been approved by the Government and is scheduled to be completed in the year 2003.

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