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The Booster Ring Cyclotrons for the RIKEN RI Beam Factory

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Abstract

An energy booster of the existing K540-MeV ring cyclotron for the RIKEN RI Beam Factory is being designed in detail to provide primary heavy ions, up to uranium ions, with energies exceeding 100 MeV/nucleon. The energy booster consists of a four-sector normal-conducting ring cyclotron (K=930 MeV) and a six-sector superconducting ring cyclotron (K=2,500 MeV). General features of the booster ring cyclotrons as well as staus of the design of them are 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 the projectile-fragment separator, RIPS [1]. In order to further promote research fields by utilizing RI beams, the RARF constructs "RIKEN RI Beam Factory" as a next facility-expanding project [2]. The factory takes the aim 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 a four-sector normal-conducting ring cyclotron and a six-sector superconducting ring cyclotron after the RRC. The ring cyclotrons 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.

2 Description of the Booster Ring Cyclotrons

2.1 General Features

In a previous design [3], a very large single superconducting ring cyclotron had been studied as an energy booster of the RRC. After further study, we have recently modified the design in such a way that it is split into two stages: a four-sector normal-conducting ring cyclotron (IRC: Intermediate Ring Cyclotron, K=930 MeV) for the first stage and a six-sector superconducting ring cylotron (SRC; K=2,500 MeV) for the 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 51 deg. and 25 deg., respectively. The maximum magnetic fields required for the IRC and the SRC are to be 1.9 T and 4.3 T, respectively.

The maximum energies of the IRC beams are 127 MeV/nucleon for light heavy ions up to around Ar, 102 MeV/nucleon for Kr^{30+}, 58 MeV/nucleon for U^{58+}. Their minimum energy is 25 MeV/nucleon. The maximum energies of the SRC beams 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+}. Their minimum energy is 60 MeV/nucleon.

The structure and size of the IRC are similar to those 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 system.

2.2 IRC

Fig. 1 shows a schematic layout of the IRC. The IRC consists mainly of four sector magnets, two main rf resonators and a flattop resonator, and injection and extraction systems. Total weight of the sector magnets is 2,400 tons.

Initially the main coil was designed to be superconducting. Further investigation, however, has revealed that the power consumption can be as small as 320

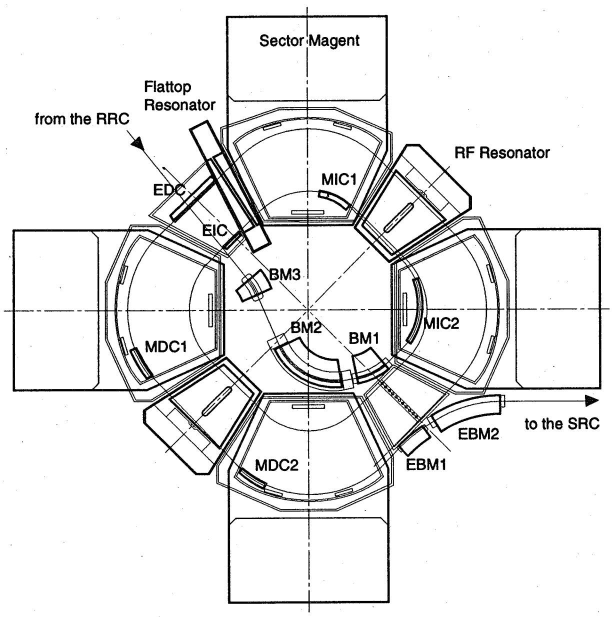

Fig.1 Layout of the IRC.

kW in total even for a normal-conducting coil. Therefore, we have designed the main coil to be normal-conducting.

The main rf resonators are of a double-gap type with a structure similar to that for the RRC [4]. Their resonant frequency ranges from 18 MHz to 38 MHz, which is the same as that for the RILAC and the RRC. The flattop resonator with the third harmonic frequency is of a single-gap type.

2.3 SRC

Fig. 2 shows a schematic layout of the SRC. The SRC consists mainly of six sector magnets, three main rf resonators and a flattop resonator, and injection and extraction systems. Total weight of the sector magnets is 4,000 tons.

Magnetic fields and related characteristics were calculated with a three-dimensional computer program TOSCA [5]. 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 in order to avoid any dangerous resonances [6].

Fig. 3 shows a cross-sectional view of the sector magnet. Main components of the sector magnet are super-conducting and normal-conducting 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 normal-conducting trim coils are also arranged on the upper and lower sides of the beam chamber. A remarkable feature of this sector magnet is the cold-pole arrangement [7]. 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. The pole pieces are separated from the iron yoke and are cooled down 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 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. One of the important issues in the design is how to fix the coil vessel to the side of pole piece. The detailed design study is in progress, considering the stresses due to the thermal contraction and electromagnetic force. The vertical force of 1,150 tons is supported with the pole links between the upper and lower cold-poles. The radially shifting force of 100 tons, which is generated by the arrangement of six sector coils and the asymmetric configuration of the coils and irons, is supported with a large-size thermal insulated supports between the cold-mass and the side yoke.

We have started to construct a full-scale model sector magnet of the SRC without a yoke to verify particularly the mechanical design of magnet and the cryogenic design of the main and trim coils, which are designed to be cryogenically stable [8]. The superconductors for the main and trim coils have already been complete. Construction of the whole system is scheduled to be completed by the middle of 1998.

For the field isochronization, a major correction is made with superconducting trim coils, and the remnant error field is corrected with normal-conducting trim coils. By use of five sets of superconducting trim coils, the error field reduced within ± 10 gauss, or ± 0.1 % of the isochronous field. Further fitting using twenty sets of normal-conducting trim coils was then carried out. The

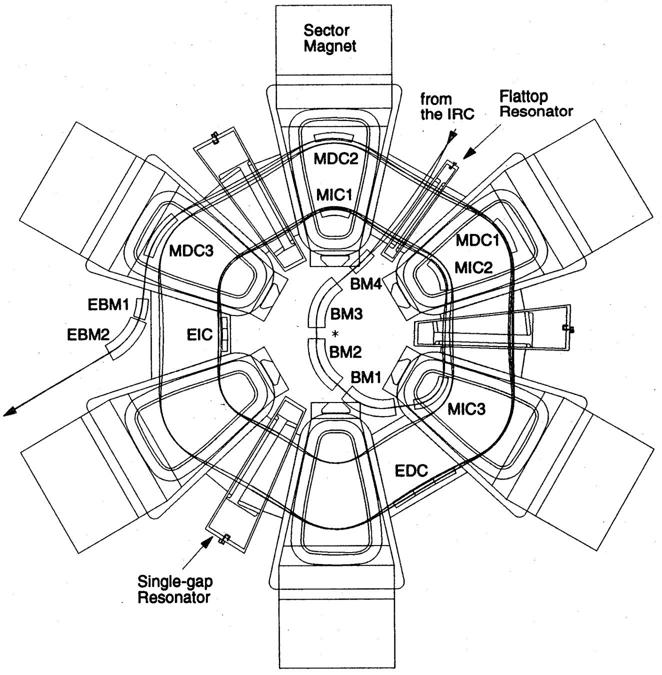

Fig. 2 Layout of the SRC.

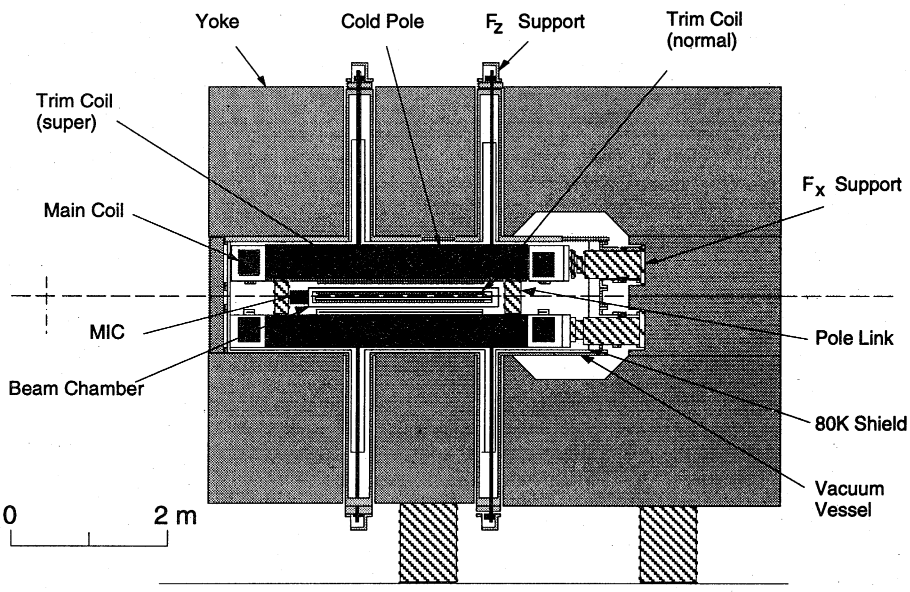

Fig. 3 Cross-sectional view of the sector magnet of the SRC.

field error is less than ± 0.05 % for the case of the five superconducting trim coils, which meets our criterion of field isochronism.

The injection system consists of four bending magnets (BM1, BM2, BM3 and BM4), three magnetic channels (MIC1, MIC2 and MIC3) and an electrostatic channel (EIC), as shown in Fig. 2. The MIC's are inserted in the pole gaps. The problem in the SRC injection system 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 is required to be radially movable by about 10 cm and its curvature should be changeable to some extent. The apertures of the other elements should also be wide enough to accept the difference of trajectories. The four bending magnets and the MIC3 are superconducting. The extraction system consists of an electrostatic channel (EDC), three magnetic channels (MDC1, MDC2 and MDC3) and two bending magnets (EBM1 and EBM2), as also shown in Fig. 2. The two bending magnets and MDC3 are superconducting. Details of orbit analysis in the injection and extraction systems and the design of the elements are described in refs. [9] and [10], respectively.

The main rf resonators are designed to be of a single-gap type, because there is no enough space for inserting a double-gap resonator particularly in the injection region. Their resonant frequency ranges from 23 MHz to 46 MHz instead of from 18 MHz to 38 MHz. This is because it is difficult to make the single-gap resonator to resonate in the frequency lower than 23 MHz. The beam with the energy of less than 100 MeV/nucleon (corresponding to the frequency lower than 23 MHz) is accelerated with the frequency that is twice the frequency of the RILAC, the RRC and the IRC: from 36 MHz to 46 MHz. The flattop resonator with the third harmonic frequency is also of a single-gap type.

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 months for cooling them from room temperature to 4.5 K. By taking the two-refrigerator 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.

4 Summary

Two ring cyclotrons with normal-conducting four-sector and superconducting six-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 is 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 six-sector ring cyclotron SRC adopts a cold-pole arrangement and a cryogenically-stable method for the main and superconducting trim coils. A full-scale model 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 2002.

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