STATUS OF THE SUPERCONDUCTING RING CYCLOTRON AT RIKEN RI BEAM FACTORY

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Abstract

A superconducting ring cyclotron (SRC) was successfully commissioned to work as the final energy booster of the RI beam factory (RIBF) in RIKEN. SRC is the world's first ring cyclotron that uses superconducting magnets, and has the strongest beam bending force among the cyclotrons. It can boost the ion beam energy up to 440 MeV/nucleon for light ions and 350 MeV/nucleon for very heavy ions such as uranium nuclei to produce intense radioactive beams. The ring cyclotron consists of 6 major superconducting sector magnets with a maximum field of 3.8 T. The total stored energy is 235 MJ, and its overall sizes are 19 m diameter, 8 m height and 8,300 tons. The magnet system assembly was completed in August 2005, and successfully reached the maximum field in November 2005. After magnetic field measurements for two months, the other hardware than the superconducting magnets was installed. The first beam was extracted from SRC on 12/28/2006. From May 2007 we started to supply uranium beams to nuclear scientist to produce RI beams.

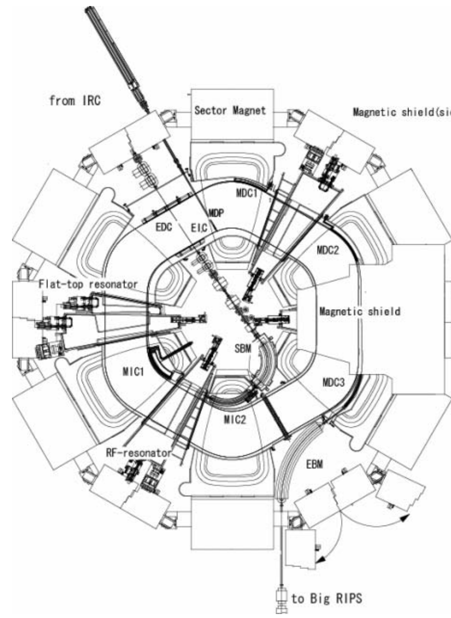

Figure 1: Schematic view of the SRC.

INTRODUCTION

The Radioactive Isotope Beam Factory (RIBF) at RIKEN Nishina Center will be a next generation facility which is capable of providing the world's most intense RI beams over the whole range of atomic masses [1]. Three new ring cyclotrons have been constructed as post-accelerators for the existing facility in order to provide the intense heavy-ion beam for the RI beam production by using a in-flight separation method. Superconducting Ring Cyclotron (SRC) [2] is the final booster in the RIBF accelerator complex, which provides a wide range of heavy ion beams, boosting energies up to 440 MeV/nucleon for light ions and 350 MeV/nucleon for very heavy ions up to uranium. The SRC is the world's first superconducting ring cyclotron with the ever largest K-value of 2600 MeV, which expresses the maximum bending power of extracted beam from the cyclotron. The SRC was successfully commissioned via 345 MeV/nucleon $^{238}U^{86+}$ beam on March 23rd 2007 [3]. The first experiment at the RIBF was carried out from mid-May to early June using the uranium beam. This article describes the milestones that were achieved during the commissioning as well as some of the issues that still need to be resolved.

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HARDWARE OF THE SRC

Figure 1 shows a schematic view of the SRC. Diameter and height of the SRC are 19 m and 8 m, respectively. The mean injection radius is 3.56 m and the mean extraction radius is 5.36 m. The SRC mainly consists of six-superconducting sector magnets with 25 deg sector angle, four main RF resonators, one flat-top RF resonator, injection/extraction elements including Superconducting Bending Magnet (SBM), and beam diagnostics [4]. The remarkable point of this cyclotron is the iron plates of about 1 m thickness which cover the magnetic valley regions between the sector magnets, used as an additional magnetic and radiation shielding. They reduce the leakage field from the sector magnets and decrease magneto motive forces for the maximum bending power. The total weight amounts to 8300 tons.

Each sector magnet is 7.2 m in length, 6 m in height, and weights about 800 tons. The sector magnet has a pair of superconducting main coils, four sets of superconducting trim coils, a cryostat combined with a beam duct, thermal insulation support links, twenty-two pairs of normal conducting trim coils, warm-poles, and a yoke. The maximum main-coil current is 5000 A, and the maximum current of each trim coil is 3000 A. The sector magnet generates the maximum sector field of 3.8 T, translating to the average bending power of 8 Tm. The total stored energy of superconducting coils in the six sector magnets is 235 MJ.

The superconducting coils are cooling by the helium refrigerator which has the capacity of 620 W at 4.5 K, 4000 W at 70 K, and 4 g/s gas helium for current lead cooling. The cooling capacity of the system has been designed to be more than 1.5 times of estimated heat loads of the whole superconducting magnets. It takes three weeks to cool down the cold masses of 142 tons from room temperature to 4.5 K with this cooling system. The temperature of the inlet gas from the helium refrigerator is so tuned that temperature difference of the inlet gas and the cold mass is hold less than 50 K to reduce the thermal stress.

The main resonators [5] for acceleration are single-gap type and work with a sextuple frequency of the beam revolution frequency. The resonant frequency of the resonator varies from 18-42 MHz by symmetrical adjustment of two large capacitor-panels. Their maximum voltage is set to be 600 kV/gap depending on the frequency. Flat-top acceleration is realized by the third/fourth-harmonic resonator with the available frequency range of 72-126 MHz. The flat-top resonator is also single-gap type, and their frequency is tuned by a pair of sliding short plate. The main amprifiers for the acceleration resonator and the flat-top resonator provide the RF power of 150 kW and 60 kW, respectively.

COMMISSIONING

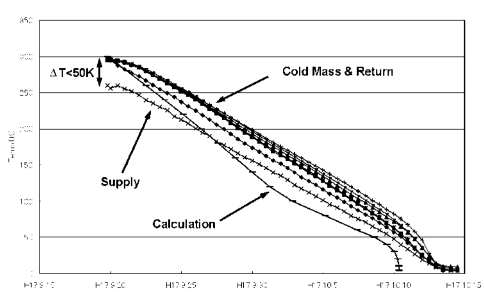

Figure 2: Cool-down curves of the SRC superconducting magnets.

The assembly of the superconducting sector magnets was completed in August 2005. The first cool-down was started at September 2005. Figure 2 shows a cool-down curve in the first trial. The temperatures of the cold masses smoothly fell into the liquid helium temperature by 23 days. The coil currents were made to increase day by day with frequent shut-down tests. All the superconducting coils were successfully excited with the maximum currents on November 7th 2005. They have never quenched so far, which is important to keep research activity of the facility stable and efficient. In the excitation the magnetic forces applied on the coil support links were continuously measured using strain gauges. The measurement clarified that the forces were smaller than the designed limit and enough to keep displacements of the coils small in excitations. A fast shutdown test from full excitation was performed to check their safety. Main coil current decays in a time constant of about 60 second. All the coils were successfully shut down even in emergency.

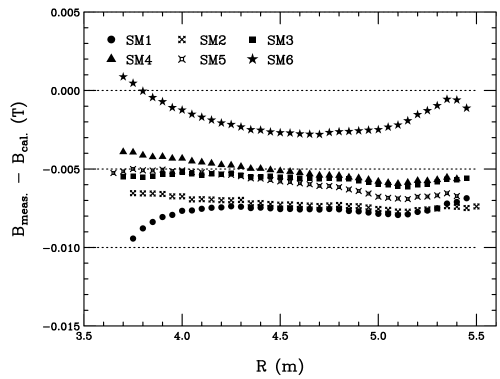

Figure 3: The deviation of average magnetic field of each sector magnet at the main coil current of 5000 A.

The magnetic field mapping [6] was performed in the spring of 2006 to check the qualities of the magnetic fields and calculate parameters for isochronous magnetic field with the harmonic-field correction. The magnetic fields generated by the superconducting main and trim coils were measured by Hall probes for every 50 mm in a whole orbit area at the main-coil current from 1800 A to 5000 A. Figure 3 shows the radial distributions of the differences between the measured and calculated average field for the main coil current of 5000 A. The injection and extraction magnets were not excited for that case. The average magnetic field of the SM6 is obviously high because the magnetic field in the adjacent valley region is absorbed by the iron yokes of the injection and extraction bending magnets. The deviation from the TOSCA calculations is smaller than 100 G, and the dispersion between the sectors can be adjusted by the correction coils in the magnetic channels and the auxiliary power supplies connected with the main and the trim coils.

Four acceleration resonators and one flat-top resonator were installed on June 24th 2006. Installation of the power amplifiers and low-level controls was made from July to October 2006. After the resonators were carefully aligned, they were connected with the sector magnets to make a vacuum chamber for ion beams. The two vacuum chambers, which enclose the electrostatic channel or phase pickups, were installed in the two valley regions where no resonators fill the space. Evacuation pumps and beam diagnostics were also installed. Initial pumping of the beam chamber started from September 29th. After the leak hunt, cryopumps were turned on and the vacuum pressure reached to 5.0×10^{-6} Pa at the end of October, which is the designed value. The power test of RF system was started on 13th November. On 27th November, the first resonator became operational in cw mode with a magnetic field of the sector magnets. The superconducting coils were fully excited several times to check whether the installed components could work properly under stray fields from the sector magnets. Many local magnetic shields made of iron were put to the parts which did not work properly under the stray fields.

The beam commissioning of the SRC started on December 17th 2006 using $^{27}Al^{10+}$ beam from the Intermediate-stage Ring Cyclotron (IRC). The first beam extraction of the SRC was accomplished at 16:00 on December 28th by the 345 MeV/nucleon $^{27}Al^{10+}$. After the various improvement of the hardware, the first RI beam production at RIBF was achieved by the fragmentation of 345 MeV/nucleon $^{86}Kr^{31+}$ beam on March 15th 2007. Following the delightful event, the commissioning of uranium beam was performed in March 2007. The uranium beam is the top priority for the RIBF. The first $^{238}U^{86+}$ beam with energy of 345 MeV/nucleon was successfully extracted from the SRC on March 23rd. After passing the facility inspection, the beam became possible to utilize the experiment at April 2007. The first experiment at the RIBF was carried out using 345 MeV/nucleon of ^{238}U beam from mid-May to early in June, and a new isotope ^{125}Pd was discovered [7]. In the latest study, the beam current up to 1.1 eμA for 345 MeV/nucleon $^{86}Kr^{34+}$ was attained on November 10th 2007 at the downstream of the SRC.

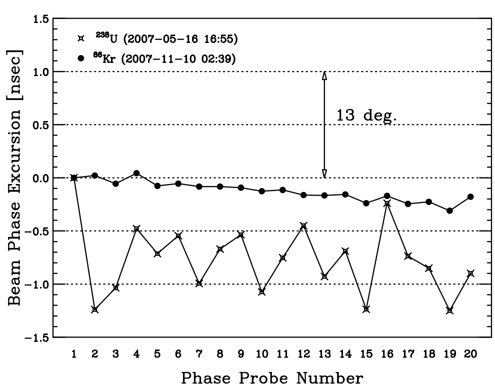

Figure 4: Isochronous condition of SRC for $^{238}U^{86+}$ and $^{86}Kr^{34+}$ beams.

The accurate isochronism is the significant condition for the cyclotron to make capable for providing the intense beam with high transmission efficiency. Figure 4 describes the excursion of periodic arrival time for revolving beam in the SRC as a function of phase pickups located along the radius vector. The result of krypton beam indicates that the isochronous condition of the magnetic field is attained to the acceptable level for the final booster in the RIBF accelerator complex. Since the intensity of uranium beam was too low to obtain the precious data set with high signal to noise ratio, the isochronous condition for the uranium beam was not able to be adjusted up to sufficient level. It is noted that the maximum voltage of 600 kV has been achieved at 36.5 MHz due to the careful conditioning of RF resonators.

OUTLOOK FOR IMPROVEMENT

The helium refrigerator of the SRC meets a serious problem at the present. The flow rate in the helium cooling system decreases gradually, increasing temperature of the 80 K stage adsorber and falling the inlet pressure of the first turbine. All this suggests that some impurity accumulate somewhere around the first turbine. We have to stop the refrigerator every two months to warm it up to room temperature and transpire the impurity. Recently, it has been found that the impurity is the lubricant oil from screw compressors passing through the cascade of oil separators. The oil has polluted the entire refrigerator. To rinse out the impurity, heat exchangers have been taken out from the refrigerator and are going to be washing away. The reconstruction of the refrigerator will be performed at July. Additional 3.5th and 5th oil separators will be installed as well.

The transmission efficiency of the SRC is less than 70%, that inhibits to provide the intense beam due to the large heat load and activation. One of the reasons is that the flat-top acceleration is not mastered yet. It is needed to improve the performance of main differential probe to optimize the phase and voltage of the flat-top resonator. The higher-order mode from the flat-top resonator overrides on the differential probe and the radial beam pattern is collapsed. For the uranium beam, huge number of secondary-electrons also disturb the pattern. Another reason is that the longitudinal emittance of the uranium beam is too large to accept by the SRC. This is the major cause not only for the SRC but also for the IRC not to realize the high transmission efficiency. The emittance broadness is caused that the uniformity of the charge stripper is insufficient and the operation of fixed-frequency Ring Cyclotron is not adequate. These difficulty should be resolved.

Some other hardware has to be prepared in near future. The acceleration of 500 MeV polarized-deuteron is going to be performed and the diagnostics for the beam is required. The cryopumps are heated up by the heat load of RF shield on resonators. Water-cooling attachment is fabricated now.

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