HARDWARE COMMISSIONING OF THE RIKEN SUPERCONDUCTING RING CYCLOTRON

H. Okuno, K. Yamada, J. Ohnishi, N. Fukunishi, N. Sakamoto, O. Kamigaito, M. Fujimaki,
H. Hasebe, K. Kumagai, T. Maie, M. Nagase, S. Yokouchi, K. Ikegami, M. Kase, A. Goto and
Y. Yano, RIKEN Nishina Center, Saitama, Japan.

Abstract

Since 1997, RIKEN Nishina Center has been constructing the Radioactive Isotope Beam Factory (RIBF) and succeeded in beam commissioning of its accelerator complex at the end of 2006 [1,2]. The world's first superconducting ring cyclotron (SRC) is the final booster in the RIBF accelerator complex. Assembling of its superconducting sector magnets was completed in August 2005. The superconducting coils were successfully cooled down and excited for tests from the various points of view: magnetic force, coil protection and quality of magnetic field, showing that they work as designed. After a series of the test the other components than the sector magnets were installed and tested under stray fields from the sector magnets. After setups of beam vacuum and radio frequency, beam commissioning started. The first beam was extracted at the end of 2006 and the first uranium beam was extracted in March 2007.

INTRODUCTION

RIKEN Nishina Center has been constructing the Radioactive Isotope Beam Factory (RIBF) to open and develop new fields in the nuclear science and technology since 1997. The RIBF 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. Fig. 1 shows a plan view of the superconducting ring cyclotron (SRC) which is the final booster in the RIBF accelerator complex. It is the first superconducting ring cyclotron with the ever largest K-value of 2600 MeV. The SRC mainly consists of six superconducting sector magnets [3], four main RF resonators [4], one flattop RF resonator, injection/extraction elements and beam diagnostics [5]. The maximum stored energy is 235 MJ. The total weight amounts to 8300 t. Its diameter and height are 19 m and 8m, respectively. The remarkable point of this cyclotron is the iron plates of about 1m 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. Each sector magnet is 7.2 m in length and 6 m in height and weighs about 800 t. The sector angle is 25 deg. The maximum sector field is 3.8 T. Main components of the sector magnet are a pair of superconducting main coils, four sets of superconducting trim coils, a cryostat, thermal insulation support links, twenty-two pairs of normal conducting trim coils, warm-poles and a yoke. All the magnets were assembled in the vault in August 2005, proceeding to the commissioning of the SRC.

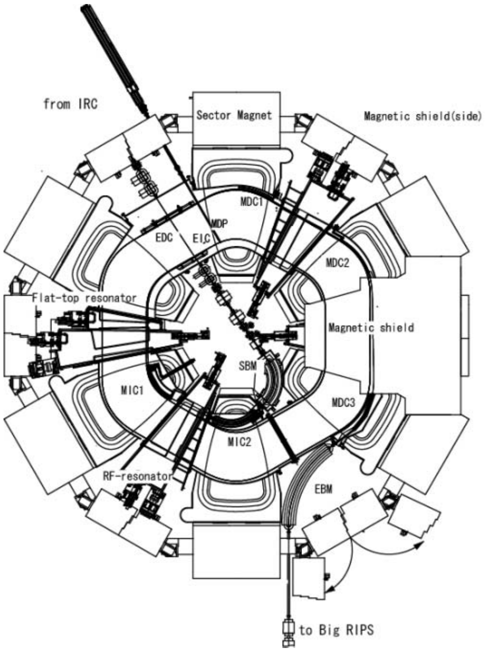

Figure 1: A plan view of the SRC.

The commissioning comprises the following two phases. In the first phase the superconducting magnets were tested from the various points of view. They were cooled down and excited. We performed magnetic field measurements to check the qualities of the magnetic fields. A fast shutdown test from full excitation was performed to check their safety. In the second phase all the parts necessary for the first beam were installed and tested. The beam commissioning for the SRC started after beam vacuum and radio frequencies were ready. The first beam was extracted at the end of 2006. The first uranium beam was extracted in March 2007 [6]. In May uranium beams were supplied for new isotope search experiments.

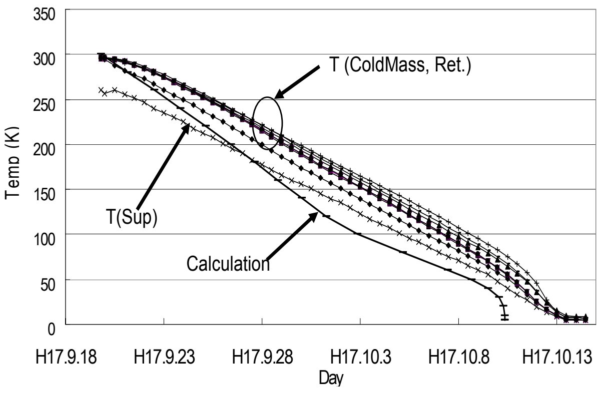

Figure 2: Cool-down curves of the SRC superconducting magnets.

COOL-DOWN AND EXCITATION

Fig. 2 shows a cool-down curve in the first trial. The temperatures of the cold masses smoothly fell into the liquid helium temperature. The temperature of the inlet gas from the He refrigerator was so tuned that temperature difference of the inlet gas and the cold mass can be less than 50K. A curve obtained from a simple calculation is also shown in Fig. 2. It took 23 days to cool down the coils. All the coils were successfully excited with the maximum currents on Nov. 7th 2005. They have never quenched so far, which is important to keep research activity of the facility stable and efficient. Huge magnetic forces are applied on the support structure for the coils in excitation. The forces were estimated using TOSCA code. Expansion force is 260 t/m, vertical force is 330 t toward the upper yoke and radial shifting force is 18 t. Based on these calculations the mechanical supports were designed as shown in Fig. 8 of ref.[3]. Especially radial shifting forces are difficult to calculate, because they are generated from differences between two large forces which have similar values. We were concerned that errors of the calculations could be serious. But the data of the measured forces proved to have agreed with the calculated ones as shown in Fig. 3. The radial support sustains the forces up to 90 t, which is well within the limit. Fig. 4 shows the coil voltage in the fast-shutdown from full excitation. Main coil current decays in a time constant of about 60 second. Decay curves of the trim coils have two components. Time constant for the fast component due to self inductance is about 1~2 seconds. The slow components come from mutual inductance between trim and main coil. These data show that all the coils were successfully shut down even in emergency. Fig. 5 shows the differences between the measured and calculated fields along the sector-centre lines when the main coil current is 4500 A [7]. They show satisfactory agreement within accuracy of 0.16~0.35 %. The field dispersion among the sectors is narrow because we use low carbon iron and each iron slab of the different sectors was made from identical charges in steel making processes. But of course some field disturbances are inevitable. The fields of SM1 deviate from those of the others because SM1 has a slightly different shape for a certain reason. Iron shims in the MIC2 and MDC3 which are magnetic channels for beam injection and extraction, disturb the field in the inner region of SM1 and the outer region of SM6, respectively. But the disturbances are slight enough to be adjusted by the correction coil in the magnetic channels and the auxiliary power supplies of the main coils and the trim coils

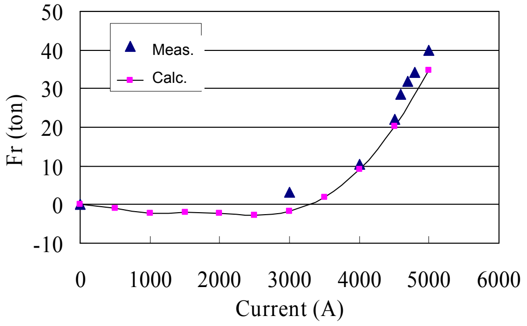

Figure 3: Radial shifting forces as functions of the main coil currents.

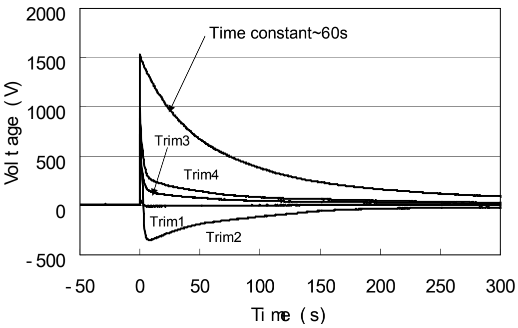

Figure 4: Coil voltages in a fast shut-down from full excitation.

TOWARD BEAM COMMISIONING

Four acceleration resonators and one flattop resonator were installed on June 24th 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 EIC/EDC (Electrostatic Inflection/Deflection Channel) and phase probes were installed in the two valley regions where there were no resonators filling the space. Evacuation pumps and beam diagnostics were also installed. From September 29th initial pumping of the beam chamber started for leak tests. As a result, the several simple leaks were found at flanges. On October 24th cryogenic pump was switched on and vacuum reached 5.0 x 10^{-6} Pa which is a designed value. The superconducting coils were fully excited several times to check whether the installed

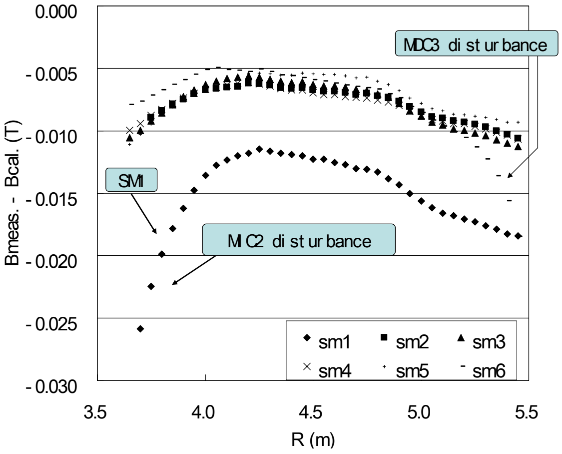

Figure 5: The differences of the measured and calculated fields along the sector-centre line.

components could work properly under stray fields from the sector magnets. The RF resonators were located very close to the sector magnets and the RF amps were placed just behind the back yoke of the sector magnets. Our two concerns arising from their locations were that the noises of RF amp might cause the coil quench and that the vacuum tubes in the RF amps could not work properly. These two points, however, were verified otherwise. Many local magnetic shields made of iron were put to the parts which did not work properly under the stray fields. For example, in the central region of the SRC many important devices locate and stray field reaches about 400 gauss. AC servo motors for trimmers of the resonators were shielded in iron boxes. Quadruple magnets, PFs (profile monitors) and FC (Faraday cup) need flow switch and solenoid valves in which magnetic elements are used. They were moved into the insides of the bases for the yokes where stray fields are less than 10 gauss. After many such detailed preparatory procedures the beam commissioning of the SRC started. Beams of ^{27}Al $^{10+}$from the IRC were injected to the SRC on Dec. 17th, 2006. The first beam was extracted from the SRC at 16:00 of Dec. 28th.

After the successful extraction of first beam we stepped up to the next stage of the beam commissioning. The first uranium beam (^{238}U^{86+}) was extracted on March 23rd 2007. Uranium beams are the top priority for our facility. In the middle of May the uranium beams were supplied to the experiments of new isotope search. On the other hand we had to improve the hardware which had some troubles in the first beam commissioning. The RF resonators were miserably difficult to excite. In some cases it took more than one day to excite the resonators. This was simply because of the lack of time for the RF conditioning. RF conditioning was done in January and February of 2007. In the RF conditioning the main coil current was increased gradually keeping pulsed radio frequencies sufficiently input to the resonators. It took about 20 days to increase the main coil current from 0 A to 5000 A as shown in Fig. 6. Iron yoke starts to saturate and distribution of stray field drastically change around 3000 A. The increase of the current is very slow around 3000 A. The current trend in June is also shown in Fig. 6, revealing that their condition has greatly been improved. Performances of EIC/EDC were also miserable. Their specification is 120 kV in the gap of 12 mm. During the first beam commissioning dark currents reached 2 mA at the voltage of about 90 kV. We could not excite higher voltages due to the limit of the power supplies. We studied how to clean the septum (ground) and cathode made of Cu and Ti-alloy, respectively, applying supersonic cleaning, buff polishing. These two graphs show how markedly the cleaning has improved the performance of the EDC. The left one summarize the V-I plot before the cleaning and the right one summarize that after the cleaning.

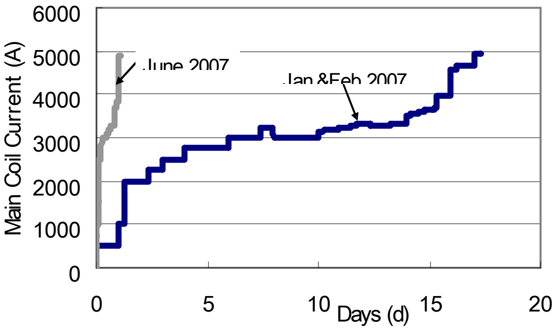

Figure 6: Trend graphs of main coil current in the RF conditionings.

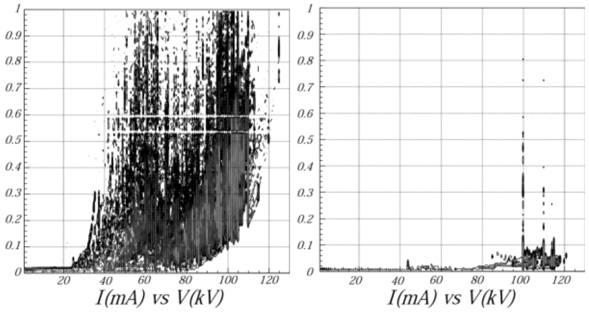

Figure 7: Improvements of performances of the EDC. The left and right graphs show V-I plots before and after its cleaning, respectively.

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