

COMMISSIONING OF RIKEN RI BEAM FACTORY

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Abstract

On Dec. 28, 2006, the first beam was successfully extracted from the Superconducting Ring Cyclotron (SRC) of the RIKEN RI Beam Factory (RIBF), which has been constructed since 1997. The ion kind and energy of the beam were $^{27}\text{Al}^{10+}$ and 345 MeV/nucleon, respectively. This signifies that we actually completed the world's first and world's most powerful cyclotron. The first beam of $^{238}\text{U}^{86+}$ ions with the same energy was also extracted from the SRC on March 23, 2007; a new isotope (^{125}Pd) was discovered in June 2007 using a superconducting fragment separator in a test experiment with the uranium beam. The construction and commissioning of the RIBF accelerators as well as future upgrades planned are presented.

INTRODUCTION

The RIKEN RI Beam Factory (RIBF) is a facility-expanding project that aims at producing a variety of radioactive isotope (RI) beams with the world-highest intensities [1,2]. The old facility, which houses a ring cyclotron as a main accelerator and its two injectors - a heavy-ion linac and an AVF cyclotron - was constructed in the period of from 1975 to 1990 and has been operated for experiments in various fields of heavy-ion science. They include nuclear physics, astrophysics, atomic physics, material irradiation, application to biology (plant

breeding [3,4,5]), etc. This accelerator complex has allowed us to accelerate all kinds of ions from proton to uranium as well as to produce RI beams; however the kinds of RI's available are limited up to atomic masses of around 50 due to relatively low energies of primary beams. The construction of new booster ring cyclotrons thus started in 1997 to meet strong demands from users for all kinds of RI beams up to uranium. We completed three ring cyclotrons including a superconducting ring cyclotron in the autumn of 2006.

OVERVIEW

Fig. 1 shows a layout of the RIBF. The accelerator complex of the RIBF consists of two injectors – a world's unique variable-frequency heavy-ion linac and a K78 MeV AVF cyclotron – and four ring cyclotrons with K-values of, from the upstream, 540 MeV, 570 MeV, 980 MeV and 2,600 MeV. These ring cyclotrons are called RIKEN Ring Cyclotron (RRC), fixed-frequency Ring Cyclotron (fRC), Intermediate-stage Ring Cyclotron (IRC) and Superconducting Ring Cyclotron (SRC). The SRC is the world's first and world's most powerful superconducting ring cyclotron.

This accelerator complex allows us to accelerate all kinds of ions from proton to uranium up to high energies in the following acceleration modes: 1) fixed-energy mode, 2) variable-energy mode and 3) polarized-deuteron mode. In the fixed-energy mode (see Fig. 2), particularly

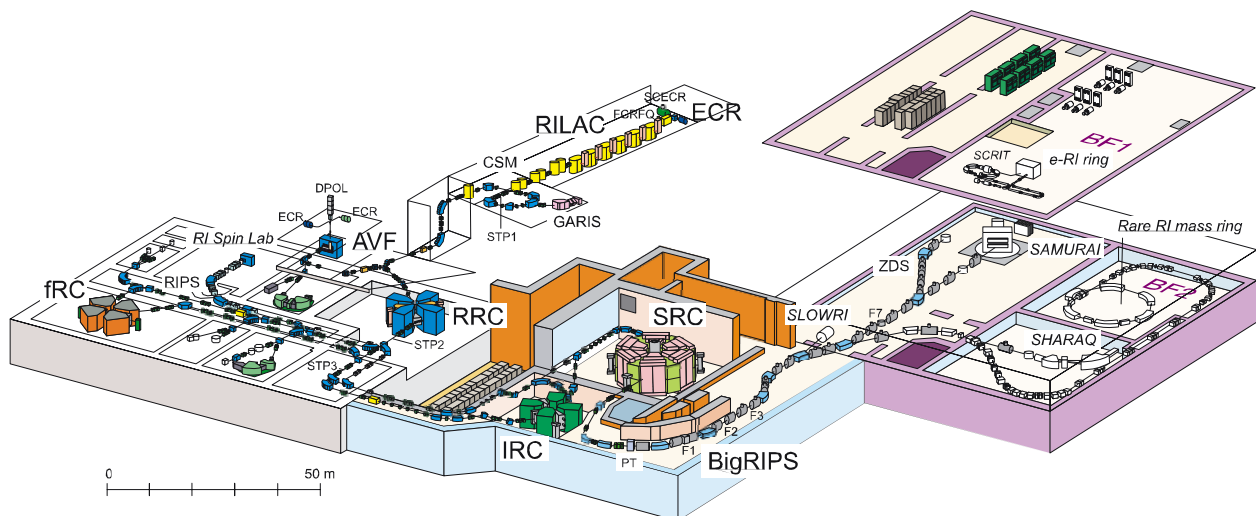


Figure 1: Layout of the RIKEN RI Beam Factory.

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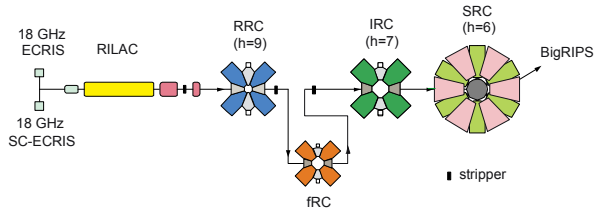


Figure 2: Fixed-energy mode.

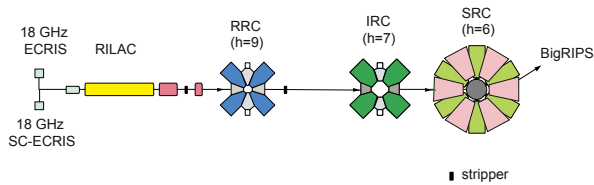


Figure 3: Variable-energy mode.

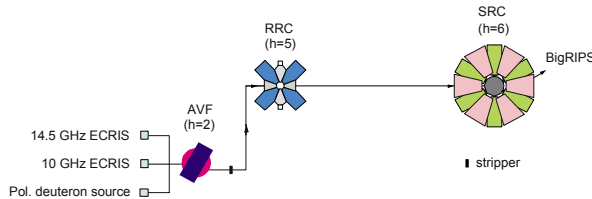


Figure 4: Polarized-deuteron mode.

very heavy ions up to uranium are accelerated with a combination of the RILAC, RRC, fRC, IRC and SRC at 345 MeV/nucleon. The energy is fixed in this mode since the rf frequency of the fRC is fixed. In the variable-energy mode (see Fig. 3), ions are accelerated using the RILAC, RRC, IRC and SRC (by bypassing the fRC). The energy in this mode is 400 MeV/nucleon at the maximum for relatively light ions up to atomic masses of around 40. In the polarized-deuteron mode (see Fig. 4), a polarized deuteron or ions whose mass-to-charge ratio is 2 are accelerated using the AVF, RRC and SRC at 440 MeV/nucleon at the maximum. In these modes charge strippers are used after the RILAC, (AVF), RRC or fRC depending on the kind of ion beam accelerated [6]. The acceleration performance of the RIBF is shown in Fig. 5.

These energetic heavy-ion beams are converted into intense RI beams via projectile fragmentation of stable isotopes or in-flight-fission of uranium isotopes by a superconducting fragment separator, BigRIPS [7].

HISTORY OF CONSTRUCTION OF NEW RING CYCLOTRONS

The construction of the three new ring cyclotrons started in 1997 after a two-year R&D. Each ring cyclotron was constructed as follows [8]; a brief history of the construction is shown in Fig. 6.

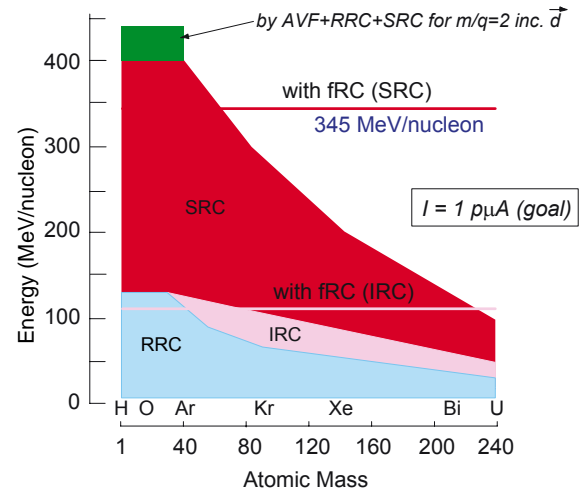


Figure 5: Acceleration performance of the RIBF.

SRC

The assembling of the superconducting sector magnets in the accelerator building started in April 2003 after a fabrication period of four and a half years from October 1998 to March 2003. The sector magnets were completed in September 2005, and were successfully excited at the maximum field level for the first time on November 7 after a cool-down period of about 1 month. However, on the morning of November 8, the next day, a serious trouble occurred that the liquid helium in the coil vessels and the control Dewar instantly evaporated and was released into the atmosphere. This was because one of the feed-throughs of the superconducting trim coils on the liquid-helium vessel of the control Dewar had cracked, allowing helium gas into the insulation vacuum. This trouble resulted in the construction falling about four months behind schedule. The field maps of the sector magnets were measured for about two months in April-June 2006 [9], and the rf resonators [10] and vacuum chambers were then installed. Details of the hardware commissioning of the SRC are reported elsewhere in these proceedings [11].

IRC

Among the three ring cyclotrons, the IRC was completed earliest. The fabrication of the components of the IRC was performed at a factory in a period of three years from April 1998 to March 2001, and the field maps of the sector magnets aligned in due positions at the factory were measured from 2000 to 2002 for about 120 days in total. The assembling in the accelerator building started in October 2003; the sector magnets were completed in March 2004 and the remaining components such as the rf resonators and vacuum pumping system in November 2004.

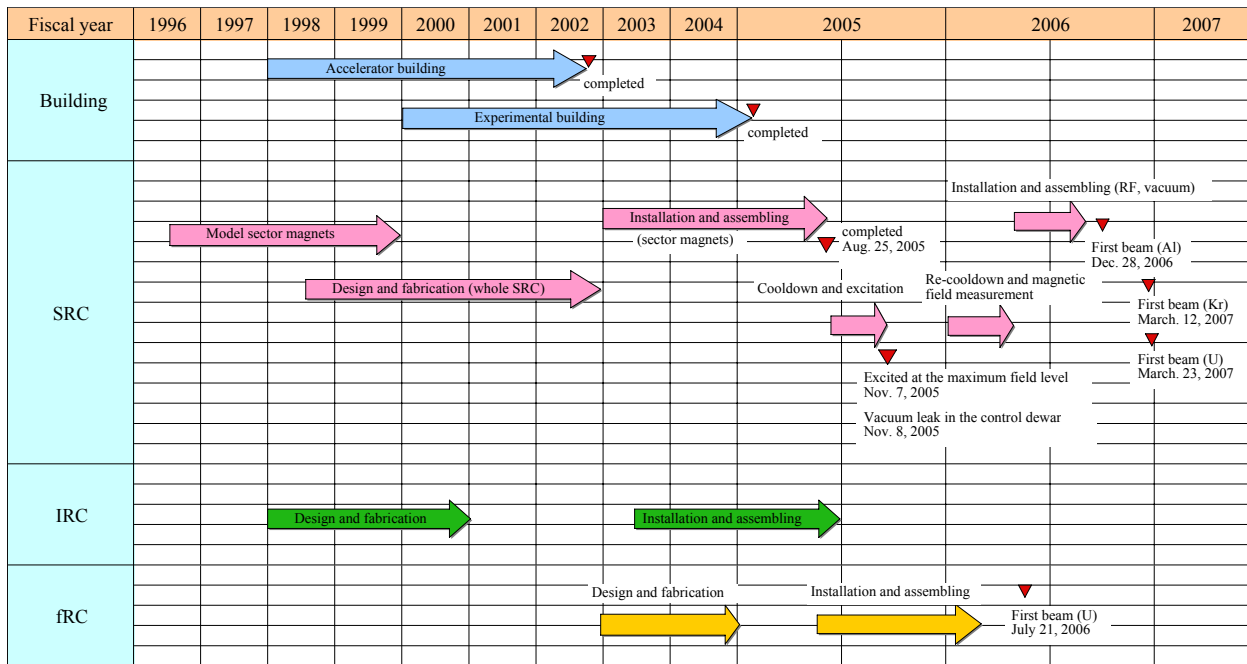


Figure 6: History of construction of three new ring cyclotrons.

fRC

The fabrication of the components of the fRC was performed at a factory in a period of two years from March 2003 to March 2005. In this period the field maps in the region of the magnet edges were measured for the sector magnets aligned in due positions at the factory. The assembling in the accelerator building started in August 2005; the main components such as the sector magnets and rf resonators were completed in March 2006, and the remaining components were completed in May 2006. Then the magnetic field measurement along each sector-center line only was carried out.

COMMISSIONING

At the start of the commissioning, we set the ion type for the first beam to be uranium. The commissioning of the fRC started in July 2006 with the acceleration of a uranium beam. The $^{238}\text{U}^{73+}$ ion beam passed through the electrostatic deflector of the fRC for the first time on July 21. From September to November, acceleration tests of the fRC using a uranium beam continued to be performed, in between which experiments using the existing facility were conducted. The commissioning of the IRC started after the rooms for the IRC and SRC were designated to be a radiation-controlled area on November 22. For the tuning of the IRC, it was decided that a krypton beam would be used, taking the low intensity of the uranium beam into account. The $^{84}\text{Kr}^{31+}$ ion beam, the charge-to-mass ratio of which is close to that of $^{238}\text{U}^{88+}$, was accelerated and extracted from the IRC for the first time on November 25; it took as little as about 2 hours for the tuning from the injection and extraction. The acceleration

of the krypton beam was performed by bypassing the fRC (variable-energy mode). For the commissioning of the SRC, the beam was switched to an aluminum beam ($^{27}\text{Al}^{10+}$) on December 13, which also has a charge-to-mass ratio close to that of the uranium beam and was expected to have higher intensity than the krypton beam. The acceleration of the aluminum beam was also performed in the variable-energy mode; the operational parameters for this acceleration is shown in Table 1. The beam injection into the SRC became possible on December 21 when the conditioning of two of the four rf resonators was complete. At this time, during the acceleration, an unexpected phenomenon occurred; a beam suddenly stopped at a position about 1,000 mm from the injection radius and did not proceed further. It was found that this was due to a quadrupole mass analyzer that had been placed by mistake at that position,

Table 1: Operational parameters for the acceleration of aluminum ion beam.

	ECRIS	RILAC	RRC	IRC	SRC
Charge	6+	10+	10+	10+	10+
Energy (MeV/u)	---	2.7	45	114	345
Frequency (MHz)	36.5	36.5	36.5	36.5	36.5
Harmonics	---	---	9	7	6

obstructing the beam passage. On December 28 at 6 am, after its removal, the evacuation of the vacuum chamber and the necessary reconditioning of the rf resonators, the beam injection and acceleration were restarted. This time, the beam was accelerated up to the outermost radius immediately, but it took more time than expected for the extraction. However, by tuning the machine carefully, for instance using a radiation survey monitor temporarily set at the exit of the SRC, the extracted beam was finally detected at 4 pm using a beam profile monitor and a Faraday cup placed 5 m downstream of the SRC. We thus could confirm the acceleration performance of the SRC with this acceleration test.

In the acceleration tests using a uranium beam performed in the autumn of 2006, we initially chose the charge state of uranium ions from the 18 GHz ECR ion source (using UF₆ gas) to be 14+ and then charge stripped to 35+ with a thin carbon stripper foil after the RILAC. We found, however, that the lifetime of the carbon foil was as short as several tens of minutes for an intensity of 10 μ A. On the other hand, in parallel with the acceleration tests, we performed R&D on the ECR ion source for the direct production of ²³⁸U³⁵⁺ ions using metal uranium and obtained the beam intensity that was equivalent to the one for the case of ²³⁸U¹⁴⁺ acceleration. Therefore, we decided to use ²³⁸U³⁵⁺ instead of ²³⁸U¹⁴⁺ from the ECR ion source. In the same acceleration tests, we also found that the quality of originally designed ²³⁸U⁷³⁺ ion beam produced using a carbon stripper foil of 0.6 mg/cm² in thickness after the RRC (11 MeV/nucleon) was worse than expected. Therefore, we also decided to choose 71+ instead of 73+ using a thinner carbon foil of 0.3 mg/cm². Furthermore, in the acceleration test performed in January 2007, we found that the most probable charge state obtained using a charge stripper of 17 mg/cm² after the fRC (51 MeV/nucleon) was 86+ instead of 88+ originally expected. The operational parameters for the acceleration of a uranium beam thus determined is shown in Table 2. Details of the charge stripping are reported elsewhere in these proceedings [6].

On March 12, 2007, the first ⁸⁶Kr³¹⁺ beam, the charge-to-mass ratio of which is the same as that of a ²³⁸U⁸⁶⁺ beam, was extracted from the SRC; the first RI beams

were generated and identified by the BigRIPS on March 15. Then, on March 23, we succeeded in accelerating a ²³⁸U⁸⁶⁺ beam up to 345 MeV/nucleon, and we successfully identified a large variety of RI beams produced via the inflight-fission of the 345 MeV/nucleon uranium beam. And eventually, a new very neutron-rich isotope, 125Pd, was discovered in the first test experiment using the uranium beam that was performed in March-June 2007 [2].

We achieved the designed energy as mentioned above. However, we have a problem that the beam intensity of the uranium beam is still quite low, despite that we performed in April some improvements such as the followings: to adopt an accel-decel method for the 18 GHz ECR ion source and to install a double-rebuncher system between the RILAC and the RRC. In the test experiment, an average beam current on the production target was 2 enA (1.4x10⁸ particles/sec; this value was measured with a calibrated Faraday cup at the BigRIPS target), while an average analyzed beam current of ²³⁸U³⁵⁺ from the ion source was 2,000 enA (3,400x10⁸ particles/sec). By considering that the yield fractions of 71+ and 86+ in the charge stripping process are 15 % and 25 %, respectively, this means that the net beam transmission efficiency through the accelerators and beam lines was only 1 %.

Main causes for this low transmission efficiency were as follows: 1) the flattop resonators of the fRC, IRC and SRC were not operational or not operated properly, 2) one of the four rf resonators of the SRC was not operational, and even the operational resonators could not excite enough voltages, 3) the curvature of the deflector channel of the IRC was incorrectly manufactured, and 4) the operation of the phases and voltages of the six tanks of the RILAC as well as the injection and extraction of the ring cyclotrons were not yet optimized.

Details of the commissioning are reported elsewhere in these proceedings [12].

FUTURE UPGRADES

Our final goal is to achieve a beam intensity of 1 μ A from the SRC for all kinds of ion beams. However, the beam intensity now available is far below this goal. In order to achieve this goal, we have the following upgrade plans other than the optimal tuning of the accelerators: 1) the installation of a flattop resonator to the RRC, 2) the installation of a new injector to the RRC equipped with a 28 GHz superconducting ECR ion source (SC-ECR), and 3) the development of a liquid Li film.

Among the five cyclotrons at the RIBF, only the RRC have no flattop resonator. It is indispensable to get a high-quality beam and to achieve high transmission efficiency through the RRC. We have already finished the design study of the resonator. The flattop will be achieved by a third-harmonic resonator that has two stems and two gaps [13].

Table 2: Operational parameters for the acceleration of uranium ion beam.

	ECRIS	RILAC	RRC	fRC	IRC	SRC
Charge	35+	35+	35+	71+	86+	86+
Energy (MeV/u)	---	2.7	11	51	114	345
Frequency (MHz)	18.25	18.25	36.5	54.75	36.5	36.5
Harmonics	---	---	9	12	7	6

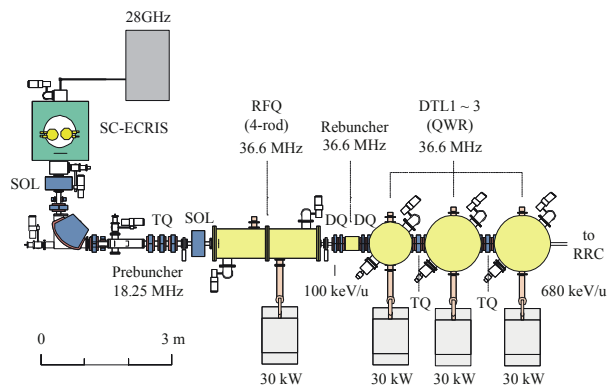


Figure 7: Schematic drawing of new injector.

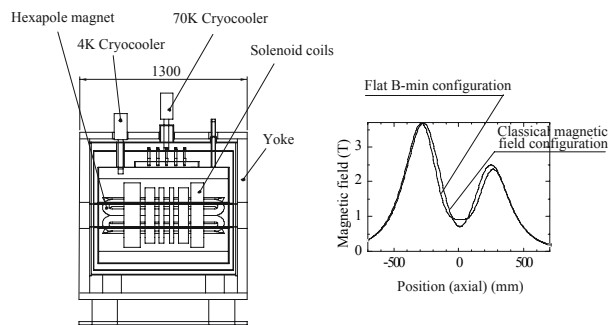


Figure 8: Schematic drawing of the 28 GHz superconducting ECRIS and the magnetic field strengths along the axial direction.

A powerful ECR ion source is a key device for us to achieve a $1 \mu\text{A}$, 345 MeV/nucleon uranium beam. On the other hand, in order to make it possible to concurrently conduct both the super-heavy-element search experiment [14] using the RILAC and the RIBF experiments, a new injector to the RRC is required. Therefore, we have started to construct it. The injector is designed to accelerate ions with a mass-to-charge ratio of 7, aiming at heavy ions such as $^{84}\text{Kr}^{13+}$, $^{136}\text{Xe}^{20+}$ and $^{238}\text{U}^{35+}$, up to an energy of 680 keV/nucleon. It consists mainly of the SC-ECR, an RFQ linac based on the four-rod structure and three drift-tube linac (DTL) based on the quarter-wavelength resonator (QWR), as shown in Fig. 7 [15]. Fig. 8 shows a schematic drawing and magnetic field strengths of the SC-ECR [16,17]. To obtain a larger resonance surface, a special geometrical arrangement of the six superconducting solenoid coils is adopted. This arrangement makes it possible to obtain the volume 3-4 times larger than that for classical magnetic field configuration. A sextupole field is generated by six racetrack superconducting coils. The maximum mirror magnetic and radial field strengths are 4 T and 2 T, respectively. Another characteristic feature of the SC-ECR is that the plasma volume is designed to be as large as $1,100 \text{ cm}^3$. The SC-ECR and the whole injector system are scheduled to be completed in the summer of 2008 and

the spring of 2009, respectively. An intensity of $^{238}\text{U}^{35+}$ ions of more than $15 \mu\text{A}$, which is required to obtain a $1 \mu\text{A}$ uranium beam on target, is expected to be produced from this SC-ECR.

Another key technology is a charge stripper such as a liquid Li charge stripper that can endure high-intensity beams. At present, we use carbon foils as charge strippers, but their lifetimes are as short as about 10 hours even for low-intensity beams. As an alternative of carbon foils, we developed a film of silicone oil before, and we successfully formed a film of about 0.1 mg/cm^2 in thickness by pulling up oil with a rotating disk [18]. However, it endured only 8 W/cm^2 heat deposit at maximum with 500 keV $^4\text{He}^+$ ions, while it will be 10 kW/cm^2 for $1 \mu\text{A}$ 345 MeV/u U beam. Therefore, we plan to develop this type of stripper using liquid Li, which has higher boiling temperature. We have just started an endurance test of this silicone film using a uranium beam in the autumn of 2007.

SUMMARY

We completed three new ring cyclotrons, including a world's first and world's most powerful superconducting ring cyclotron, in the autumn of 2006 for the RIBF, which aims at producing a variety of radioactive isotope (RI) beams with the world-highest intensities. We accelerated an $^{27}\text{Al}^{10+}$ ion beam at 345 MeV/nucleon on December 28, 2006 for the first time and a $^{238}\text{U}^{86+}$ ion beam at the same energy on March 23, 2007, and discovered a new very neutron-rich isotope, ^{125}Pd , in the first test experiment using the uranium beam that was performed in March-June 2007. We have a problem that the beam intensity is still low (by the order of 10^4 lower than the design goal of $1 \mu\text{A}$ for a uranium beam), although we have achieved the designed energy. We therefore need to undertake upgrade plans such as a 28 GHz superconducting ECR ion source and a liquid Li film that can endure high-intensity beams.

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