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RECENT PROGRESS IN RIKEN RI BEAM FACTORY

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Abstract

Recent efforts at the RIKEN RI Beam Factory (RIBF) are aimed at increasing the beam intensity for very heavy ions such as xenon and uranium. This paper presents upgrade programs carried out over the past few years, including modifications of the RF cavities of the RIKEN Ring Cyclotron and improvements of the charge stripper. The current performance of the RIBF accelerators and future plans to further increase the beam intensity are also presented.

OVERVIEW OF RIBF

The Radioactive Isotope Beam Factory (RIBF) at RIKEN is a cyclotron-based accelerator facility that uses fragmentation or fission reactions of intense heavy-ion beams to produce intense RI beams over the whole atomic mass range [1, 2]. The RIBF started beam delivery in 2007, after the commissioning of the three ring cyclotrons, fRC, IRC, and SRC, that were constructed to boost the energies of the beams accelerated by the RIKEN Ring Cyclotron (RRC), shown in Fig. 1. The main specifications of the four ring cyclotrons are summarized in Table 1. There are currently three injectors, AVF, RILAC, and RILAC2, that provide a wide variety of heavy-ion beams, as described below.

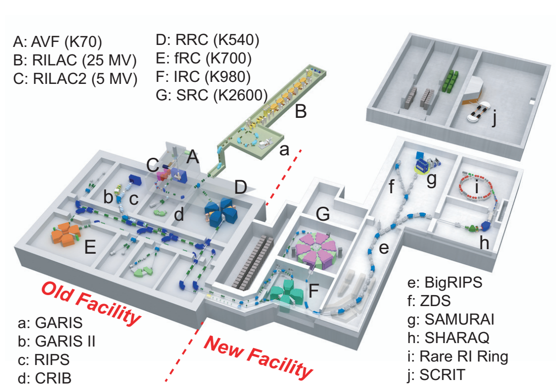

Figure 1: Schematic drawing of the RIKEN RI Beam Factory (RIBF). The accelerators (A–G) and experimental devices (a–j) are presented.

The scientific goals of the RIBF include establishing a new and comprehensive way of describing nuclei and improving the understanding of the synthesis of heavy elements in the universe. As shown in Fig. 1, distinctive experimental devices have been set up in the new facility, as well as in the old facility, which mainly uses the beams from the RRC.

We are also promoting applications of heavy-ion beams to various research fields, such as nuclear chemistry and biological science, using the heavy ion beams from RILAC, AVF, RRC, and IRC.

Table 1: Specifications of the RIBF Ring Cyclotrons

	RRC	fRC	IRC	SRC
Sectors	4	4	4	6
K [MeV]	540	700	980	2600
R_{inj} [cm]	89	156	278	356
R_{ext} [cm]	356	330	415	536
Weight [t]	2400	1300	2900	8300
Trim coils/ main coil	26	10	20	4 (SC) + 22 (NC)
RF system	2	2 + FT	2 + FT	4 + FT
Freq. [MHz]	18–38	54.75	18–38	18–38

One of the most important features of the RIBF accelerator system is the ability to accelerate all ions from hydrogen to uranium to 70% of the speed of light. To make this possible, three acceleration modes are used in the RIBF accelerators, as shown in Fig. 2.

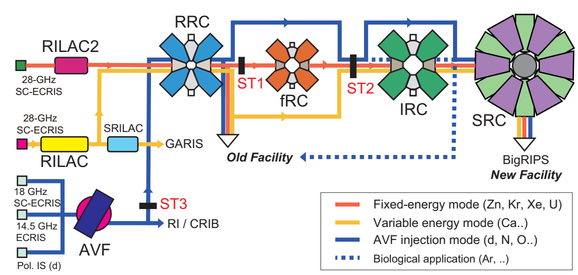

Figure 2: Accelerator chain of the RIBF. The three injectors, RILAC2, RILAC, and the AVF cyclotron, are followed by four booster cyclotrons, the RIKEN Ring Cyclotron (RRC), fixed-frequency Ring Cyclotron (fRC), Intermediate-stage Ring Cyclotron (IRC), and Superconducting Ring Cyclotron (SRC). The charge strippers are indicated by labels in red text (ST1–ST3). The superconducting linac booster, SRILAC, is under construction [3].

The first mode is a fixed-energy mode, originally intended for accelerating very heavy ions such as xenon and uranium. This mode uses the RILAC2 injector with a powerful 28-GHz superconducting ECR ion source, and boosts the beam energy up to 345 MeV/u with the four booster ring cyclotrons (RRC, fRC, IRC, SRC). Two charge strippers are used for the

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uranium beam. One is a helium gas stripper located at the exit of the RRC (E = 11 MeV/u), and the other is a rotating graphite-sheet stripper located between fRC and IRC (E = 50 MeV/u). Recently, the high performance of the ion source has made it possible to accelerate zinc and krypton beams in this mode using only the second charge stripper [4].

The second acceleration mode is a variable energy mode that uses the RILAC, RRC, IRC, and SRC to accelerate medium-mass ions such as calcium. The beam energy from the SRC can be changed over a wide range below 400 MeV/u by changing the RF frequency. The third mode uses the AVF cyclotron as an injector, with two boosters, the RRC and SRC. This mode is exclusively used for light ions such as deuterons, nitrogen, and oxygen. By changing the RF frequency, the beam energy from the SRC can also be changed in the range below 440 MeV/u.

RECENT RESEARCH & DEVELOPMENT

Among the heavy ion beams, the uranium beam is most effective because it can generate a medium-mass RI beam far from the stability line through fission reactions. Therefore, recent research and development efforts have concentrated on increasing the intensity of the uranium beam. This section gives some examples related to these efforts.

Ion Source [5]

Uranium ions are first generated in the 28-GHz superconducting ECR ion source (SC-ECRIS), and U^{35+} ions are accelerated by the RILAC2 and RRC. During the first few years after 2007, a sputtering method with a metallic uranium rod was used to generate uranium ions, and a U^{35+} beam of approximately 100 eμA could be extracted from the ion source during the beam time. However, the beam stability was not satisfactory. Therefore, in 2013, we started the development of a high-temperature oven (HTO) method. This method was expected to control the amount of vapor supplied to the ion source plasma.

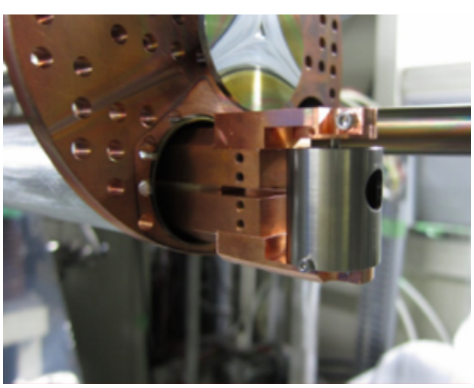

Figure 3: High-temperature oven (HTO) used in the 28-GHz superconducting ECR ion source (SC-ECRIS).

Figure 3 shows the HTO in the SC-ECRIS. The HTO is equipped with a pure tungsten crucible loaded with uranium oxide. The crucible is supported by a pair of copper rods that act as bus bars carrying DC current to heat the crucible directly. A temperature of 2000 °C is required for the crucible to bring the vapor pressure of uranium oxide to 0.1–1 Pa.

The HTO has been used in the uranium beam time since autumn 2016. In the first beam time, the U^{35+} beam was successfully supplied for 34 consecutive days with a current of 120 eμA or more. Although the vapor-ejection hole was blocked during the beam time in subsequent years, the beam intensity supplied to the RILAC2 injector was kept at 100–130 eμA at the ion source for more than one month.

Helium Gas Stripper [6]

The most important issue in the first few years of RIBF operation was the lack of a charge stripper for powerful uranium beams. In order to solve this problem, in 2012, we developed a window-less helium gas stripper based on a five-stage differential pumping system, as shown schematically in Fig. 4. The target cell of the stripper contains helium gas at approximately 7 kPa, while the gas leaked into the next stages is re-circulated to the target cell with the help of mechanical booster pumps. We found that the fraction of the charge state of 64+ is enhanced due to the atomic shell effect, and uranium ions with this charge state are accelerated by the next ring cyclotron, fRC. This system has played an essential role in increasing the uranium beam intensity. In fact, the present intensity of uranium beams injected into the stripper has reached 10^{13}/s.

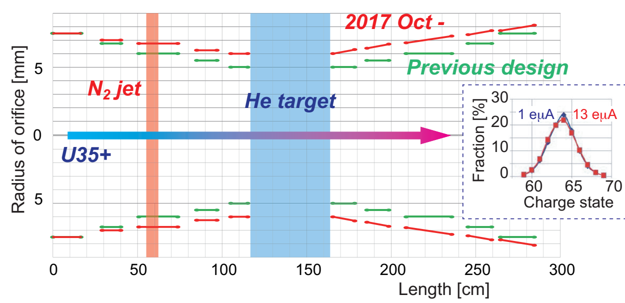

Figure 4: Orifice diameters in the helium gas stripper. The green lines represent the orifice diameters in the original structure. The N_2 gas-jet has expanded the orifice diameters to those represented by the red lines.

However, increasing the injected beam intensities has caused various difficulties in the operation of the helium gas stripper. The quality of beams injected into the stripper decreases during high-intensity operation due to space charge effects in the low energy section of the RILAC2. A small fraction of the beam loss in the stripper orifices can cause serious hardware failure or the generation of radioactivity. For efficient transmission of high intensity beams, the diameter of the orifices of the helium gas stripper had to be increased.

On the other hand, a slight leak of helium gas into the RRC located 7 m upstream of the stripper is a serious problem in high-intensity operation. Since the RRC has only cryogenic pumps, the leaked helium gas gradually accumulates in the RRC. Collisions between the uranium ions being accelerated

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and the helium atoms stored in the RRC can easily change the charge states and cause beam loss. Due to the acceleration of high-intensity uranium beams, such beam losses induce further losses because of local pressure increases due to gas desorption.

To overcome these difficulties, we developed a nitrogen gas-jet curtain method. By using a curtain-like nitrogen gas-jet separating the two chambers, the flow of helium to the low pressure side can be shut off, and the leaked gas is exchanged from He to N_2. Based on this, a N_2 gas-jet curtain was installed in the helium gas stripper and tested, as shown in Fig. 4. The sealing ability was found to be greatly improved. The gas leaked upstream in the beam line was successfully replaced with nitrogen, as desired. Also, we found that the N_2 gas-jet curtain works as a pre-stripper. Initial rapid stripping in the N_2 gas-jet curtain reduces the required pressure of helium gas by approximately 15%.

The improved system was used in the user beam time in 2017. The output intensity was increased by 25% due to improved transmission efficiency. No serious pressure rise in the RRC was observed. As shown below, the N_2 gas-jet curtain method contributed significantly to the new world record output intensity achieved in 2017 (71 pnA at 345 MeV/u).

RRC Cavity [7, 8]

The RIKEN Ring Cyclotron (RRC) has two acceleration cavities based on variable-frequency, half-wavelength resonator, constructed more than 30 years ago [9]. The resonant frequency of this cavity is varied by moving two boxes vertically, as shown in Fig. 5. The inner height of the cavities could be made as small as 2.1 m, while keeping a wide range of resonant frequency from 20 to 45 MHz. However, the frequency for uranium acceleration is 18.25 MHz, which is outside the designed range. The gap length between the dee electrode and the movable box had to be made as small as 20 mm, as shown in Fig. 5. During the acceleration of the uranium beam, the narrow gap between the dee electrode and the movable box caused a bottleneck problem limiting the cavity voltage to a maximum of 80 kV. In addition to frequent discharges during operation, this narrow gap increases the capacitance in the cavity, thus lowering the shunt impedance. Furthermore, due to the low acceleration voltage, the uranium beam current reached a space charge limit in the RRC [10].

Therefore, as shown in Fig. 5, the internal components of the cavity, the stems and the dee electrode, were replaced, leaving the external box and movable box of the cavity unchanged. The frequency range of the RRC cavity is shifted downward by the insertion of a notch into the stem, which was originally straight. Since the RRC cavities have not operated at frequencies above 39 MHz in recent years, the frequency range was set to 16–38 MHz after remodeling. The shunt impedance, voltage distribution, and frequency range were optimized by changing the notch size based on 3D electromagnetic calculations using the computer code Microwave Studio (MWS).

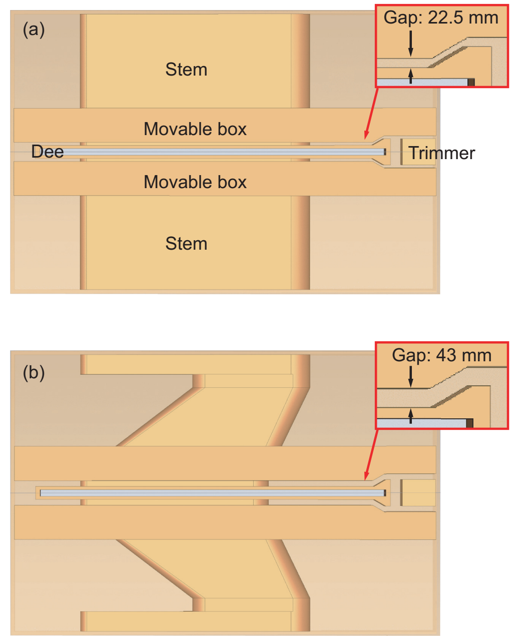

Figure 5: Calculation models for the original cavity (upper panel) and the modified cavity (lower panel). The gap length required for a resonant frequency of 18.25 MHz is shown in each panel.

The modification work was carried out from February to March 2018, and in April a low power RF test was performed with a network analyzer. Figure 6 shows a photo of the inside of the cavity after the modification. The test results showed that the frequency range covers the design range. In addition, as expected, the quality factor Q_0 almost doubled at 18.25 MHz. At the same time, the old degraded power supplies for the tetrode grids in the RF amplifiers were updated to improve the stability.

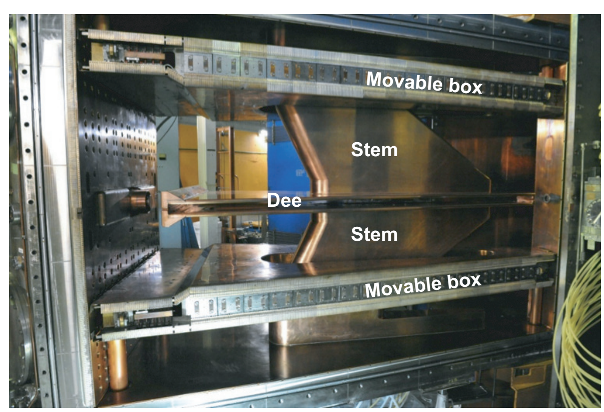

Figure 6: Internal view of the modified RRC cavity.

The new cavities have been used in beam time since May 2018 and show good operational performance from 18.25 to 32.6 MHz. In particular, stable operation was achieved at a voltage of 120 kV at 18.25 MHz. This is due to an improvement in shunt impedance and an increase in the gap length between the dee and the movable box. In fact, the

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frequency of voltage breakdown has decreased significantly, as shown in Fig. 7. The bottleneck problem during uranium acceleration was solved in this way. However, due to production problems, cooling water leaked into the vacuum several times, and we are currently considering countermeasures.

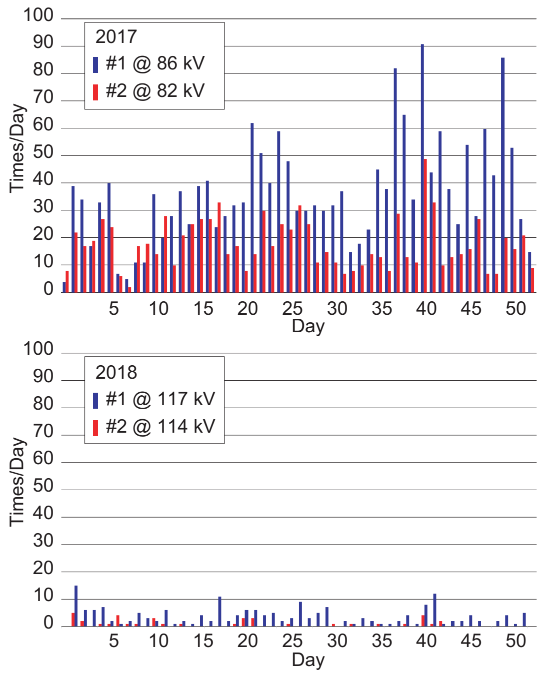

Figure 7: Comparison of frequency of voltage breakdown during the uranium beam time in 2017 (upper panel) and that in 2018 (lower panel). After the modification in 2018, the frequency of the breakdown decreased significantly despite the increased acceleration voltage.

PRESENT STATUS

The evolution of the maximum beam intensity for the ion beams accelerated at RIBF is shown in Fig. 8. Through continuous efforts including the research and development described above, the uranium intensity now exceeds 70 pnA and the beam power has reached 6 kW. The intensity of the xenon beam in 2019 is 70% higher than the previous value, mainly due to the RRC cavity modification. The beam power of medium-mass ions such as calcium and krypton already exceeds 10 kW, as shown in Fig. 8.

The transmission efficiency during uranium beam acceleration is also summarized in Fig. 9. It can be seen that the overall transmission efficiency has almost doubled over the past few years. The improvement in 2017 is due to a change in the beam tuning of the RRC with a reduced off-centering amplitude [11] in addition to the improvements in the helium gas stripper described above.

FUTURE PLANS

At present, the beam intensities extracted from the RIBF accelerator are the highest among rare isotope beam (RIB) facilities worldwide. However, a number of next-generation

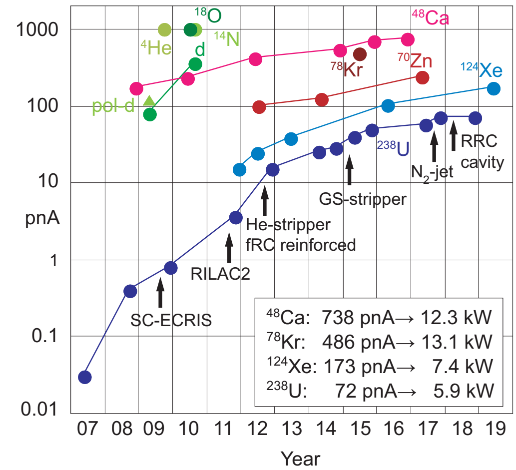

Figure 8: Evolution of the beam intensity at the exit of the SRC since the start of operation of RIBF in 2007. The maximum intensity achieved so far is presented for ^{48}Ca, ^{78}Kr, ^{124}Xe, and ^{238}U beams, along with the corresponding beam power. The main R&D items for increasing the uranium beam are also indicated.

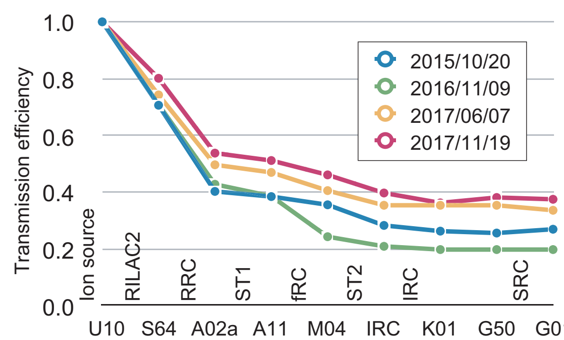

Figure 9: Transmission efficiency during uranium beam acceleration. The horizontal axis corresponds to the position of the Faraday cups in the accelerator chain. Note that the stripping efficiencies in the charger strippers are not included in the transmission efficiency.

RIB facilities are currently under construction in various parts of the world or are being planned. These include FRIB in the USA, FAIR in Germany, RAON in Korea, and HIAF in China. Some of them aim to achieve heavy ion beam acceleration at 400 kW by the early 2020s. Therefore, an upgrade plan is needed to maintain RIBF's future position as the world's leading facility in RIB science.

As mentioned above, two charge strippers are used during uranium acceleration at RIBF. In this acceleration scheme, the total stripping efficiency is 5% at most, as shown in Fig. 10. FRIB, on the other hand, will use a multi-charge acceleration method, where five charge states are accelerated simultaneously using the superconducting linac. The target effective efficiency of the stripper is approximately 85%. Unfortunately, this method is not applicable to acceleration schemes using cyclotrons.

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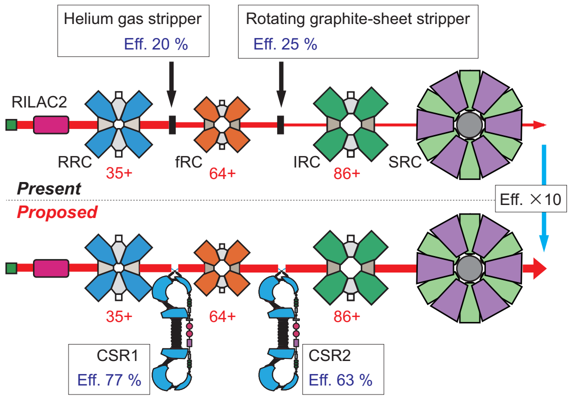

Figure 10: Present (upper panel) and proposed (lower panel) accelerator chains for the uranium beam at RIBF. The present stripping efficiency is 5%. Replacing the two charge strippers with charge stripper rings (CSR1 and CSR2) is expected to increase the total stripping efficiency to about 50%.

To reduce beam loss due to charge stripping at RIBF, a new charge stripping concept, the charge stripping ring (CSR), was proposed [6]. Figure 11 shows a schematic layout of the CSR optimized for the second stripper at 50 MeV/u. The U^{64+} beams are first injected into the ring with a charge exchange injection scheme. The energy losses in the stripper are recovered with the RF cavity following the stripper. The beams with U^{86+} are extracted using extractors based on static magnetic or electric fields. Ion beams other than those with the selected charge state (86+) circulate and reenter the stripper.

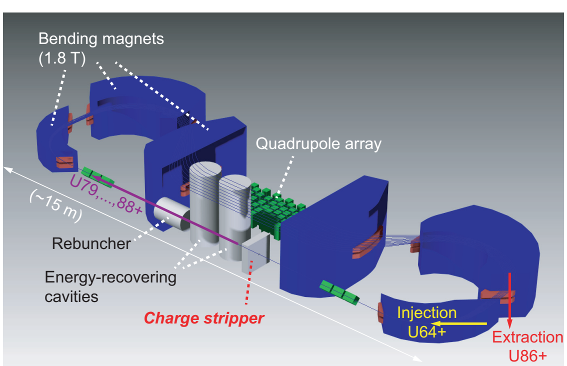

Figure 11: Schematic drawing of the charge stripper ring, optimized for the second stripping stage at the RIBF.

The key point of the CSR is that the ring is isometric for all the charge states and retains the bunch structure. In the present design, the magnetic field is 1.8 T and the size is about 15 m × 5 m. Specially designed quadrupole magnets are placed for orbits of all charge states independently at the dispersive region, where the orbit separation between two adjacent charge states is approximately 10 cm. The expected heat load on the stripper (3 mg/cm^2) is approximately 900 W. A rotating graphite-sheet stripper is a possible candidate.

According to the simulations, the effective stripping efficiency can be increased up to 77% and 63% for the first and second CSRs, respectively. Therefore, if we install the CSRs in place of the present charge strippers, the total efficiency of stripping during uranium acceleration will be 10 times the current value, as shown in Fig. 10.

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