PRESENT STATUS OF AND RECENT DEVELOPMENTS AT RIKEN RI BEAM FACTORY

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Abstract

The Radioactive Isotope Beam Factory (RIBF) is a cyclotron-based accelerator facility that is used for nuclear science studies and was completed at the end of 2006. RIBF can produce the most intense RI beams using fragmentation or fission of high speed heavy ion beams. Ever since the first beam was produced, effort has focused on increasing the intensity of uranium beams. Ions beams with high intensity and high availability have been used to produce many important scientific achievements. Upgrade programs have been proposed to further expand scientific opportunities. These programs have two goals. The first goal is to find heavier elements than element 118, which is already named. The upgrade program for the heavy ion linac (RILAC), including installation of a superconducting linac, has been funded and is under construction. The second goals is to increase the intensity of uranium ion beams up to 1 pμA, thus facilitating further investigations into the physics of unstable nuclei. This program for uranium beams is still been unfunded. We are pursuing a budget-friendly version without changing the project goals.

INTRODUCTION TO RI BEAM FACTORY

The Radioactive Ion Beam Factory (RIBF) is a cyclotron-based accelerator facility that uses fragmentation or fission of heavy ion beams to produce intense radioactive ion (RI) beams over the entire atomic range [1]. RIBF is used to explore the inaccessible region of the periodic table, to discover the properties of unstable nuclei, and advance knowledge in nuclear physics, nuclear astrophysics, and applications of rare isotopes for society. The RIBF facility consists of four cyclotron rings (RRC [2], FRC [3], IRC [4], and SRC [5]) with three injectors, including two linacs (RILAC [6, 7] and RILAC2 [8]) and one AVF cyclotron (AVF) [9]. Cyclotrons cascades can provide heavy ion beams from H_2^+ to uranium ions at more than 70% of the speed of light to efficiently produce RI beams. Three acceleration modes are available, as shown in Fig 1. The first mode is primarily used for mid-heavy ions, such as Ca, Ar, and Zn. The second mode is used for light ions, such as O and N. The third mode is used for very heavy ions such, as Xe and U. Of course many researchers use beams from the injectors. For example, synthesis of super heavy elements uses beams from RILAC,

while beams from the AVF cyclotron are used for RI production. Table 1 lists the specifications of the four ring cyclotron in RIBF. RRC has been operating since 1986. FRC and IRC have structures similar to that of RRC. The weight per K-value is listed in the table, which clearly shows that FRC is very compact compared to the other cyclotrons. Obtaining an acceleration voltage of 640 MV for uranium acceleration up to energy of 345 MeV/u is the most challenging with SRC. Design and construction of RIBF accelerators began in 1997, and we obtained the first beam at the end of 2006.
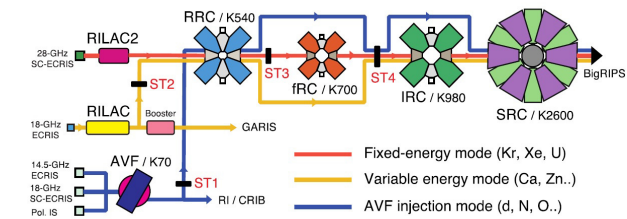

Figure 1: Acceleration modes for RIBF facility.

Table 1: RIBF cyclotron specifications. * in the table indicates that the values are shown for the case of uranium acceleration up to 345 MeV/u.

	RRC	fRC	IRC	SRC
K-value (MeV)	540	700	980	2600
$R_{inj}(cm)$	89	156	277	356
R_{ext} (cm)	356	330	415	536
Weight (ton)	2400	1300	2900	8300
K/W	0.23	0.54	0.34	0.31
N_{sec}	4	4	4	6
rf Resonator	2	2+FT	2+F	4+FT
Frequency range (MHz)	18–38	54.75	18–38	18–38
Total Acc. Volt. (MV)	2	2+FT	2+F	640
Acc. Volt. (MV/turn)*	0.28	0.8	1.1	2.0
Δr (cm)*	0.7	1.3	1.3	1.8
I_{sc}(pμA)*	1.8	11.2	3.7	2.6

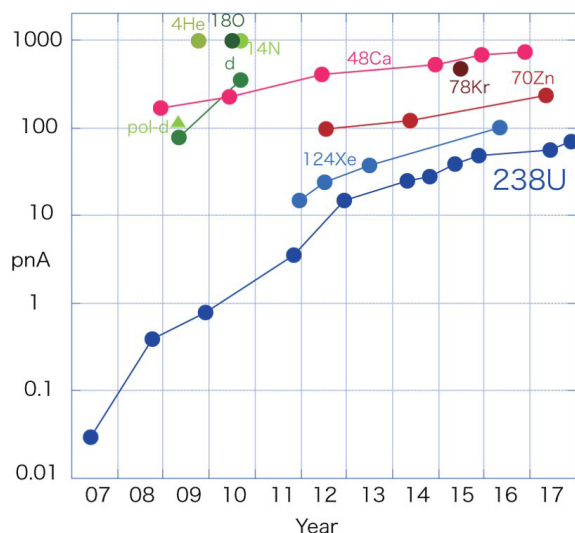* okuno@riken.jp

SUCCESSFUL OPERATION FOR TWELVE YEARS

Figure 2: History of beam intensities at the RIBF accelerator.

Operations over approximately twelve years following production of the first beam were very successful. Our continuous efforts have increased the beam intensity, especially for very heavy ions like Xe and U, as shown in Fig 2. The currently available beam intensity of uranium ion is 71 pnA, which is the world record. The beam availability has improved significantly, exceeding 90% since 2013. Such a supply of beams with high intensity and high availability have facilitated many important scientific achievements, such as obtaining the naming rights of element 113 [10], discovering 106 kinds of new isotopes [11], discovery of anomalies in magic numbers of neutron-rich nuclei [12], and cross section measurements of long lived fission products [13].

To many measures were taken to improve the accelerator performance, including upgrading the ion source and adding two charge strippers for uranium beam acceleration as follows. A 28 GHz ECR ion source using superconducting solenoids and sextuple magnets was constructed because powerful ion sources are essentially required to increase the uranium beam intensity [14, 15]. The operation of this ion source on the beam line started from 2011 with the new injector linac (RILAC2). Currently, approximately 150 eμA of U^{35+} can be stably extracted with a high-temperature oven. Charge strippers are important devices for increasing the intensity of the uranium beam because they have a high risk of bottleneck problems due to their fragility against high-power beams. After much research and development [16, 17], we developed a new stripping system based on helium gas [18] for the first stripper and a new rotating disk stripper with a highly-oriented graphene disk for the second stripper [19]. These have worked well so far.

Here we summarize the lessons learned from operating RIBF. First, it is very difficult to operate an accelerator complex where four cyclotrons are connected in series, because

one must inject and extract the accelerated beams four times. Energy matching between the cyclotrons and single turn extraction requires the greatest care and effort. Second, multi-step charge stripping should be avoided, because charge stripping reduces beam intensity at every step due to charge dispersion. Furthermore, the thickness of the charge strippers should be as thin as possible because charge strippers are always sources of emittance growth. Third, the space charge effect in the low energy cyclotron (RRC) is very severe because of the low velocity and low RF voltage. Table 1 lists the space charge limit for the four cyclotrons in the case of uranium beam acceleration according to Baartman's paper [20]. The table clearly shows that the space charge limit in the RRC is small compared to the current required to reach 1 pμA at the exit of SRC. The final point is that approximately 20% of the current from the ion source can reach the exit of SRC, excluding the charge stripping efficiency, as shown in Fig 3. This value is not particularly large, yet it is still large compared to that of other accelerators. In fact, 10 mA from the ion source is extracted to obtain 3 mA from the ring cyclotron in the case of the PSI machine. However, it is very important to understand beam loss mechanisms to improve and reduce uncontrolled beam loss.
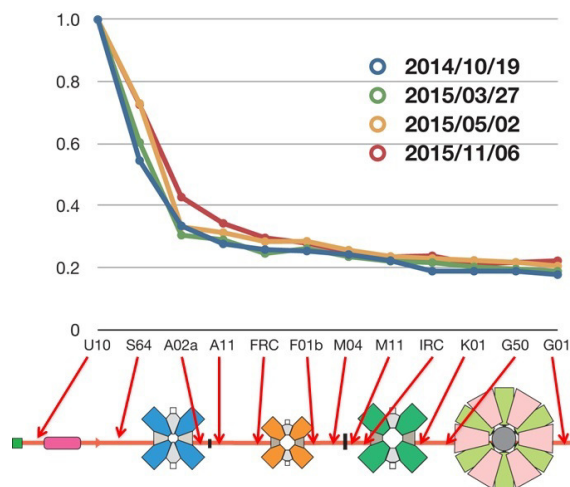

Figure 3: Transmission in the RIBF accelerator complex.

UPGRADE PLAN OF RIBF

Based on the lessons learned and scientific achievements described in the previous section, we define upgrade plans aimed towards the two following goals. The first goal is to obtain a 1 pμA uranium beam with energy of 345 MeV/u. The second is synthesis of super heavy elements, such as 119 and 120.

The program consists of three primary components for achieving these two goals, as shown in Fig 4. The first stripper is skipped to avoid beam intensity reduction due to charge dispersion after the beam passes through the stripper. This requires replacement of the existing FRC with a new one that can accept the same charge (35+) as that of the ion source, while the existing FRC can accept 64+. Skipping

the first stripper will improve the beam quality, especially in the longitudinal direction, because charge-exchange energy straggling in the first stripper is significant. This affects the extraction efficiency at the subsequent cyclotrons. The second component involves resolving problems relating to the space charge effect in the low energy cyclotron (RRC), which requires the RRC cavity be remodeled to obtain higher RF voltage. The third component focuses on an upgrade of RILAC by adding a superconducting RF linac, with the goal of producing medium-mass nuclei beams with higher current for the super heavy element program. The following subsection will describe the details and status of these three components.
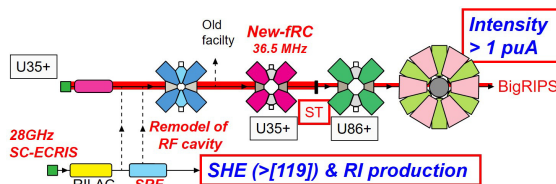

Figure 4: Upgrade plans for the RIBF accelerator complex.

Superconducting RILAC [21]

RILAC consists of an RFQ and 12 DTLs to provide intense heavy ion beams to search for super heavy elements (SHEs). $^{70}Zn^{14+}$ was accelerated to 5 MeV/u to search for element 113. The SHE experiment is used to probe the 8th row of the periodic table (A≥119). The accelerating voltage will be upgraded to provide more intense heavier ion beams with higher energy. The goal of the upgrade is to accelerate ions (A/q = 6) up to 6.5 MeV/u. The last four DTL tanks in the existing RILAC will be replaced with a superconducting linac that are based on quarter wave resonators. Figure 5 shows the structure of the new superconducting RILAC that consists of three cryomodules, including 4 or 2 superconducting cavities with a liquid helium transfer line. The differential pumping system in the narrow space is very important because the vacuum in the existing linac is ineffective compared to the vacuum required in superconducting cavities. Tablel 2 lists the SRILAC specifications required to produce an overall acceleration voltage of 18 MV for A/q = 6. This project was funded in 2016 and its construction is in progress. Six of ten bulk cavities were successfully validated so far (as of 2018/10/23), exhibiting high Q_0 values compared to the SRILAC goals. Construction will end by the end of March 2019. SHE researchers who cannot wait for completion have started searching for element 119 using RILAC2+RRC this year. This will continue until the completion of SRILAC.

Remodel of RRC RF Cavities

Figure 6 shows the structure of the RF resonator in the RRC. This structure is basically a half wave resonator. A pair of movable boxes in the cavity are used to tune the resonance frequencies by changing the capacitance from 18 to 40
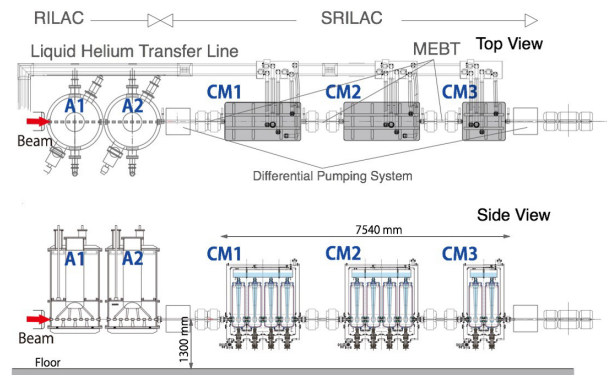

Figure 5: Plan view of SRILAC.

Table 2: SRILAC Specifications

Design Parameters	
Number of cavities	10 QWRs
Frequency (MHz)	73.0 (c.w.)
E_{inj} (MeV/u)	3.6
E_{ext} (MeV/u)	6.5
Gap Voltage (MV)	1.2
Synchronous Phase (deg.)	-25
E_{acc} (MV/m)	6.8
Target Q_0	1×10^9 at 4.5K
Beam Current (μA)	<100
RF bandwidth (Hz)	$\pm$ 60
Q_{ext}	$1 - 4.5 \times 10^6$
Amplifier Output Power (kW)	7.5

MHz. At the lowest frequency of 18.25 MHz, gaps between the movable box and the Dee electrodes are so close that discharge occurs frequently at higher voltages. The slanted stem in Fig. 7 widens the gaps at 18.25 MHz, making it possible to apply a higher voltage. This remodel is complete and this cavity is operating at 120 kV, thus increasing the space charge limit in the RRC.

Conceptual Design of the New FRC [22]

Figure 8 shows a plan view of the new FRC, and the main specifications are listed in Table 3. The new FRC contains six sector magnets and its K-value is 2200. Four accelerating RF cavities and a flattop cavity are used. The RF acceleration frequency is 36.5 MHz, which is the same as that of RILAC2. This provides wide acceptance in the longitudinal direction. The structure of the RF resonators will be similar to that used in the RIBF accelerator. We can obtain a 15 mm turn separation using similar RF cavities as those used in the RIBF accelerators. This structure looks like a standard ring cyclotron, except for the heavy weight (8000 tons). Unfortunately the budget is not approved.
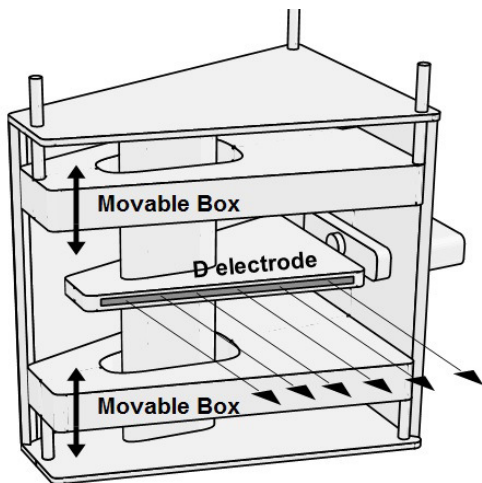
Figure 6: Structure of an RF resonator in the RRC.

Figure 7: Effective voltages for three harmonics.

Table 3: Specification of the new FRC. The number in parentheses in the weight row is the weight estimated by cutting the edge of the yoke, where iron is not saturated.

Item	new FRC	exiting FRC
K-value (MeV)	2200	700
Sectors	6	4
RF Cavities	4+FT	2+T
RF Frequency (MHz)	36.5	54.75
Injection radius (m)	2.76	1.56
Extraction radius (m)	5.67	3.30
Velocity gain	2.1	2.1
Diameter (m)	19	10.8
Height (m)	6.6	3.34
Weight (ton)	8100 (7100)	1320
Δr (cm)*	1.5	1.3

Figure 8: Plan view of new FRC.

BUDGET-FRIENDLY VERSION OF THE UPGRADE PROGRAM

Until the budget for the new FRC is approved, we are pursuing a budget-friendly version of the upgrade program without deviating from the 1 pμA uranium beam goal. The first candidate for upgrade is the charge stripper ring. The goal is to increase the stripping efficiency up to 100%. The second candidate is the high brightness ion source with low charge.
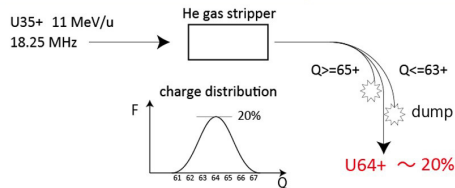
Charge Stripper Ring [23]

20% $\sim$ 30% of ions injected into the charge stripper can survive the normal stripping system due to their charge distribution, as shown in Fig. 9. The total charge conversion efficiency for RIBF is about 6% because RIBF strips charges in two steps for acceleration of uranium ions. FRIB [24] aims to provide an effective efficiency of 85% using multi charge acceleration [25] in the linac, which has large acceptance in the longitudinal direction. The proposed charge stripper ring (CSR) can recycle ions with charge states that do not match the objective charge state until they reach the objective charge, as shown in Fig. 9. Installation of two CSRs in the RIBF accelerator complex could provide a stripping efficiency of nearly 100%.

Figure 10 shows a plan view of the CSR optimized for the second charge stripper at 50 MeV. The ring consists of an isometric ring with quadruple array, charge stripper, and RF cavities for energy compensation. This structure will preserve the bunch structure in order to match to the acceptance of subsequent cyclotrons. Careful analysis of transverse and longitudinal motion in the CSR is underway to minimize emittance growth due to the installation of this ring.

Present scheme at RIBF (conventional)
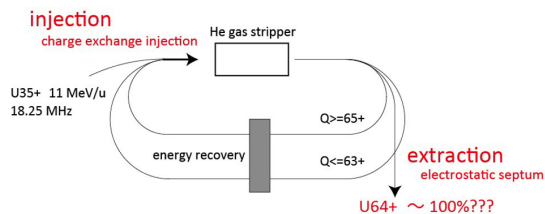

Stripper-ring scheme

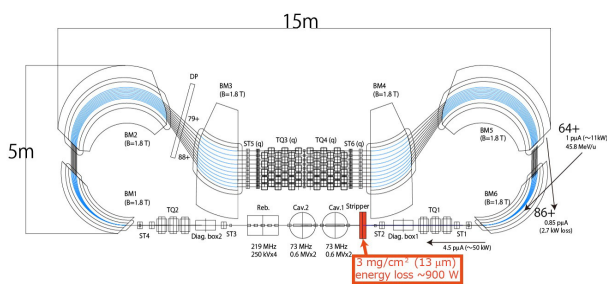Figure 9: Concept of the charge stripper ring.

Figure 10: Plan view of the charge stripper ring.

Low Charge Ion Source with High Brightness

The next candidate is the low charge ion source with high brightness. In this idea, the accelerators after the RRC remain unchanged, as shown in Fig.11. Only the input current from the ion source increases up to 1 pμA. Generally speaking, beam emittance from the ion source increases as the beam intensity from the ion source increases. We need a high brightness ion source in order to maintain total transmission through subsequent accelerators. To achieve this goal, we are studying the use of ion sources with such charges as low as 10+, which require another stripper and decelerator. Figure 12 shows a very primitive design of the ion source. This is an EBIS-based ion source. 1+ ion generated by the electron beam in this cell travels with the electron beam to the extraction electrode. The electron density and voltage at the intermediate extraction point are tuned such that the charge state is 10+.
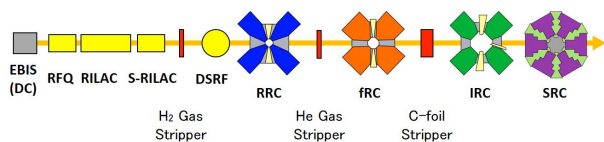

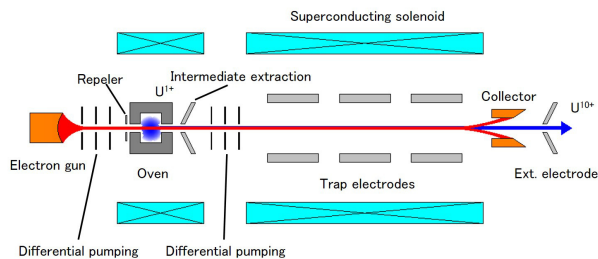Figure 11: Accelerator scheme for the low charge ion source.

Figure 12: Conceptual design of the DC EBIS for low charge uranium ions.

SUMMARY AND OUTLOOK

Successful operation and many important scientific achievements motivate us to upgrade the RIBF accelerator complex. The first portion of the upgrade program is the installation of a superconducting linac, with the goal of synthesizing superheavy elements (119 and 120). The budget for the SRILAC was approved by the government. Construction will end by March 2019. The other portions involve increasing the space charge limit in the low energy cyclotron in the RRC and skipping the first stripper, requiring replacement the existing FRC. The RF cavities in the RRC were remodelled to increase the space charge limit; this remodel is now complete. The budget for the new FRC has not been approved. Thus, we are pursuing a budget-friendly version of the upgrade program that focuses on upgrading the charge stripper ring and low charge ion source with high brightness.

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