STATUS OF RIBF ACCELERATORS AT RIKEN

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Abstract

Recent achievements and upgrade programs in the near future at RIKEN Radioactive Isotope Beam Factory (RIBF) are presented. The beam intensity and available ion species are increasing at RIBF, owing to the continuous efforts that have been made since the first beam in 2006. So far, we accelerated deuteron, helium, nitrogen, oxygen, aluminum, calcium, krypton, and uranium beams with the superconducting ring cyclotron, SRC. The extracted beam intensities reached 1,000 pnA for the helium and oxygen beams. From the operational point of view, however, the intensity of the uranium beam should be much increased. We are, therefore, constructing a new injector linac for the RIBF, consisting of a superconducting ECR ion source, RFQ, and DTL, which will be commissioned in this fiscal year. By using this injector, we also aim at independent operation of the RIBF and GARIS facility for super-heavy element synthesis.

INTRODUCTION

The Radioactive Isotope Beam Factory (RIBF)[1] at RIKEN has been constructed to produce the most intense RI beams over the whole range of atomic masses. The powerful RI beams will give us a means to access the unexplored region on the nuclear chart, far from the stability line. The scientific goals of the RIBF include establishment of a new comprehensive way to describe atomic nuclei and improvements of our understanding on the synthesis of the heavy elements in the universe. We are also promoting applications of the RI beams into various research fields such as nuclear chemistry and biological science.

The accelerator chain of the RIBF is schematically shown in Fig. 1. It consists of two injectors (heavy-ion linac: RILAC[2] and AVF cyclotron[3]), and four booster cyclotrons (RRC[4], fRC[5], IRC[6] and SRC[7]). There are three accelerating modes in the RIBF. The first one uses the RILAC, RRC, IRC and SRC for the acceleration of medium-mass ions such as calcium and krypton. The beam energy from the SRC can be changed in a wide range below 400 MeV/u by varying the rf frequency. The second one is the fixed-energy mode, which uses the fRC between the RRC and IRC. The beam energy from the SRC is fixed at 345 MeV/u, due to the fixed frequency operation of the fRC. This mode is used for the acceleration of very heavy ions such as uranium and xenon. The third mode uses the AVF cyclotron as the injector, and two boosters, the RRC and SRC. This mode is exclusively used for light ions such as deuteron and nitrogen. We can change the beam energy from the SRC below 440 MeV/u, by varying the rf frequency.

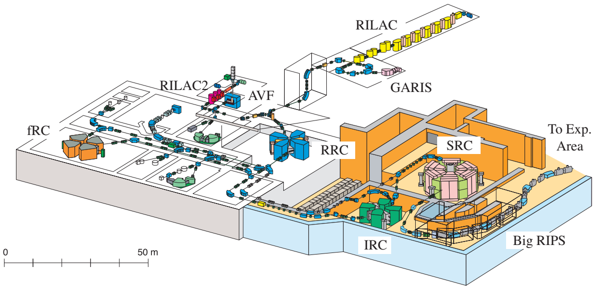

Figure 1: Birds-eye view of accelerator chain of RIBF at RIKEN. Two injectors, RILAC and AVF(K70MeV), are followed by the four booster cyclotrons: RRC (RIKEN Ring Cyclotron, K540 MeV), fRC (fixed-frequency Ring Cyclotron), IRC (Intermediate-stage Ring Cyclotron), and SRC (Superconducting Ring Cyclotron). The new injector (RILAC2), which will be commissioned in FY2010, is also indicated. The specifications of the three new cyclotrons are summarized in Table 1.

The commissioning of the three new cyclotrons, whose specifications are listed in Table 1, started in 2006, and the first beam from the SRC was extracted on December 28[8]. In 2007, two new isotopes, ^{125}Pd and ^{125}Pd, were produced in the BigRIPS spectrometer[9] using the energetic uranium beam from the SRC[10].

ACCELERATOR IMPROVEMENTS

In 2007, however, the transmission efficiency of the uranium beam was as low as 2 % excluding the charge stripping efficiency, which provided low beam intensity of 0.05 pnA at maximum from the SRC. Moreover, the stability of the beam was not good. A lot of obstacles prevented us from getting higher transmission efficiency and stability, and we improved the accelerator system in the last three

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Table 1: Specifications of RIBF cyclotrons. FT stands for the flat-topping resonator.

	fRC	IRC	SRC
K-number (MeV)	570	980	2600
Number of sectors	4	4	6
Velocity gain	2.1	1.5	1.5
Number of trim coils	10	20	4+22
Number of rf resonators	2+FT	2+FT	4+FT
Rf frequency (MHz)	54.75	18-38	18-38

years[11, 12]. Several examples of the efforts are shown in the following subsections.

Beam Monitors

One of the most significant achievements was the completion of the beam-phase monitor based on the commercially available lock-in-amplifiers (SR844)[13]. It measures the beam phase at relevant positions in the beam lines as well as the beam phase in the cyclotrons, so as to maintain the stable beam delivery in the long-term experiments.

The Faraday cups used in the relevant positions along the beam lines were modified to have a stronger suppressor of the secondary electrons[12]. Calibration of the cups were also performed for various ion beams with a long, designated Faraday cup[14]. This modification made it possible to get accurate information on the beam losses and consequently help us to tune the accelerators effectively.

Radial Probes

In the early stage of the commissioning, the turn patterns in the fRC and SRC could not be measured due to the secondary electrons in the radial probes. This prevented us from adjusting the rf-phase of the flat-topping (FT) resonators precisely. Therefore, we modified the radial probes as follows[11, 12]. In the fRC, the differential electrode in the radial probe was shifted away from the integral electrode which was the origin of the secondary electrons. In the SRC, a thin tungsten ribbon was attached as a new differential electrode in front of the integral electrode at intervals of 10 mm.

Another problem was that the electromagnetic wave from the FT resonators disturbed the small beam signal in the radial probes in the IRC and SRC. We put sliding contacts in the upper gap between the probe shaft and the vacuum chamber in each of these cyclotrons; this modification made the boundary condition more symmetric, and reduced the coupling between the radiated TE_{01} wave from the FT resonator and the beam signal in the coaxial cable in the probe[12].

Finally we achieved single-turn extractions in the three new cyclotrons and obtained high quality beams, which increased the transmission efficiency.

Emittance Analysis

Intensive study has been done to evaluate the beam emittance by the beam dynamics analyses on the measured data of the profile monitors[11]. It has been found that the emittance growth was not notable in the calcium acceleration. On the other hand, significant growth of horizontal emittance was found in the uranium acceleration, which probably comes from the non-uniformity of the thickness of the first stripper between the RRC and fRC. The turn patterns in the cyclotrons were also simulated to estimate the rf voltage and phase.

Rf Systems

The monitoring system of the beam phase mentioned above is also designed to measure the rf-phase and voltage of all the rf resonators. According to the measured data, long-term stability of the first four resonators of the RILAC was not satisfactory. Therefore, the low-level circuit of these resonators have been replaced by newly designed ones. An automatic voltage regulator has been implemented at the same time for these circuits to improve the stability against the fluctuation of the commercial electric voltage. In addition, the signal dividers have been omitted, because it was found that their output phase was strongly dependent on the temperature around the dividers. The reference signal is now delivered by a directional coupler from a single cable to each low-level circuit in the RILAC[15, 16].

The rf resonators of the SRC had been suffered from heavy multipactoring in the high magnetic fields; long conditioning was required to feed the rf power after voltage breakdown in the early stage of the commissioning. The situation has been improved, owing to the experiences on the surface cleaning and rf-conditioning. Implementation of an additional cryogenic pump to each resonator also helped to reduce the conditioning time[15].

Helium Cryogenic System

The helium cryogenic system of the SRC and BigRIPS have had a serious problem since their starting time in 2005; we had to stop the helium refrigerator every two month due to gradual degradation of the refrigeration capacity in the continuous operation.

It was found in February 2008 that the origin of the degradation was the contamination of the oil from the helium compressor. Therefore, we took out the heat exchanger to wash it, and replaced the charcoal in the adsorber by a new one. At the same time, two oil separators were added in the compressor units. These modifications, which took 200 days, improved the system dramatically; no degradation has been found so far[17].

PRESENT STATUS

Owing to the efforts shown above, the beam intensity has remarkably increased, as shown in Table 3. The intensities of light ions and medium-heavy ions are reaching our final goal of 1000 pnA.

Table 2: Maximum beam intensities extracted from SRC so far.

Ion	E (MeV/u)	I (pnA)	Achieved in
pol-d	250	120	May 2009
^{4}He	320	1000	Oct. 2009
^{14}N	250	80	May 2009
^{18}O	345	1000	Jul. 2010
^{48}Ca	345	230	Jun. 2010
^{86}Kr	345	30	Nov. 2007
^{238}U	345	0.8	Dec. 2009

The transmission efficiency through the accelerator chain has been significantly improved as well, as shown in Table 3[18]. It should be noted that the designed transmission through the RILAC is around 70 %, not 100 %, since the longitudinal acceptance is limited[19]. As shown in Table 3, 16 % of the beam is transported from the ion source to the exit of the SRC, excluding the stripping efficiency of 5 % in the uranium acceleration. The transmission efficiency from the exit of the RILAC to the exit of the SRC has exceeded 65 % in the calcium acceleration, excluding the stripping efficiency of 32 %. In the ^{18}O acceleration in 2010, the efficiency through the three cyclotrons (RRC, IRC and SRC) reached 85 %.

Table 3: Transmission efficiencies in % from ion source to exit of each accelerator. Stripping efficiencies in the charge strippers are excluded. Note that the observed currents include an error of 10 %.

	^{238}U (Nov. 2008)	^{48}Ca (Jun. 2010)
ECRIS	100	100
RILAC	40	62
RRC	30	67
fRC	35	-
IRC	23	53
SRC	16	44

Table 4: Operational statistics of RIBF accelerators from July 2009 to July 2010. MS stand for the machine study where the IRC and SRC were not used.

Beam	^{238}U	^{48}Ca	^{18}O	^{4}He	MS(U, Xe, Zn)
Time (h)	1088	1153	406	401	546

Table 4 shows the operational statistics from July 2009 to July 2010. The RIBF accelerators were operated in one of the three accelerating modes for about 3000 hours in this period. About half of the operation time is used for the experiments, and the other half for tuning. We also spent 500 hours for the machine study. The reliability index, which is defined as the ratio of an actual beam service time to a scheduled beam service time, has also increased. It exceeded 85 % in 2010, whereas it was below 70 % in 2008 and 2009[18].

Using the uranium beam in 2008, 45 new neutron-rich isotopes were created in four days in the BigRIPS spectrometer[20]. The intense calcium beams were used to study the halo structure and large deformation of neon isotopes far from the stability line[21, 22]. Thus the exploration into the nuclear extremes was really started.

FURTHER DEVELOPMENTS AND PLANS

From the operational point of view, it is clear that we need more beams from the ion source for very heavy ions such as uranium. We are planning to upgrade the intensity as shown below.

Superconducting ECR Ion Source

In order to meet the demand mentioned above, a new superconducting ECR ion source (SC-ECRIS) has been constructed, which is capable of the microwave power of 28 GHz[23, 24]. The main features of the ion source are as follows. First, the size of the ECR surface is large; it has as large plasma volume as 1100 cm^{3}. Second, the field gradient and surface size at the ECR zone can be changed independently to study these effects on the ECR plasma. The excitation test of the coil system was successfully performed in October 2008. After assembling the cryostat, the ion source was brought to RIKEN in December 2008.

The source was installed on the high-voltage platform of the existing Cockcroft-Walton preinjector of the RILAC, as shown in Fig. 2, in order to deliver the intense uranium beam as soon as possible[25]. Since the extraction voltage of the ion source in this scheme could be set higher than that of the RFQ-injection scheme, we expected higher beam currents and reduced emittance growth due to the suppression of the space charge effects.

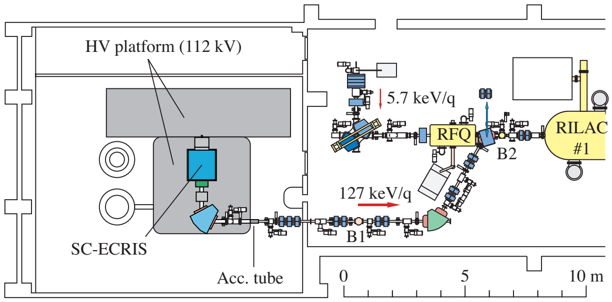

Figure 2: Preinjector for RILAC equipped with new superconducting ECR ion source. This scheme was terminated in May 2010 after the uranium beam delivery from November 2009 to April 2010.

The vacuum evacuation of the SC-ECRIS started in April 2008, and the first beam was obtained on May 11 with an existing microwave power source of 18 GHz. The construction of the medium-energy beam-transport (MEBT) line between the high-voltage terminal and the RILAC was completed in June[26]. We performed the acceleration test of a ^{136}Xe^{20+} beam from the SC-ECRIS successfully with RILAC on September 11. Developments of uranium beam started based on the sputtering method at the end of October, soon after the generation tests of gold ions had been done. On November 13, we got 12.6 eμA (360 pnA) of U35+, which was six times higher than that available with the original 18-GHz ECRIS.

The maximum intensity from the SRC was, however, 72 enA (0.8 pnA), which was only twice that had been achieved in 2008 with the original ion source; the transmission efficiency was not sufficiently high. The low transmission could be partially attributed to a large emittance of the beam extracted from SC-ECRIS in the initial stage. Another reason was the lack of tuning experience for the beam from the new ion source. We also met a lot of unexpected troubles during the beam time. The developments of uranium beam have been continued after the beam time, and the maximum current from the source reached 24 eμA. The rms emittance could be made as small as 22π mm·mrad[27, 28].

New Injector (RILAC2) for RIBF

The success in the synthesis of the super-heavy element (SHE)[29] using the GARIS spectrometer in the RILAC facility strongly encourages us to pursue the search for the heavier elements. This compels us to provide a longer beam time for the SHE experiments. However, the SHE research and RIBF conflict with each other, because both of them use the RILAC. Therefore, construction of a new additional injector linac (RILAC2) has been started since 2008[25].

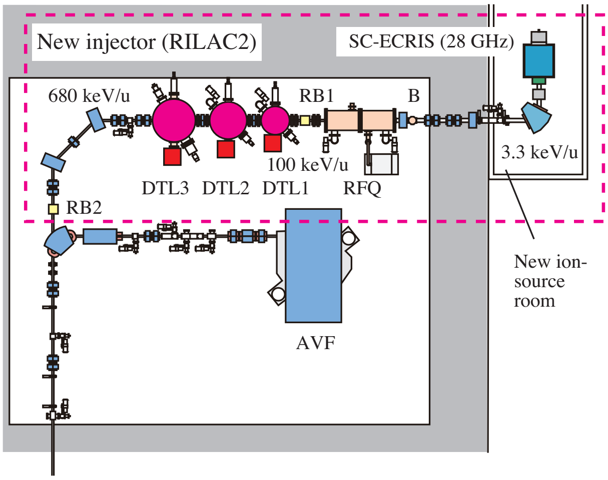

Figure 3: Schematic drawing of new injector. It is placed in the AVF cyclotron room. A prebuncher, denoted by "B", is operated at the fundamental frequency of 18.25 MHz, whereas the other resonators are operated at the second harmonic (36.5 MHz). RB1 and RB2 stand for the first and second rebunchers, respectively.

The RILAC2, placed in the AVF cyclotron room as shown in Fig. 3, is used exclusively in the fixed-frequency operation of the RIBF. It is designed to accelerate ions with a mass-to-charge ratio of 7, aiming at very heavy ions such as ^{136}Xe^{20+} and ^{238}U^{35+}, up to an energy of 680 keV/u in the cw mode. The output beam will be injected to the RRC without charge stripping.

The RILAC2 consists of the SC-ECRIS, a low-energy beam-transport (LEBT) line including a prebuncher, an RFQ linac based on the four-rod structure, and three DTL resonators (DTL1 - 3). There is a rebuncher resonator (RB1) between the RFQ and DTL1 and another rebuncher (RB2) in the high-enegy beam-transport (HEBT) line after the DTL3. The rf resonators excluding the prebuncher are operated at a fixed rf frequency of 36.5 MHz, whereas the prebuncher is operated at 18.25 MHz. Strong quadrupole magnets are placed in the beam line between the rf resonators.

We modified an RFQ linac, which was originally developed by Nissin Electric Co., Ltd. in 1993[30], to be used in the RILAC2; the resonant frequency has been changed from 33.3 MHz to 36.5 MHz by putting a block tuner into every gap between the posts supporting the vane electrodes. High power tests have been done successfully in August 2010[31], using a newly constructed rf amplifier having the maximum output of 40 kW. It is now possible to accelerate ions from 3.3 keV/u to 100 keV/u without changing the vane electrodes. The design parameters of the RFQ are listed in Table 5.

Table 5: Design parameters of RFQ.

Frequency (MHz)	36.5
Duty	100 %
Mass-to-charge ratio (m/q)	7
Input energy (keV/u)	3.28
Output energy (keV/u)	100
Input emittance (mm·mrad)	200 π
Vane length (cm)	222
Intervane voltage (kV)	42.0
Mean aperture (r_0 : mm)	8.0
Max. modulation (m)	2.35
Focusing strength (B)	6.785
Final synchronous phase	$-29.6°$

The structure of the DTL resonators is based on the quarter-wavelength resonator (QWR). The dimensions of the resonators were optimized with the Microwave Studio by taking the power loss and the voltage distribution into account. The main parameters of the DTL are listed in Table 6. The inner diameter of the resonators ranges from 0.8 to 1.3 m, depending on the velocity range of the beam. The maximum electric field on the drift tubes is kept below 1.2 Kilpatrick.

In order to save the construction cost and space for the rf amplifiers, direct coupling scheme has been adopted for the rf system, as shown in Fig. 4. Detailed simulations and

Table 6: Design parameters of DTL.

Resonator	DTL1	DTL2	DTL3
Frequency (MHz)	36.5	36.5	36.5
Duty	100 %	100 %	100 %
Mass-to-charge ratio (m/q)	7	7	7
Input energy (keV/u)	100	220	450
Output energy (keV/u)	220	450	680
Length (= Diameter: m)	0.8	1.1	1.3
Height (m)	1.320	1.429	1.890
Gap number	10	10	8
Gap voltage (kV)	110	210	260
Gap length (mm)	20	50	65
Drift tube aperture (a: mm)	17.5	17.5	17.5
Peak surface field (MV/m)	8.2	9.4	9.7
Synchronous phase	$-25°$	$-25°$	$-25°$

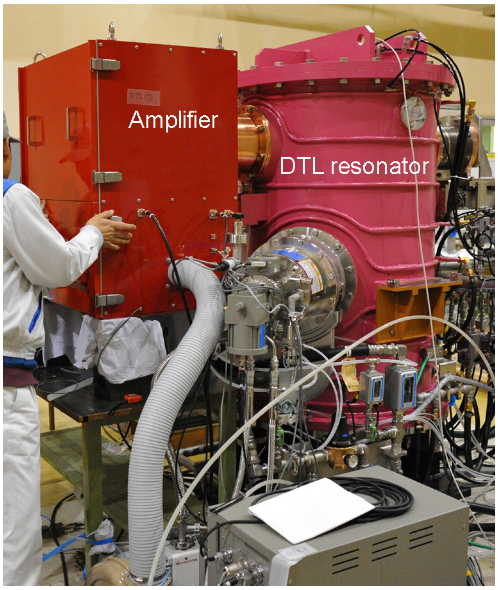

Figure 4: Photograph of DTL resonator and amplifier.

rf measurements have been done to optimize the coupling between each resonator and amplifier[32]. The maximum outputs of the amplifiers are 25 kW for the DTL1, and 40 kW for DTL2 and DTL3. High power tests have been already carried out in the AVF cyclotron room.

The LEBT line was designed by taking possible space-charge effects into account[33]. There are two sets of paired solenoids in the LEBT, that have been adopted to reduce beam envelopes without transverse coupling. Since the RFQ vanes are inclined by 45°, it is important to make the input beam symmetric in the vertical and horizontal planes. The beam matching into the RFQ will be achieved by the four quadrupoles. The analyzing magnet has been constructed according to the design by the LBNL[34]. The large pole gap of 180 mm leads to beam aberration due to fringing fields. Corrective measures have been taken by shaping the pole faces in such a manner as to introduce aberration countering sextupole moments to the beam.

The SC-ECRIS was brought to a newly constructed room from the Cockcroft-Walton terminal in June 2010. The excitation test has been performed successfully there. A dummy-load test is in preparation for the 28 GHz power source. Commissioning of the RILAC2 will be started in FY2010 with a xenon beam. We are planning to deliver the uranium beam of 5 pnA in FY2011. Figure 5 shows a photograph of the RILAC2 in the AVF cyclotron room.

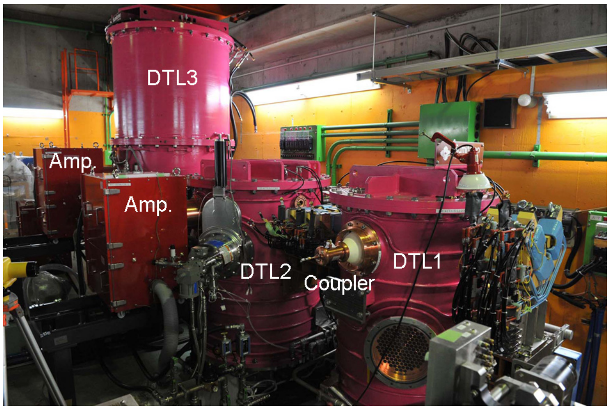

Figure 5: Photograph of DTL resonators of RILAC2 placed in AVF cyclotron room.

Charge Strippers

One of the most important issues in the acceleration of intense heavy-ion beams is the choice of the charge strippers. A carbon foil of 0.3 mg/cm^2 is currently used for the first stripper for the uranium acceleration at RIBF; it changes the charge state from 35 to 71 at 11 MeV/u after the RRC. The lifetime is, however, about 12 hours for the present beam intensity, which is far below the goal intensity of 1000 pnA. Moreover, the stripper causes emittance growth which limits the transmission efficiency, as mentioned above. In order to increase the lifetime, we have been developing polymer-coated carbon (PCC) foils [35] on the rotating-cylinder stripper system[36]. In spite of the long efforts, the lifetime had been about several minutes at the rotation speed of 100 rpm.

Recently, the rotating-cylinder system was modified to rotate very slowly, and the irradiation test of a PCC foil was carried out with the uranium beam from the SC-ECRIS. It was found that, at the rotation speed of 0.05 rpm, the foil survived for 38 hours at the beam intensity of 1.7 eμA. No significant damage was found on the foil[37]. This result shows that the mechanical stress of rotation affects the lifetime of the foils significantly. On the other hand, we found a large fluctuation of the intensity in the downstream of the stripper section, which indicated the uniformity of the foil was not sufficiently good. Further study is required to make the foils uniform enough.

We are also developing a gas stripper system as another candidate of the strippers for intense beams[38]. It was found last year that the average charge state of xenon ions of 11 MeV/u is 40.5 in N_2 gas, which means that the xenon beam is acceptable in the fRC. Actually, acceleration test of the xenon beam in the fRC was successfully performed with the gas stripper. On the other hand, the average charge state of uranium ions was found to be 56 in the N_2 gas, far below the acceptable charge state of 69.

In April 2010, we measured cross sections of electron stripping and electron capture of uranium ions in helium gas at 11 MeV/u. The result was remarkable; the equilibrium charge state is estimated to be 66, which is close to the acceptable charge state in the fRC[17]. It implies that the helium gas stripper is a strong option for the future stripper system. Therefore, we have started a new development program to make a thick gas stripper of helium. The uranium intensity will be increased to 50 - 100 pnA when this system is operational.

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