COMMISSIONING OF A NEW INJECTOR FOR THE RIKEN RI-BEAM FACTORY

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Abstract

A new injector for the RIKEN RI-Beam Factory (RIBF) was fully commissioned in October 2011. The injector accelerates ions of $m/q = 6.8$ up to 670 keV/u. To save cost and space, a direct coupling scheme was adopted for RF coupling between the DTL cavity and amplifier, based on an elaborate design with the Microwave Studio software package. The new injector has been successfully commissioned and worked very stably for beam service time, increasing the uranium beam intensity by an order of magnitude. Moreover, it is now possible to independently operate the RIBF and GARIS facilities for super-heavy element synthesis.

INTRODUCTION

Role of new injector

Since 2008, the accelerator complex at the RIKEN RI-Beam Factory (RIBF) has provided various heavy ion beams according to the programs of the RIBF experiments. The developed beams so far are polarized- and unpolarized-deuteron, ^{4}He, ^{14}N, ^{18}O, ^{48}Ca, ^{70}Zn, ^{124}Xe and ^{238}U. Among them the experiments of the new RI production require intense beams. Initial experiment using the uranium beams was carried out in November 2008, at 0.4 pnA. This intensity is insufficient for radio isotope production experiments at the RIBF. Our final goal is to realize a 1 pμA beam current for each ion.

The new injector project started because the main injector, the RIKEN Heavy Ion Linear Accelerator (RILAC) [1], was tasked with super-heavy elements (SHE) search [2]. This was a problem because the RIBF experiments could not be performed when SHE search experiments were performed. Also, the beam currents for uranium and xenon beams were unsatisfactory. Therefore we designed and built a new injector, the RIKEN Heavy Ion Linear Accelerator (RILAC2), dedicated for the acceleration of intense uranium and xenon beams to energies of 670 keV/u, which is the injection energy of the RIKEN Ring Cyclotron (RRC) [3].

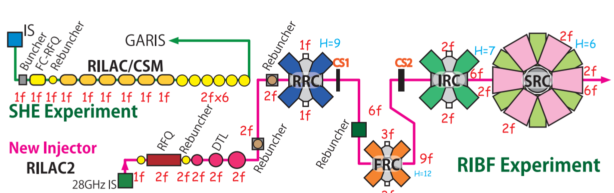

Figure 1: RIBF accelerator complex.

Xe and U acceleration by cyclotron cascades

In RIBF, Xe and U beams are accelerated by cyclotron cascades of RRC, the fixed frequency ring cyclotron (fRC) [4], the intermediate-stage ring cyclotron (IRC) [5], and the world first separate-sector superconducting ring cyclotron (SRC) [6]. In this scheme shown in Fig. 1, the intense $^{238}U^{35+}$ beams from the ion source can be accelerated by the RRC without charge stripping, before injection to the RRC. Using the stripper after the RRC, the charge state is converted to 71+ at an energy of 10.75 MeV/u for injection into the fRC. Then $^{238}U^{71+}$ beams are accelerated using the fRC with velocity gain of about 2 to suit the injection energy of the IRC. Before injection to the IRC, the charge state is converted to 86+.

For uranium, the first stripper (CS1) utilizes a 0.3 mg/cm^2 carbon foil and the stripping efficiency is about 18%. The second stripper (CS2) utilizes 17$\sim$19 mg/cm^2 carbon foil, and the stripping efficiency is about 33%. Owing to the heat load by the intense beams, these efficiency values go down with increased beam dose.

To maximize the average current, the stripper foils are changed frequently, typically 2 or 3 times/day. To increase the beam current, the stripper foil lifetime must be extended.

Injection to RRC

The beams from the RILAC2 are injected into the RRC. Layout of the key devices of the RRC is shown in Fig. 2. The function of the isochronous cyclotron is to increase the velocity of ions by the ratio of the extraction radius to the injection radius. The velocity gain of the RRC is four and the energy of the extracted beams is 10.75 MeV/u. In the case of $^{238}U^{35+}$ acceleration, the magnetic rigidity is 3.2 T·m, which is 91% of the maximum value of the RRC. The operating dee-voltage of the resonator is about 60 kV. The resonators of double-gap type with a dee angle of 23.5° provide 230 kV/turn acceleration voltage with a harmonic number of 9, resulting the total number of revolutions of 325. The gap between turns at the extraction radius is only 5.5 mm, excluding the effect of betatron motion. Therefore beam loss during cyclotron acceleration is prone to occur in the electrostatic deflection channel (EDC). Acceleration

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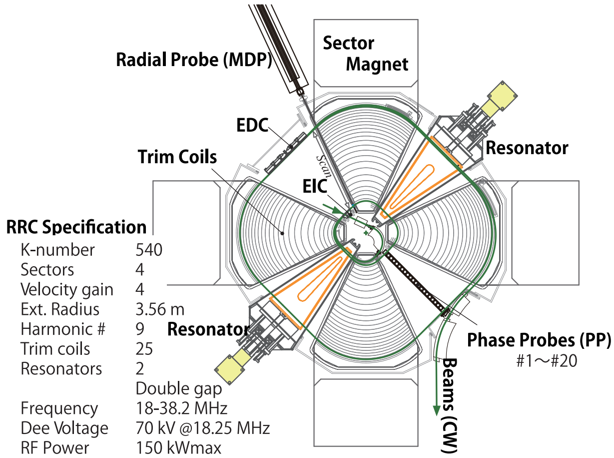

Figure 2: Layout of RRC showing injection and extraction orbits and diagnostic devices of radial-probes and 20 set of phase-probes.

voltage error is required to be within ±0.1% amplitude and ±0.1° phase, because unstable acceleration voltage causes fluctuations in the beam orbit and size [7]. As an injector of cyclotrons, stability of the RILAC2 RF system is required so that the injection timing of the beams remains within the acceptance of the cyclotron RF.

NEW INJECTOR RILAC2

Overview

As RILAC2 was to be installed in the remaining space of the AVF cyclotron hall, a compact design was needed. The picture after installation is shown in Fig. 3a.

The RILAC2 consists of a superconducting ECR ion source (SC-ECRIS), low-energy beam transport line (LEBT), prebuncher (BUN), RF quadrupole linac (RFQ), rebuncher, drift tube linac (DTL), and high-energy beam transport line (HEBT). Figure 5 shows a schematic of the RILAC2. While the prebuncher is operated at the fundamental frequency of 18.25 MHz, RFQ and DTL cavities are operated at the second harmonic.

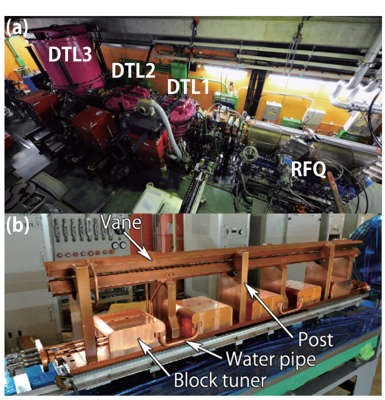

Figure 3: Pictures of RILAC2. (a)The RILAC2 accelerators installed in the AVF hall.(b)Resonator of RFQ showing the tuner blocks for frequency modification.

Superconducting ECR ion source

A new SC-ECRIS was designed and constructed to provide uranium beams 100 times more intense than those from the RIKEN 18-GHz ECRIS at RILAC [8]. Owing to the set of six solenoid coils, the plasma volume is as large as 1100 cm^3 and it is able to produce various magnetic field distribution on axis, which is both of classical B_{min} and so-called "flat B_{min}" [9]. Beam commissioning was performed in 2008 using a 18 GHz microwave power source. Last year, a new 28 GHz gyrotron power source was introduced, aiming for much higher intensity. The achieved intensities for $^{124}Xe^{25+}$ and $^{238}U^{35+}$ are 250 eμA and 60 eμA, respectively. The value 60 eμA is 30-fold that of the 18-GHz ECRIS.

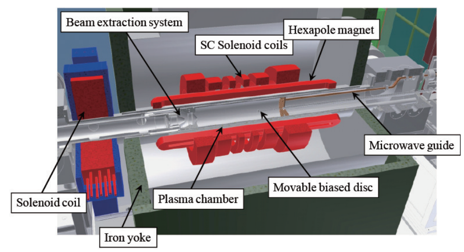

Figure 4: Cut view of SC-ECR.

RFQ Linac and Drift Tube Linac

Table 5 summarizes the design parameters of the RFQ linac and the DTL.

The RFQ linac is based on the four-rod structure. The cavity was originally developed by Nissin Electric Co., Ltd. [10]. While the original cavity had a resonant frequency of 33.8 MHz and accelerated m/q = 16 ions up to 84 keV/u in continuous wave (CW) mode, this was later modified to have a resonant frequency of 36.5 MHz and to accelerate m/q = 6.8 ions up to 100 keV/u [11]. The modification was made by adding tuner blocks between the posts which support the vanes (Fig.3b). The wall loss of the tuner blocks was estimated as 2 kW in total with the designed inter-vane voltage of 42 kV. The unloaded Q value was about 80% of ideal. The main amplifier is based on the tetrode (EIMAC 4CW50,000E) which is basically the same as that for the RILAC injector RFQ [12]. The RF power is fed through a capacitive coupler which matches the input impedance of the cavity to 50 Ω. The maximum output power is 40 kW. Owing to its relatively low frequency, the RFQ has a large focusing strength (B) of 6.8 with 42 kV inter-vane voltage, which is provided with only 18 kW RF power. The maximum modulation (m) is 2.35.

The main accelerator part of the RILAC2 is a drift tube linac (DTL) with newly designed cavities. These cavities operate in CW mode as same as RFQ. As minimization of the installation space was required, the cavities were based

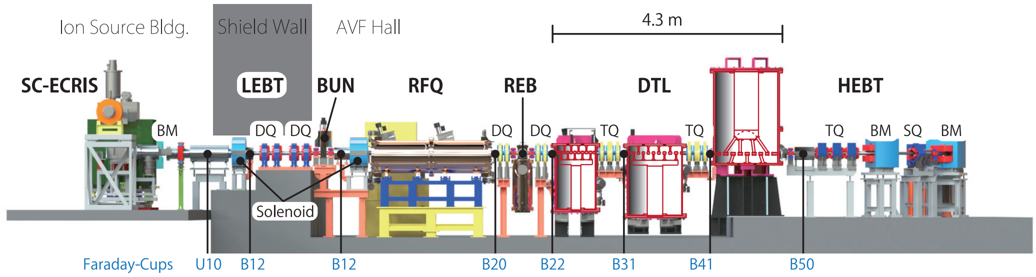

Figure 5: Side view of RILAC2 (DQ: Doublet Q lens; TQ: Triplet Q lens; SL: Solenoid magnet).

Table 1: Design parameters of RFQ and DTL.

	RFQ	DTL1	DTL2	DTL3
Frequency (MHz)	36.5	←	←	←
Duty (%)	100	←	←	←
m/q	6.8	←	←	←
E_{input} (keV/u)	3.28	100	220	450
E_{output} (keV/u)	100	220	450	670
Aperture (mm)	8*	17.5	17.5	17.5
Gap Number	-	10	10	8
Voltage(kV)	42	110	210	260
ϕ_{sync} (deg.)	-29.6**	-25	-25	-25
$P_{wall\ loss}$ (kW)	18	7	13	20

* Mean aperture (r_o), **Final synchronous phase.

the quarter-wavelength structure with a resonant frequency of 36.5 MHz, twice the 18.25 MHz beam frequency. The DTL cavities are directly coupled to amplifiers without using long coaxial lines, further compacting the DTL structure. The DTL cavities were carefully designed to accommodate the significant frequency change due to direct coupling of the tetrode (EIMAC 4CW50,000E) [13]. The coupling was designed by using Micro Wave Studio (MWS) under the following assumptions: that the Q of the actual cavity is 78% of ideal; that the resonant frequency of the cavity itself as obtained from the calculation using MWS is 75 kHz less than that of the actual cavity; that the capacitance of the tetrode is 55 pF; and that the load resistance of the tetrode is ~700 Ω.

Low-power tests were carried out with the actual DTL cavity coupled with the amplifier (Fig. 6). In the case of DTL3, the resonant frequency of the cavity was about 0.1% higher than that of the calculation by MWS package. The unloaded Q value was 78% of ideal. The position and the size of the coupling disk of the coupler were determined by measuring $|S_{11}|$ using a network analyzer. Afterward, the coupler position was finely tuned by performing high-power tests.

When the first excitation of the DTL3 cavity by pulsed-power from the amplifier, the RF power was completely reflected due to multipactoring. After 24 hour conditioning with pulsed-power, it was observed that the pickup signal of the cavity was gradually developed. Subsequently, we

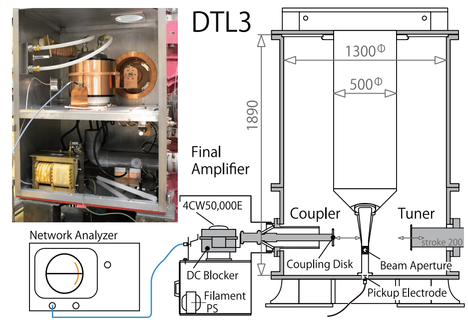

Figure 6: Setup of low-power test showing amplifier is directly coupled to DTL cavity through a capacitive coupler.

changed the conditioning power mode to CW operation, in which a large ratio of the reflection was allowed, and the gap voltage increased up to 35 kV in the first 15 minutes overcoming of levels of multipactoring.

Long-term test was performed measuring the amplitudes and the phases of the cavities continuously using commercially available RF lock-in amplifiers (SR844). The monitor system [14] is useful for determining whether the RF-feedback system works normally or not. The low-level circuit, which consists of auto-gain control and phase-lock, is based on analog feedback. The long-term stability of the amplitude and the phase of the RFQ and DTL cavities are $|\Delta V/V| \leq$0.1% and $\Delta\phi \sim$0.1°, respectively (Fig. 7).

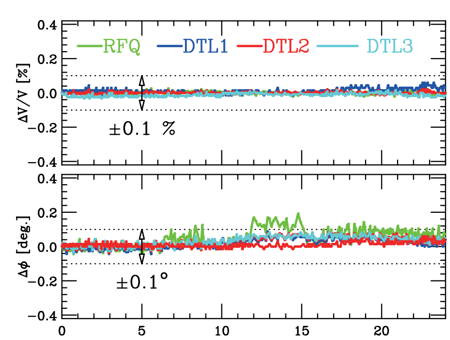

Figure 7: Amplitude and phase errors over 24 h.

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BEAM COMMISSIONING

Acceleration test

Since the first beam of ^{124}Xe was successfully accelerated on Dec. 12, 2010, production of ^{124}Xe and ^{238}U beams has been repeatedly performed. Beam tuning was made starting with design parameters and fine adjustment was performed to maximize the beam transmission efficiency. As a result of the work described in Ref. [15], the transmission efficiency of RILAC2 has recently improved to 70∼80% (Fig. 8a). The beam energy was tuned by changing voltages and phases in the RILAC2 RF systems to 670 keV/u, as confirmed by the TOF method.

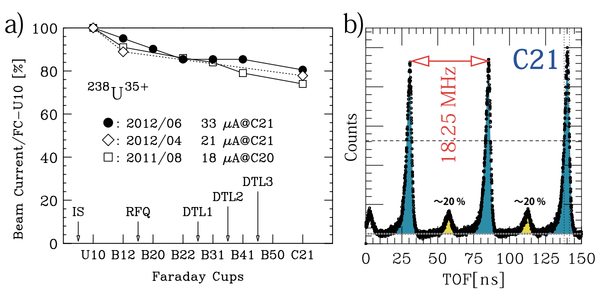

Figure 8: a) Ratio of beam current, as measured by Faraday cups, to IS. b) TOF spectrum at C21.

As shown in Fig. 8b, a prebuncher converts DC beams to bunched beams with frequency 18.25 MHz. Bunching efficiency is typically 80%, the remainder (denoted by yellow hatch in Fig. 8b) lost at RRC injection. In the case of ^{238}U^{35+}, if 75% of the 60 eμA beams from the ion source are accelerated by RILAC2 and RRC transmission efficiency of 80% is achieved, the beam current at the RRC is about 1 pμA, which corresponds to 2.6 kW. Because the cooling of the EDC stands less than 300 W, the extraction efficiency better than 90% is desirable.

The intensity and TOF timing of the beams are continuously monitored by detecting a signal from pickup electrodes induced by bunched beams. Figure 9 shows changes in the PP-S71 pickup signal over 24 hours. The longitudinal acceptance of the RRC is about ±3° in the RF phase. The corresponding timing is ±0.2 ns. Owing to stable operation of the RF system of the RILAC2 and the double rebuncher system (B7 and S6) downstream of the RILAC2, beam intensity and injection timing were stable enough for injection to the RRC (see Fig. 10). .

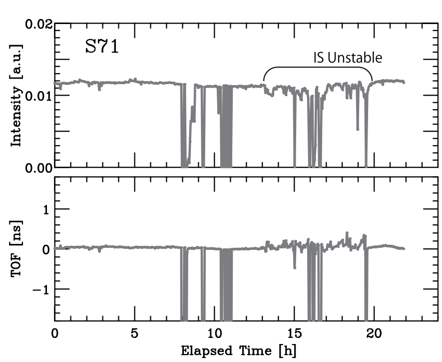

Figure 9: Measured intensity and timing at S71.

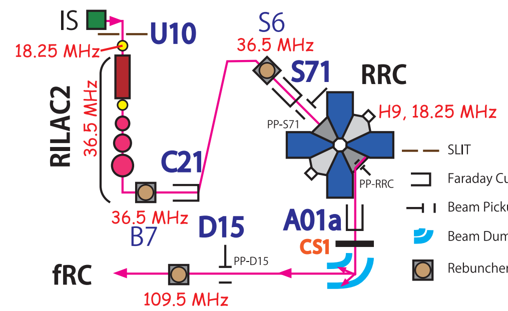

Figure 10: Schematic layout of acceleration with RRC.

Commissioning to RIBF

To date, RILAC2 has provided ^{238}U and ^{124}Xe beams for nuclear physics experiments at the RIBF, as listed in Table 2. During beam service time, RILAC2 operation has been very stable and the break time resulting from the rf down time of RILAC2 was less than 0.3% of the total scheduled beam service time. Nonetheless, maximizing the beam current on target requires elaborate tuning, and transmission efficiency of the RRC was as low as 50∼60%, as obtained from the ratio of measured current of A01a to that of S71.

Due to bunching efficiency, 20% of beams are lost at RRC injection. To extract the accelerating beams with 100% efficiency, beam-turns must be separated at EDC. The turn-pattern of beams circulating in the cyclotron is measured using a differential probe. Figure 11 shows data measured during ^{124}Xe beam service time in 2012. The turn separation at the extraction radius was particularly poor. Experimentally, the turn pattern was measured by cutting the beam at the exit of IS in horizontal and vertical directions, using a set of slits at U10 (Fig.11b). Nonetheless, the separation obtained remains imperfect.

The poor turn separation is partly due to the low voltage of the acceleration cavity. It is difficult to increase the voltage because the 18.25 MHz operation frequency is the lower limit of the cavity, and the tuners are very close to the dee electrode. The turn separation cannot be obtained if the beam's longitudinal emittance from RILAC2 does not match the acceptance of RRC. This problem has not yet been solved.

Table 2: Beam production for RIBF using RILAC2.

Nuclei	Beam Service Time	RRC out	SRC out
^{238}U	17/10/11∼ 07/12/11	0.3 pμA	3.5 pnA
^{124}Xe	11/12/11∼ 18/12/11	0.7 pμA	15 pnA
^{124}Xe	16/06/12∼ 05/07/12	1 pμA	24 pnA

RRC out:FC-A01a, SRC out:FC-G01.

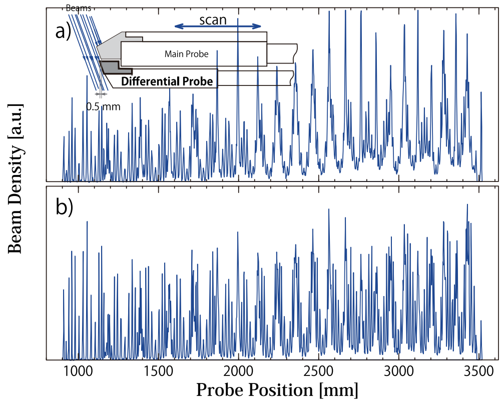

Figure 11: Turn pattern of the circulating beams in RRC. a) U10 slits were set ±5 mm in horizontal and vertical directions. b) ±1 mm and ±2 mm in horizontal and vertical directions, respectively.

Lifetime of charge strippers

Although the transmission efficiency of the RRC remains unsatisfactory, the beam current from the RRC has been greatly improved. As already reported in Ref. [16], the lifetime of the carbon stripper foil was as short as 0.5 days with 4 eμA beams during beam service time in December 2009. Exchanging the stripper foils requires several hours, and due to differences in their thickness, the RF-phase of following accelerators must be retuned. Since the beam intensity at FC-A01 was expected to exceed 10 eμA last year, we have developed carbon nanotube/sputter-deposited carbon (CNT-SDC) foil on a rotating cylinder system [17]. Its rotational speed was 0.05 revolutions per minute. It worked very well over the beam service time in December 2011, the lifetime being 4$\sim$5 days with the maximum beam current of 3.5 pnA at the SRC. This intensity was 4-fold than in December 2009.

For ^{124}Xe acceleration, it is necessary to strip the charge from 19+ to 46+ using a fixed carbon foil. The beam intensity on the stripper foil in June 2012 was about 18 eμA. The frequency of the foil exchange was 3 times/day. Due to the heat load of energy loss at the foil, the foil became significantly thinner within a few hours. The intensity and the timing of the stripped ^{124}Xe beams observed at D15, which is located about 34 m downstream from the stripper, were gradually decreased and advanced as shown in Fig. 12. The beam intensity at the SRC was 24 pnA to the maximum.

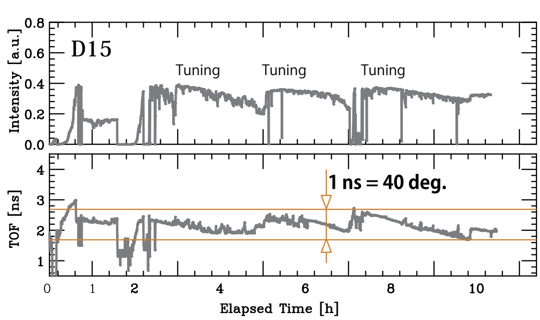

Figure 12: Intensity and timing change at D15.

SUMMARY AND PLANS

In December 2011, ^{238}U beams were successfully provided from RILAC2 and accelerated to 345 MeV/u for a beam service time of 50 days. The reliability fo the rf part of the RILAC2 was more than 97.7% during the beam service time listed in Table 2. Because it is no longer realistic to use carbon foils, we are now preparing a gas stripper system with He [18] for the beam service time scheduled this fall. The gas stripper system with N_2 is also useful for Xe acceleration. In addition, the beam chamber of the analyzing magnet downstream from the charge stripper (see Fig. 10) has been equipped with a beam dump, allowing it to withstand a 10 kW beam load.

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