BEAM COMMISSIONING AND OPERATION OF NEW LINAC INJECTOR FOR RIKEN RI BEAM FACTORY

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Abstract

A new linac injector called RILAC2 has been successfully commissioned at the RIKEN RI beam factory (RIBF). RILAC2 can accelerate very heavy ions with a mass-to-charge ratio (m/q) of 7, such as $^{124}\text{Xe}^{20+}$ and $^{238}\text{U}^{35+}$ from a 28-GHz superconducting electron cyclotron resonance ion source (SC-ECRIS), up to an energy of 680 keV/u in the cw mode. The key features of RILAC2 are the powerful SC-ECRIS; improved rf voltage stability, rf phase stability, and vacuum level compared to the existing linac injector; and the compact equipment yet to be installed in the azimuthally varying field (AVF) cyclotron vault. Beam acceleration was first achieved on December 21, 2010. After conducting several beam acceleration tests in 2011, we started to operate RILAC2 to supply beams for experiments conducted at the RIBF.

ROLE OF NEW LINAC INJECTOR

The Radioactive Isotope Beam Factory (RIBF) [1] at the RIKEN Nishina Center was established in order to produce the world's most intense radioactive isotope (RI) beams over the entire range of atomic masses. Such powerful RI beams facilitate the expansion of our nuclear foothold to previously impenetrable regions on the nuclear map and open up new possibilities for gaining a unified understanding of nuclear structures for the explication of elemental synthesis and for enabling new scientific discoveries and applications. The RIKEN Nishina Center has four separate-sector cyclotrons: the RIKEN ring cyclotron (RRC [2], K = 540 MeV, 1987), the fixed-frequency ring cyclotron (fRC [3], K = 570 MeV, 2006), the intermediate-stage ring cyclotron (IRC [4], K = 980 MeV, 2006), and the world's first superconducting ring cyclotron (SRC [5], K = 2600 MeV, 2006). These cyclotrons are combined in a cascade with different types of injectors: a variable-frequency heavy-ion linac (RILAC) [6], and a K70-MeV azimuthally varying field (AVF) cyclotron [7]. The cascade of RILAC-RRC-fRC-IRC-SRC can accelerate very heavy ions such as uranium and xenon to a fixed energy of 345 MeV/u. The cascade of RILAC-RRC-IRC-SRC can control the final energy of medium-mass ions such as calcium and krypton as a variable-frequency mode. The AVF-RRC-SRC mode is used for light ions such as deuteron and carbon. These energetic heavy-ion beams are converted into intense RI beams via the in-flight fission of uranium ions or the projectile fragmentation of stable ions by a superconducting in-flight fragment separator, BigRIPS [8].

The existing linac injector, RILAC, plays another important role of supplying intense beams for the synthesis of super-heavy elements (SHEs) using the GARIS spectrometer [9]. Since a long beam time is required for the synthesis of SHEs, the intensive series of RIBF experiments is disturbed on account of the conflicting function of RILAC as an injector. In addition, the deterioration of RILAC, which is over 30 years old, causes the beam to be unstable and have low intensity of beam for very heavy ions such as uranium. Therefore, a new linac injector, called RILAC2, was proposed and constructed at the RIKEN Nishina Center so that the experiments at the RIBF and research on SHEs could be conducted independently and beam intensity could be increased drastically.

CONSTRUCTION OF NEW INJECTOR

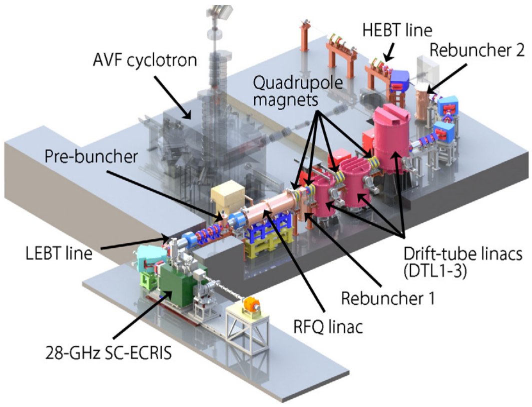

Figure 1: View of RILAC2, newly built injector in the AVF cyclotron vault.

RILAC2 is designed to accelerate heavy ions with a mass-to-charge ratio (m/q) of 7, such as $^{124}\text{Xe}^{20+}$ and $^{238}\text{U}^{35+}$, up to an energy of 680 keV/u in the cw mode [10]. The output beam is injected into the RRC without charge stripping. As shown in Fig. 1, RILAC2 consists of a 28-GHz superconducting electron cyclotron resonance ion source (SC-ECRIS) [11, 12], a low-energy beam-transport (LEBT) line [13] including a pre-buncher, a radio-frequency quadrupole (RFQ) linac, three drift-tube

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linacs (DTL1-3), a rebuncher between the RFQ and DTL1, and strong quadrupole magnets placed between the rf resonators for transverse focusing. A double rebuncher system is introduced in a high-energy beam-transport (HEBT) line from DTL3 to the RRC. The rf resonators, excluding the pre-buncher, are operated at a fixed rf frequency of 36.5 MHz, whereas the pre-buncher is operated at 18.25 MHz. The construction of RILAC2 was started at the end of fiscal year 2008 [14].

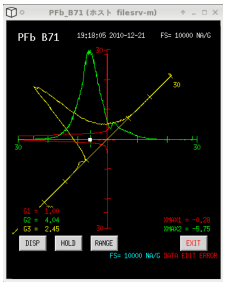
The SC-ECRIS, which was originally fabricated for RILAC in 2008, was relocated to a new room to function as the ion source of RILAC2 in 2010. It has a large plasma volume of 1100 cm^3, and its six sets of superconducting solenoid coils and superconducting hexapole coil can be used for adjusting a flat magnetic field region between mirror fields. This feature enables optimization of the magnetic-field distribution for the efficient ionization of beams. The other equipment of RILAC2 was placed in the existing AVF cyclotron vault.

In order to save costs, we decided to recycle a four-rod RFQ linac kindly provided by Kyoto University in November 2007. The original RFQ linac was developed by Nissin Electric Co., Ltd., in 1993 [15] for ion implantation; the RFQ linac was able to accelerate heavy ions with an m/q of 16 up to 84 keV/u in the cw mode and with an rf frequency of 33.3 MHz. If the RFQ resonator is modified to have a resonant frequency of 36.5 MHz, ions with an m/q of 7 can be accelerated to 100 keV/u at RILAC2 without changing the vane electrodes. For modifying the resonant frequency, we inserted a block tuner into the gaps between the posts supporting the vane electrodes. An offline low-power test was performed, and the resonant frequency was found to be successfully changed to 36.5 MHz in April 2010. The installation of an RFQ resonator, rf amplifier, low-level circuits, and control system was completed by August 2010, and the RFQ resonator was successfully excited in situ with a rated voltage of 42 kV by an rf power of 18 kW.

The structure of the DTL is based on a quarter-wavelength resonator. DTL1 and DTL2 were newly designed, whereas DTL3 was obtained by modifying an existing resonator for boosting energy in RILAC [16]. A plate electrode of a 4CW50000E vacuum tube in the rf amplifier was directly connected to the capacitive coupler mounted on the DTL resonator, in order to reduce the construction cost and the space occupied by the equipment. When the amplifier was mounted on the resonator, the resonant frequency decreased because of their series/parallel capacitance. Thus, we had to set the target frequency of the resonator such that this decrease in the resonant frequency was compensated for. Immediately after the completion of DTL fabrication in January 2010, the rf characteristics of each DTL were measured. A high-power test was performed with a load impedance setting of 700-1000 Ω depending on the resonator. After one day of conditioning, the rated voltage was successfully achieved for every resonator. The DTLs were installed in the AVF cyclotron vault in February 2010, and the high-power test was performed again. Further tests and modifications were performed in fiscal year 2010 to improve the long-term rf stability of the DTLs [17].

BEAM COMMISSIONING

The beam acceleration test of RILAC2 was begun on December 21, 2010. First, the beam was accelerated using RILAC2 only downstream of the 90° bend (B71) in the AVF cyclotron vault. After validating each piece of equipment of RILAC2 one by one, we succeeded in accelerating the first beam on day 1 by using all the rf resonators of RILAC2. Figure 2 shows a profile of the first beam measured at B71 by a wire scanner. In this study, a ^{124}Xe^{20+} beam was accelerated up to an energy of 674 keV/u. When the intensity of the beam supplied by the SC-ECRIS was 9.5 eμA, where the beam was attenuated by a movable slit downstream of the SC-ECRIS, the beam was accelerated and transported to B71 with an intensity of 7.1 eμA.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PFb B71 19:18:05 2010-12-21 FS= 10000 NA/G

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G2 = 4.04
G3 = 2.45

XMAX1 = -0.28
XMAX2 = -5.75

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Figure 2: Profile of the first beam accelerated using all rf systems.

As listed in Table 1, several studies involving RILAC2 with/without post-accelerators were conducted using xenon and uranium beams in order to increase the transmission efficiency and beam intensity of the RIBF and to test the charge strippers. Post the completion of the rebuncher at B71 in January 2011, beam acceleration through the fRC has been performed with a ^{124}Xe beam. The beam energy accelerated by the RRC was 10.75 MeV/u; the ^{124}Xe beam was charge-stripped by a nitrogen-gas stripper from 20+ to 38+ for the fRC, and we were able to smoothly extract the beam from the fRC. In these studies, the beam energies from both RILAC2 and the RRC were found to be slightly higher and to cause large off-centering in the cyclotrons. In May 2011, after installing the time-of-flight measurement system, we measured the beam energy and adjusted the acceleration energy of RILAC2 to 669 keV/u, which was optimal for the RRC. The ^{124}Xe beam was successfully accelerated and extracted from the final stage accelerator SRC on May 17.

Next, the ^{238}U beam was accelerated by RILAC2 for the first time, and studies on charge strippers located downstream of the RRC were conducted. Following these studies, the vacuum pumping system on the beam transport line between RILAC2 and the RRC improved, because the vacuum level of the beam line, around 10^{-5} Pa, had been found to be insufficient for the uranium beam. The loss

Table 1: History of beam acceleration tests at RILAC2. "C.S." indicates a charge stripper test.

2010/12/21	^{124}Xe	first beam acceleration
2010/12/22	^{124}Xe	RILAC2 solo
2011/01/21	^{124}Xe	RILAC2 solo
2011/02/14-16	^{124}Xe	RILAC2-RRC-fRC
2011/05/07-21	^{124}Xe	RILAC2$\sim$SRC
2011/06/15-30	^{238}U	RILAC2-RRC-fRC (C.S.)
2011/08/26-29	^{238}U	RILAC2-RRC
2011/09/24-26	^{238}U	RILAC2-RRC (C.S.)
2012/04/26-28	^{238}U	RILAC2-RRC (C.S.)

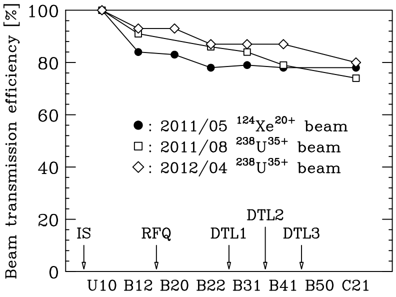

Figure 3: Transmission efficiency of RILAC2.

of the uranium beam caused by charge exchange reactions, which was about 10% in each section between the bending magnets, improved to less than 3%. Figure 3 shows the beam transmission efficiency through RILAC2 in the test experiments.

OPERATION

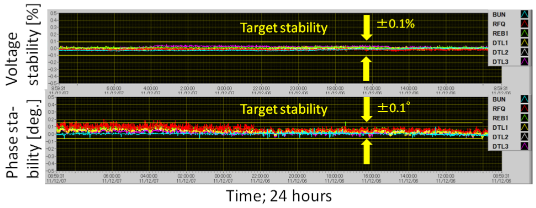

Figure 4: RF voltage stability and rf phase stability of RILAC2 resonators.

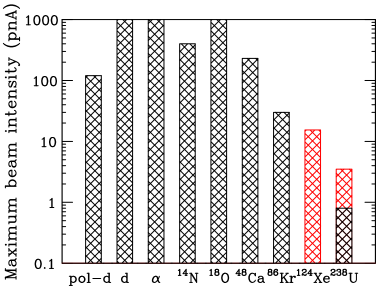

Figure 5: Maximum beam intensity extracted from the SRC until December 2011. The red bars are attributed to RILAC2.

RILAC2 successfully began supplying uranium beams for the series of RIBF experiments from October 2011. The rf stability of the RILAC2 resonators over one day is shown in Fig. 4. The upper panel shows the rf voltage stability, and the lower panel shows the rf phase stability. The target values are indicated by yellow lines in the figure (±0.1% for the voltage, ±0.1° for the phase). The stability of RILAC2 is sufficient to attain the target values. During the experiment, the average intensity of the uranium beam supplied by the SC-ECRIS was 25 eμA. The typical 4σ emittance of the uranium beam from the SC-ECRIS was $x = 76\pi$ mm·mrad and $y = 93\pi$ mm·mrad. The maximum intensity of the uranium beam extracted from the SRC increased to 3.5 pnA(300 nA), which is about five times that in the previous experiment performed in 2009. A xenon beam with an intensity of 15.4 pnA(800 nA) was also used in the RIBF experiment in December 2011. Moreover, the break time during the series experiments, resulting from the downtime of RILAC2, was less than 0.3% of the total scheduled beam time. The maximum intensities of various beams achieved at the RIBF until December 2011 are shown in Fig. 5. Owing to the increase in the intensity of the beam supplied by the SC-ECRIS, beams with much higher intensities are expected to be accelerated by RILAC2 and in the RIBF accelerator complex.

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