PROGRESS TOWARDS HIGH-INTENSITY HEAVY-ION BEAMS AT RIKEN RIBF

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Abstract

Since the extraction of the first beam in late 2006, the RIKEN Radioactive Isotope Beam Factory (RIBF) has been successfully operating with the aim of accessing the unexplored region on the nuclear chart, far from the stability line. The continuous efforts over these six years have significantly enhanced the performance of the RIBF accelerator complex. Thus far, we have achieved the target intensity of 1,000 pnA for helium and oxygen beams and about half of the target intensity for the calcium beam. The intensity of uranium beams, however, is still to be improved, requiring extensive measures to reach the target intensity. To address this situation, we constructed a 28-GHz superconducting electron cyclotron resonance ion source and a new injector linac. Furthermore, we developed a helium gas charge stripper as an alternative to the standard carbon-foil stripper. This paper presents recent results obtained in the commissioning of the new injector system, the report of the R&D work on the gas charge stripper, and a brief summary of the present performance of the RIBF accelerator complex.

INTRODUCTION

The Radioactive Isotope Beam Factory (RIBF)[1] at RIKEN is aimed at producing the most intense RI beams over the whole range of atomic masses. These powerful RI beams are expected to provide us with 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 to our understanding of the synthesis of the heavy elements in the universe. We are also promoting applications of the RI beams to various research fields such as nuclear chemistry and biological science.

The schematic of the RIBF accelerator chain is shown in Fig. 1. It consists of three injectors (the AVF cyclotron and two heavy-ion linacs, RILAC and RILAC2) and four booster cyclotrons (RRC, fRC, IRC, and SRC). The RIBF has three accelerating modes. The first mode uses the AVF cyclotron as the injector and two cyclotrons, RRC and SRC, as the energy boosters. This mode is exclusively used for light ions such as deuteron and nitrogen. The beam energy from the SRC can be varied below 440 MeV/u by varying the rf frequency. The second mode 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 also be controlled within a wide range below 400 MeV/u by varying the rf frequency. The final mode is the fixed-energy mode, which uses the fRC placed between the RRC and the IRC. The beam energy from the SRC is fixed at 345 MeV/u, because of the fixed frequency operation of the fRC. This mode is used for the acceleration of very heavy ions such as uranium and xenon. The injector for this mode, RILAC2, was fully commissioned in 2011, and is shown in the schematic in Fig. 1.

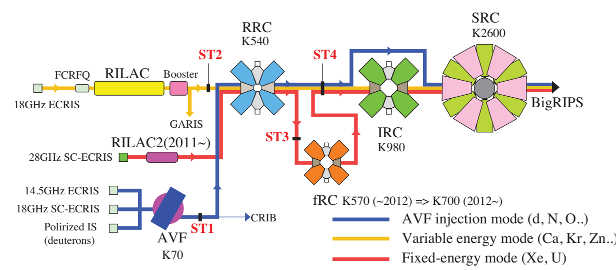

Figure 1: Accelerator chain of RIBF at RIKEN. Three injectors — AVF cyclotron, RILAC, and RILAC2 — are followed by the four booster cyclotrons — RRC (RIKEN Ring Cyclotron), fRC (fixed-frequency Ring Cyclotron), IRC (Intermediate-stage Ring Cyclotron), and SRC (Superconducting Ring Cyclotron). The K-values of the cyclotrons are indicated in the figure in MeVs. The charge strippers are indicated by labels in the red text (ST1 - ST4).

The beam intensities for the light and medium-mass ions was greatly improved by 2012. For instance, 1000 pnA of ^{18}O and 415 pnA of ^{48}Ca were extracted from the SRC at the beam energy of 345 MeV/u. The remaining issue is that of increasing the beam intensity of very heavy ions. For this purpose, we initiated the upgrade programs presented below[2].

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RECENT UPGRADES

Superconducting ECR Ion Source

In 2009, a new superconducting ECR ion source (SC-ECRIS), capable of a microwave power of 28 GHz, was constructed[3]. The main features of this ion source are as follows. First, the size of the ECR surface is large; it has a plasma volume as large as 1100 cm^3, owing to a set of six solenoid coils. Second, it is possible to generate magnetic fields of various distributions on the axis[4].

The full commissioning of the SC-ECRIS started in 2010 with a power source based on a 28-GHz gyrotron, after relocation to the RILAC2 site. The intensity and long-term stability of the SC-ECRIS have been greatly improved so far. For example, the duration of the uranium beam, provided with the sputtering method, has been extended to one month, while the intensity has been maintained around 2.5 pμA, as shown in Fig. 2. The typical emittances (4 rms) were around 100 (π) mm·mrad for this beam in both the transverse planes.

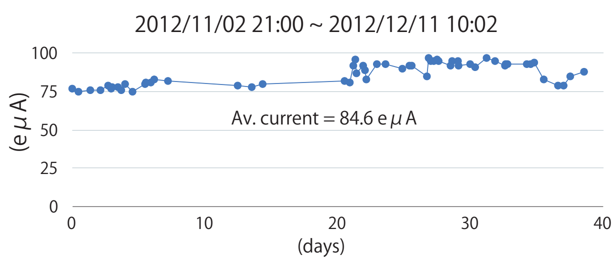

Figure 2: Beam intensity of U^{35+} from the SC-ECRIS, measured in the LEBT of the RILAC2 during beam servicing in 2012.

New Injector (RILAC2) for RIBF

The RILAC2 injector, placed in the AVF cyclotron room as shown in Fig. 3, is designed to accelerate ions with a mass-to-charge ratio of 6.8, aiming at very heavy ions such as ^{136}Xe^{20+} and ^{238}U^{35+} up to an energy of 670 keV/u in the cw mode. The output beams are injected to the RRC without charge stripping. The RILAC2 consists of the 28-GHz SC-ECRIS, a low-energy beam-transport (LEBT) line (including a prebuncher), an RFQ linac, three DTL resonators (DTL1 - 3), and two rebunchers. The rf resonators excluding the prebuncher are operated at a fixed rf of 36.5 MHz, whereas the prebuncher is operated at 18.25 MHz.

The RFQ resonator is based on the four-rod structure. We modified the resonator originally developed by Nissin Electric Co., Ltd[5] to have a resonant frequency of 36.5 MHz[6]. Owing to its relatively low frequency, the RFQ has a large focusing strength (B) of 6.8 with an inter-vane voltage of 42 kV, which is obtained with an rf power of only 18 kW. The DTL resonators are based on the quarter-wavelength structure. We adopted a direct coupling scheme for the rf coupling between the resonator and the amplifiers in order to reduce the construction cost and space. The

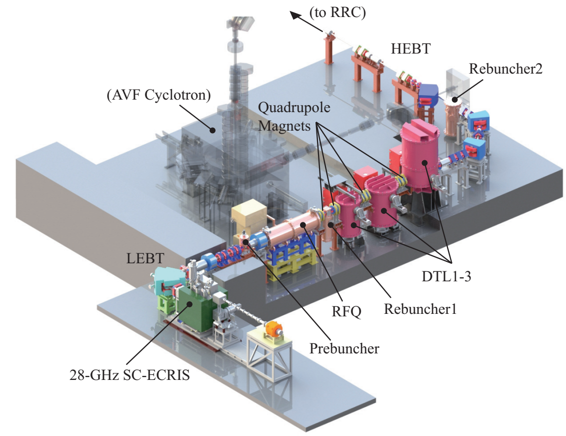

Figure 3: Schematic of RILAC2 injector.

DTL resonators were, therefore, carefully designed using a computer code to accommodate the frequency change due to the direct coupling of the tetrode to the resonator[7]. The actual structure exhibits almost the same performance as that predicted by the computer simulations. The power loss per resonator remains below 20 kW.

The beam commissioning of the RILAC2 started in December 2010, and RILAC2 has thus far provided ^{238}U and ^{124}Xe beams for nuclear physics experiments at the RIBF. During beam servicing, the RILAC2 operation has been very stable and the interval in operation resulting from the rf down time of RILAC2 was less than 0.3% of the total scheduled beam servicing time. The long-term stabilities of the amplitude and phase of the RFQ and DTL cavities are $|\Delta V/V| < 0.1\%$ and $|\Delta\phi| \approx 0.1^\circ$, respectively[8].

Charge Strippers

The most crucial problems in the uranium acceleration were the limited lifetime of the carbon-foil strippers and the deterioration of the beam quality owing to the non-uniform thickness of the strippers. In 2011, we measured the charge evolution for the uranium ions through a 0.5-m-long windowless helium gas cell[9], based on the basic study on charge-stripping processes in low-Z gases[10].

From the measured data, we concluded that the helium gas charge stripper can be used for practical operation by increasing the maximum bending power of the fRC to accept U^{64+}, as shown below. A new helium gas stripper equipped with a unique helium recycling system was constructed; without this recycling system, the wastage of helium gas would be 280 m^3/day. We carried out a long-time operation with uranium beams of more than 1 pμA at the stripper in the autumn of 2012 and confirmed that the system functioned quite stably[11].

fRC upgrade

When we use the helium gas stripper, the available charge state becomes lower than that realized when using

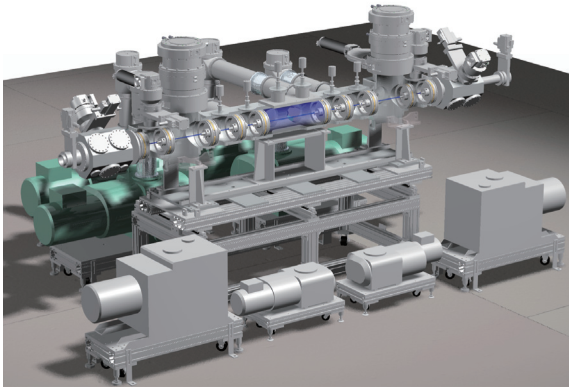

Figure 4: Schematic of helium gas stripper.

the carbon-foil stripper, as mentioned above. The fRC has been modified, so that it can accelerate 64+ of uranium beams, in the following manner. First, the magnet power supplies of the main coils have been upgraded to increase the maximum current from 650 A to 900 A. Second, the injection magnet (BM) and the iron core of the extraction magnet (EBM) have been newly fabricated to accommodate the lower charge state. Third, the magnetic inflection channel and its power supply (MIC2) have been upgraded. In addition, a couple of steering magnets have been inserted into the injection system of the fRC to correct the injection orbit affected by the increased stray magnetic field due to the upgrade. It has been confirmed that the modification was successful[12].

PRESENT PERFORMANCE

The evolution of the maximum beam intensities for beams accelerated at RIBF is summarized in Fig. 5 and Table 1. The maximum currents in the RILAC2 injection mode are 15 pnA for ^{238}U and 24 pnA for ^{124}Xe. We are planning to increase these intensities by at least a factor of three in the coming five years.

The beam availability, defined by the ratio of the actual beam servicing time to the scheduled beam servicing time, is another important index for the accelerator facility from the viewpoint of effective operation. The availabilities in the AVF injection mode and the variable energy mode have become as high as 90%, owing to the steady improvements and daily maintenance in the recent years[2]. Availabilities in the fixed energy mode are being improved, mainly with the introduction of the gas charge stripper, exceeding 90% in the uranium beam time in December 2012. They are expected to be further improved by the upgrade of the second stripper in the coming few years.

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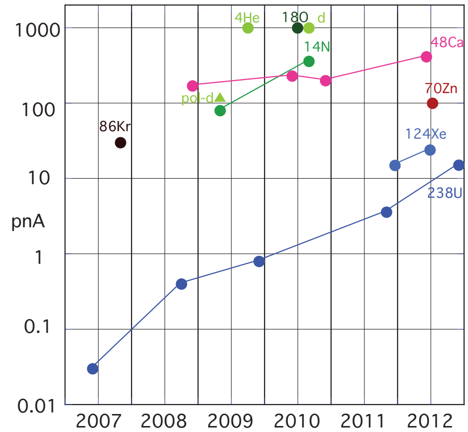

Figure 5: Evolution of maximum beam intensities at RIKEN RIBF.

Table 1: Maximum beam intensities extracted from SRC thus far.

Ion	E (MeV/u)	I (pnA)	Achieved in
pol-d	250	120	May 2009
^{4}He	320	1000	Oct. 2009
^{14}N	250	360	Oct 2010
^{18}O	345	1000	Jul. 2010
^{48}Ca	345	415	Jun. 2012
^{70}Zn	345	100	Jul. 2012
^{86}Kr	345	30	Nov. 2007
^{124}Xe	345	24	Jun. 2012
^{238}U	345	15	Dec. 2012

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