RECENT ACHIEVEMENTS AND UPGRADE PROGRAMS AT RIKEN RADIOACTIVE ISOTOPE BEAM FACTORY

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Abstract

The RIKEN Radioactive Isotope Beam Factory (RIBF) has been successfully operating for over five years since the first beam at the end of 2006 with the aim of accessing the unexplored region on the nuclear chart, far from stability. The continuous efforts over these five years have improved the performance of the RIBF accelerator complex. Thus far, we have achieved the target intensity for He and O ions and about one-fourth of the target intensity for the Ca ion. The intensity of U beams, however, is still very low, requiring drastic measures to achieve the target intensity. This has motivated us to construct a 28 GHz superconducting electron cyclotron resonance (ECR) ion source and a new injector linac. Furthermore we developed a He gas charge stripper as an alternative to the standard C-foil stripping. This paper summarized the successful results for the commissioning of the new injection system and the R&D work of the He gas charge stripper, after a brief summary of the operation of the RIBF accelerator complex from October 2010 to April 2012.

INTRODUCTION

The RIKEN Nishina Center for Accelerator-Based Science constructed the RIBF (Radioactive Isotope Beam Factory) [1] with the aim of creating a next-generation facility that can provide the world's most intense RI beams at energies of several hundred MeV/nucleon over the entire range of atomic masses. The RIBF requires an accelerator complex that can accelerate ions over the entire range of masses and deliver high-power U beams at an energy of 345 MeV/nucleon. Figure 1 shows a bird's-eye view of the RIBF. The structure on the left is the old facility that was completed in 1990. Many fruitful experiments were carried out with light-ion RI beams using the four-sector K540-MeV RRC (RIKEN ring cyclotron) with two injectors, the RILAC (RIKEN linear accelerator) and the AVF cyclotron (K70 MeV), because the RRC can accelerate relatively light ions up to 100 MeV/nucleon, which is the lower limit for RI beam production. In order to extend the mass range for RI beam production up to uranium, three ring cyclotrons, fRC (fixed-frequency ring cyclotron), IRC (intermediate-stage ring cyclotron), and the SRC (superconducting ring cyclotron), were designed and constructed as energy boosters for the RRC. The main specifications for the three ring cyclotrons are listed in Table 1. The first beam was extracted from the SRC on December 28, 2006. Since the first beam, many improvements have been made to the accelerators to increase beam intensity and for commissioning new beam species to meet the requirements of different experiments. Table 2 lists the beams accelerated thus far [2, 3].

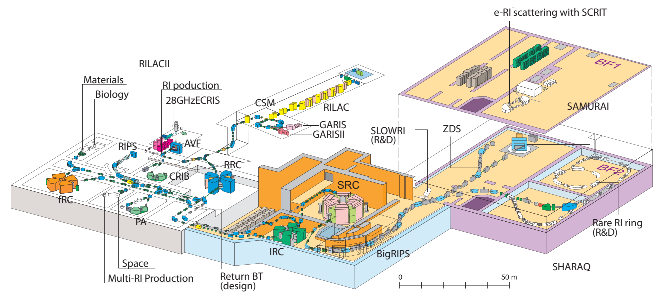

Figure 1: Bird's-eye view of RIBF

Table 1: Specifications of the three new cyclotrons in the RIBF. FT stands for flat-topping.

	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

OPERATION FROM OCTOBER 2010 TO APRIL 2012

Table 3 summarizes the operation of the RIBF accelerator from October 2010 to April 2012. The ^{14}N (^{2}H) and ^{48}Ca beam experiments were carried out after summer maintenance in 2010, although there was trouble from a vacuum leak from extraction element (MDC1) for the RRC due to the high-power ^{48}Ca beam. The earthquake

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Table 2: Beams accelerated at the RIBF accelerator complex with the maximum beam intensity achieved. The beam intensities are expressed in pnA (6×10^9 particles/s).

Ion	Energy (MeV/nucleon)	Intensity (pnA)	Month/Year
pol-^{2}H	250	120	May 2009
^{4}He	320	1000	Oct 2009
^{14}N	250	80	May 2009
^{18}O	345	1000	Jun 2010
^{48}Ca	345	230	May 2010
^{86}Kr	345	30	Nov 2007
^{124}Xe	345	15.4	Dec 2011
^{238}U	345	3.5	Oct 2011

Table 3: Summary for the operation of the RIBF accelerator complex from November 2010 to April 2012.

Start	End	Ion	Energy (MeV/nucleon)
2010/10/1	2010/10/17	^{14}N	250
2010/10/19	2010/10/23	^{2}H	250
2010/11/25	2010/12/17	^{48}Ca	345
2011/5/30	2011/6/12	^{18}O	345
2011/10/17	2011/12/17	^{238}U	345
2011/12/12	2011/12/19	^{124}Xe	345
2012/2/21	2012/2/26	pol-^{2}H	300
2012/3/16	2012/3/23	^{18}O	294
2012/3/31	2012/4/19	^{18}O	230

on March 11, 2011 forced us to cancel all scheduled experiments until the RIBF accelerator was checked using ^{18}O at the end of May. During this period, we suffered from an electricity shortage, but a CGS (co-generation system) providing up to 6 MW contributed significantly to the operation. A 28 GHz superconducting ECR (electron cyclotron resonance) ion source (SC-ECRIS) [4] and a new injector linac (RILAC2) [6] were operated for the first time for U and Xe from October 2011 to December 2011. The maximum intensity of the U beam was approximately 3.5 pnA which is about four times that of the formerly available intensity. Large CNT (carbon nanotube)-based foils on the rotating cylinder were successfully used as the first charge stripper, surviving for 4-5 days, whereas the lifetime of the fixed C-foil is expected to be about 2-3 h. Xe beams were also accelerated using the new injection system and the maximum intensity was 15.4 pnA. The beam experiments from February to April 2012 were concentrated on light ions such as polarized ^{2}H and ^{18}O which were accelerated using only the RRC and SRC with the injector of the AVF cyclotron. In these experiments, we achieved high availability greater than 95%.

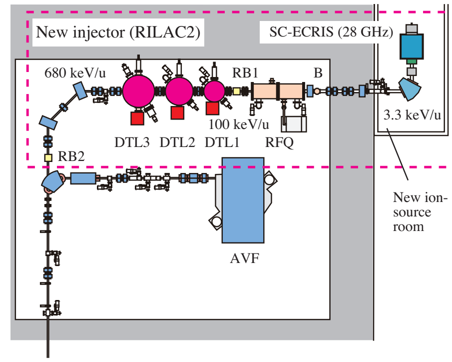

Figure 2: A schematic of the new injection system, including SC-ECRIS and RILAC2.

INTENSITY UPGRADE FOR URANIUM BEAM

Figure 2 shows a schematic drawing of the RILAC2 with SC-ECRIS. This section describes the R&D work and commissioning results of the SC-ECRIS, RILAC2, and the He gas charge stripper. These are key components for the intensity upgrade for very heavy ions beams, such as U and Xe.

Superconducting ECR ion source (SC-ECRIS)

In order to meet the requirements for the intensity upgrade for U and Xe beams, the SC-ECRIS was constructed, which is designed to have a plasma volume as large as 1100 cm^3 and which provides a flat magnetic field distribution in the central region by exciting the solenoids independently [5]. The superconducting coil was successfully excited to the designed level in October 2008. The testing of the ECR source began in April 2009 with an 18-GHz power supply. The intensity of the uranium beams reached 24 eμA based on the sputtering method, which is about twelve times that of the beams from the previously used ion sources. Four times the rms emittance could be reduced to as small as 90π mm mrad. Testing with a 28 GHz power supply started from April 2011. The generation test for Xe ions clearly showed enhancement of the ion beam intensity with the higher frequency of 28 GHz. The development of U ion beam generation is in progress. A high-temperature oven for U ion generation will be installed for a further intensity upgrade.

Injector linac (RILAC2)

The RILAC2 was designed to efficiently accelerate ions from the new powerful ion source with a mass-to-charge ratio of 7, aiming at heavy ions such as ^{136}Xe^{20+} and ^{238}U^{35+}, up to an energy of 680 keV/nucleon. The new injector system will also contribute to solving the conflict between the RIBF research and the super heavy element research which has been successful using the GARIS spectrometer. The RILAC2 mainly consists of a low-energy

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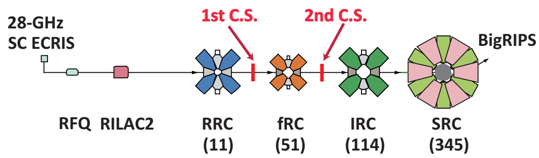

Figure 3: Acceleration scheme for uranium beams at the RIBF. The uranium beams from the SC-ECRIS are accelerated using RILAC2, RRC, fRC and SRC. Two charge strippers are located downstream of the first and second cyclotrons, RRC and fRC, respectively. The numbers in the brackets below the cyclotrons denote the extraction energies in MeV/nucleon.

beam-transport line that includes a prebuncher, an RFQ linac, and three DTL resonators (DTL1 - 3) with two rebunchers (RB1 and RB2). Construction of RILAC2 began in 2008. All the main components have been installed, and the excitation tests for all the accelerator tanks were performed in the AVF cyclotron room. Commissioning of the RILAC2 began in mid-December 2010 and the first beam was obtained at the end of December. After several machine studies, RILAC2 began feeding stable U and Xe ion beams to the RRC from October 2011. Details of the commissioning results can be found in reference [7].

Charge stripper

Figure 3 shows the acceleration scheme for U beams using two charge strippers. The U beams are accelerated using SC-ECRIS, RILAC2, RRC, fRC, IRC, and SRC. The first charge stripper is located behind the RRC, with an energy of 11 MeV/nucleon, and the second one is located behind the fRC, with an energy of 51 MeV/nucleon. C-foils have been used in both charge strippers. The typical thicknesses of the foils for the first and second charge strippers are 300 μg/cm^2 and 17 mg/cm^2, respectively. The use of the first charge stripper involves a serious problem. Its typical lifetime is approximately 12 h at an intensity of 1 eμA. The currently available beam intensities do not pose any problems. However, in the future, with the completion of the aforementioned upgrade programs, the intensity of U beams will increase more than hundred-fold, thereby leading to a requirement of much stronger charge strippers. However, Intense R&D programs using large foils mounted on a rotating cylinder and a N_2 gas charge stripper, which were initiated in 2008, were not successful.

A low-Z (He or H_2) gas charge stripper is a possible candidate because it is expected to provide high equilibrium charge states due to suppression of the electron capture process. In April 2010, we measured cross sections of electron stripping and electron capture of U ions in He 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 [8]. This means that the helium gas charge stripper is a strong option for the future charge stripper system. Therefore, we have started a new devel-

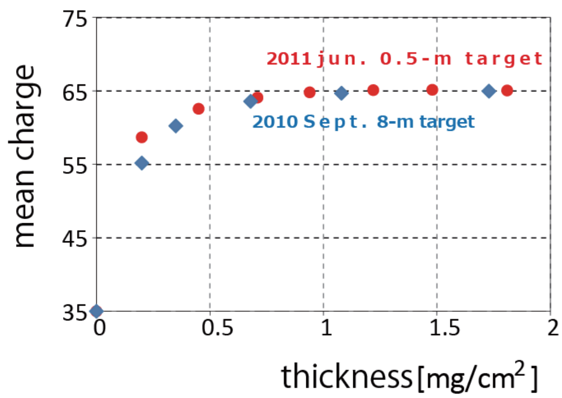

Figure 4: The measured mean charge of U ion after He gas

opment program to make a thick He gas charge stripper, which is indispensable for increasing the U beam intensity to 50-100 pnA. We successfully measured the charge evolution for the U ions through the He and H_2 windowless gas cells of 8 m and 0.5 m in length, respectively, as shown in Fig. 4 [9]. The measured mean charge reached up to about 65, which is consistent with that estimated from the previously measured cross sections for electron loss and capture. The measured data has led us to decide that the He gas charge stripper can be used for the practical operation by increasing the maximum bending power of the fRC to accept U^{65+}. Therefore a new He gas charge stripper was built and installed for operation with the U beam in January 2012. This system has a unique He recycling system, otherwise, 280 m^3/day of He gas will be waisted. We intend to carry out several tests using U beams before the U experiments scheduled for the next autumn.

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