HEAVY-ION BEAM ACCELERATION AT RIKEN FOR SUPER-HEAVY ELEMENT SEARCH

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Abstract

The RIKEN heavy-ion linear accelerator (RILAC) comprises a variable-frequency Wideröe linac as the main linac, an 18 GHz electron cyclotron resonance ion source, a variable-frequency folded-coaxial radiofrequency quadrupole linac as a pre-injector, and a charge-state multiplier system as a booster. An experiment to search for a super-heavy element (Z=113) was carried out using the RILAC at the RIKEN Nishina Center for Accelerator-Based Science, from September 2003 to August 2012. As a result, three events for Z=113 were successfully observed. This paper presents heavy-ion beam acceleration at RIKEN for the super-heavy element search.

INTRODUCTION

The project to construct a heavy-ion accelerator complex (linac-cyclotron) at RIKEN was initiated in 1974. The construction of six RIKEN heavy-ion linear accelerator (RILAC) resonators (RILAC No.1 - No.6) was completed in 1980 [1]. These are variable-frequency Wideröe linac-type resonators. The frequency tunable range of the resonators is from 17 to 45 MHz. The stand-alone mode operation of the RILAC to supply ion beams for experiments was started in 1981. The injection-mode operation of the RILAC to inject ion beams into the K540MeV RIKEN Ring Cyclotron (RRC) [2] was initiated in 1986.

In 1996, the pre-injector of the RILAC, a direct-current (DC) high-voltage terminal, was converted into a combination of a powerful 18 GHz electron cyclotron resonance ion source (18GHz-ECRIS) [3] and a very efficient low-β accelerator, which is a variable-frequency folded-coaxial radiofrequency quadrupole linac (FC-RFQ) [4]. The frequency tunable range of the FC-RFQ is from 17.7 to 39.2 MHz.

A new project for the RIKEN Radioactive Isotope Beam Factory (RIBF) [5] was proposed to extend radioactive isotope beams to heavy mass range. Since the project aimed principally at producing an intense heaviest-ion (uranium) beam, a charge-state multiplier system (CSM) [6] was proposed to minimize the inevitable beam-loss during the charge stripping process after the RILAC. In 2000, as an energy upgrade program of the RILAC in collaboration with the Center for Nuclear Study, University of Tokyo, six CSM resonators (CSM A1-A6) were installed after the existing accelerator of the RILAC. CSM A1 and CSM A2 are variable-frequency type resonators that have a frequency tunable range from 36.0 to 76.4 MHz. The other four resonators (CSM A3-A6) are

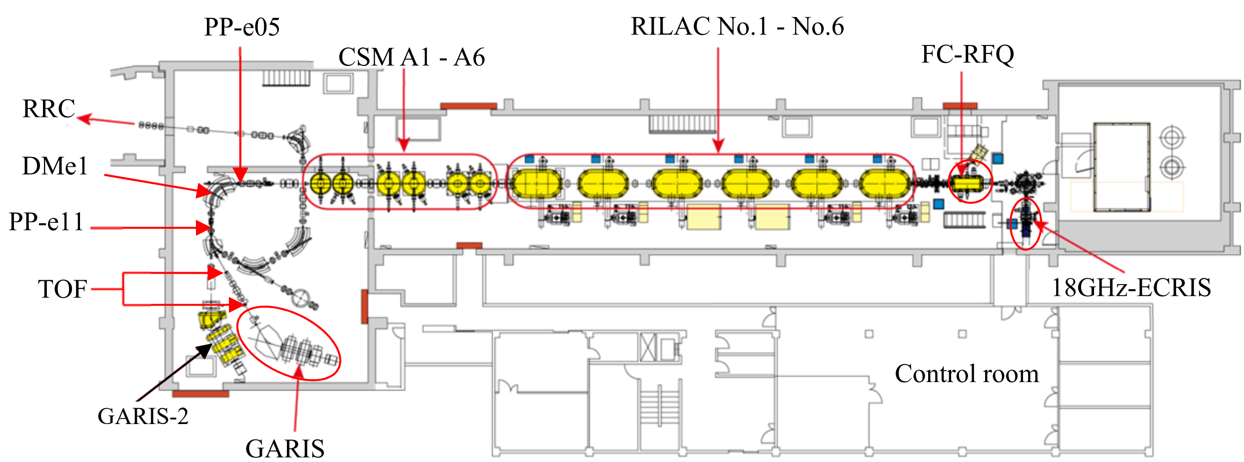

Figure 1: Layout of RILAC and GARIS.

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fixed-frequency type set at 75.5 MHz. Therefore, the RILAC operation with these accelerators improved the maximum beam energy to 6 MeV/nucleon [7], meeting the requirement of the gas-filled recoil ion separator (GARIS) [8]. The GARIS was moved from the E1 experiment room of the RRC to the experiment room of the RILAC in 2000. The layout of the RILAC and the GARIS is shown in Fig. 1.

RILAC OPERATION

Ion Source

The photograph of the 18GHz-ECRIS is shown in Fig. 2. The micro wave frequency is 18 GHz. The maximum magnetic field on-axis of the normal-conducting mirror coils is 1.4 T. The field strength on the surface of the permanent hexapole magnet is 1.4 T. ^{70}Zn (enrichment of 80-95%) vapor was generated from a ceramic rod (4×4×40 mm^3), which was inserted into the ECR plasma. By adjusting the relative position of the rod to the plasma, ^{70}Zn was charged into the plasma by heating. At the beginning, $^{70}Zn^{16+}$ was used, which subsequently changed to $^{70}Zn^{15+}$ to produce higher intensity beam without minding $^{14}N^{3+}$ being mixed in the projectiles. The beam current at the ion source was maintained above 19 eμA (1.2 pμA), and a periodic decrease of approximately 10% was always observed; the current loss was usually recovered by adjusting the rod position. The ion source could function very well, at least, for more than one month without the need to clean or exchange the ceramic rod. The consumption rate of ^{70}Zn was usually approximately 0.4 mg/h.

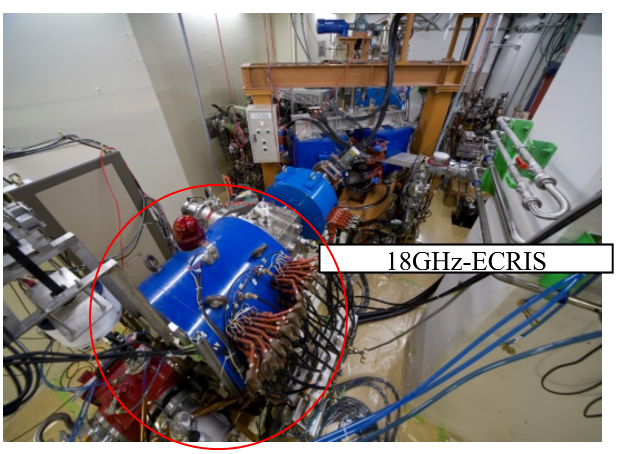

Figure 2: Photograph of 18GHz-ECRIS.

Accelerator

The photograph of the FC-RFQ resonator, the RILAC resonators, and the CSM resonators is shown in Fig. 3. The FC-RFQ resonator and the six RILAC resonators were operated at a frequency of 37.75 MHz. The six CSM resonators were operated at 75.5 MHz. The final energy of the ion beam could be varied continuously by tuning radiofrequency voltages and/or radiofrequency phases in the last two CSM resonators (CSM A5 and CSM A6). The RILAC had been providing the around 5 MeV/nucleon beam with an intensity of 0.4-0.7 pμA.

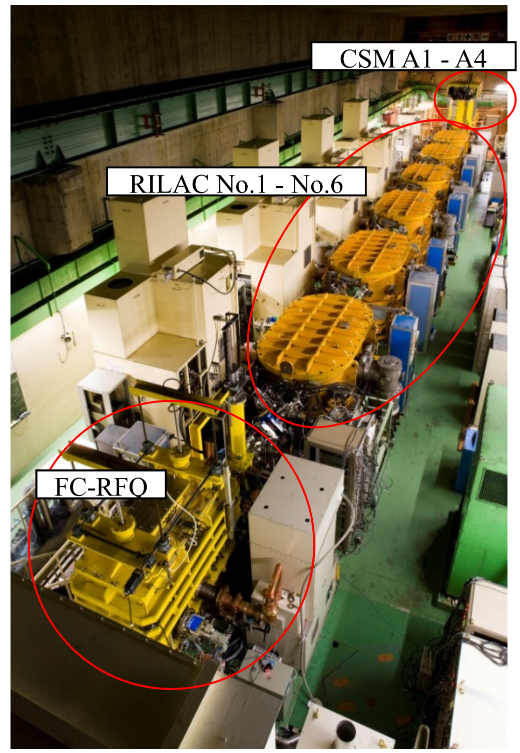

Figure 3: Photograph of FC-RFQ, RILAC, and CSM.

Beam Monitor

The ion beam energy was checked with a 90° analyzing magnet (DMe1) placed after CSM A6. Moreover, the time of flight (TOF) measurements were performed using two sets of beam phase picked-up that were installed along the straight beam line right in front of the GARIS target, as shown in Fig. 1. During the GARIS experiment, the signals from two sets of phase probes, denoted as PP-e05 and PP-e11 in Fig. 1, were analyzed, and the amplitude and phase of the third harmonic signal were always displayed. Therefore, the $^{70}Zn^{+15}$ beam intensity could be maintained at more than 0.5 pμA.

GARIS EXPERIMENT

Target

A plan view of the GARIS is shown in Fig. 4. The target was located right in front of the dipole magnet. The ^{209}Bi target [9], a metallic bismuth layer, which is such as a 450 μg/cm^2 thick, was attached to such as a 60 μg/cm^2 thick backing carbon foil. Several targets were mounted on the rotating wheel. The wheel was rotated during irra-

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diation at around 3000 rpm. To prevent the beam from hitting the frame, it was chopped with a duty cycle of 80% by a parallel-plate deflector placed after the 18GHz-ECRIS. A set of targets were replaced with new targets every week. After the experiment was started, the elastic scattering of the projectile on the target was observed continuously using a solid-state detector. The spectrum of them showed how the target was damaged and indicated when it should be changed.

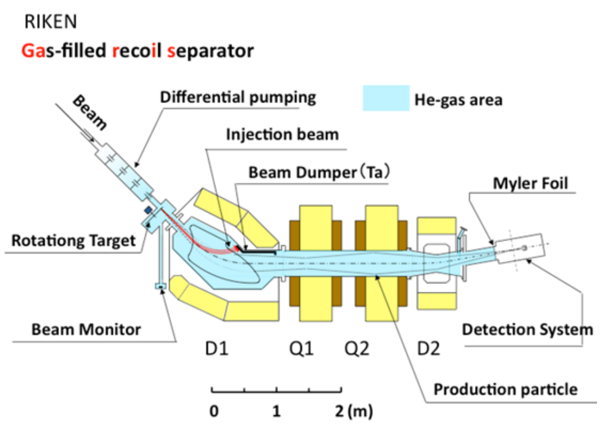

Figure 4: A plan view of GARIS.

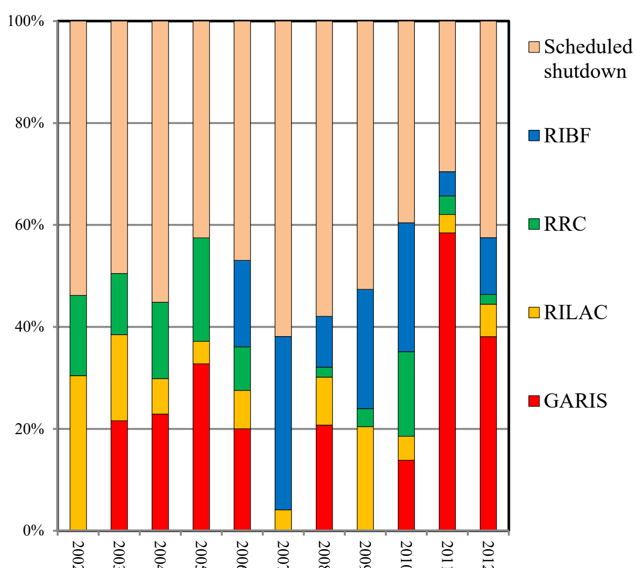

Figure 5: The operation statistics of RILAC from 2002 to 2012. In each year, 8760hr corresponds to 100%.

Experiment

The operation statistics of the RILAC from 2002 to 2012 are shown in Fig. 5. After the preliminary experiments for identification of the super-heavy element, the GARIS experiment, a search for the super-heavy element (Z=113), was carried out from September 2003 to August 2012, as shown by the red bars in Fig. 5. In 2007 and 2009, the GARIS experiment was not conducted because the RILAC was engaged in the commissioning of the RIBF, as shown by the blue bars in Fig. 5. In 2011, after the completion of construction of a new linac injector (RILAC2) for the RIBF [10], the GARIS experiment was conducted exclusively. The beam availability for this experiment was about 90%.

CONCLUSION

The GARIS experiment, a challenging search for the super-heavy element (Z=113), was conducted at the RIKEN Nishina Center for Accelerator-Based Science in the period from September 5, 2003 to August 18, 2012. The RILAC provided an around 5 MeV/nucleon ^{70}Zn beam with an intensity of around 0.6 pμA [11,12]. The net irradiation time was 553 days with a total beam dose of 1.351×10^{20}. As a result, three convincing candidate events for the isotope of the 113th element were successfully observed for the first time on July 23, 2004 [13], followed by the observations on April 2, 2005 [14] and finally August 12, 2012 [15].

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