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

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Abstract

In RIKEN Nishina center, the experiment on the super-heavy element (Z=113) search has been carried out since 2003. The RILAC has been supplying a ^{70}Zn beam with energies around 5.5MeV/nucleon. The beam intensity is required around 1 pμA on the target. So far two events for Z=113 have been observed during a net irradiation time of 10,345 hours (431 days) with a total dose 1.1 x 10^{20}. The heavy operation of RILAC will be reported.

INTRODUCTION

The project to construct a heavy-ion accelerator complex (linac-cyclotron) at RIKEN was started in 1974. The RIKEN variable-frequency Linac (RILAC) was completed as an injector in 1980 and the K560MeV RIKEN Ring Cyclotron (RRC) [1] was completed as a post-stripper accelerator in 1986. Then heavy-ion beams in the wide mass range became available and their energies were 10-50 MeV/nucleon.

From the beginning of the project, a challenging program of search for super-heavy elements (SHE) had been considered as the 1st-ranked experiment using these beams. For the SHE experiments, the apparatus of GARIS [2] (GAs filled Recoil Separator) was constructed in early and installed in the best position just after RRC. But GARIS experiment required very intense beams with energies lower than the original limit of RRC.

As the second injector of RRC, AVF cyclotron equipped with a 10GHz ECR ion source was lined up in 1989. Since the ECR works very powerful to produce an intense beam of lighter ions, the AVF-RRC scheme could provide an intense beam with high energy (50-135 MeV/nucleon). Simultaneously the need for the RI beams was remarkably enhanced and these beams were very actively used to produce RI beams for the nuclear physics research in a new field.

On the other hand, the efforts to improve the RILAC beam were continued. The pre-injector of RILAC (a dc high voltage terminal) was converted into a combination of a powerful 18GHz ECR ion source [3] and a very efficient low-β accelerator, that is, the frequency-tunable RFQ linac [4]. In addition, the RRC operation in the higher harmonics mode was established to lower the beam energy beyond the limit, and finally the RILAC-RRC operation was ready for the GARIS experiment. In fact, a 5.5MeV/nucleon Kr beam with high intensity was used several times, though its operation faced to much instability due to a long-pass inefficient acceleration.

A new project of the RI beam factory [5] was proposed to extend RI beams to heavy mass range. Since the project aimed principally the intense and heaviest-ion (uranium) beam, the CSM [6] (Charge-State Multiplier) was proposed as the original device to minimize the inevitable beam-loss during the charge stripping process

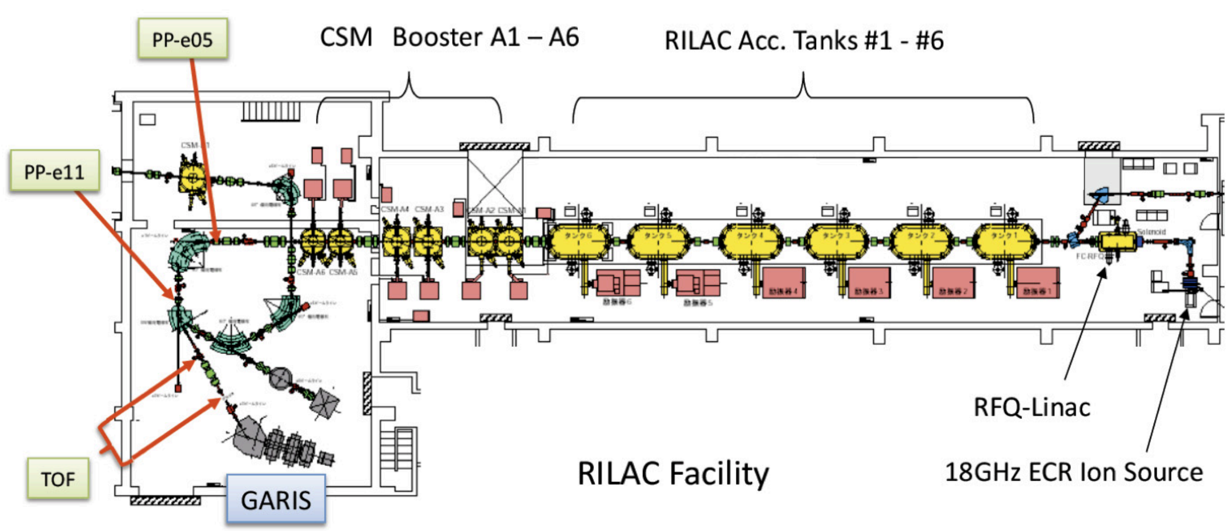

Figure 1: Layout of RILAC just after GARIS was installed, in 2002.

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after RILAC. The accelerators of the first stage of CSM were constructed in advance and installed from 2001 to 2002. The RILAC operation with these accelerators upgraded the beam energy reaching around 6MeV/nucleon [7], meeting the GARIS requirement.

On the other hand, as the design of the RIBF progressed, it turned out that the GARIS should be removed for a space of the beam line from RRC to the new RIBF building.

In these circumstances, it was decided that the GARIS was moved to the RILAC. After all, the GARIS was installed to the one of beam line of RILAC, as shown in Fig. 1.

BEAM PREPARATION

After preliminary experiments for the identification of SHE was carried out, the GARIS experiment, a search for the super-heavy element (Z113), was started in 2003. The requirements for projectiles are always such as 5 MeV/nucleon ^{70}Zn beam with the maximum intensity.

Ion Source

^{70}Zn ions are produced initially with the 18GHz ECR ion source shown in Fig. 2. Zn (enriched more than 90%) vapor is provided from a ceramic rod (4x4x40 mm), shown in Fig.3, which is inserted into the ECR plasma. By adjusting the relative position of the rod to the plasma, ^{70}Zn are charged into the plasma by heating. At the beginning, a charge-state of 16+ was used and afterward changed to 15+ for obtaining more beam without minding $^{14}N^{3+}$ being mixed in the projectiles.

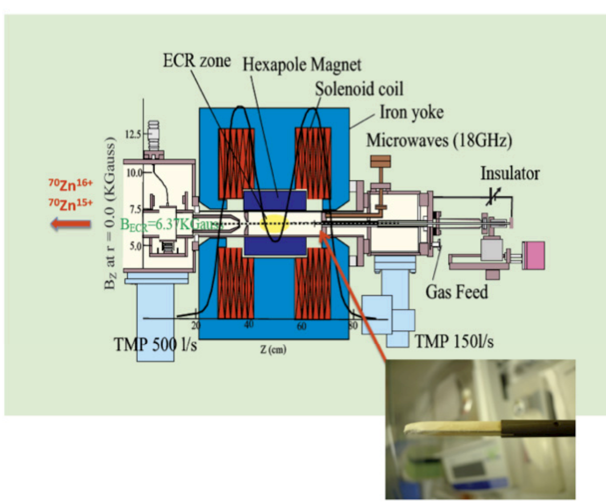

Figure 2: A cross-sectional view of 18GHz ECR Ion Source and Zn ceramic rod (photo).

Acceleration

The RILAC six cavities are operated at a frequency of 37.75 MHz, and the CSM six cavities at 75.5 MHz. The final energy of beam can be varied continuously by tuning rf voltages and/or rf phases in the last two CSM cavities. (A5 and/or A6).

Beam Monitor

The energy was checked with an analyzing magnet after RILAC, and the TOF measurements using two sets beam-phase picked-up installed along the straight beam line in just front of the GARIS target. Although the projectile energy is a very intrinsic parameter for this kind of cold-fusion reaction, the precise value of energy is not required, because of a relatively thick target as descried below.

During the experiment, the signals from two sets of phase probes (PP-e04 and PP-e11 in Fig. 1) are always analyzed and amplitude and phase of 3rd harmonic signal are always displayed. (see Fig. 5)

Target

A plan view of GARIS is shown in Fig. 3. The target is just in front of the dipole magnet. The ^{209}Bi target [8], 450g/cm^2 in thickness, is attached on the backing carbon foil (60g/cm^2). Several targets are mounted on the rotating wheel. The wheel is rotating around 3000 rpm. To prevent the beam from hitting the frame, the beam is chopped with a duty of 80% by the parallel-plate deflector just after the ion source.. A set of target was exchange into new every week.

After the experiment was started, the elastic scattering of the projectile on the target was observed continuously with a SSD. The spectrum of them tells how the target is damaged and when it should be changed.

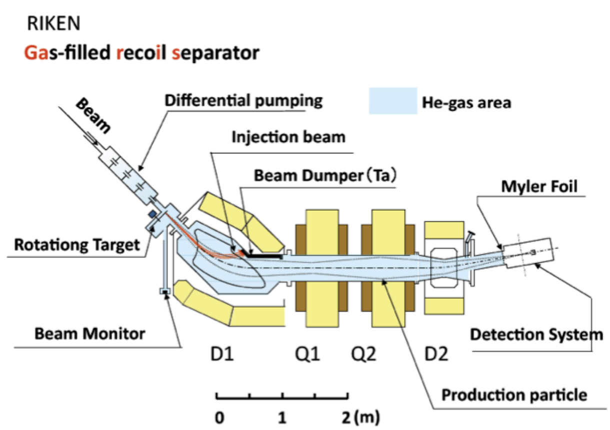

Figure 3: A plan view of GARIS.

GARIS EXPERIMENT

In Fig. 4, the operation statistics of RILAC from 2002 to 2011 are shown. In 2002, for all the year, RILAC was shutdown due to the construction work of the 1st stage of CSM. The GARIS experiment, a search for SHE (Z113), was started in 2003, as shown by red bars in Fig. 4. In 2007 and 2008, because RILAC was very busy for the commissioning of the RIBF (shown by blue bars in Fig. 4), the GARIS experiment was not conducted at all. In 2011, after a new injector, RILAC2 [9], for RIBF was completed, the GARIS experiment was conducted exclusively.

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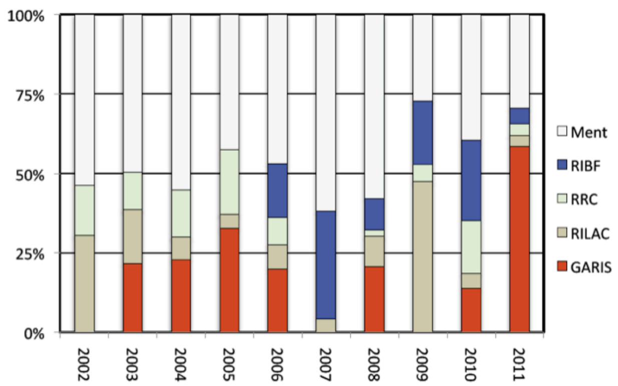

Figure 4: The operation statistics of RILAC, 2002 - 2011. In each year, 8760hr corresponds to 100%.

In these experiments, the RILAC had been proving the $^{70}Zn^{+15}$ beam with an intensity 0.4-0.7pμA, with energy around 5MeV/nucleon from the beginning to the present.

A typical example of operation is shown in Fig. 5. Two trend curves of amplitudes of 3rd harmonic signals from the two phase probes (PP-e05 and PP-e11), measured in the non-destructive way, are shown during one month from 14 March 2012 to 15 April 2012. Since these signals give a rough idea about beam intensity, the beam intensity can be seen more than 0.5pμA all the time. Some variations in the figure are due to the ion source. Though the beam current at the ion source was kept more than 19μA (1.2pμA), the periodic decrease about 10% were always observed, which were normally recovered by adjusting the rod position.

The ion source could work very well, at least, more than one month without cleaning or exchanging the ceramic rod. The consumption rate of ^{70}Zn was normally around 0.4mg/hr.

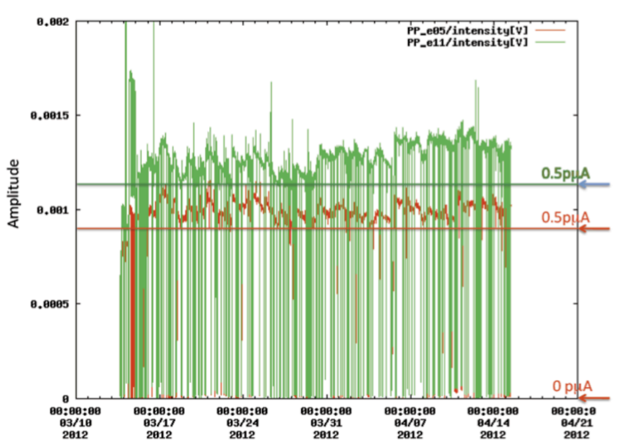

Figure 5: The 3rd harmonic signals from PP-e05(red curve) and PP–e11(green curve) measured from 14 March 2012 to 15 April 2012. Two calibration lines corresponding to 0.5pμA for each probe are shown. Red line is for e05, and green one for e11.

As shown in Fig. 5, the beam was interrupted frequently. Most of them were due to the interlock-signals originating from one of 13 RF systems (RFQ, six RILAC's, and six CSM's). But they were recovered very shortly, and the beam availability had been more than 95% over the period of this experiment, if the target-exchange times were excluded. The target system should be exchanged every one week (two or three hours were necessary for each exchange).

CONCLUSION

The GARIS experiment, a challenging search for the super-heavy element (Z113), was started at RILAC in 2003. The RILAC has been providing the 5 MeV/nucleon ^{70}Zn beam with intensity around 0.6pμA, for the duration more than 10,000hr. A total dose on the target has reached to 1.1×10^{20}. As the result, the two events have been successfully observed so far [10, 11]. The experiment will continue for a while to search eagerly for the next event.

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