

## PRESENT STATUS OF RIKEN HEAVY-ION LINAC

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### Abstract

The RIKEN heavy-ion linac (RILAC) has been used as an injector for the RIKEN RI-Beam Factory (RIBF) since 2006. Results of the acceleration tests of  $^{48}\text{Ca}$  and  $^{238}\text{U}$  performed recently in the RIBF are reported; we got 270 pA of  $^{48}\text{Ca}$  at an energy of 114 MeV/u after the Intermediate-stage Ring Cyclotron (IRC). On the other hand, the intensity of the uranium beam is still far below the design goal. Therefore, we are planning to install a superconducting ECR ion source, which is under construction, on the high-voltage platform of the Cockcroft-Walton pre-injector. It will be possible to test this new pre-injector in April 2009. A plan to construct an alternative injector for the RIBF, consisting of an ECR ion source, an RFQ, and three DTLs, is also illustrated, which aims at independent operation of the RIBF experiments and super-heavy element synthesis.

### INTRODUCTION

The RIKEN heavy-ion linac (RILAC), which has been operated since 1981, accelerates various kinds of ions by changing the rf frequency from 18 to 38 MHz in the continuous-wave (cw) mode. The voltage gain is 16 MV in the whole frequency range, and the acceptable mass-to-charge ratio ( $m/q$ ) of the ions ranges from 5.5 at 38 MHz to 25 at 18 MHz. The original Cockcroft-Walton pre-injector to the RILAC was replaced by an RFQ pre-injector equipped with an 18-GHz ECR ion source in 1996.

In 2001, a booster linac for the RILAC was constructed, which consists of two variable-frequency resonators and four fixed-frequency resonators; the maximum energy of

the RILAC facility has been increased to 5.8 MeV/u [1]. By using the high-intensity beams from the booster, experimental study has been started for searching super-heavy elements (SHE) since 2002. The beam time provided for the SHE experiments so far has exceeded 10,000 hours. The present layout of the RILAC facility is illustrated in Fig. 1.

On the other hand, commissioning of the RI-Beam Factory (RIBF) [2] started in 2006 [3], where the RILAC is used as an injector. Results of the acceleration tests performed recently in the RIBF are given in the next section, as well as a brief introduction of the RIBF accelerators.

### RILAC AS RIBF INJECTOR

Figure 2 shows a conceptual layout of the accelerator chain of the RIBF, which consists of the RILAC injector and four booster cyclotrons (RRC, fRC, IRC and SRC) in a cascade. The fRC is exclusively used for very heavy ions such as uranium and xenon, where the rf frequency of the RILAC is fixed to 18.25 MHz and the beam energy at the exit of the SRC is 345 MeV/u. For medium-mass ions such as calcium and krypton, the fRC is skipped; it is possible to operate the accelerator chain in the variable-energy mode. There is another acceleration mode in the RIBF, where the AVF cyclotron (K70 MeV) is used as an injector for the acceleration of light ions such as deuteron and carbon.

In this year, acceleration tests were performed up to the exit of the IRC using  $^{48}\text{Ca}$  and  $^{238}\text{U}$  beams.

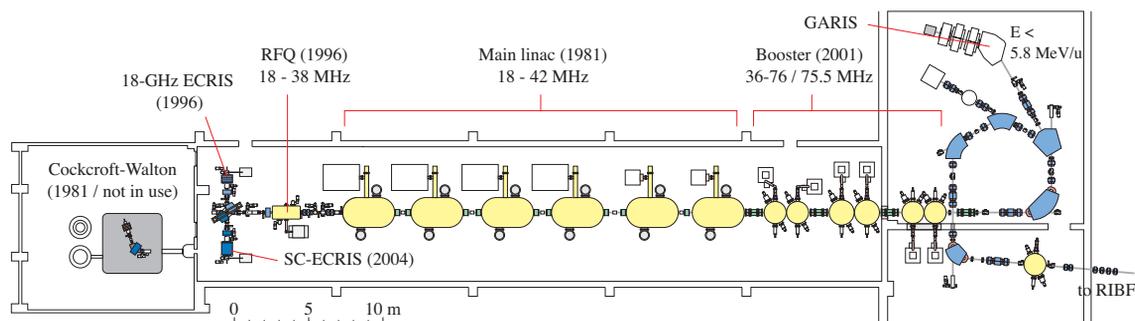


Figure 1: Plan view of the RIKEN Heavy-Ion Linac (RILAC).

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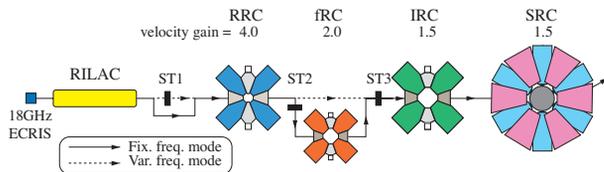


Figure 2: Conceptual layout of the accelerator chain of the RI-Beam Factory (RIBF). The RILAC injector is followed by the booster cyclotrons: RRC (RIKEN Ring Cyclotron, K540 MeV), fRC (fixed-frequency Ring Cyclotron, K570 MeV), IRC (Intermediate-stage Ring Cyclotron, K980 MeV), and SRC (Superconducting Ring Cyclotron, K2600 MeV). The charge strippers are indicated by ST1 - ST3.

### Calcium Acceleration

The acceleration test was carried out in June using the  $^{48}\text{Ca}^{10+}$  ions from the 18-GHz ECR ion source. The rf frequency of the RILAC was 36.5 MHz, which corresponds to the beam energy of 114 MeV/u at the exit of the IRC.

The calcium ions were generated from a  $^{48}\text{CaO}$  rod with support gas of  $\text{O}_2$  in the ion source. At the extraction voltage of 16.0 kV, the beam current was 40 e $\mu\text{A}$  at the first Faraday cup after the analyzing magnet. The charge state was changed into 17+ with a carbon foil of 40  $\mu\text{g}/\text{cm}^2$  at the beam energy of 2.7 MeV/u after passing through the RILAC. The transmission efficiency through the RILAC was 53 % and the stripping efficiency was 35 %. We used another stripper of carbon foil of 1 mg/cm $^2$  after the RRC, which fully stripped the calcium ions with an efficiency of 87 % at the energy of 46 MeV/u. Finally, we got 270 pA at the exit of the IRC, corresponding to  $1.6 \times 10^{12}$  pps. In the test, we used a beam attenuator of 50 % after the RILAC in order to keep the beam current below 300 pA, which is the maximum intensity allowed by the operating license.

The rf system of the RILAC and the charge strippers were stable throughout the beam study. We are planning to accelerate the calcium beam through the SRC in November 2008.

### Uranium Acceleration

We performed the test using the  $^{238}\text{U}^{35+}$  ions from the 18-GHz ECR ion source in May and July. The rf frequency of the RILAC was 18.25 MHz, corresponding to the beam energy of 114 MeV/u at the exit of the IRC.

We used a rod of metallic uranium with support gas of helium in the ion source. The beam current at the first Faraday cup was 2 e $\mu\text{A}$  at the extraction voltage of 5.7 kV, and the transmission efficiency through the RILAC was 30 %. The beam was injected directly into the RRC without charge stripping. As shown in Fig. 2, the extracted beam from the RRC went through two charge strippers placed on both sides of the fRC. The final beam current at the exit of the IRC was 0.35 pA, which corresponds to  $2 \times 10^9$  pps.

### Proton and Ion Accelerators and Applications

One of the reasons for the low transmission efficiency through the RILAC comes from the mismatch of the emittance of the output beam from the ion source to the acceptance of the RFQ. We also found the vacuum pressure in the low energy part of the RILAC is not sufficient for the highly charged ions like  $^{238}\text{U}^{35+}$ .

During the acceleration, the rf voltage, rf phase and beam phase were measured with a monitoring system which has been newly developed based on lock-in amplifiers [4]. The measured data shows that the rf voltage and phase of the first four resonators of the RILAC sometimes moved out of the required range of  $\pm 0.1$  % and  $\pm 0.1$   $^\circ$ , respectively, and the beam phase in the following accelerators was influenced by these fluctuations. The origin of the variation of the rf systems is under investigation.

### NEW PRE-INJECTOR FOR RILAC

From the operational status mentioned in the previous section, it is clear that we need more beams from the ion source, especially for the uranium acceleration. To increase the intensity, we are constructing a new superconducting ECR ion source capable of the microwave frequency of 28 GHz [5]. It is designed to have as large plasma volume as 1100 cm $^3$ .

The superconducting coil system of this ion source consists of six solenoids and a set of sextupole coils to make a confinement magnetic field. The maximum axial magnetic fields are 3.8 T at the rf-injection side and 2.2 T at the beam-extraction side. The inner solenoid coils are used for introducing a flat magnetic field region between the mirrors. The coils use a NbTi-copper conductor and are bath-cooled in liquid helium. The superconducting coils were already assembled and the excitation test is under progress. After the test, the assembling of the cryostat for these superconducting coils will be started. The ion source will be brought to RIKEN in December 2008.

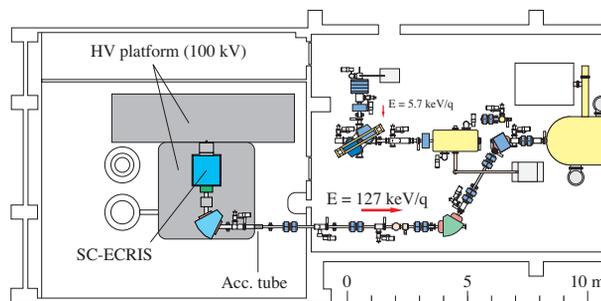


Figure 3: Configuration of the new pre-injector for the RILAC.

Low frequency operation of the RILAC at 18.25 MHz requires, however, such low extraction voltage as 5.7 kV in the  $^{238}\text{U}^{35+}$  acceleration. High power beams of 5.7 kV surely grow up due to their space charge forces in the low-energy transport line. On the other hand, RILAC requires such low injection energy as 127 kV. Therefore, we de-

cided to put the superconducting ECR ion source as well as the analyzing magnet [6] on the high-voltage terminal of the original Cockcroft-Walton pre-injector so that extracted beam from the source can be directly injected to the RILAC, skipping the RFQ, as shown in Fig. 3. We expect that the emittance growth can be suppressed in the beam transport system.

The design study of the medium-energy beam transport system is under progress, for which we plan to use recycled magnets. The original power generator of 50 kVA will be used for the devices on the platform as well as an additional power transformer of 50 kVA. We expect to start the test of the superconducting ECR ion source in April 2009.

## NEW LINAC INJECTOR FOR RIBF

The recent success in the synthesis of SHE [7] using the GARIS (gas-filled recoil ion separator) system in the RILAC facility strongly encourages us to further pursue the search for the heavier elements and to more extensively study physical and chemical properties of SHEs. This compels us to provide a longer machine time for these experiments. However, the SHE research and RIBF research conflict with each other, because both of them use the RILAC.

Therefore, a new additional injector linac to the RRC has been proposed [8], which will make it possible to conduct the SHE and RIBF research studies independently. The new injector, which will be placed in the AVF-cyclotron vault, will be used exclusively to produce primary beams of 345 MeV/u from the SRC.

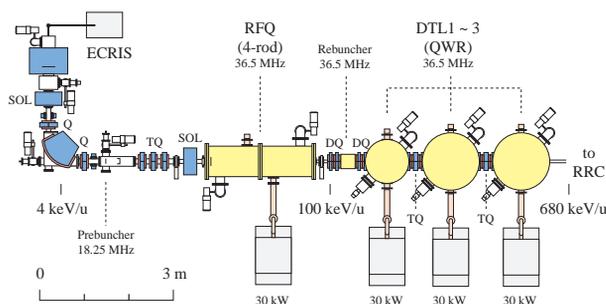


Figure 4: Schematic layout of the new injector.

The injector is designed to accelerate ions with a mass-to-charge ratio of 7, aiming at heavy ions such as  $^{136}\text{Xe}^{20+}$  and  $^{238}\text{U}^{35+}$ , up to an energy of 680 keV/u in the cw mode. It consists of an ECR ion source, a low-energy beam transport system including a pre-buncher, an RFQ linac based on the four-rod structure, and three DTLs based on the quarter-wavelength resonator (QWR), as shown in Fig. 4. The rf resonators are supposed to be operated at a fixed rf frequency of 36.5 MHz. Strong quadrupole magnets will be placed into the beam line between the rf resonators. The output beam will be injected to the RRC without charge stripping.

In November 2007, an RFQ system including two post accelerators and their rf amplifiers was transferred to

RIKEN through the courtesy of Kyoto University, as shown in Fig. 5 This RFQ system was originally developed by Nissin Electric Co., Ltd. in 1993. [9] Since the termination of its acceleration tests in the company, the RFQ system has been maintained in the Advanced Research Center for Beam Science, Kyoto University for several years.



Figure 5: Photograph of the four-rod RFQ settled in the RIBF building for high power tests.

The RFQ linac, based on a four-rod structure, accelerates heavy ions of  $m/q = 16$  up to an energy of 84 keV/u in the cw mode with an rf frequency of 33.3 MHz. When the RFQ resonator is modified so as to have a resonant frequency of 36.5 MHz, it becomes possible to accelerate ions of  $m/q = 7$  to 100 keV/u, which is the required energy in the new injector system, without changing the vane electrodes.

We plan to perform high-power tests of the RFQ resonator at the original frequency of 33.3 MHz in this year, after reassembling the rf amplifier.

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