PERFORMANCE OF NEW INJECTOR RILAC2 FOR RIKEN RI-BEAM FACTORY

N. Sakamoto*, M. Fujimaki, N. Fukunishi, Y. Higurashi, O. Kamigaito,
H. Okuno, K. Suda, T. Watanabe, Y. Watanabe, K. Yamada,
Nishina Center, RIKEN, Wako, Japan
R. Koyama, SHI Accelerator Service Ltd., Tokyo

Abstract

New injector called RILAC2 [1] was designed and constructed to provide intense uranium beams with A/q≈7 with an energy of 0.67 MeV/u which are injected to the succeeding ring cyclotron, RIKEN Ring Cyclotron, called RRC [2]. After the last LINAC conference where the commissioning of the RILAC2 was reported [3], some modifications and improvements with RILAC2 have been made aiming at stable operation. Recently, transmission efficiency and stability of the beams have been improved and the average beam current more than 20 pnA for uranium 345 MeV/u acceleration has been realized. In this paper the modifications and improvements of the RILAC2 together with the present performance are reported.

ACCELERATION OF U, Xe BEAMS AT RI-BEAM FACTORY

RIBF Accelerators

The layout of the RIBF is shown in Fig.1. The accelerator complex consists of cascading four ring cyclotrons and three injectors [4]. The RIBF provides the world's most intense uranium beams with an energy of 345 MeV/u at the moment. Though the goal intensity is 1 pμA the beam currents of very heavy ions like uranium and xenon are still low. The mission of the new injector project is to raise the situation of low intensities. For the RILAC2, as an injector, beam quality is also required to match to the acceptance of the RRC so as to minimize beam losses at the succeeding cyclotrons.

Figure 1: Schematic of RIBF.

RILAC2

The schematic of the RILAC2 and the RRC is shown in Fig.2. The main accelerator part of the RILAC2 consists of an RFQ and three drift tube linacs which operate in c.w. mode. The RFQ is based on the four-rod structure and the cavities of the DTLs are based on quarter wave length structure (QWR) which operate at a frequency of 36.5 MHz i.e. second harmonic of the beam frequency. The performance of the cavities has been reported in Ref. [3] and their amplitude and phase stabilities of the rf field satisfy a requirement of $|\Delta V/V| \leq \pm 0.1\%$ and $|\Delta\phi| \leq 0.1°$, respectively. Intense uranium beams with mass to charge ratio of 7 ($^{238}U^{35+}$) are produced by a superconducting ECR-ion-source (SC-ECRIS) [5] which utilizes superconducting coils for mirror and sextupole field and injection of two different frequency power sources of 18 GHz klystron and 28 GHz gyrotron. The energy of the extracted beams is 3.24 keV/u. The d.c. beams from the ion source are bunched by pre-buncher that is operated at a frequency of 18.25 MHz and injected into the RFQ and the DTLs and are accelerated to 0.67 MeV/u. The amount of the unbunched part of the beam is about 20%. The beams provided by RILAC2 are bunched and compressed again using a double-rebuncher system (B7 and S6 rebuncher) into the phase acceptance of the succeeding booster cyclotron RRC which accelerates the uranium ions to 11 MeV/u. Since the RRC is not equipped with a flat-top acceleration system, its phase acceptance is very small. According to the criterion in Ref. [6], the resoluton of the energy gain by the cyclotron rf cavity is required to be better than 10% of the inverse of the turn number that is 250 in this case to have a sufficient turn separation. This means that the injection beam phase stays within ±0.24 ns with an rf frequency of 18.25 MHz. For cyclotrons, a beam energy deviation causes a radial shift of the beam and results in sizable beam loss at the extraction device.

Beam Service

The beam services utilizing RILAC2 since the last LINAC conference are listed in Table 1 together with logged beam currents at U10(the exit of the ion source), S71(before injection into the RRC), A02a (extracted from the RRC), and G01 located at the exit of the final-stage-booster called SRC [7] when the maximum beam current at the G01 was obtained. Owing to the K-value upgrade of the fRC [8], the installation of the new gas stripper [9] and the rotating beryllium disk stripper [10], the acceleration efficiency from A02a to G01 has been greatly improved.

* nsakamot@ribf.riken.jp

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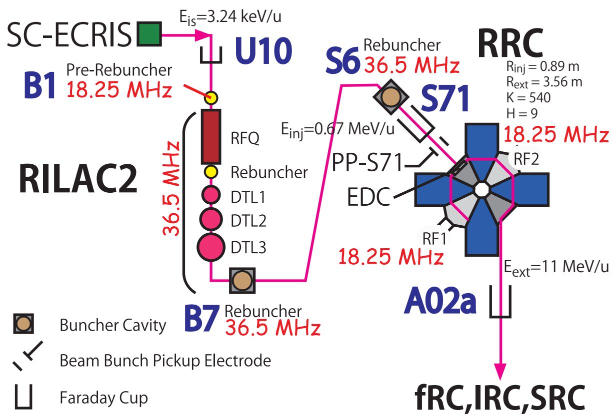

Figure 2: Layout of RILAC2 and RRC.

Table 1: Beam current logged when the maximum beam current at FC-G01 was recorded during beam service time. FC-G01 measures the beam current extracted the superconducting ring cyclotron (SRC).

Beam Service (DD/MM/YY)	Nuclei	U10 pμA	S71 pμA	A02a* pμA	G01 pnA
04/11/12~18/12/12	^{238}U	2.8	1.7	1.7	15
28/04/13~27/05/13	^{238}U	1.3	0.94	1.0	24
08/06/13~01/07/13	^{124}Xe	2.9	2.2	2.2	38
23/03/14~13/05/14	^{238}U	2.9	2.1	2.2	25

*Note that the FC-A02a seems to overestimate the beam current by a factor of 1.3 based on the measured results for the bunching efficiency of 80% and the extraction efficiency of ≥90%.

During the uranium beam service time at the end of 2012, a hardware failure concerning the RRC occurred. As shown in Fig. 3, a septum electrode of the electric deflection channel (EDC) which deflects the circulating beam to the extraction orbit got seriously damaged.

The beam current of 1 pμA with an energy of 11 MeV/u corresponds to the beam power of 2.6 kW. For the RRC, since the septum electrode of the EDC withstands the heat load of less than 300 W, so that extraction efficiency must be better than 88 %.

Figure 3: Hardware failure of the electrodes of the electric deflection channel (EDC) of the RRC.

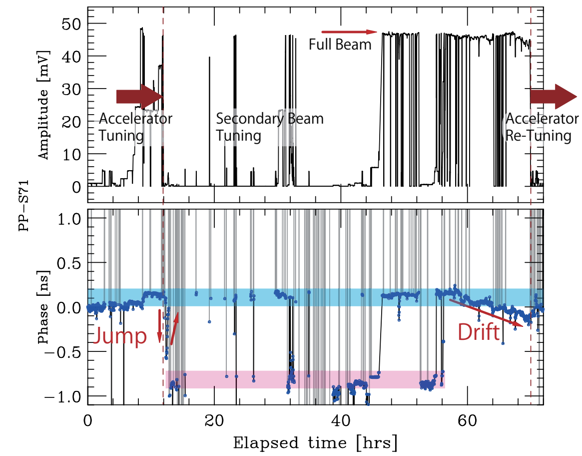

Figure 4: Measured intensity and timing of the pick up signal of the uranium beams at S71 were plotted for 72 hours. Blue and red bands indicate width of ±0.1 ns.

One of the reasons to make beam losses at EDC was considered as the drift of the injection timing of the beams. The beam injection timing was continuously monitored with a pickup electrode installed at S71 (see Fig.4). The stability of the injection beam phase was insufficient in comparison with the criterion mentioned above. In this situation, it was very important to fix sources of the observed instability and tune manually, with great care, the devices causing the instability to maintain the well-tuned injection condition. However, it was too difficult for the operators to maintain the good injection condition without a beam interlock system to prevent mis-operation. Hence, we experienced a partial damage on the EDC, interrupted the beam service and tuned the accelerators again to reduce the beam loss only 60 hours later the completion of the first accelerator tuning. Unfortunately, the severe condition continued and finally we got a fatal damage on the EDC 10 days later. The beam service was aborted to replace the damaged EDC with its spare parts. After this event we decided to introduce a beam interlock system of the EDC which has been installed to the SRC.

HARDWARE R&D

In these two years, we made efforts to make the accelerated beams much more stable. Hardware R&D made are described below.

28GHz-ECRIS

Recent developments of the SC-ECRIS are as follows.

- RF injection with additional rf power of different frequency enables us to make the B_{min} lower so that the ECR plasma became much more stable [11].
- It has been succeeded to reduce the sputtering voltage from 5.5 kV to 2 kV. As a result, consumption rate of the sputtering material was minimized [12]. This is helpful to make long-term operation.

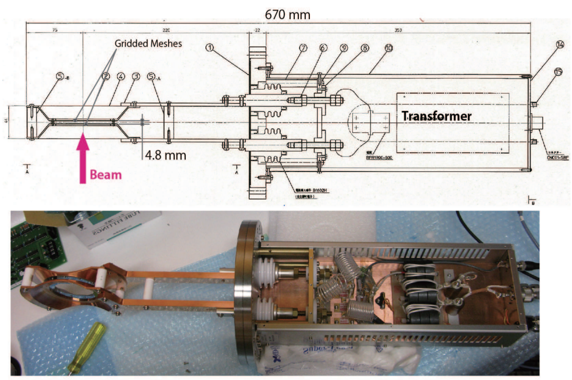

Figure 5: Drawing and photo of the new pre-buncher.

- Parameters of the ion source operation was studied to minimize the effect on X-ray heat load which causes destruction of insulation materials in the cryostat chamber.
- It was found that the transverse emittance of the extracted uranium beams fairly depends on the magnetic field distribution [13].

Pre-Buncher

A new gridded single-gap buncher (Fig.5) was installed replacing the drift tube type buncher (DTB). The gap between the pair of meshed grids is 4.8 mm while the $\beta\lambda/2$ is 22 mm. In comparison with the DTB, the transit time factor and an uniformity of the rf field are better. The new buncher is capable of the multi-harmonic operation so that saw-tooth shape rf field is available in stead of sinusoidal wave shape. To place the new buncher as close as possible to the RFQ, modification of the impedance of the transformer part from 200 Ω to 450 Ω was performed so as to have a peak gap voltage of 0.71 kV with a power dissipation of 560 W. The gridded mesh made of molybden has an effective opening ratio of about 95‰. Installation was successfully completed this year and it worked stably during the beam service from March 2014. There found no damage on the meshes after one month beam service.

Other Issues

- A beam interlock system monitoring the temperature rise of the EDC septum electrode of the RRC has been installed to keep the heat load due the beam loss below 300 W.
- Some parts of the RILAC2 and the transport line to the RRC had vacuum pressure above 1e-5 Pa. We made efforts to find out where the leak occurs and tried to fix it by adding extra pumps and/or replacing sealing parts.
- The operation parameters of DTLs were studied to optimize the transmission efficiency of the RRC by changing the injection energy. And also it is tried to optimize the double rebuncher system.

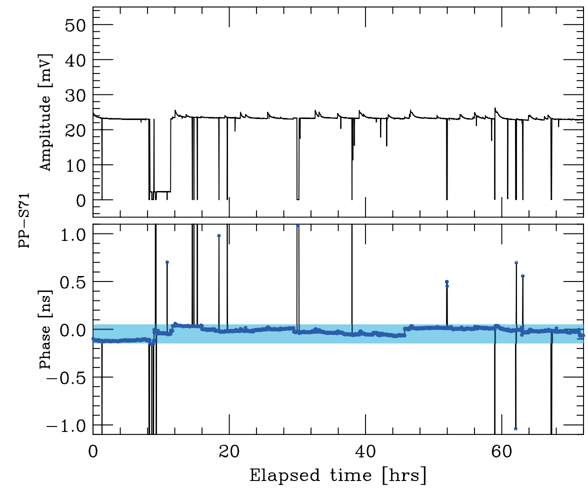

Figure 6: Measured time-of-flight at S71 for 72 hours during the beam service time of 2014.

PRESENT PERFORMANCE

The timing of the uranium beams injected to the RRC measured during the beam service time of this year is shown in Fig.6. As shown in the figure, the phase stability of the uranium beam has been successfully improved. Owing to the improved stability of the beams accelerated by RILAC2 and the other improvement mentioned above, the averaged beam current more than 20 pnA for uranium 345 MeV/u acceleration has been realized. The average current of 20 pnA is 1.6 times larger than that during the beam service time of 04/11/12~18/12/12. Though the RFQ and the DTLs look stable enough, further improvement of the beam phase stability, i.e. better than 0.1 ns, might require much more long-term stability.

SUMMARY & PLANS

The RILAC2 is capable to accelerate more than 2 pμA uranium. Though the beam quality including the stability was improved, it looks close to the capability of the acceptance of the RRC. Aiming to realize further improvement of the transmission efficiency and stable operation, we plan to introduce flattop system to the RRC [14]. The third harmonic rf is added to the fundamental rf with a deceleration phase to make the acceptance as large as ±16°. The large phase acceptance is expected to allow a phase drift of the injection beams to some extent.

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REFERENCES

[1] K. Suda et al., Nuc. Instrum. Methods **A277**(2013)55.

[2] Y. Yano, "RECENT ACHIEVEMENTS AT THE RIKEN RING CYCLOTRON", I-21, CYCLOTRONS'92, Vancouver, Canada (1992).

[3] N. Sakamoto et al., "COMMISSIONING OF A NEW INJECTOR FOR THE RI-BEAM FACTORY" MO3A02, LINAC'12, Tel Aviv, Israel (2014).

[4] Y. Yano, Nucl. Instr. Meth.**B261**(2007)1009.

[5] T. Nakagawa et al., Rev. Sci. Instrum. **81**,02A320(2010).; Y. Higurashi et al., Rev. Sci. Instrum. **83**, 02A308(2012).

[6] W. Joho, "Tolerances for the SIN RING-CYCLOTRON", SIN REPORT TM-11-4(1968).

[7] H. Okuno et al., IEEE Trans. Appl. Supercond., **17**(2007)1063.

[8] N. Fukunishi et al., "ACCELARATION OF INTENSE HEAVY ION BEAMS IN RIBF CASCADED-CYCLOTRONS", MO1PB01, CYCLOTRONS'13, Vancouver, BC, Canada (2013).

[9] H. Imao et al., "R&D OF HELIUM GAS STRIPPER FOR INTENSE URANIUM BEAMS", TU3PB03, CYCLOTRONS'13, Vancouver, BC, Canada (2013).

[10] H. Hasebe et al., RIKEN Accel. Prog. Rep. **46**(2013).

[11] Y. Higurashi et al., Rev. Sci. Instrum. **85**, 02A953(2014).

[12] Y. Higurashi et al., "RECENT DEVELOPMENT OF RIKEN 28 GHZ ECRIS", to be published, ECRIS'14, Nizhny Novgorod, Russia (2014).

[13] Y. Higurashi et al., "EMITTANCE MEASUREMENT FOR RIKEN 28GHZ SC-ECRIS", to be published, ECRIS'14, Nizhny Novgorod, Russia (2014).

[14] S. Lukas et al., "STUDY OF NEW FLAT-TOP RESONATOR FOR THE RIKEN RING CYCLOTRON", FP50, the 3rd Annual Meeting of Particle Accelerator Society of Japan, Sendai Japan (2006).

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