ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-MOPRI082

ACCELERATION OF HIGH-INTENSITY HEAVY-ION BEAMS AT RIKEN RI BEAM FACTORY

O. Kamigaito*, T. Dantsuka, M. Fujimaki, N. Fukunishi, H. Hasebe, Y. Higurashi, E. Ikezawa,
H. Imao, M. Kase, M. Kidera, M. Komiyama, H. Kuboki†, K. Kumagai, T. Maie,
T. Nagatomo, T. Nakagawa, M. Nakamura, J. Ohnishi, H. Okuno, K. Ozeki,
N. Sakamoto, K. Suda, S. Watanabe, T. Watanabe, Y. Watanabe, K. Yamada, H. Yamasawa
RIKEN Nishina Center for Accelerator-Based Science, Wako-shi, Saitama 351-0198, Japan

Abstract

Recent efforts concerning the RIBF accelerators in RIKEN have been directed towards achieving higher beam intensities of very heavy ions such as uranium and xenon. As presented in the last IPAC conference in 2013, the intensities of these ion beams have significantly improved due to the construction of a new injector, RILAC2, which is equipped with a 28-GHz superconducting ECR ion source, the development of a helium gas stripper, and upgrading of the bending power of the fRC. In this light, this paper presents the subsequent upgrade programs carried out in the last couple of years, such as developments of a new air stripper for xenon beams and a micro-oven for metallic ions. The current performance level of the RIBF accelerator complex, as well as a future plan to further increase the beam intensities, are also presented.

INTRODUCTION

The Radioactive Isotope Beam Factory (RIBF) [1, 2] at RIKEN is aimed at generating the most intense RI beams over the whole range of atomic masses. The primary beams of very heavy ions are powerful tools to produce rare isotopes far from the stability line. For example, a uranium beam is used to effectively generate a large number of very exotic nuclei in the medium mass region, and uranium beams are required by about 30% of the approved programs at RIBF. In addition, the ^{124}Xe beam is most suited to producing nuclei of ^{100}Sn and its atomic-mass vicinity.

As presented in the last IPAC conference in 2013 [3], the intensities of these ion beams, as well as the stability of beam acceleration, have been significantly improved due to the construction of a new injector (RILAC2) equipped with a 28-GHz superconducting ECR ion source, the development of a helium gas stripper and upgrading of the bending power of the fRC. Figure 1 shows the currently operational accelerator setup at the RIBF.

This paper presents recent R&D efforts that have been carried out in the last couple of years in the light of further enhancing the accelerator performance.

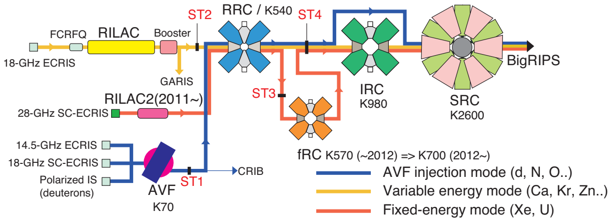

Figure 1: Accelerator chain of RIBF at RIKEN. The three injectors—the AVF cyclotron, RILAC, and RILAC2—are followed by the four booster cyclotrons—RRC (RIKEN Ring Cyclotron), fRC (fixed-frequency Ring Cyclotron), IRC (Intermediate-stage Ring Cyclotron), and SRC (Superconducting Ring Cyclotron). The K-values of the cyclotrons are indicated in the figure in MeV. The charge strippers are indicated by labels in the red text (ST1–ST4).

RECENT UPGRADES

Charge Stripper for Xenon Beam

The increased beam intensity of ^{124}Xe has led to the problem of the reduced lifetime of the second-stage charge stripper. The availability of the accelerator during beam time in the spring of 2012 deteriorated because the carbon foils for the second stripper had to be changed almost every 8 h. Therefore, we developed a new gas stripper system using air as the stripping material. The required thickness for this stripper is significantly larger because of the high energy of the xenon ions to be stripped. In addition, this stripper works as an energy degrader to match the beam speed to be accepted by the subsequent cyclotron, the IRC. Actually, this stripper is thirty times as thick as the first-stage stripper developed for uranium beams in 2012.

Figure 2 shows the new second stripper installed in the E1 room of the RIBF in 2013. The stripper employs 17 vacuum pumps to set up a differential pumping system with five stages, which reduces the pressure of the target cell at 25 kPa down to the beam line vacuum of 10^{-5} Pa over a length of 1 m. We successfully achieved the required thickness of 20 mg/cm^2 by injecting compressed air at the rate of 400 STL/min into the target cell with a length of 51 cm.

This air stripper was commissioned during beam time in June 2013. We also used nitrogen gas (0.2 mg/cm^2) as the first-stage stripper at 11 MeV/u during this beam time; this was the first success of the acceleration only with gas strippers at the RIBF. The beam availability has been signif-

---

[*] kamigait@riken.jp

[†] Present Address: High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305 -0801, Japan

icantly improved due to the use of these downtime-free gas strippers, as mentioned below.

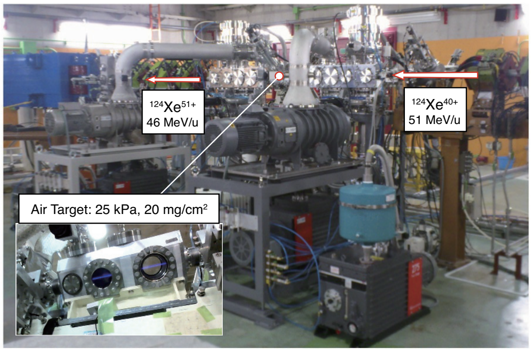

Figure 2: Air stripper for xenon beams at 50 MeV/u [4].

ECR Ion Source

One of the crucial requirements for ion sources in the RIBF is the provision of a continuous beam supply over a long period of one month or more. A sputtering method has been used for the uranium beam production, since large amounts of uranium material can be held in the ion source chamber. Owing to the various R&D efforts since the construction, it is now possible to extract 180 eμA of U^{35+} ions with an input rf power of 4 kW [5]. Moreover, U^{35+} beams were extracted at an average current of 90 eμA for more than one month during beam time in 2013, as shown in Fig. 3 [6].

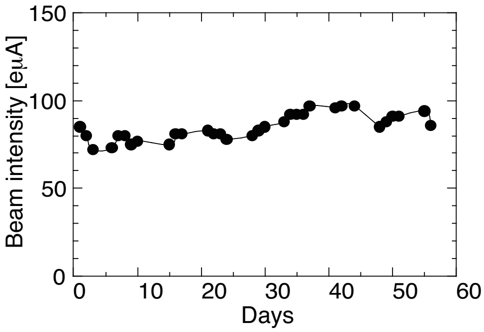

Figure 3: Beam intensity of U^{35+} from the SC-ECRIS during RIBF beam time in 2013 [6].

On the other hand, we are also making efforts to enhance the intensity of ^{48}Ca beams from the 18-GHz ECR ion source at the RILAC for effective production of medium-mass rare isotope beams. We have long used CaO rods for the production of calcium ions. However, the beam intensity obtained with these rods was not very stable, and we had to tune the ion source often to ensure the constant beam currents. In order to overcome this problem, we recently developed a micro-oven for generating calcium beams. The oven includes a crucible made of stainless steel, which has an inner volume of 0.7 cm^3, that provides metallic calcium ions through reduction of CaO with Al powder in the ion source; the CaO material is prepared beforehand through reduction of CaCO$_3$ at 900 °C in the oven prior to the insertion to the ion source. After several tests, we succeeded in the generation of a high-intensity calcium beam, as can be observed from Fig. 4. The beam intensity was very stable when we positioned a hot liner in the ion source; the consumption rate was as small as 0.44 mg/h for a current of 30 eμA of Ca^{11+} [7].

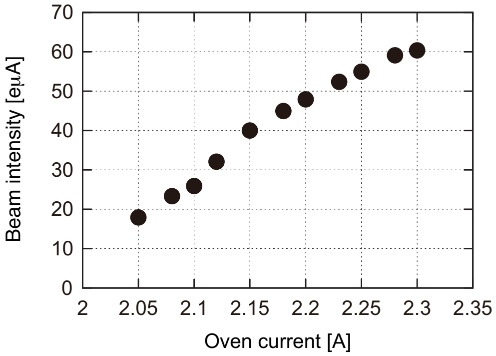

Figure 4: Beam intensity of Ca^{11+} from the 18-GHz ECRIS equipped with a micro-oven [7]. The supplied RF power was 400 W.

Replacement of RRC Main Coils

The stability of the RRC, which has been operating since 1986, is critical to the functioning of the RIBF, since all the beams pass through the RRC. However, the RRC components have undergone wear and tear, which cannot guarantee stable operation. Actually, in 2012, an interlayer short occurred in one of the main coils of one of the four sector magnets; this coil was also previously subjected to such a short in 1999, and the coil repair has only been temporary thus far. We attempted to implement temporary measures to address this shorting issue, but the stability of the magnetic field did not recover completely. Therefore, we replaced the two main coils of the sector magnet by new ones. It was a difficult task to disassemble the sector magnet in the limited space, cut many cooling pipes of the trim coils, replace the coils, and reassemble them. Finally, after two months of continuous work, the stability was recovered, as indicated in Fig. 5 [8].

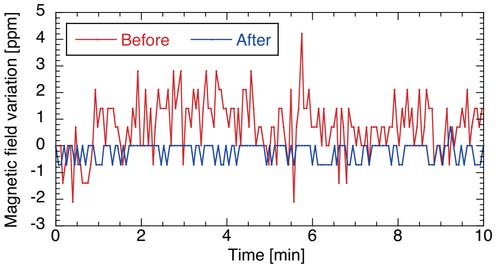

Figure 5: Fluctuation of magnetic field in RRC before and after replacement of main coils [8].

PRESENT PERFORMANCE

The evolution of the maximum beam intensities for the ion beams accelerated at RIBF is summarized in Fig. 6. The intensity of the xenon beam has been increased to 38 pnA; the air stripper mentioned above has been stably operated during beam service time. The uranium intensity has reached 25 pnA due to improvements in the ion source.

The beam availability, which is defined as the ratio of the actual beam servicing time to the scheduled beam servicing time, exceeded 90% in 2013 for a total beam time of 1,380 h. We believe that this value is satisfactory for the fixed-energy mode, which requires four cyclotrons.

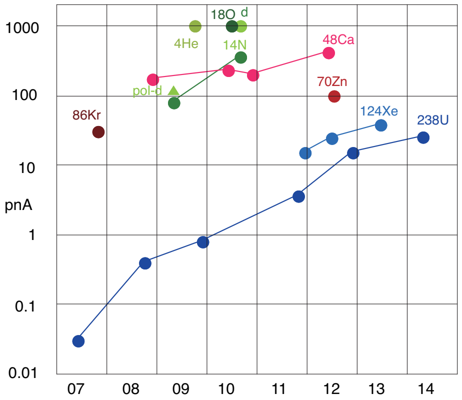

Figure 6: Evolution of maximum beam intensities at RIKEN RIBF.

In order to further improve accelerator performance, some of the issues that need to be addressed include the degraded temperature control system of the RRC, dated rf systems of the injector part, and the space charge effect in the low-energy section. Consequently, we can expect R&D efforts to continue for several years to come.

FUTURE PLAN

At present, the beam intensities extracted from the RIBF accelerators are the highest among the rare-isotope beam (RIB) facilities in the world. However, a number of next-generation RIB facilities are currently under construction or being planned worldwide; these include FAIR in Germany, FRIB in the USA, and RAON in Korea. Some of these facilities have aimed at accelerating heavy-ion beams at 400 kW by the late 2010s. Consequently, a long-term plan is necessary to maintain our position as the world's leading facility in RIB science in the future.

Recently, a plan to upgrade the RIBF has been proposed in the light of providing increased scientific opportunities to study nuclear reaction mechanisms using RIBs by further enhancing the beam intensities at the RIBF; the corresponding schematic is shown in Fig. 7. The plan includes the construction of the following new accelerators. First, the fRC is to be replaced by a new cyclotron (the New fRC) that is designed to accept U^{35+} ions from the ion source without charge stripping; consequently, the required K-value will be 2,300 MeV. Since the first stripping stage will be omitted, the stripping efficiency will be increased by a factor of five. Second, a new linac, mainly consisting of superconducting (SC) cavities operated at 73 MHz, is to replace the RRC. The frequency-mismatch problem of the RRC in the present acceleration scheme is expected to be resolved by this SC-linac. This linac is also expected to be free from the potential risk of space charge effects expected in the RRC at higher beam currents.

Via these modifications, we aim to increase the beam intensity by two orders of magnitude with respect to the current beam intensity. Basic design studies of the new accelerators are currently under progress [9, 10].

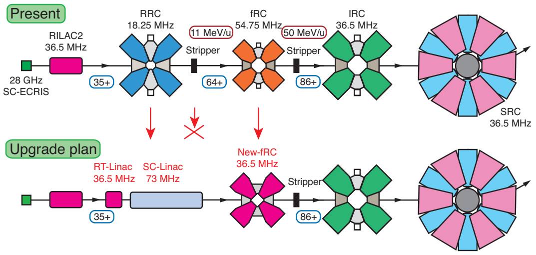

Figure 7: Present (upper panel) and proposed (lower panel) accelerator chains for accelerating uranium beams at RIBF. The final beam energy is 345 MeV/u. The rf frequencies, stripping energies, and charge states are also indicated.

REFERENCES

[1] Y. Yano, Nucl. Instrum. & Methods **B261** (2007) 1009.

[2] H. Okuno, N. Fukunishi, O. Kamigaito, Prog. Theor. Exp. Phys. (2012) 03C002.

[3] O. Kamigaito et al., Proceedings of IPAC2013, Shanghai, China, MOPFI025 (2013), and references therein.

[4] H. Imao et al., Proceedings of IPAC2014, Dresden, Germany, THPME067 (2014).

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

[6] Y. Higurashi et al., Proceedings of Cyclotrons2013, Vancouver, BC, Canada, TU1PB04 (2013).

[7] K. Ozeki et al., Rev. Sci. Instrum. **85** (2014) 02A924.

[8] Y. Watanabe et al., to be published in RIKEN Accelerator Progress Report **47** (2014).

[9] J. Ohnishi et al., Proceedings of Cyclotrons2013, Vancouver, BC, Canada, MOPPT022 (2013).

[10] K. Yamada et al., Proceedings of SRF2013, Paris, France, MOP021 (2013).