PRESENT STATUS AND FUTURE PLAN OF RIKEN RI BEAM FACTORY

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Abstract

Recent efforts concerning the accelerators of the RIKEN RI Beam Factory (RIBF) have been directed towards achieving higher heavy-ion beam intensities. As shown at the IPAC2014 conference, the intensities of these ion beams have improved significantly following the construction of the new injector, RILAC2, which is equipped with a 28-GHz superconducting ECR ion source, development of the helium gas stripper, and upgrading of the bending power of the fRC. In this respect, this paper presents the subsequent upgrade programs conducted in the past two years, such as the development of a new charge stripper for uranium beam and a new acceleration scheme of krypton beam. 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 aims to generate the most intense radioactive isotope (RI) beams over the entire atomic-mass range. Primary beams of heavy ions are powerful tools that can produce rare isotopes far from the stability line. As shown in Fig. 1, a uranium beam is used to effectively generate a large number of neutron-rich nuclei in the medium mass region, and primary beams of ^{48}Ca and ^{70}Zn are used to produce neutron-rich nuclei in the lighter-mass region. In addition, a ^{124}Xe beam is most suited to producing proton-rich nuclei in the vicinity of the doubly magic nucleus of ^{100}Sn.

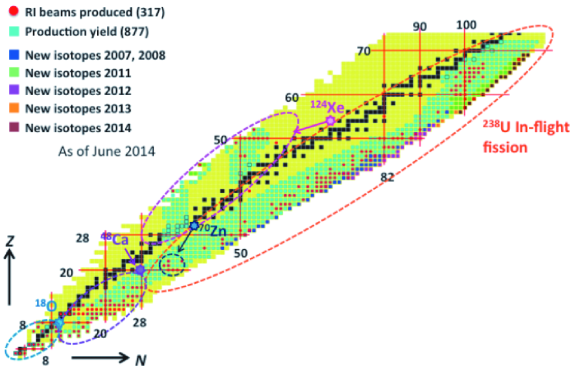

Figure 1: Status of RI beam production at BigRIPS as of June 2014 [3].

As shown at the IPAC2014 conference [4], the intensities of these ion beams, as well as the stability of the beam acceleration, have been significantly improved by the construction of a new injector (RILAC2) equipped with a 28-GHz superconducting ECR ion source (SC-ECRIS), the development of a helium gas stripper, and upgrade of the bending power of the fixed-frequency Ring Cyclotron (fRC). Figure 2 shows the currently operational accelerator setup at the RIBF.

In the next section, recent R&D efforts implemented in the past two years are discussed, with regard to further enhancement of the accelerator performance.

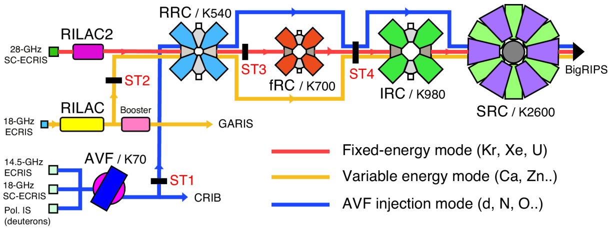

Figure 2: RIBF accelerator chain at RIKEN. The three injectors—the AVF cyclotron, RILAC, and RILAC2—are followed by the four booster cyclotrons—the RIKEN Ring Cyclotron (RRC), fixed-frequency Ring Cyclotron (fRC), Intermediate-stage Ring Cyclotron (IRC), Superconducting Ring Cyclotron (SRC). The K-values of the cyclotrons in MeV are indicated in the figure. The charge strippers are indicated by labels in red text (ST1–ST4).

RECENT UPGRADES

New Charge Stripper for Uranium Beam [5]

The increased intensity of very heavy ions such as uranium and xenon delivered from the 28-GHz SC-ECRIS caused a the problem in that the lifetime of the second-stage charge stripper at 50 MeV/u, which is indicated by "ST4" in Fig. 2, was reduced. The required thickness for this stripper is as large as 15–20 mg/cm^2, because this device also works to degrade the beam energy by approximately 10 %; this reduces the beam speed so that it is accepted by the subsequent cyclotron, the Intermediate-stage Ring Cyclotron (IRC). Both the heat deposit on the stripper and the uniform thickness were the central issues affecting this stripper. For the uranium acceleration, we introduced a rotating stripper based on a beryllium disk in 2012, as shown in Fig. 3A, in place of the static carbon-foil stripper.

This beryllium stripper worked quite well. In fact, we achieved an intensity of 28 pnA for the uranium beam in

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2014. When the stripper was irradiated with 10^{18} uranium ions, however, we found that it became cracked and heavily deformed, as shown in Fig. 3B.

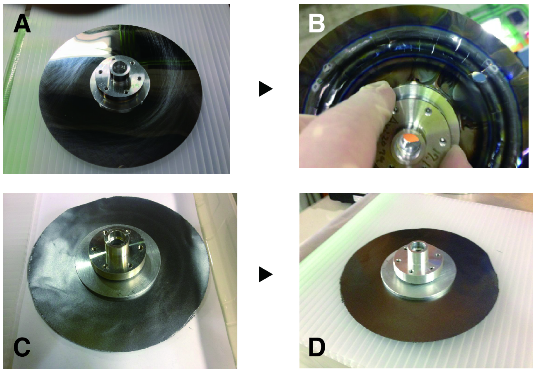

Figure 3: Charge strippers for uranium beams at 50 MeV/u [5]. A: Beryllium disk stripper (16 mg/cm^2) before use. B: Beryllium disk stripper after irradiation with approximately 10^{18} uranium ions. C: Graphite sheet stripper (2×7 mg/cm^2) before use. D: Graphite disk stripper after rradiation with approximately 1.4×10^{18} uranium ions. Each stripper has an outer diameter of approximately 100 mm.

In order to solve this problem, we introduced a new material, the "highly oriented graphite sheet" (GS) produced by the Japanese company, KANEKA Corporation [6], which is shown in Fig. 3C. A prominent feature of the GS is its very high thermal conductivity of 1500 W/m·K in the planar direction; thus the temperature increase at the beam spot is expected to be suppressed. The other notable features of the GS include high density and uniform thickness. In addition, the GS is mechanically strong and can be handled easily.

The performance of the rotating GS stripper is remarkable. As shown in Fig. 3D, a total of 1.4×10^{18} uranium ions with an average intensity of 15 eμA, which corresponds to a thermal load of 205 W, caused no damage to the disk, apart from a slight color change. The maximum temperature of the disk was estimated to be approximately 600 K, according to an ANSYS calculation. Although the lifetime of the GS stripper is now under investigation, it is clear that we can increase the beam intensity further without encountering problems related to the charge strippers.

New Acceleration Scheme for Krypton Beam [7]

There is a strong demand for an intense ^{78}Kr beam to study the nuclear structure of proton-rich nuclei in the vicinity of Z=30. This beam was originally intended to be delivered via the variable-energy mode using the RILAC injector. However, we found that the lifetime of the charge stripper positioned after the RILAC, labeled "ST2" in Fig. 2, was as short as 10 h, when the beam intensity after the SRC exceeded 100 pnA, even for a lighter ion beam of ^{70}Zn. Therefore, the delivery of krypton beams has been suspended.

On the other hand, the fRC was upgraded to accept the lower charge state of the uranium beam in 2012 [8], which led to a proposal to accelerate the ^{78}Kr beam using the fixed-energy mode. A significant advantage of this scheme is that the first stripper at 11 MeV/u after the RIKEN Ring Cyclotron (RRC), which is indicated by "ST3" in Fig. 2, is no longer necessary for this beam, because of the upgraded fRC bending power. Another advantage is that we can use an intense beam from the 28-GHz SC-ECRIS in this mode.

Beam time was assigned in the period of May to June, 2015. We employed the GS stripper presented above at 50 MeV/u, which converted the charge state from 21+ to 36+ with an efficiency of 86 %. During this beam time, the krypton beam was delivered to users at 200–300 pnA with a beam availability of 90.1%. We also achieved maximum beam current of 486 pnA, which corresponds to 13.4 kW, in the acceleration test conducted after the beam time.

PRESENT PERFORMANCE

The evolution of the maximum beam intensities for the ion beams accelerated at RIBF is summarized in Fig. 4. Through use of the GS stripper discussed above, the uranium intensity has reached 49 pnA, which corresponds to a 4.0-kW beam power. The ^{48}Ca beam intensity has been increased significantly through R&D of the low-temperature oven in the ECR ion source; the maximum intensity is now 689 pnA, corresponding to a beam power of 11.4 kW. Moreover, the intensity of the ^{124}Xe beam recently exceeded 100 pnA; we achieved 4.4-kW power for this beam.

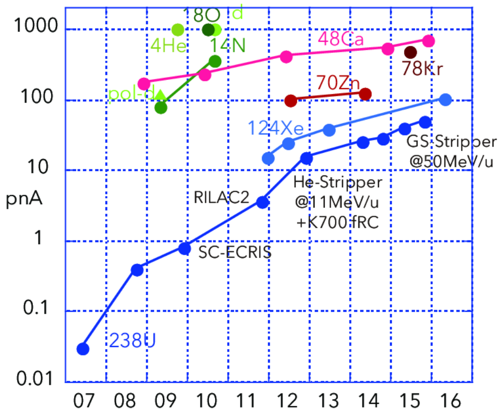

Figure 4: Evolution of maximum beam intensities at RIKEN RIBF.

The beam availability, which is defined as the ratio of the actual to the scheduled beam service time, is another important index for the accelerator facility as regards effective operation. Figure 5 shows the availability indexes recorded since 2008. Although the availabilities were as low as 50–70% for the fixed-energy mode in the initial stage, these values have since been improved significantly. In fact, the annual availabilities have exceeded 90% since 2013. We believe that this value is satisfactory, because the majority of the beam time in these years involved very heavy ions, which require a chain of four cyclotrons and the injector linac; for example, more than 30 large rf systems are used in this fixed-energy mode of acceleration. It should be noted here that steady improvements to and daily maintenance of a large number of relatively dated devices in the facility have played a key role in increasing the beam availability, supplementary to the various R&D efforts mentioned above.

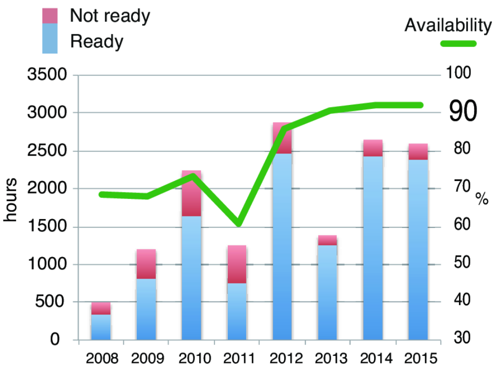

Figure 5: Evolution of machine availabilities at RIKEN RIBF.

UPGRADE PLAN

At present, the beam intensities extracted from the RIBF accelerators are the highest among the rare-isotope beam (RIB) facilities worldwide. However, a number of next-generation RIB facilities are currently under construction in various parts of the world or are being planned; these include FRIB in the USA, FAIR in Germany, and RAON in Korea. Some of these facilities aim to realize heavy-ion beam acceleration at 400 kW by the early 2020s. Consequently, a long-term plan is necessary in order for the RIBF to maintain its position as the world's leading facility in RIB science in the future.

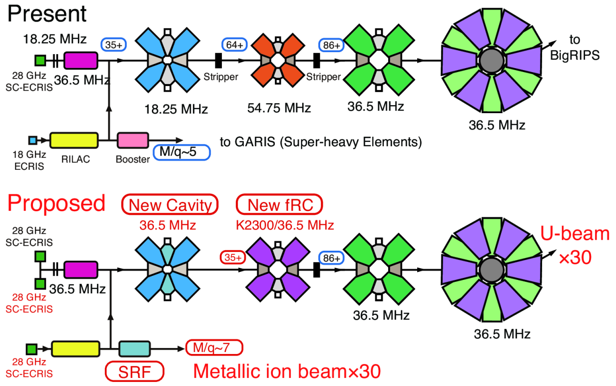

Figure 6: Present (upper panel) and proposed (lower panel) accelerator chains at RIBF to supply the uranium beam to the BigRIPS experiments and the metallic ions to the GARIS experiments. The rf frequencies, stripping energies, and charge states for the uranium beam acceleration are also indicated.

Upgrade plans for the RIBF accelerators are being discussed continuously, with the aim of providing increased scientific opportunities through further enhancement of the beam intensities at the RIBF. The present plan, recently revised with consideration of the construction cost, is shown in Fig. 6.

This plan includes the construction of the following new devices. 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. As the first stripping stage will be omitted, the overall stripping efficiency will be increased by a factor of five. Second, the rf resonators of the RRC are to be replaced by new resonators that will operate at 36.5 MHz, instead of the original frequency of 18.25 MHz. These new resonators are expected to solve the space charge problems that have recently manifested in the RRC, because they will be operated at an rf voltage that is higher than the present value by at least a factor of three. Furthermore, the frequency-mismatch problem in the present acceleration scheme is expected to be resolved completely in the new configuration. Through these modifications, we aim to increase the beam intensity thirty fold with respect to the current value. Basic design studies of the new devices are currently in progress.

The upgrade plan also includes major RILAC modifications intended to enhance the opportunity for synthesis of super-heavy elements [9]. In order to increase the beam intensities of metallic ions thirty fold with respect to the current values, a 28-GHz SC-ECRIS will be constructed on the front end of RILAC. In the upgraded scheme, we plan to accelerate ions with lower charge states provided by this ion source, which requires a higher acceleration voltage. Superconducting rf cavities, based on the QWR structure [10] will be used to replace the present booster part in order to increase the acceleration voltage.

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