ELECTRON STRIPPING OF HIGH-INTENSITY ^{238}U ION BEAM WITH RECIRCULATING He GAS

H. Imao*, H. Okuno, H. Kuboki, O. Kamigaito, H. Hasebe, N. Fukunishi, Y. Watanabe, M. Fujimaki, T. Maie, T. Dantsuka, K. Kumagai, K. Yamada, T. Watanabe, M. Kase, Y. Yano
RIKEN Nishina Center for Accelerator-Based Science, Saitama, Japan

Abstract

Next-generation in-flight RI beam facilities such as RIBF pursue powerful and energetic ^{238}U ion beams to produce thousands of new isotopes. For their efficient acceleration, a durable electron stripper in the intermediate energy region around 10-20 MeV/u is indispensable. However, there is no available stripper for the ^{238}U ion beams with the intensity of more than 1 puA so far because of the lifetime problem of thin solid strippers caused by high energy loss. In the present study, a novel electron stripping system employing high-flow rate He gas circulation (200 L/min) has been developed. He gas with the thickness of 0.6 mg/cm^2 is confined and separated from beamline vacuum using five-stage differentially-pumped sections. To avoid huge gas consumption, a clean gas recycling is achieved with multi-stage mechanical booster pump array. The recycling rate of He gas was achieved as more than 99%. The system was successfully operated in user runs with U^{35+} beams more than 1 puA injected at 10.8 MeV/u for the first time. U^{64+} beams were stably delivered to subsequent accelerators with the stripping efficiency more than 20% without any deterioration of the system.

INTRODUCTION

Recently, the RIKEN Radioactive Isotope Beam Factory (RIBF) [1] has focused on research and development toward a high-intensity uranium beam; this is indispensable to achieving our primary goal, which is to dramatically expand the nuclear chart. A new injector, RILAC2 [2, 3], which includes a 28-GHz superconducting electron cyclotron resonance ion source [4], has been successfully developed and became fully operational in fiscal 2011. To further accelerate the uranium beams generated by this powerful injector, a number of issues must be resolved, including those related to beam acceleration with multistage cyclotrons, space charge effects, heat loading, and radiation damage. In particular one of the highest priorities is to explore a new electron stripping method for the "destructive" beams. The lifetime problem of the conventional carbon-foil stripper due to the high energy loss of uranium beams around 10 MeV/u (e.g., three thousand times larger than protons with the same energy) was a principal bottleneck for the intensity upgrade in the present acceleration scheme.

Figure 1 shows the acceleration scheme for ^{238}U and ^{48}Ca ions before 2011 at the RIBF, where the charge state of ions are converted twice with thin carbon foil strippers [5]. The intensity of the uranium beams reduces with increasing energy. This is caused by the difficulty in the electron stripping of uranium beams.

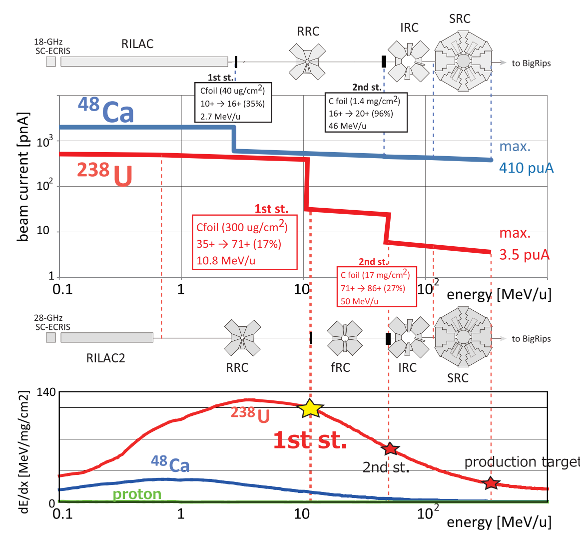

Figure 1: The acceleration scheme of uranium and calcium ions in 2011 at the RIBF. The energy dependence of dE/dx for ^{238}U, ^{48}Ca and proton are also shown at the bottom of the figure.

As shown in Fig. 1, $^{238}U^{35+}$ beams generated from RILAC2 are accelerated to 11 MeV/u in the RIKEN Ring Cyclotron (RRC) and then converted to $^{238}U^{71+}$ beams using a thin carbon foil with a thickness of approximately 0.3 mg/cm^2. After the beams are further accelerated to 50 MeV/u by the fixed frequency cyclotron (fRC), the charge state is converted to 86+ with a relatively thick carbon foil stripper (approximately 17 mg/cm^2). After the second stripper, $^{238}U^{86+}$ beams are further accelerated to the final energy of 345 MeV/u by the intermediate-stage cyclotron (IRC) and the superconducting ring cyclotron (SRC), and then sent to the RI beam separator BigRIPS. For very heavy ions such as uranium ions, the binding energies of the inner shell electrons are very large. One requires sufficient injection energy to strip strongly bound electrons, and so, the stripper thickness correspondingly increases. But increased stripper thickness causes emittance growth, which reduces the beam transmission efficiency in the subsequent cyclotrons. Furthermore, the most serious problem is the damage caused to the strippers by the uranium beams. As shown at the bottom of the figure, dE/dx of uranium ions is very large. It is thousands times higher

* imao@riken.jp

ISBN 978-3-95450-122-9

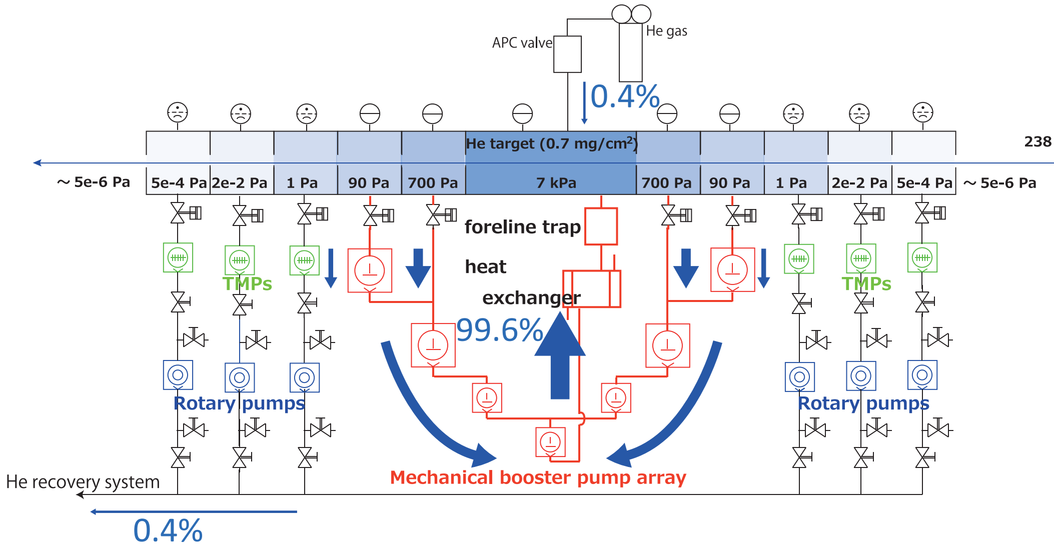

Figure 2: Schematic of the He recirculating system. The multistage MBP array consists of 7 MBPs.

than that of protons and near maximum at the injection energy of 11 MeV/u at the first stripper.

Developing the stripper for high-intensity uranium beams is a worldwide challenge faced among other big heavy-ion projects such as the FAIR at GSI [6] and the FRIB at MSU/ANL [7]. In the present study, we developed a recirculating He-gas stripper characterized by basically infinite lifetime even for the irradiation of the world's most intense uranium beams at the RIBF.

R&D OF He GAS STRIPPER

Charge strippers using helium gas simultaneously provides durability, uniform thickness, and a high charge state equilibrium of the low-atomic number (Z) gas [8, 9]. One of the major technical challenges for realizing a He gas stripper is the windowless accumulation of He gas in the beamline vacuum. A low-Z gas such as He is very leaky because of its low mass ($\propto\sqrt{m}$). In addition, a thick target is required to obtain charge state equilibrium because of the small charge-exchange cross sections of He atoms (Z). For example, the thickness required for charge equilibrium of uranium ions injected at 11 MeV/u is about 1 mg/cm^2 for He gas but only approximately 0.15 mg/cm^2 for nitrogen gas.

In preliminary studies, our group developed a prototype charge-stripping system that can confine He gas up to a thickness of 2 mg/cm^2 [9]. By actually injecting ^{238}U^{35+} beams with an energy of 11 MeV/u into the prototype system, an equilibrium charge state up to 65+ (e.g., 56+ in N_2 [10]) has been measured. It was also found that the energy spread of the beam passing through the He gas target was suppressed to approximately one-half of that with the fixed carbon foil stripper because of the uniform thickness of the gas.

We decided to adopt the He gas stripper as a replacement for the carbon foil stripper used in uranium acceleration and began the modification of the fRC for the acceleration of charge state 64+ (the current acceptable charge state of the fRC is more than 69+) and the development of a practical charge stripping system using He gas.

The major technical challenges for our actual system were the windowless accumulation of thick He gas ($\leq$ 1 mg/cm^2) with large beam aperture diameters ($\geq \phi$10mm) and high-flow recirculation (~200 L/min) of pure He gas with low gas consumption rates ($\leq$ ~1%). Especially, in the recirculation system, the purity of the He gas is an important parameter because the charge-exchange cross sections of He atoms are quite low ($\propto Z^{4.2}$).

All requirements were fulfilled by using an unprecedented scheme with a powerful multistage mechanical booster pump (MBP) array consisting of four foreline MBPs and three back MBPs with a total nominal pumping speed of 11,900 m^3/h (Fig. 2). An off-line test confirmed that the performance actually improved in this configuration, and the operating temperature was acceptable (about 80 C). Because oil contamination due to the MBP array is negligible in this configuration, the evacuated He gas can be returned to the target through a simple combination consisting only of a foreline trap and a heat exchanger. Although such a recirculation system is unprecedented, it can replace the complex high-flow purification system required for a system with oil rotary pumps. The recirculation system with multistage MBPs has great advantages not only for cost reduction but also for realizing target stability and system reliability. The system is designed to recirculate He gas with an efficiency of 99.5% and to reduce the pressure by nine orders of magnitude from the target pressure of ~10 kPa to the beamline vacuum of ~10^{-5} Pa with five-stage differential pumping systems involving the MBP array.

OPERATION

The system was successfully installed at the A02 site in the RRC room. We verified that the basic performance was as desired in offline tests. Since April 2012, a series of beam irradiation tests was also performed. According to Schlachter's semi-empirical formula [11], the electron capture cross section of heavy ions is proportional to $Z^{4.2}$, where Z is the target atomic number. Therefore, the obtained charge state of the uranium beams after the He stripper is very sensitive to the amount of possible high-Z contamination in the He gas target, such as leaked air, remaining water, and pump oil. We confirmed that there is no evidence of target impurities, and no problems occurred when it was used with U^{35+} beams injected at 11 MeV/u with the intensity up to 0.3 pμA .

After the commissioning, the system was actually operated in user runs this fall with the beams of more than 1 pμA for the first time (Fig. 3). Electron-stripped U^{64+} beams were stably delivered to subsequent accelerators without any deterioration of the system for six weeks. The con-

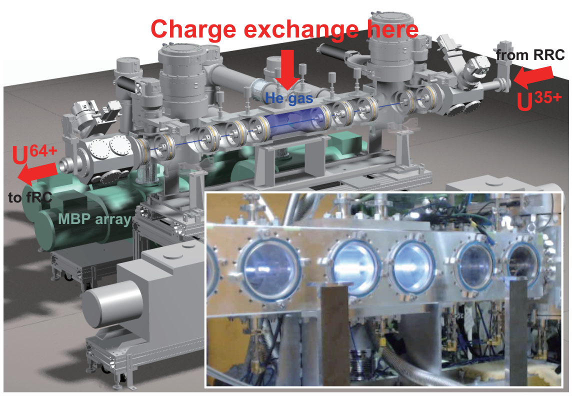

Figure 3: Cross sectional view of the He gas stripper and picture of glowing 1-pμA uranium beams.

version efficiencies for U^{64+} with a typical operational target thickness of 0.6 mg/cm^2 are as high as 23% due to the electron shell effect in the charge-exchange reactions. The temperature increase in the water-cooled tube orifices was tolerable ($\leq$ 150°C) with the transmission efficiency reaching about 80%. The reduction of the target density along the beam path due to the heat load was found not to be serious. The intensity of the beam through the first stripper is drastically increased from that in 2011 (Fig 4). The intensity of 2011 was mainly limited by the lifetime problem of the carbon foil strippers. The blue line in Fig 4 indicates the rough application limit of the carbon foil stripper. The new He gas stripper contributed important bottleneck breakthrough.

The peak intensity after the SRC has reached 15 pnA, almost 10^{11} per second. Service rate and mean intensity are also increased due the downtime-free stripper. The average intensity of uranium beams provided to the user became approximately ten times higher than it was in 2011.

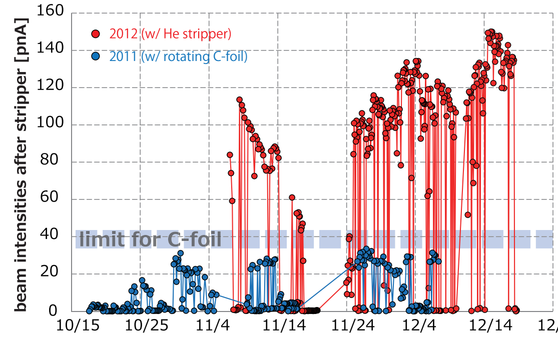

Figure 4: The intensity of the beam through the first stripper in 2011 and 2012.

CONCLUSION

The new He gas stripper, which removed the primary bottleneck in the high-intensity uranium acceleration, and the success of some other remarkable accelerator upgrade performed in this year at the RIBF (e.g., ion source, high-power beam dump, K700-fRC and 2nd rotating Be stripper) brought the tenfold increase of the average output intensity of the uranium beams from the previous year. We realized new acceleration scheme with He gas stripper which is applicable for high-power uranium beams. Further sophistication of this new acceleration scheme for greater uranium beam intensities is in progress.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the cyclotron crews for providing high quality beam and for their help during the preparation and the measurements.

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ISBN 978-3-95450-122-9