R&D OF HELIUM GAS STRIPPER FOR INTENSE URANIUM BEAMS

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

Intensity upgrade of uranium beams is one of the main concerns at the RIKEN Radioactive Isotope Beam Factory (RIBF). The lifetime problem of carbon-foil strippers due to the high energy loss of uranium beams around 10 MeV/u was a principal bottleneck for the intensity upgrade in the acceleration scheme at the RIBF. We have developed a recirculating He-gas stripper as an alternative to carbon foils for the acceleration of high-power uranium beams. The new stripping system was actually operated in user runs with U^{35+} beams of more than 1 puA. Electron-stripped U^{64+} beams were stably delivered to subsequent accelerators without serious deterioration of the system for six weeks. The new He-gas stripper, which removed the primary bottleneck in the high-power uranium acceleration, greatly contributed to the tenfold increase of the average output intensity of the uranium beams in 2012 from the previous year.

INTRODUCTION

Intensity upgrade of uranium beams up to our ultimate goal intensity of 1 puA is one of the main concerns at the RIKEN Radioactive Isotope Beam Factory (RIBF) [1]. A new injector, RILAC2 [2, 3], which includes a 28-GHz superconducting electron cyclotron resonance ion source (ECRIS) [4], has been successfully developed and became fully operational in fiscal 2011. To further accelerate the uranium beams generated by this powerful injector, one of the highest priorities is to explore a new charge stripper for the high-power uranium beams. The possible output intensity of uranium beams at the RIBF was mainly limited by the lifetime problem of the carbon foil strippers.

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]. In the acceleration of for ^{238}U, highly charged uranium ions, $^{238}U^{35+}$, generated by 28-GHz ECRIS [4] are accelerated with RILAC2 up to the energy of 0.67 MeV/u. They are further 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). $^{238}U^{86+}$ beams are 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 production target with the RI beam separator BigRIPS.

* imao@riken.jp

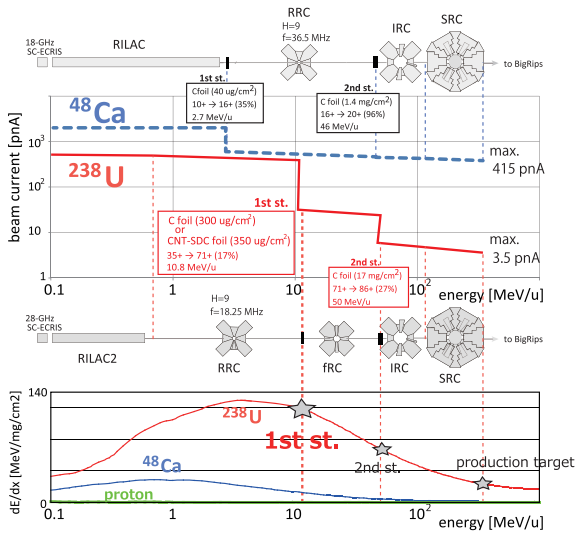

Figure 1: The acceleration scheme of uranium and calcium ions before 2011 at the RIBF. Calculated energy dependences of dE/dx for ^{238}U, ^{48}Ca and proton are also shown at the bottom of the figure.

There are some intrinsic difficulties in the electron stripping of uranium ions compared with that of calcium ions. 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 increase the charge–mass ratio q/m of uranium ions by stripping strongly bound electrons. As shown in Fig. 1, the injection energies for the first stripper at the RIBF are 2.7 MeV/u for ^{48}Ca and 10.8 MeV/u for ^{238}U. The stripper thickness correspondingly increases at the higher injection energy. Increased stripper thickness causes emittance growth, which reduces the beam transmission efficiency in the subsequent cyclotrons.

The most serious problem for the acceleration of the high-intensity uranium beams is the damage caused to the strippers by high energy loss of uranium ions as shown at the bottom of Fig. 1. The energy loss ($\propto \sim Z_p^2 Z_t/A$) of uranium ions is thousands times higher than that of protons and near maximum at the injection energy of 11 MeV/u at the first stripper.

The foil thickness required at the energy of the first carbon foil stripper is very thin less than 1 μm. The problems of using such thin foil stripper for high-power uranium beams include the fragility, thickness non-uniformity, and poor thermal conductivity. The previously measured lifetime of the fixed carbon foil stripper is as short as 15 h when it is irradiated by uranium beams with intensities of up to 20 pnA [6]. The use of rotating foil strippers of

ISBN 978-3-95450-128-1

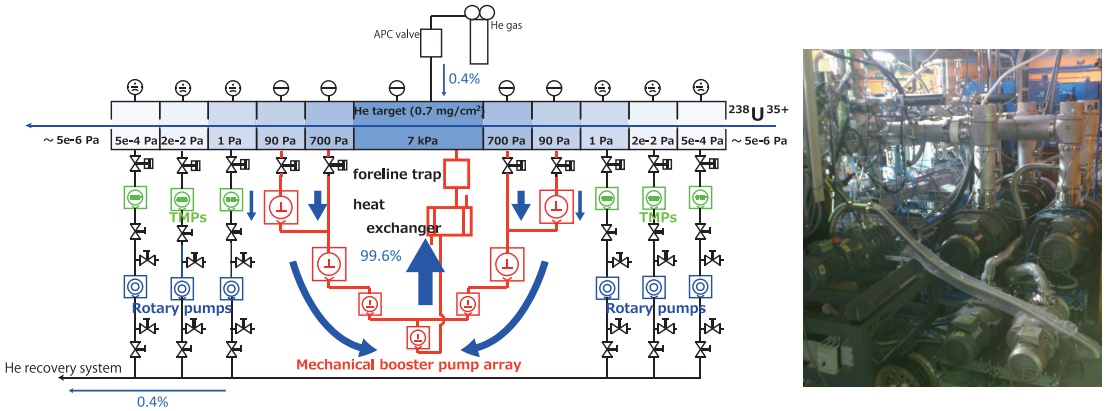

Figure 2: Schematic of the He recirculating system (left) and a picture of the multistage MBP array (right). The multistage MBP array consists of 7 MBPs.

carbon-nanotube/sputter-deposited carbon (CNT-SDC) developed at the RIBF [5] provided some positive results. In the actual use of the rotating foil stripper in 2011, the survival time was drastically increased to typically 3-5 days for irradiation by uranium beams up to 250 pnA. However, further innovation is required to drastically improve the foil durability and thickness uniformity for the acceleration of high-intensity uranium beams, e.g., more than 1 puA. We note that developing the stripper for high-intensity uranium beams is a worldwide challenge also faced among other big heavy-ion projects such as the FAIR at GSI [7] and the FRIB at MSU/ANL [8].

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.

HE GAS STRIPPER

Our group has pursued a stripping method using gas to replace the carbon foil. The first attempt with a nitrogen (or argon) gas stripper for uranium beams at 11 MeV/u produced the equilibrium charge state up to 56+ [9]. Unfortunately, the value is too low for our use because the minimum acceptable charge state is 69+ for the original fRC.

The use of low-Z (Z; atomic number) gas (e.g., He or H_2 gas) is a possible pathway to improve the mismatch. The electron capture cross sections (σ_{cap}) for low-Z gas is particularly suppressed due to poor kinematical matching when the ion velocity significantly exceeds the velocity of target electrons [10]. Therefore, charge strippers using low-Z gas simultaneously provides durability, uniform thickness and a high charge state equilibrium.

One of the major difficulties for realizing a low-Z gas stripper is the windowless confinement with required thickness in the beamline vacuum. A low-Z gas is very leaky because of its low mass (conductance is protpotional to$\sqrt{m}$). In addition, a thick target is required to obtain charge state equilibrium because of the small charge-exchange cross sections of low-Z atoms. 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.

For the first demonstration of the effect of low-Z gas on the charge state equilibrium, the cross sections for electron loss and electron capture for uranium in helium were successfully measured with thin targets which can strip or attach only one electron at three energies 11, 14 and 15 MeV/u [10]. More directly, the charge state distribution and the evolution both for helium and hydrogen gases were measured at the injection energy of 11 MeV/u by preparing the thick targets (8 m in length) required for their charge equilibrium, respectively [11]. The results of these experiments clearly indicated that the equilibrium charge states (e.g., 65+ at 11 MeV/u for helium) for low-Z gas strippers are significantly higher than those for higher-Z gas strippers (e.g., 56+ in N_2 [9]). We also found that He gas is the better candidate for our first stripper compared with H_2 gas because of the easier confinement, the smaller energy deposition, the smaller impurity susceptibility and the no explosion hazard. Also in terms of the application of the atomic shell effect, the equilibrium charge state of He is favorable as discussed later.

Our group further developed a realistic prototype charge-stripping system that can confine He gas up to a thickness of 2 mg/cm^2 within a 0.5-m target region [11]. By actually injecting $^{238}U^{35+}$ beams with an energy of 11 MeV/u into the prototype system, the equilibrium charge state of 65+ with a transmission efficiency of around 70% has been measured. We also found that the fraction of 64+ in the charge state distribution is transiently enhanced due to the atomic shell effect of the uranium ion (e.g., 27% for 64+ and 21% for 65+). 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.

The charge state 64+ is a good candidate for acceleration because one can obtain this charge state with a thinner target less than the thickness required for the charge equilibrium around $\sim$ 1 mg/cm^2 with a higher conversion effi-

ISBN 978-3-95450-128-1

ciency compared with that of 71+ with carbon foils (about 17%). We decided to adopt the He gas stripper as a replacement for the carbon foil stripper and correspondingly modified the fRC for the acceleration of charge state 64+ (the previous acceptable charge state of the fRC is more than 69+) [12].

ACTUAL SYSTEM DEVELOPMENT

In the actual system, it is required to confine thick He gas ($\leq$ 1 mg/cm^2) in beamline vacuum with large beam aperture diameters ($\geq \phi$10mm). It is also required to realize high-flow recirculation ($\sim$200 L/min) of He gas with low gas consumption rates ($\leq \sim$1%). Especially, in the recirculation system, the purity of the He gas is an important parameter because the charge-exchange cross sections of He atoms are quite low ($\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). The system is designed to recirculate He gas with an efficiency of approximately 99.6% and to reduce the pressure by nine orders of magnitude from the target pressure of $\sim$10 kPa to the beamline vacuum less than $\sim 10^{-5}$ Pa with five-stage differential pumping systems involving the MBP array.

Off-line tests for the multistage MBP array confirmed that the performance for pumping actually improved in this configuration and the operating temperatures (about 80 °C) of MBPs were acceptable for long-term operations. Because oil contamination due to the MBP array is negligible, the evacuated He gas can be returned to the target chamber through a simple combination consisting only of a foreline trap and a heat exchanger. The recirculation system with multistage MBPs has great advantages not only for in terms of cost reduction but also for realizing target stability and system reliability.

OPERATION OF HE GAS STRIPPER

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. We confirmed that there is no evidence of target impurities, and no serious problems occurred when it was used with U^{35+} beams injected at 11 MeV/u with the intensities up to 0.3 pμA .

After the commissioning, the system was actually operated in the user runs started from November 2012 with the injected beams of more than 1 pμA (Fig. 3). Electron-stripped U^{64+} beams were stably delivered to subsequent accelerators without any serious deterioration of the system for six weeks. The conversion efficiencies for U^{64+} with a typical operational target thickness of 0.6 mg/cm^2 are as high as 23%. The temperature increase of 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 of uranium beams was found not to be serious. The intensities of the electron-stripped beams provided from the first stripper in 2012 are drastically increased from that in 2011 (Fig 4). The new He gas stripper contributed an important bottleneck breakthrough.

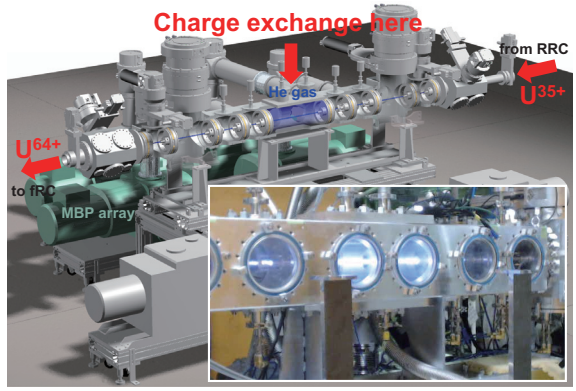

Figure 3: Cross sectional view of the He gas stripper and picture of glowing 1-pμA uranium beams.

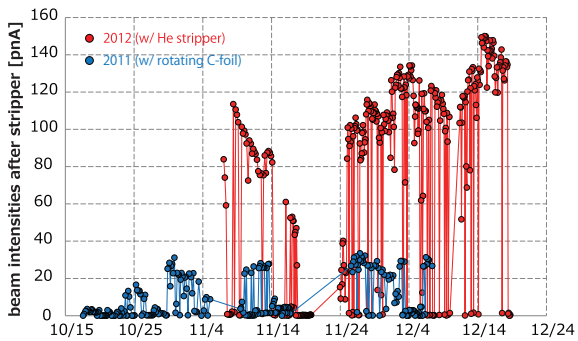

Figure 4: The intensity of the beam through the first stripper in 2011 and 2012. The new He gas stripper removed the primary bottleneck for the high-power uranium acceleration.

The peak intensity after the SRC has reached 15 pnA, almost 10^{11} ions per second. Service rate (56.7% $\rightarrow$ 80.3%) and mean intensity (1.6 pnA $\rightarrow$ 10.2 pnA) are also increased primary due to the downtime-free stripper. The average intensity of uranium beams provided to the user became approximately ten times higher than it was in 2011.

RECENT ACTIVITY OF GAS STRIPPER

As another recent activity of the gas stripper at the RIBF, the 2nd gas stripper with air dedicated for 50-MeV/u ^{1}24Xe beams was developed. The same technology for differential pumping as the prototype He gas stripper [11] was applied to the new system. We confined a very thick gas target, up to 20 mg/cm^2 of air, in a 0.5-m target chamber. High-flow compressed air is introduced to the target chamber. One good feature of using air is that it can be inexhaustible for our use. We do not need any recirculation

ISBN 978-3-95450-128-1

system in the air stripper. The stripper was constructed in March 2013 and stably operated in user runs performed in June 2013. The service rate in the user runs reached 91% [12]. The maximum beam intensity reached 38 pnA and the average intensity provided to users becomes approximately four times higher than it was in 2012. Actually, we replaced the 2nd carbon foil strippers every ∼8 hours due to the damage by Xe beams in user runs in 2012. The down-time free gas strippers greatly contributed to these improvements.

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 in future. The technology developed for He stripper was successfully applied to the 2nd air stripper recently developed for Xe beams. Further sophistication of the new acceleration scheme with gas strippers for greater very-heavy ion 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.

REFERENCES

[1] Y. Yano, Nucl. Inst. Meth. Phys. Res. **B261**, 1009 (2007).

[2] O. Kamigaito *et al.*, HIAT09, MO11T (2009).

[3] K. Yamada *et al.*, IPAC'10, Kyoto, May 2010, MOPD046; K. Yamada *et al.*, IPAC'12, New Oreans, May 2012, TUOBA02.

[4] Y. Higurashi *et al.*, Rev. Sci Instrum. **83**, 02A308 (2012); Y. Higurashi *et al.*, Rev. Sci Instrum. **83**, 02A333 (2012); Y. Higurashi *et al.*, Cyclotrons 2013. Vancouver, Canada (2013).

[5] H. Hasebe *et al.*, Nucl. Inst. Meth. Phys. Res. **A 613**, 453 (2010); H. Hasebe *et al.*, INTDS 2012, Mainz, Germany (2012).

[6] N. Fukunishi *et al.*, PAC09, MO3GRI01 (2009).

[7] W. Henning, Nucl. Phys. **A805**, 502c (2008).

[8] FRIB, http://frib.msu.edu/.

[9] H. Kuboki *et al.*, Phys. Rev. ST-AB **13**, 093501 (2010); H. Kuboki *et al.*, Phys. Rev. ST-AB **14**, 053502 (2011).

[10] H. Okuno *et al.*, Phys. Rev. ST-AB **14**, 033503 (2011).

[11] H. Imao *et al.*, Phys. Rev. ST-AB **15**, 123501 (2012).

[12] N. Fukunishi *et al.*, Cyclotrons 2013. Vancouver, Canada (2013).