Realization of recirculating He-gas stripper

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The intensity upgrade of uranium beams up to our goal intensity of 1 pμA has been 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 year 2011. The possible output intensity of uranium beams at the RIBF at that time was mainly limited by the lifetime problem of the carbon foil strippers.[5] To further accelerate the uranium beams generated by this powerful injector, one of the highest priorities was to explore a new charge stripper for the high-power uranium beams. It has been a long-standing open problem despite extensive worldwide research efforts to find next-generation strippers involving the other huge heavy-ion projects such as the FAIR at GSI[6] and the FRIB at MSU.[7]

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/nucleon produced an equilibrium charge state up to 56+.[8] Unfortunately, the value is too low for our use because the minimum acceptable charge state is 69+ for the original fRC.

The use of a 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 for low-Z gases are particularly suppressed owing to poor kinematic matching when the ion velocity significantly exceeds the velocity of the target electrons.[9] Therefore, charge strippers using a low-Z gas simultaneously provide durability, a uniform thickness, and a high charge state equilibrium.

For the first demonstration of the effect of a low-Z gas on the charge state equilibrium, the cross sections for the electron loss and electron capture for uranium in He were successfully measured with thin targets that can strip or attach only one electron at three energies of 11, 14 and 15 MeV/nucleon.[9] More directly, the charge state distribution and the energy spread after the stripper both for He and H_2 gases were measured at an injection energy of 11 MeV/nucleon by preparing the thick targets (8 m in length) required for their charge equilibrium.[10] The results of these experiments clearly indicated that the equilibrium charge states (e.g., 65+ at 11 MeV/nucleon for He) for low-Z-gas strippers are significantly higher than those for higher-Z-gas strippers (e.g., 56+ in N_2[8]). We also found that the fraction of 64+ in the charge state distribution is transiently enhanced owing to the atomic shell effect of the uranium ion. 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 and correspondingly modified the fRC for the acceleration of charge state 64+ (the previous acceptable charge state of the fRC is more than 69+).[11]

The major technical challenges were the windowless accumulation (more than 10-mm$^{\phi}$ beam apertures) of very thick He gas (about 1 mg/cm^2) and high-flow recirculation (300 m^3(STP)/day) of pure He gas with low gas consumption rates (less than 0.5%). It was realized by using an unprecedented scheme with a powerful multistage mechanical booster pump array. The system is designed to reduce the pressure by nine orders of magnitude from the target pressure of $\sim$10 kPa to the beamline vacuum of 10^{-5} Pa within a length of approximately 2 m. About 300 m^3/day of He gas is recirculated by the multistage MBP array consisting of four foreline MBPs and three back MBPs with a total nominal pumping speed of 11,900 m^3/h (Fig. 1).

The system was successfully installed at the A02 site in the RRC room (Fig. 2). 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/nucleon with intensities up to 0.3 pμA.

After commissioning, the system was actually operated in user runs started from November 2012 with injected beams of more than 1 pμA (Fig. 2). Electron-stripped U^{64+} beams were stably delivered to subsequent accelerators without any serious deterioration in the system for six weeks.

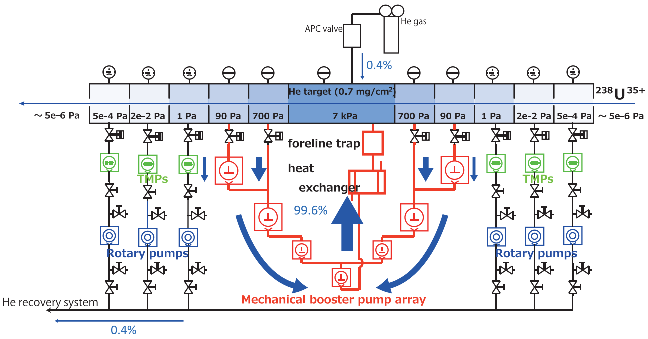

Fig. 1. Schematic of the He recirculating system. The multistage MBP array consists of seven MBPs.

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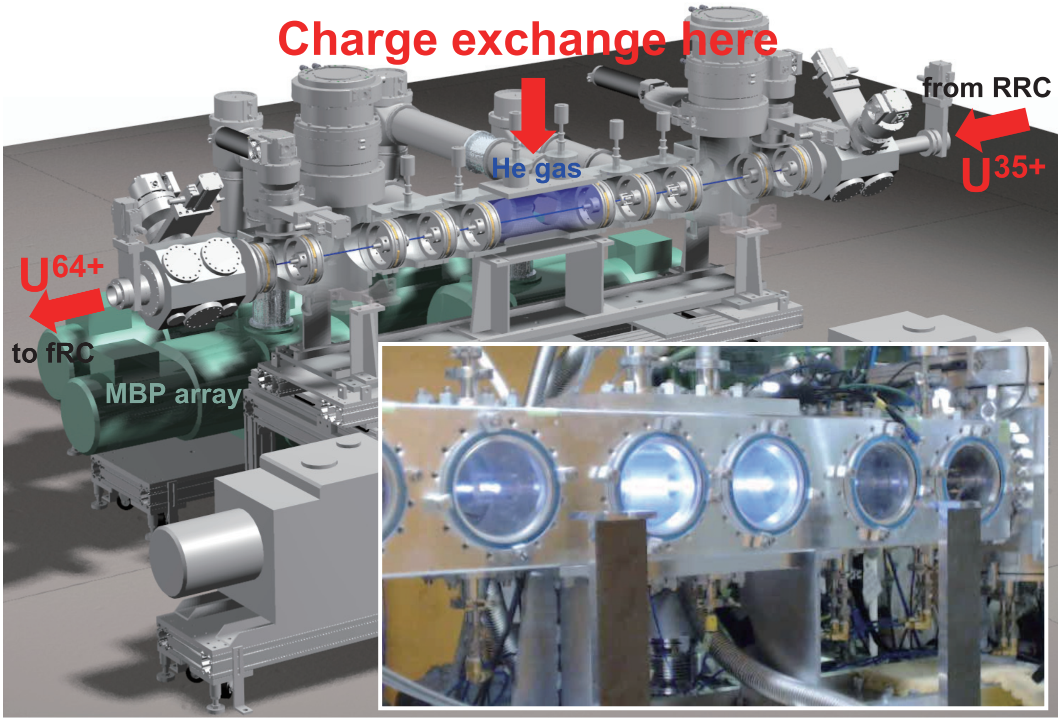

Fig. 2. Cross-sectional view of the He-gas stripper and a photograph of glowing 1-pμA uranium beams.

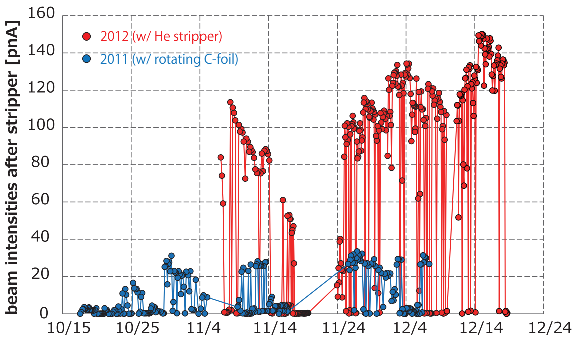

Fig. 3. Intensities of the beam through the first stripper in 2011 and 2012. The new He-gas stripper removed the primary bottleneck for high-power uranium acceleration.

The intensities of the electron-stripped beams provided from the first stripper in 2012 are drastically increased from that in 2011 (Fig. 3). The peak intensity after the SRC has reached 15 pnA, almost 10^{11} ions per second. The service rate (56.7% $\rightarrow$ 80.3%) and the mean intensity (1.6 pnA $\rightarrow$ 10.2 pnA) are also increased, primarily owing to the downtime-free stripper. The average intensity of the uranium beams provided to the user became approximately 10 times higher than it was in 2011.

The new He-gas stripper, which removed the primary bottleneck in the high-intensity uranium acceleration, and the success of some other remarkable accelerator upgrades performed in 2012 at the RIBF (e.g., ion source, high-power beam dump, K700-fRC, etc.) resulted in a tenfold increase in the average output intensity of the uranium beams from the previous year.

The realization of the new acceleration scheme of uranium beams with the He-gas stripper in 2012 has been an important breakthrough for the recent progress of the RIBF.

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