CHARGE STRIPPING OF URANIUM-238 ION BEAM WITH LOW-Z GAS STRIPPER

H. Imao*, H. Okuno, H. Kuboki, S. Yokouchi, N. Fukunishi, O. Kamigaito, H. Hasebe, T. Watanabe, M. Kase, Y. Yano, RIKEN Nishina Center for Accelerator-Based Science, Saitama, Japan
A. Goto, NIRS, Chiba, Japan

Abstract

A charge stripper using low-Z gas is an important candidate to replace existing carbon foil strippers for application to high-intesity ^{238}U beams. Here, the maximum mean charge state and the charge evolution of ^{238}U beams injected at 10.75 MeV/u were investigated using thick H_2 and He gas strippers. The charge states achievable with the low-Z gas strippers (around 65+) are superior to those of medium-Z gas strippers around 55+.

INTRODUCTION

A critical issue at the RIKEN RI-beam facility (RIBF) [1] is the need to improve the present intensity of ^{238}U beams (∼0.8 pnA) towards the intensity goal of 1 pμA, which is expected to provide an enormous breakthrough for exploring new domains of the nuclear chart. The construction of a new injector, RILAC2 [2], which has a 28-GHz superconducting electron cyclotron resonance ion source [3], was completed at the end of 2010. This was an important step in the intensity upgrade of ^{238}U beams.

Before high-power ^{238}U beams are realised with the powerful injector, various problems must be resolved. These problems are associated with the acceleration of beams 100 times more intense than previous beams in the facilitys four cyclotrons: the RIKEN ring cyclotron (RRC) [1], a fixed-frequency ring cyclotron (fRC) [5], an intermediate-stage ring cyclotron (IRC) [6] and a superconducting ring cyclotron (SRC) [7] at the RIBF. The development of a reliable, efficient electric charge stripping method applicable to high-intensity uranium beams is a key issue, affecting the overall acceleration performance.

In the present acceleration of uranium beams at the RIBF, two carbon-foil charge strippers [8] are used after the RRC and the fRC, respectively. Although solid carbon-foil charge strippers provide good charge–stripping efficiency, two serious problems are emerging, especially in the first foil stripper: (1) a short usable time and (2) non-uniform thickness. Uranium beams having intensities as low as 10 pnA passing through the simple carbon foil becomes out of the acceptance of the subsequent cyclotrons after as little as 12 hours presumably owing to radiation damage [8].

A charge stripper using low-Z (Z: atomic number) gas is a possible candidate for replacing the existing carbon foil strippers [8]. Because the electron capture process is suppressed, low-Z gas is expected to provide high-equilibrium charge states that maintain the non-destructive feature of the fluid [9]. However, data about the charge evolution of H_2 and He gas is not available because of the difficulty of preparing thick windowless gas targets. Furthermore reliable charge-changing cross sections for ^{238}U colliding with a low-Z gas at energies around 10 MeV/u are not yet available. In the present study, the maximum mean charge state (the mean charge state reaching a maximum gradually becomes lower because of energy attenuation) and the charge evolution of ^{238}U beams injected at 10.8 MeV/u was investigated using thick H_2 and He gas.

TARGET SYSTEM

A key component for realising a massive low-Z gas charge stripper is a windowless connection between the high-vacuum beamline (≈10^{-3} Pa) and the high-pressure target region. The differential pumping performance for H_2 and He gas is much lower than that in comparison with that for ordinal medium-Z gases such as N_2. ^{238}U colliding with a low-Z gas has lower electron-loss (EL) and electron-capture (EC) cross sections than ^{238}U colliding with N_2. As a result, the injected ions have a larger mean free path of the injected ions, which causes slow equilibration. A simple estimation of the charge evolution using theoretical EL and EC cross sections for He [9] indicates that a thickness greater than 1 mg/cm^2 is required for 10.8 MeV/u ^{238}U beams to attain the maximum charge state. However, a value of only 0.4 mg/cm^2 is required for N_2 [10].

To overcome these difficulties, two dramatic improvements were made to the gas accumulation method in the present study: (1) a long gas stripper (∼8 m) was used in which the low-Z gas was directly accumulated in the beamline and (2) the design of the differential pumping systems was optimised and improved. To accumulate thick gas in a high-vacuum beamline, a long gas-filled region with conductance limiting tubes having small apertures is favourable. However, a long stripper increases the lateral spread of the beam. Further, the narrow apertures intercept part of the beam. The design of the gas charge-stripping system was optimized by considering these constraints and the calculated beam trajectories.

The charge-stripping system consists primarily of two huge differential pumping systems located at either end of the 8-m charge stripping section and a gas inlet line connected to the gas-handling system (Fig. 1). In the differential pumping systems, the conductances among the vacuum chambers are limited by the diameters of the tubes,

* imao@riken.jp

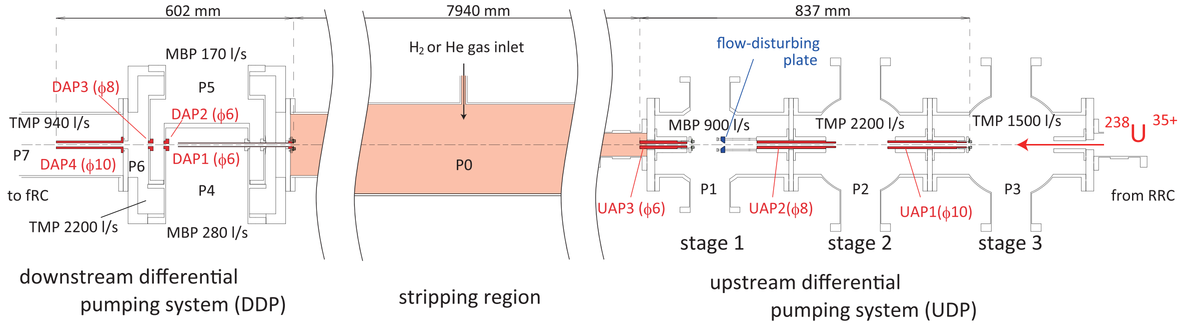

Figure 1: Cross-sectional view of the charge stripping system.

which are 6−10 mm (UAP1-3 and DAP1-4). In the current setup, the gas-cell system used in the previous system [10] was fully devoted to one-sided evacuation as a differential pumping system on the downstream side (DDP) (Fig. 1).

For the upstream system (UDP), a new tube-separated three-stage differential pumping system was designed and constructed. Vacuum was achieved in stage 1 of the UDP by using a powerful mechanical booster pump backed by a rotary oil pump. A high-throughput turbomolecular pump was used in stage 2 and an ordinal one was used in stage 3. Flow-disturbing plates were placed between UAP1 and UAP2; they were specially designed to slow the flow of the supersonic gas jet from UAP1 to UAP2.

Performance tests of the UDP and DDP were performed separately by shutting down the system not being tested. The measured pressure distributions for H_2 and He gas in the UDP and the DDP are shown in Fig. 2. The UDP exhibited high differential pumping ability; its performance was more than 3 times better that of the DDP. Although the length of the UDP was as small as 1 m and the diameter of the beam passage was more than 6 mm, a pressure transition from 15 kPa for He (3 kPa for H_2) to 10^{-2}∼10^{-4} Pa was achieved. The pressure of the upstream beamline was one order of magnitude lower than the third-stage pressure.

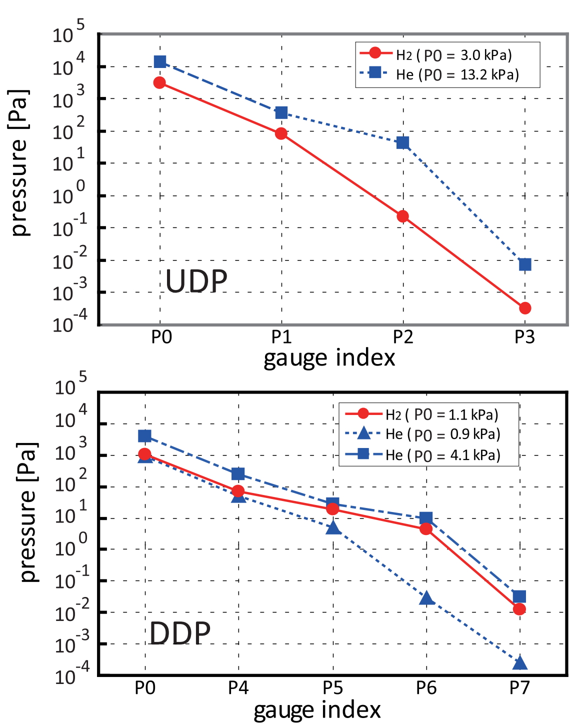

Figure 2: Pressure distributions in the UDP and DDP.

In the current 8-m charge-stripping system, a thickness of 1 mg/cm^2 for H_2 and 5 mg/cm^2 for He was achieved while maintaining a tolerable beamline pressure. These are reasonable values for achieving the maximum charge state for 10.8 MeV/u ^{238}U beams. The achievable gas pressure in the two differential pumping systems is limited by the performance of the DDP. The H_2 gas pressure is also limited by the flow limit of 20 SLM, which was determined on the basis of the facilitys safety regulation standards.

The effect of the flow-disturbing plates on the differential pumping performance is shown in Table 1. Note that the maximum gas pressure is greater by a factor of approximately three in the presence of the plates.

Table 1: Effect of the Flow-disturbing Plates

gauge index	P0 [kPa]	P1 [Pa]	P2 [Pa]	P3 [Pa]
w/o disturber	6.3	104.5	56.0	8.2×10^{-3}
with disturber	16.2	433.0	46.5	5.4×10^{-3}

EXPERIMENT

In the experiment, the 8-m-long low-Z gas-charge-stripping system was placed on the beamline between the RRC and the fRC at the RIBF. The 0.68 MeV/u U^{35+} beams extracted from RILAC were accelerated to 10.8 MeV/u using the RRC. The beams extracted from the RRC (100−200 enA in the present measurements) passed through the 8-m-long gas charge stripper. We transported the ^{238}U beams passing through the 8-m charge stripping section with up to 50% transmission efficiency by fine adjustment of the magnet parameters on the basis of calculations. The charge distributions of the beams passing through the stripper were analysed with the two dipole magnets and the faraday cup downstream.

MEAN CHARGE-STATE EVOLUTION

The fraction, $F(q_i)$, of the charge state, q_i, was determined by using the same procedure as that used in previous measurements [10]. We used the measured injected-beam currents $I_{\rm inj}$ and the analyzed ones $I_{\rm ana}$ with a dipole magnet to deduce $F(q_i)$=$1/N\{(I_{\rm ana}/q_i)/(I_{\rm inj}/q_{ini})\}$, where N and q_{ini} are normalized factor and the initial charge state (equal to 35^+), respectively. Gaussian functions were fitted to the obtained $F(q_i)$ for H_2 and He gas to determine the mean charge states, q_{mean}. The mean charge q_{mean} for the H_2 and He strippers are plotted as functions of the calculated gas thicknesses (Fig. 3). For comparison with

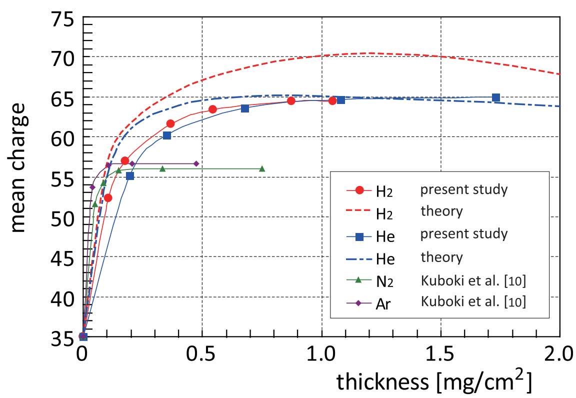

Figure 3: Measured and calculated charge state evolution.

previous measurements [10], plots for N_2 and Ar are also shown.

The charge states for the H_2 and He strippers increased gradually with thickness up to 1 mg/cm^2; at greater thicknesses, they remained constant. As expected, the charge states obtained with low-Z gas strippers were considerably higher than those obtained with medium-Z strippers. To analyse the charge-state evolution, we used the Monte Carlo method with the EL cross sections for ^{238}U based on the binary encounter model [11] and Schlachter's semiempirical EC cross sections [12]. In the simulation, we used the charge-dependent energy-loss cross sections calculated using the CasP code, which is based on the unitary-convolution approximation [13].

The maximum mean charge state for He, which is around 65^+, agrees well with the calculated one, but the thickness required for equilibration was greater than the calculated value. The slow equilibration could be attributed to the reduced charge-changing cross sections. These tendencies were consistent with the results of the measurements performed using thin He gas targets [9]. The maximum mean charge state for H_2 gas, which was around 65^+, was significantly lower than the calculated value, which was around 70^+. Unexpectedly, the measured maximum mean charge state for H_2 was almost the same as that for He. Further investigations are being conducted to determine the nature of charge stripping in low-Z gas.

CONCLUSION

In this study, the charge state evolution of ^{238}U beams injected at 10.8 MeV/u was measured using H_2 gas targets with a thickness of 0.11−1.05 mg/cm^2 and He gas targets with a thickness of 0.20−1.73 mg/cm^2 and the newly developed low-Z gas target system. The obtained maximum mean charge state for the low-Z gas targets was approximately 65^+, which is considerably higher than that of medium-Z gas targets such as N_2 and Ar (around 55^+). The results indicate that a charge-stripping system involving the use of low-Z gas is an attractive choice for high-intensity uranium beams with energies near 10 MeV/u.

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