EXPERIENCE WITH STRIPPING HEAVY ION BEAMS

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Abstract

Charge strippers play a critical role in many high-intensity heavy ion accelerators. Recent progress on accelerator technology make charge strippers so critical that traditional carbon foils can easily reach the limit of their application due to their short lifetime. In fact, three major heavy ion accelerator facilities (GSI, MSU/ANL, and RIKEN) have extensively studied alternatives to carbon foils to realize high-intensity acceleration of very heavy ions such as uranium. For example, the liquid lithium stripper was developed at MSU/ANL, and the helium gas stripper and rotating beryllium disk stripper were developed at the RIKEN radioactive-isotope beam factory (RIBF). The RIBF two strippers greatly contributed to the increase in the uranium beam intensity. However, we believe the Be disk stripper will reach its limit in near future due to its large deformation and requires further development for the RIKEN RIBF intensity upgrade program.

INTRODUCTION TO CHARGE STRIPPERS

The production of high-intensity radioactive-isotope (RI) beams is one of the important applications of heavy ion accelerators. The three major heavy ion accelerator facilities (RIKEN, MSU/NSCL, and GSI) are each operating or constructing facilities (Radioactive-Isotope Beam Factory (RIBF) [1], the Facility for Rare Isotope Beams (FRIB) [2], or the Facility for Antiproton and Ion Research (FAIR) [3], respectively) to produce high-intensity RI beams using in-flight fission or projectile fragmentation of accelerated uranium ions in order to explore inaccessible regions of the nuclear chart. These facilities adopted different accelerator schemes, such as cyclotrons for RIBF, superconducting linear accelerators (linacs) for FRIB, and synchrotrons for FAIR. However, all facilities begin the acceleration with low charge state ions from the ion source and strip their charge once or twice during acceleration to increase the energy gain or decrease magnetic rigidity.

After passing through a stripper thick enough to reach a charge equilibrium, the charge state is an increasing function of projectile energy. Figure 1 shows the equilibrium charge state of uranium ions in solid as a function of projectile energy. In this study, we focus on charge strippers for uranium ion acceleration because these strippers encounter the most difficult problems due to largest heat deposits and heaviest radiation damage. The lines in Fig. 1 show the paths of the charge states at the three facilities. To increase the charge from 4+ to 28+, FAIR uses an N_2 gas stripper at 1.4 MeV/u because the acceleration of the low charge state to 28+ is essential for reducing space charge forces in the pulsed operation. To increase the charge from 33.5+ to 78+ on average, FRIB uses a liquid lithium stripper at 17 MeV/u. About 80% of the input ions can be gathered using multi-charge-acceleration technique. Finally, RIBF adopted two-step charge stripping at 11 MeV/u and 51 MeV/u to increase the charge from 35+ to 86+. We identify the following requirements for charge strippers:

- High charge state,
- High stripping efficiency,
- Small energy spread,
- Long lifetime,
- Good stability.

A high charge state is required to reduce the total accelerating voltage and cost. In this sense, solid or liquid strippers are preferred because the density effect provides about 20% higher charge states compared to gas strippers. Suppression of electron capture in low-Z materials is another method for obtaining a higher charge state [4]. This suppression comes from the slow velocity of electrons in low-Z materials, and the resulting stripping efficiency should be high. The typical stripping efficiency of a charge stripper is around 10–30%. Using too many strippers decreases beam intensity to zero. In some cases, the shell effect aids the high stripping efficiency. Moreover, the energy spread after the beam passes through the stripper should be small. There are the main two causes for the energy spread: non-uniformity in the stripper thickness, and straggling charge state energy arising from the fluctuation of charge states in the material [5]. The lifetime of the charge stripper should be long. In particular, lifetime-related problems are critical to high-power beam operation. Finally, good stability contributes to the stable operation of the accelerator complex.

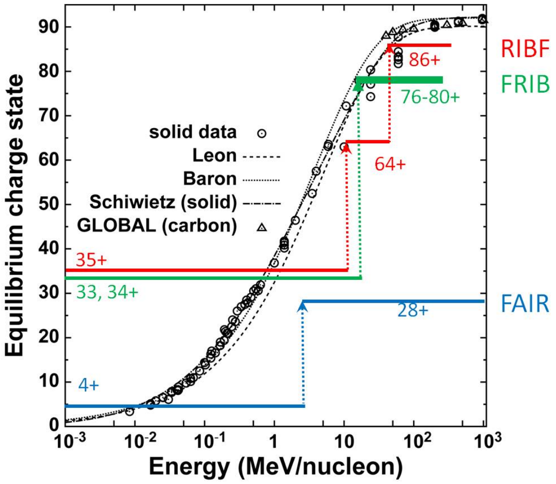

Figure 1: Charge evolutions in uranium acceleration for FAIR, FRIB, and RIBF as a function of projectile energy with an equilibrium charge state.

RESEARCH AND DEVELOPMENT (R&D) RESULTS FOR FRIB AND RIBF

This section describes the R&D results on the charge strippers for FRIB and RIBF to show how the requirements discussed in the previous section can be fulfilled.

Liquid Lithium Stripper at FRIB

The FRIB liquid lithium charge stripper was developed in collaboration with Argonne National Laboratory (ANL) [6]. The charge stripper module primarily consists of a vacuum chamber to produce thin liquid film and a compact electromagnetic pump. The length of the module is 2 m in the beam line. This stripper is used for electron stripping light ions to uranium at 17 MeV/u. The designed maximum power deposition is 30 kW/mm^3. A round lithium jet from nozzle is impacted on the edge of the deflector to produce films as thin as 10 μm. The velocity of the lithium liquid is 50 m/s, and the temperature is approximately 200°C. The electromagnetic pump makes lithium flow in a helical tube using coupling between the radial field from a permanent magnet and current in the axial direction. The experimental work was performed with low-energy proton beams from the Low-Energy Demonstration Accelerator (LEDA) source at the Los Alamos National Laboratory (LANL). The beam was deposited on the liquid lithium film with a power density deposition similar to the maximum expected at FRIB when accelerating 400 kW of uranium. The film was not perturbed at the beam impact point as shown in Fig. 2. To test the stability and reliability of the charge stripper, FRIB will construct the charge stripper module within the next 6 months using continuous flow.

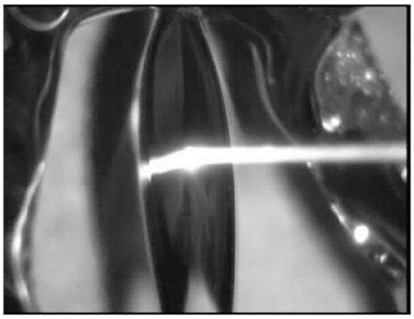

Figure 2: A photo of the high speed lithium film being impacted by a 70 keV, 300 W proton beam.

Charge Strippers at RIBF

Figure 3 shows the acceleration scheme for uranium ion beam at RIBF. The 35+ ions from the 28 GHz superconducting electron cyclotron resonance (SC-ECR) ion source [7] are accelerated using four ring cyclotrons: RIKEN Ring Cyclotron (RRC), fixed-frequency ring cyclotron (fRC), intermediate-stage ring cyclotron (IRC), and superconducting ring cyclotron (SRC). The two charge strippers are installed at 11 MeV/u and 51 MeV/u to enhance the charge state from 35+ to (64+/71+) and from (64+/71+) to 86+, respectively. After 2006, our continuous efforts greatly increased the uranium beam intensity from 0.03 pnA to 25 pnA. In particular, the new injector with 28 GHz SC-ECR was commissioned in 2011 [8]. Figure 4 shows the beam intensity of uranium ion at the exit of SRC, which was the last ring cyclotron in 2007. Even when the beam intensity is about one-ten-thousand of the goal intensity of 1 pμA, this decrease in the beam intensity clearly shows the degradation of the conventional carbon foil used as the first stripper, which motivated us to begin extensive R&D studies.

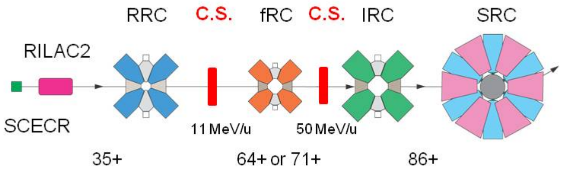

Figure 3: Acceleration scheme for uranium beams using two strippers.

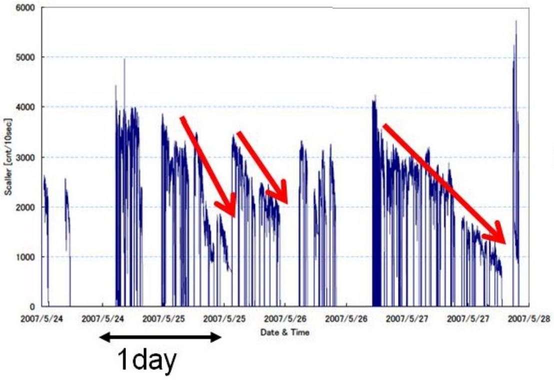

Figure 4: The current trend at the exit of SRC in 2007.

In our R&D for the first stripper, we consider both foils and gas strippers in parallel. We first considered rotating cylinder foils with large carbon foils to expand the irradiation area. The first test failed catastrophically, and the foil broke in 3 min. However, from measurements, we identified the importance of the slow cylinder rotation and the robustness of the carbon nanotube (CNT) foils. Finally, we found that slowly rotating CNT-based foils can survive for a long time, as shown in a user run in 2011 [9]. We further studied a gas stripper, which measured equilibrium charge states in N_2 and Ar gas, using a small gas cell with a differential pumping system [10]. The charge states in these materials are far below the acceptable charge states for fRC. However, we suggested that low-Z gases can increase the charge state [4]. The experimental results of the cross-sectional measurements for electron-loss and electron-capture using the small gas cell were promising and encouraged us to make prototypes to measure fundamental data such as the evolution of the charge state and the energy spread after the stripper [11]. Finally, we determined that the helium gas stripper practical

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even though some technical issues remained. In particular, the most challenging issue is the sufficient confinement of the thick helium gas in order to reach charge equilibrium. However, we realized the helium gas stripper for practical operations after overcoming the confinement issue [12], and it has been working well since November 2012.

Figure 5 and 6 illustrate the fundamental data for the charge evolution and energy spread of the uranium ion after the stripper. Figure 5 clearly shows higher charge states in He gas than those in Ar and Ne. Here, we note that the charge reaches equilibrium slowly in He gas compared to other gases because the electron-loss cross-section is proportional to the square of the atomic number, resulting in a smaller cross-section in He than that in other gases. The obtained equilibrium charge states are consistent with the cross-section measurements that show significant charge-state enhancement in He gas compared to that in the reference N_2 gas [4]. Figure 6 shows the energy spread of the uranium ion. Charge state straggling is dominant in He gas, while non-uniformity is dominant in carbon foils. The red circled points show the energy spread in the operational points. In real operations, a smaller energy spread can be expected in He than that in fixed carbon foils. Moreover, when rotating strippers are used, an additional energy spread occurs due to non-uniformity in large carbon foils. Figure 7 shows the jitter of beam timing after the He stripper and rotating carbon foil, and the periodic behavior shows the non-uniformity of the thickness distribution in the large foil.

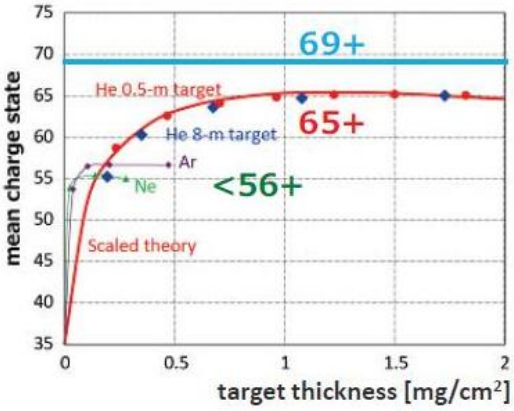

Figure 5: Measured and calculated charge-state evolution for He, Ne, and Ar.

There was little R&D activity for the second stripper before the new injector system was commissioned because the foil temperature can be kept low in low-intensity beams. After the new injector operation began, the lifetime of the fixed carbon foil became as short as 5–10 h due to high temperatures of the foils. We then tested Be, Ti, and C wheel strippers. Figure 8 shows the measured charge distribution after the Be and Ti wheel strippers. The charge-state distribution after the Be stripper is similar to that after the fixed carbon foil stripper, reaching a maximum at charge state of 86+. However, the charge state after the Ti wheel stripper is low. The charge distribution after the carbon wheel could not be measured because of the poor uniformity of thickness. The energy distribution after the disks was measured by a scintillation counter placed downstream of the second stripper. The data shows that energy width after fixed carbon foil, Ti disk, and Be disk are comparable, while rotating carbon disk had a very broad distribution. Based on the fundamental data, we decided to use the Be disk [13]. We had also measured the charge distribution in gas. However, the mean charge after the N_2 and He gases was more than three times lower than that after the carbon foil. The lowest acceptable charge state is 86+ for the last cyclotron, but we could not achieve a sufficiently high charge state in gas.

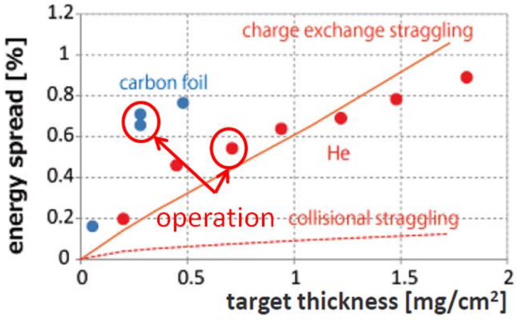

Figure 6: Obtained energy spread for He and carbon-foil strippers as a function of the target thickness.

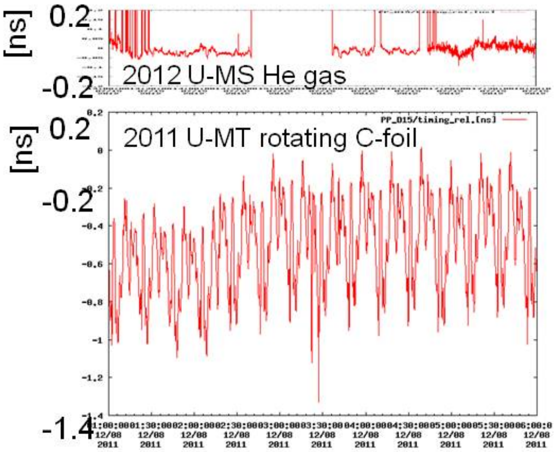

Figure 7: Jitter of the beam timing after the He gas stripper and the rotating carbon-foil stripper.

OPERATIONAL EXPERIENCES AT RIBF

Table 1 lists the charge strippers adopted for user runs after extensive R&D studies. In 2011, to accept the increasing beams, we used large rotating CNT-based foils, which greatly contributed to the extraction of a 2.4-pnA uranium beam from SRC. In 2012, we replaced the carbon-foil-based system with the He gas stripper and the Be disk stripper. The fRC was modified to increase the bending power to accept 64+ for this replacement. These new charge stripping sys-

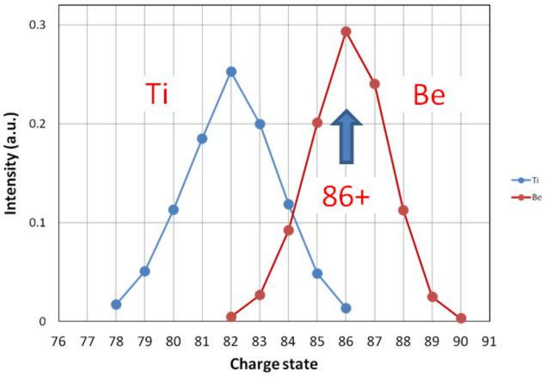

Figure 8: Charge distributions of the uranium ion at 51 MeV/u after rotating Be and Ti disks.

Table 1: Charge Strippers Used during User Runs at RIBF

Year	Q1	1st C.S.	Q2	1st C.S.	Q2	Iext. (pnA)
2007-2009	35	C-foil	71	C-foil	86	0.8
2011	35	Rotating CNT -SDC foil	71	C-foil	8+	2.4
2012-	35	He gas	64	Rotating Be disk	86	15-25

tems greatly contribute to the extraction and stable supply of 15-pnA and 25-pnA uranium beams from 2012 to 2014. Figure 9 shows the helium gas stripper [12], where 7 kPa of He gas can be accumulated over a cell length of 50 cm. The total thickness of He is 0.7 mg/cm^2. Using 21 pumps, about 430 m^3/day of He gas can be circulated. The five stage differential pumping allows eight order pressure reduction. The resulting beam aperture is greater than 10 mm. The stripper has a unique recycling system wherein gas leaking through through the orifices in the gas cell is evacuated by mechanical booster pumps (MBPs) and directly returned to the gas cell chamber. Moreover, this system does not have problems with oil contamination because the MBP is effectively oil free. This system was utilized in real operations beginning in November 2012. In practical operations, we were concerned that the target thinning caused by the heat load due to uranium beams will determine the application limit of gas stripper. We measured the time-of-flight (TOF) of U^{64+} beams as a function of the beam intensity using phase probes during the operation. Figure 10 shows the time difference of the ions. A large time difference indicates the early arrival of the ion, which further indicates target thinning due to increasing gas temperature. The beam intensity at the gas stripper is around 0.6 pμA at maximum, which corresponds to an energy deposit of 50 W. The data shows that the increase in temperature is about 15 K which does not affect on beam operation so much, suggesting that that gas is not heated as expected. We believe some suppression mechanism of the heat efficiency exists. We will perform a spectroscopic study of the mechanism in the near future. The second concerning point is impurity because the practical stripper recycles the helium gas where impurity could easily be contained. The effect of impurity (air, water, hydrocarbon) on the charge state can be large for the low-Z gas stripper because the capture cross-section is proportional to $Z^{4.2}$. The level of impurity must be less than 100 ppm to avoid affecting the charge state. Thus, the charge state in the gas is very sensitive to impurities. Charge states with recycled helium are compared to the charge evolution obtained in Fig. 6; no significant difference could be identified.

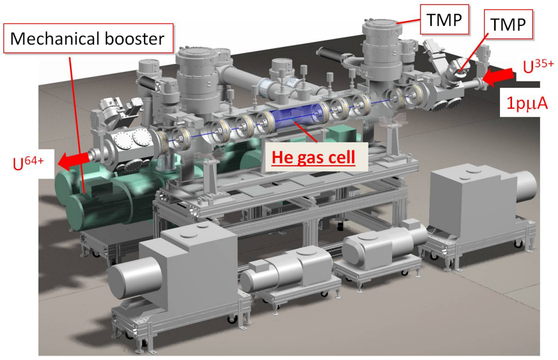

Figure 9: Cross-sectional view of the newly constructed recirculating He gas stripper.

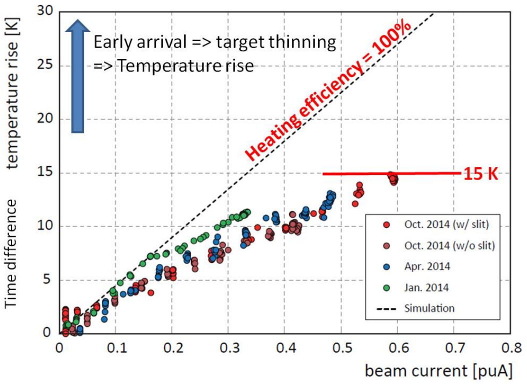

Figure 10: Time difference in ion arrival from the He gas stripper as a function of the beam current. Time difference of 1 ns corresponds to a temperature rise of 22 K.

As discussed previously, Be rotating disks were used for the second stripper. The rotating disk module can provide rotation speeds of about 1000 rpm at maximum and 60 times the irradiation area of the beam spots [14]. Figure 11 shows the disk before, during, and after irradiation. The disk thickness is 0.1 mm, and the heat load on the stripper is around 90 W. The Be disk survived more than one month of beam irradiation although the disk was severely deformed [13]. Beryllium is ductile above 400°C and brittle below 400°C. Thus, the deformation is a result of thermal cycle properties and has an effect on the beam quality after the stripper. In fact, beam loss occurs in the operation due to fluctuation of

Table 2: Candidates for Second Charge Strippers at RIBF

Material	Status/Merits	Demerits	Future work
CH_4 (gas)	Experience in RIBF	Combustible	Charge state
Be (solid)	Experience in RIBF	Large deformation	Improvement of structure
C (solid)	Experience in RIBF	Poor uniformity in thickness	New material
SiC (solid)	Heat resistant	Low charge	Charge state
Li (liquid)	Experience in FRIB/ANL and BNCT	Combustible	Study using water

the beam after the second stripper as a result of the large disk deformation.

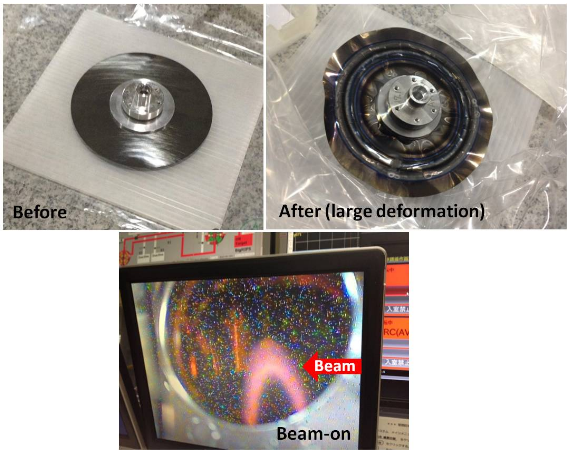

Figure 11: The Be disk stripper before, during, and after beam irradiation.

OUTLOOK AND SUMMARY

The Be disk will reach its application limit in the near future due to its large deformation, and we need a stripper that can survive beam irradiation with 2–3 times the present beam intensity to realize 100 pnA at the SRC exit, which is our goal intensity. Furthermore, more extensive R&D studies will be performed because the charge stripper is highly important to the future goal intensity. Figure 12 explains a proposed upgrade plan. The present scheme for the uranium beam uses two charge strippers to breed the charge from 35+ to 64+ and from 64+ to 86+. Only 5% of the initial beam reaches the final accelerator with two-step charge stripping. In essence, our upgrade plan disregards the first stripper to increase the beam intensity by a factor of five and to improve the beam quality. Moreover, the present fRC should be replaced with a superconducting fRC to increase the bending power for an acceptance of 35+. As a result, the load to the charge stripper will be more severe. We will test the candidates listed in Table 2, including methane gas, beryllium with an improved structure, carbon disks with good uniformity, silicon carbide, liquid lithium, and oil.

In summary, the charge stripper is a key issue for heavy ion accelerators with high intensity. The liquid Li stripper research is continuing successfully at FRIB. Moreover, the helium gas stripper solved the bottle-neck problem in uranium acceleration, and the Be wheel was successfully applied for the second stripper. For further intensity upgrade, we need to continue research for the second stripper (CH_4 gas, C, Be, SiC, and liquid Li).

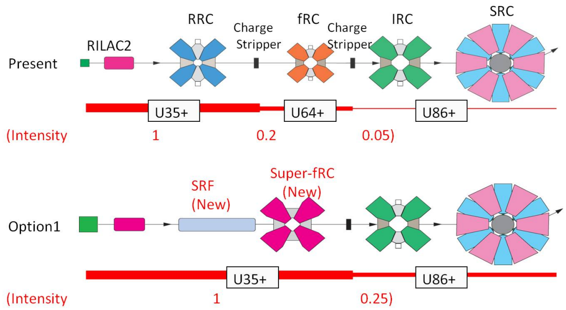

Figure 12: Acceleration scheme for optional intensity upgrades using the present plan.

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