# REALIZATION OF NEW CHARGE-STATE STRIPPER FOR HIGH-POWER URANIUM ION BEAMS

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### *Abstract*

Recent works to realize the new charge-state stripper using recirculating helium gas are presented. Very limited lifetimes of conventional solid-state strippers due to huge dE/dx for very heavy ion beams (e.g., for uranium ions, several thousand times larger than protons at the energy around 10 MeV/u) were a principal bottleneck for their multi-stage acceleration at high intensities. The new stripping system is characterized by its infinite lifetime, efficient stripping and small beam degradation even for the world's most intense uranium ion beams provided by the RIBF (more than 1 pμA at the injected energy of 11 MeV/u). Successful operations of the system in 2012 greatly contribute to the remarkable expansion of the accelerator performance of the RIBF that will allow an enormous breakthrough for exploring new domains of the nuclear world in the next several years; the peak intensity of the uranium beam has reached 15.1 pnA (almost $10^{11}$ pps) at 345 MeV/u and the average intensity provided for the users has become approximately ten times higher than it was in 2011.

## PRESENTATION

I would like the readers of this manuscript to refer to my transparencies which I displayed in the prize presentation session (they are included in the present proceedings.) The followings are the presentations for each slide. Some more information is added.

### *Slide No.1*

First of all, I would like to express my sincere gratitude to the ACFA/IPAC organizing committee and the prize selecting committee for this prestigious prize. I feel highly honored to receive this prize and to be able to speak you today. I would like to talk about a new charge-state stripper using helium gas which contributed recent intensity upgrade of uranium beams at the RIBF.

### *Slide No.2*

In this presentation, I will first explain the uranium acceleration by discussing recent problems of charge strippers. Next, I am going to explain how we have realized the newly constructed re-circulating helium gas stripper. Further, I will show you some of the highlight data obtained from the recent runs with uranium beams. Finally, I will briefly summarize my presentation and talk about future prospects.

### *Slide No.3*

OK, first let me mention why we decided to conduct the present study. What you see here is the bird view of the RIKEN RI beam factory (RIBF) [1], which is a cyclotron-based heavy-ion accelerator complex. The RIBF is designed to accelerate the whole mass range of heavy ions from hydrogen to uranium, and our target beam intensity is 1 pμA. In particular, the intensity upgrade of uranium beams is critical to significantly expand the nuclear chart.

This figure shows the timeline of the achieved beam intensity of light, medium-heavy, and heavy elements at the RIBF [2]. Our group has already achieved the goal intensities for light elements and also near goal for medium-heavy elements. But, the present intensity of the heavy elements is quite low. Especially for uranium beams the achieved intensity is 3.5 pnA in 2011, which is less than 1% of our ultimate goal. The competing FAIR [3] and FRIB [4] projects will begin operation in the next 5-7 years. So, we would like to accelerate the development of high-power uranium beams. The charge stripper is a key factor for that purpose.

### *Slide No.4*

One of the important features in multi-stage heavy ion accelerators is the flexibility of the charge state of ions during the acceleration. The charge state is controlled by the ion source and the charge-state strippers.

This figure shows the charge state changing during the acceleration at the RIBF, FAIR and FRIB projects. In the FAIR project, they will generate and accelerate the uranium ions with the lower charge state to reduce the space charge effects, because they use synchrotrons with pulsed beams. The RIBF and the FRIB generate highly charged uranium ions from the ion sources and the beam charge state is transformed at intermediate energies to increase the acceleration efficiency. In these DC beam facilities, the problem is that there is no established ways of electron stripping for high-current uranium beams at the intermediate energy region.

### *Slide No.5*

This figure shows the original acceleration scheme of uranium and calcium ions at the RIBF. In the graph shown, the horizontal axis indicates the beam energy and the vertical axis indicates the beam intensity. The charge state is transformed twice using thin carbon foil strippers for both beams. As you can see, the intensity of the uranium beams reduces with increasing energy.

This is caused by the difficulty in the electron stripping of uranium beams. For very heavy ions such as uranium ions, the binding energies of the inner shell electrons are

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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, fRC, IRC and SRC.

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 [5]. It is thousands times higher than that of protons and near maximum at the injection energy of 11 MeV/u at the first stripper.

## *Slide No.6*

Actually, the problem for high-power uranium acceleration was concentrated on this first carbon foil stripper. The foil thickness required at this energy is very thin less than 1 µm [6, 7]. The problems of using such thin foil stripper for high-power uranium beams include the fragility, thickness non-uniformity, and poor thermal conductivity. This is a primary bottleneck of uranium acceleration.

Roughly speaking, the maximum possible injection current of the present best carbon foil stripper for the stable operation is only about 0.02 pµA [8]. Even for the rotating carbon foil stripper we recently developed, the possible current is as low as 0.3 pµA. The injection current up to 10 pµA is required to get the goal intensity of 1 pµA after the SRC. Therefore, some drastic improvement to the first stripper was emergently required.

## *Slide No.7*

Our group has been developed a low-Z gas stripper replace to the conventional carbon-foil stripper [9, 10]. This stripper is non-destructive and simultaneously provides uniform thickness and high charge state equilibrium of the low-Z gas.

The high charge equilibrium is owing to the slow velocity of the 1-s electrons of low-Z gas. Such slow electrons are difficult to transfer to fast projectiles because of poor velocity matching. So, the electron capture process is strongly suppressed. You can imagine the importance of velocity matching in transfer process from this picture.

This graph shows the calculations of electron loss [11] and capture cross sections [12] for various gas strippers. The charge equilibrium is determined from the intersection of the electron loss and capture. If the capture cross section decreases, the charge equilibrium increases [9].

## *Slide No.8*

However the realization of the low-Z gas stripper is very difficult. One of the primary technical challenges in realizing the He gas stripper is gas confinement in a windowless vacuum because helium gas is very diffusive. At the same time, we require a thick target because of the small charge exchange cross sections of He. The charge equilibrium becomes slower as shown in the figure.

In our preliminary research, we developed prototype He strippers. We examined the feasibility of He gas confinement and obtained some fundamental data regarding charge state distribution, energy spread, and beam transmission.

## *Slide No.9*

This is the first prototype system for low-Z gas confinement [13]. Hydrogen or helium gas was directly confined within the beamline. The charge states of the beams through the 8-m target were analyzed using dipole magnets.

## *Slide No.10*

This is the second prototype for helium gas confinement [10]. It could confine 2 mg/cm$^2$ of He within a 50-cm target region. We note that this system could also confine 30 mg/cm$^2$ of nitrogen. You can see the difficulty of the helium gas confinement from this difference.

## *Slide No.11*

This slide shows our obtained data with the prototype strippers. The top figure shows the measured charge evolution in various gas. The maximum mean charge state for the He gas stripper is 65+. Unfortunately, this is lower than 69+, which is the minimum acceptable charge state of the fRC. But this value is significantly higher than the value of 56+ obtained with a high-Z gas stripper like nitrogen [14].

Further, we found that the obtained energy spread with He gas was half of that obtained with the fixed carbon foil [10]. This indicates good thickness uniformity of the gas stripper.

Moreover, the transmission efficiency was around 70% for the second prototype system.

The strategies for the practical system development are listed here. We determined the beam acceleration for charge states of 64+ and correspondingly modified the fRC to ensure low-charge acceleration. We found that, in practice, the target thickness should be reduced to avoid emittance growth and that the beam orifice should be enlarged to improve transmission.

## *Slide No.12*

This image shows the actual design of the He gas stripper. The charge state of uranium 35+ ions coming from the RRC is transformed here and uranium 64+ ions is send to the next cyclotron, fRC. The system consists of two 5-stage differential pumping systems, one on each side of the 50-cm target region. 22 pumps are used in the system. The stripper is designed to achieve vacuum reduction from the target pressure of 7 kPa to $10^{-5}$ Pa within a length of 2 m while ensuring a 10-mm beam path. The He gas flow is about 300 cubic meters per day.

In this practical system, huge gas flow is very problematic. If we evacuate them, we require the gas cylinders bundle shown here every day. This is completely unfeasible, so we recirculated the He gas. I will show you a key idea to realize the high-flow recirculation.

### *Slide No.13*

Here, you see the schematic of a typical recirculating system with rotary pumps. In this configuration, we require a high-flow gas purification system to remove oil contamination due to the rotary pumps.

We simplified the system by using only the mechanical booster pumps (MBPs) as shown in the figure. Oil contamination due to the MBP is negligible in this configuration. Therefore, we were able to reduce the complexity of the purification system.

The use of such a recirculating system is unprecedented to our knowledge. It is highly advantageous not only in terms of cost reduction but also for realizing a stable target and a reliable stripper system.

### *Slide No.14*

This is a schematic of the actual recirculating system. The multistage MBP array consists of 7 MBPs. The total nominal pumping speed is 12000 $m^3$/h. About 200 L/min of helium gas is recirculated. The maximum recycling rate is 99.6%. About 0.4% of the gas is evacuated and send to the liquefaction facility at the RIBF, but this slow replacement of the target gas is very important to avoid the accumulation of impurities and target activation. The system uses an auto pressure control valve to maintain a constant target pressure.

### *Slide No.15*

This is a time schedule of R&D works performed in 2012. The system has been installed in January. Offline tests of gas confinement have also been performed. We verified that the gas confinement and recirculation performance were as per the designed performance values. After performance tests with uranium beams, we actually operated the system in user runs at the end of the last year.

### *Slide No.16*

Let me show you some highlight data. Checking the effect of possible impurities on the charge state is important. The charge state of the beams after the He stripper is very sensitive to contamination by impurities because the cross section of He is very small. Unfortunately, at the present target pressure of around 10 kPa, there is no simple method to measure the impurity concentration. In this sense, the measurement of the charge state distribution is the most sensitive test of impurity contamination.

This figure shows the data for the charge state evolution in He gas. The red circles indicate the data obtained with a recycling rate of 99.6%. These values correspond to the data obtained with no recycling, as indicated by the blue and green plots. Both data are overlapped. Thus, we see that the impurities have reduced to a satisfactory level.

### *Slide No.17*

This is just a comparison of the beam intensities after the strippers between 2011 with the rotating carbon foil strippers and 2012 with the He stripper. The system was successfully operated without any deterioration in user runs during 1.5 months in 2012. As you can see, the intensity is drastically increased. The blue line indicates the expected application limit of the rotating carbon foil stripper for the stable operation. The new He stripper contributed an important bottleneck breakthrough.

The peak intensity after 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 become ten times higher than it was in 2011. This is good result.

### *Slide No.18*

Finally, here is a video showing the glow of uranium beams within the stripper. This blue line indicates the uranium beams. Watch as the intensity slowly increases. This is the current maximum intensity, 1 pμA. The temperature increase in the water-cooled tube orifices as shown in the picture was tolerable with the transmission efficiency about 80%.

### *Slide No.19*

OK. I would like to summarize my talk. The new He gas stripper removed the primary bottleneck in the high-intensity uranium acceleration. Some other remarkable accelerator upgrades as listed here have been also successfully performed at the RIBF. These improvements brought the tenfold increase of the average output intensity of the uranium beams from the previous year. In summary, we realized a new acceleration scheme with the He gas stripper which is applicable for high-power uranium beams.

In future, of cause, we will aim further intensities by sophisticating this new acceleration scheme. I believe that worlds RI beam facilities will enter further interesting and exciting period in the next decade.

### *Slide No.20-22*

I would like to acknowledge my mentors, colleagues, collaborators and all people who worked with me. I am here completely because of them. I also acknowledge my family for their understandings. Thats all. Thank you very much for your attention.

## REFERENCES

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

[2] H. Okuno *et al.*, Prog. Theor. Exp. Phys. 03C002 (2012).

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

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

[5] O.B. Tarasov, D. Bazin, Nucl. Instrum. Methods Phys. Res. **B266**, 4657 (2008).

[6] H. Hasebe *et al.*, Nucl. Instrum. Methods Phys. Res. Sect. **A613**, 453 (2010).

[7] H. Hasebe *et al.*, Nucl. Instrum. Methods Phys. Res. Sect. **A655**, 57 (2011).

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

ISBN 978-3-95450-122-9

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

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

[11] M. Gryzinski, *et al.*, Phys. Rev. **A138**, 305, 322, 336 (1965).

[12] A. S. Schlachter *et al.*, Phys. Rev. **A27**, 3372 (1983).

[13] H. Imao *et al.*, IPAC11, TUPS088 (2011).

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

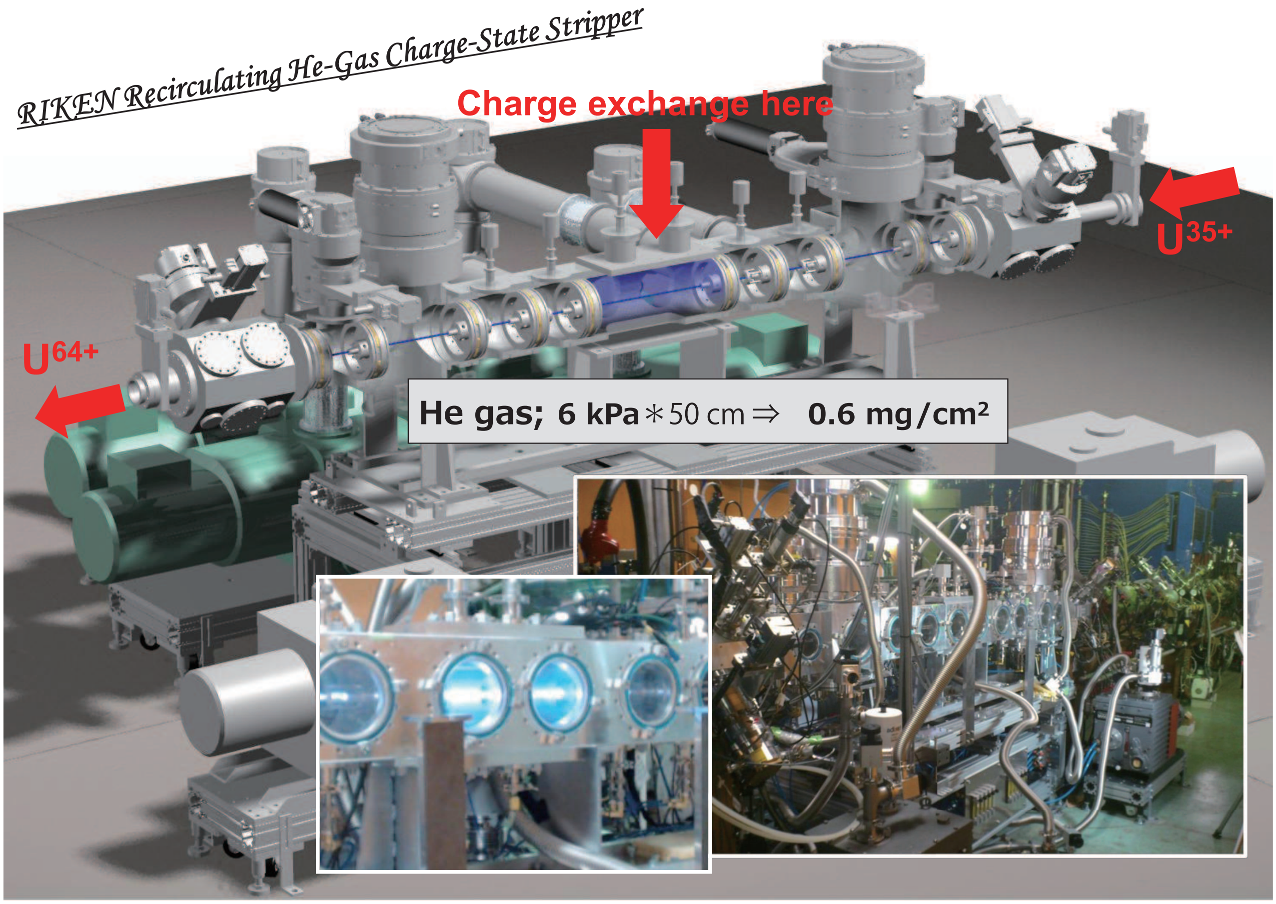

Figure 1: Cross sectional view of the newly constructed recirculating He gas stripper and pictures of the actual stripper and the glowing 1 pμA uranium beams in He gas.

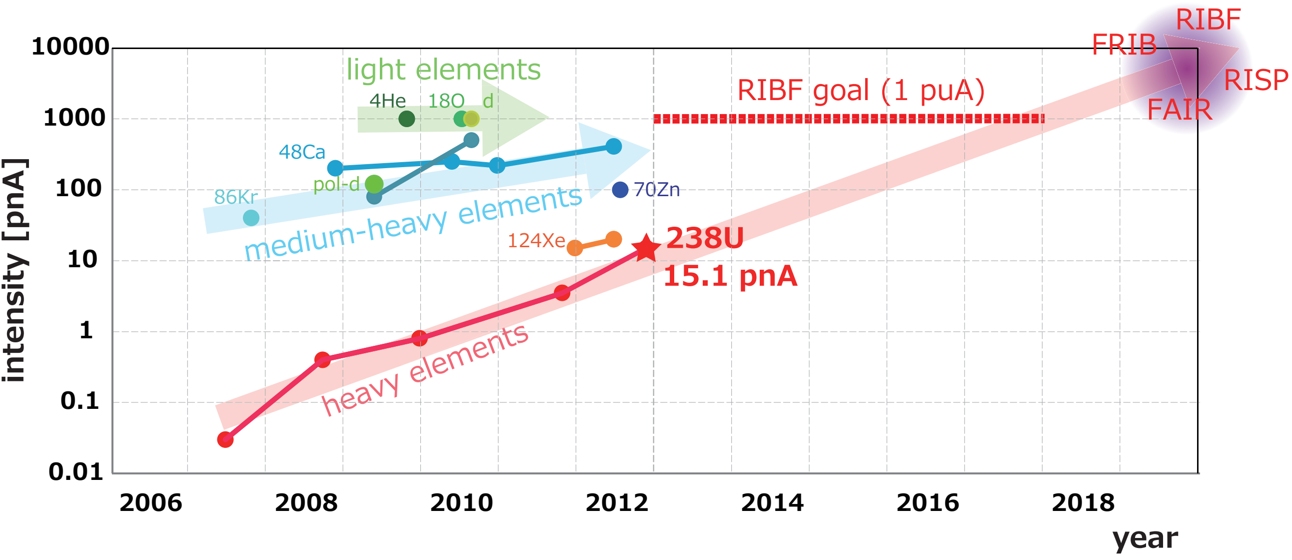

Figure 2: Evolution of maximum beam intensities at RIKEN RIBF and a very rough prediction.