ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-MOZGBE1

DEVELOPMENT OF GAS STRIPPER AT RIBF

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Abstract

Charge strippers are almost inevitable for accelerations in heavy-ion accelerator complex. The fixed solid strippers including carbon-foil strippers are difficult to be used in on-going or upcoming new-generation in-flight RI beam facilities, e.g., RIBF (RIKEN, Japan), FAIR (GSI, Germany), FRIB (NSCL/MSU, US), HIAF (IMP, China) and RAON (RISP, Korea). The He gas stripper developed at RIBF is the first successful stripper significantly beyond the applicable limit of the fixed carbon-foil strippers. We discuss the development of the gas strippers at RIBF and overview the related new-generation strippers being developed in the world.

INTRODUCTION

Charge strippers are very common and almost inevitable in most high-energy hadron accelerator complex. For proton accelerators, the charge-exchange injection techniques to the booster or storage rings are very common [1,2]. In heavy-ion accelerators, the strippers are important to increase the energy gain during the acceleration at the post accelerators. The performance of the charge stripper determines the whole design and performance of the heavy-ion accelerator complex.

Traditionally, the carbon foils are widely used for strippers. The carbon foils are relatively easy to make thin foil strippers and they works well even at high temperatures. Most of high-intensity proton accelerators and relativistic heavy ion colliders [3] use various fixed carbon foils successfully. However, the fixed solid strippers including carbon-foil strippers are difficult to be used in upcoming new-generation in-flight RI beam facilities.

The dE/dx of very heavy ions, such as U and Xe, is huge, which may cause fatal heat load and radiation damage on carbon foils. For uranium ions at the intermediate energies (e.g., 1-50 MeV/u), the energy deposits are thousands times higher than that of the protons. New-generation in-flight facilities demand the stripper for uranium ions at these energies. Roughly speaking, the fixed carbon foil strippers provide the applicable limit when we use them with the uranium beams of the intensities around 10^{11}/s at the intermediate energies.

Figure 1 shows an example of the operation at the application limit of fixed carbon-foil strippers at RIBF. It shows the variation of the beam intensities during a machine time for xenon beams performed in 2012 at the RIKEN RI Beam Factory (RIBF [4]). Green lines show the timing of the replacement for the first carbon foil stripper and blue line shows the timing for the second carbon stripper. During 20 days of the whole machine time, the carbon foils were replaced about 70 times. The mean lifetime for the first carbon foil was around 5 hours and around 12 hours for the second one. The decay curves of carbon foils after the replacements are seen clearly in Fig. 1. Upcoming in-flight RI beam facilities in the world would share the same difficulties

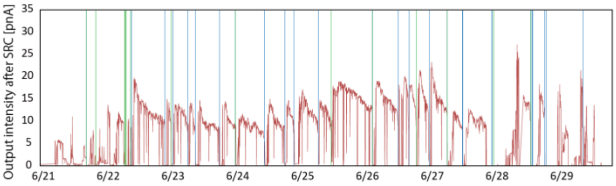

Figure 1: Variation of the beam intensities during a machine time for Xe beams performed in June 2012 at the RIBF.

New-generation in-flight RI beam facilities with drastically enhanced performance in producing RI beams are planning and developing in the world. Among the new-generation facilities, only the RIBF in Japan is currently in operation. The Facility for Antiproton and Ion Research (FAIR [5]) at the site of GSI (Germany) and the Facility for Rare Isotope Beams (FRIB [6]), at the site of NSCL in MSU (US) are under construction. In Asia, the High-Intensity Heavy Ion Accelerator Facility (HIAF [7]) in China and RAON facility [8] in Korea are launched. These facilities are aiming the intensities around 10^{12}/s or more and the fixed carbon foil strippers cannot be applied simply.

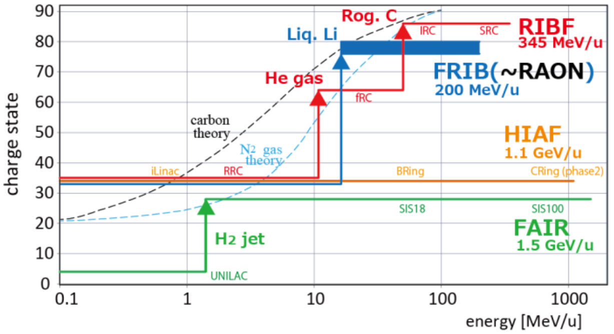

Figure 2: Charge changing during an acceleration of uranium ions for RIBF, FRIB, RAON, HIAF and FAIR.

Figure 2 shows the charge changing during the acceleration for uranium ions at RIBF, FRIB, RAON HIAF and FAIR projects. The charge states of the ions are controlled by the combination of an ion source and charge-state strippers. In HIAF (for phase 1), they will generate the high-charge state (U^{34+}) from a pulsed afterglow ECR ion source directly and accelerate them without stripper using synchrotrons (Bring and CRing). The development of the ion source is a key issue in their acceleration scheme. In FAIR project, they will generate relatively

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lower charge state (U^{4+}) from ion sources. They use a stripper at relatively low energy to accelerate uranium ions with the lower charge state to reduce the space charge effects in subsequent synchrotrons (SIS18 and SIS100). In FRIB and RAON, they will use stripper at around 20 MeV/u and will accelerate several charge states at the same time after the stripper using a superconducting linac. At the RIBF, the charge strippers are used twice to fully use the acceleration abilities of four ring cyclotrons (RRC, fRC, IRC and SRC).

The requirements for the strippers for the new-generation in-flight RI beam facilities are listed here.

- Long lifetime,
- High charge state,
- Stripping efficiency,
- Thickness uniformity and stability,
- Safe handling.

New strippers should have long lifetime to resist the huge heat load and the radiation damage due to powerful uranium beams. Fluid strippers or moving solid strippers is a possible candidate. Although high charge states are always desired, low-density media such as gas provides lower charge state due to the lack of the density effect. Stripping efficiency related with the atomic shell and multi-electron process is important to increase the output intensities. The thickness uniformity and stability are also important parameters to reduce the beam loss in the subsequent accelerators. Safe handlings should be cared. Table 1 shows the parameters of main strippers developed at FAIR, FRIB and RIBF.

Table 1: Parameters of Strippers at FAIR, FRIB and RIBF

	FAIR	FRIB	RIBF	
Form	H2 gas	Liq. Li	He gas	Rot. disk
Energy [MeV/u]	1.4	~20	10.8	50.8
Input charge	4	33, 34	35	64
Output charge	28	76-80	64	86
Intensity [pps]	~1x10^{12}	~5x10^{13}	~1x10^{13}	~2x10^{12}
Thickness [mg/cm^2]	~0.03	~0.5	0.7	14
Energy loss [W]	~10	~700	180	270
key tech.	Pulse op.	Liq. film Safe op.	Windowless accumulation	Good material

STRIPPERS FOR FAIR

The injector of FAIR is the existing linac, UNILAC. The charge stripper is placed there and the injection energy is 1.4 MeV/u. The charge state is converted from 4+ to 28+. Recent prominent works are those related with the pulsed H_2 gas-cell stripper [9]. In the system, the gas injection is synchronized with the pulsed timing of the accelerator (<200 µs in the duration and <3 Hz in the reputation for FAIR). The pulsed scheme is very effective to reduce the gas load on their 4-stage differential pumping system. Thus, it is possible to make thick low-Z gas target (He or H_2) with the lower gas consumption rates. An optimal H_2 target thickness of around 14µg/cm^2 is available.

The H_2 gas-cell stripper was tested at GSI for the FAIR project in 2015 and 2016 [10]. The equilibrium charge state becomes higher due to the effect of low-Z gas compared with the continuous N_2 gas stripper used previously. Also, the width of the equilibrated charge distribution becomes narrower for H_2 presumably due to the suppression of multi-electron loss and capture processes. As a result, the charge stripping efficiency was drastically enhanced from 12.7(5)% for N_2 (U^{28+}) to 21.0(5)% for H_2 (U^{29+}). The horizontal brilliance of the output beams is also increased reaching to 20.29 mA/µm. The maximum output pulse intensity is 11.5 emA achieved in 2016, which is close to the required intensity for FAIR (15 emA).

Plasma strippers are also suggested for a new stripping media for FAIR [11, 12]. The plasma stripper is free from thermal issues due to the beams. Also, higher charge states can be expected because electron capture processes with free electrons are strongly suppressed kinematically. Frankfurt group working at GSI is making important steps in this direction. They are using some kind of pinch plasma for the stripper. High electron densities up to 3.6x10^{16}/cm^3 are achieved. They demonstrated the charge state enhancement with Au^{26+} beams with the energy of 3.6 MeV/u at GSI. The maximum charge state with a fully ionised hydrogenplasma is between 27+ to 30+ whereas with cold gas the main charge distribution is between 26+ to 28+.

STRIPPERS FOR FRIB

FRIB is a folded superconducting linac aiming the energy of 200 MeV/u and the beam power of 400 kW on the target. The liquid lithium (Li) stripper for FRIB has been developed in collaboration between MSU and ANL [13]. A high pressure Li jet impinging on a deflector produces a thin Li film (~10 µm). The stripping energy is about 20 MeV/u. The beam power at the stripper is about 40 kW and the total energy deposit on the Li film is up to 700 W. The moving speed is about ~ 50 m/s to take the heat away. The lithium is circulated with an electromagnetic pump specially designed. Film stabilities were demonstrated with proton beams (65 kV, 4.6 mA, 300 kW, σ=0.7 mm in the best focused condition) depositing similar power densities as an uranium beam at FRIB conditions [14].

Hazard mitigation is also an important issue. Secondary vessel encloses the entire Li loop and provides a safety barrier (Fig. 3). The vessel atmosphere is maintained as an argon environment during operation (i.e. when Li is not solid). The detection of abnormal situation (i.e. excessive pressure in vacuum chamber or in secondary vessel)

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triggers a shutdown of lithium pump and controlled shutdown of the system. The system is ready to load lithium.

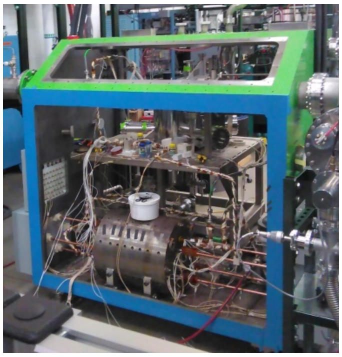

Figure 3: Complete Li loop enclosed in a 2.5 cm steel vessel. Over one hundred temperature sensors included.

ACTIVITIES IN RIBF

Acceleration Scheme for ^{238}U at RIBF

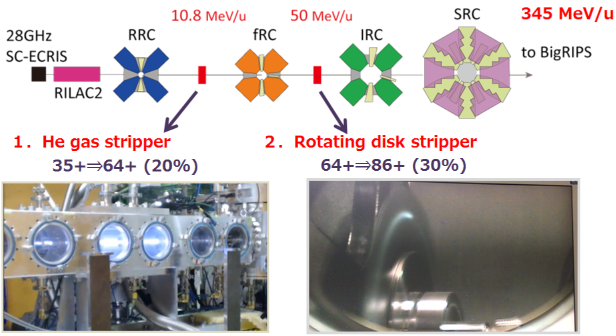

Figure 4: Acceleration scheme for ^{238}U at RIBF.

Figure 4 shows the acceleration scheme of uranium ions at RIBF. The charge state is transformed twice. We used the He gas stripper and a rotating carbon-disk stripper. U^{35+} ions generated with the 28-GHz superconducting ECR ion source is converted to U^{64+} at the first stripper at 10.8 MeV/u and then further converted to U^{86+} at the second stripper at 50.8 MeV/u.

He Gas Stripper

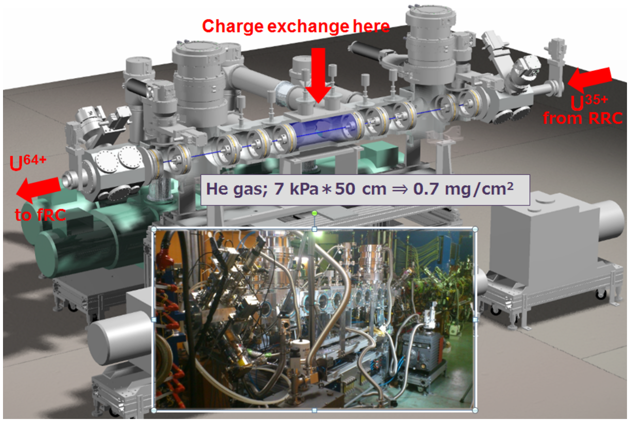

Figure 5: Recirculating He gas stripper at RIBF.

Our group has developed a low-Z gas stripper to replace the traditional carbon-foil strippers [15, 16, 17, 18]. The 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 that the electron capture process is strongly suppressed.

One of the primary technical challenges in realizing the He gas stripper is gas confinement in a windowless vacuum because He gas is very diffusive. Figure 5 shows the actual design of the He gas stripper. The system consists of two 5-stage differential pumping systems, one on each side of the 50-cm target region. 26 pumps are used in the system. The system 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 rate is about 300 m^3/day.

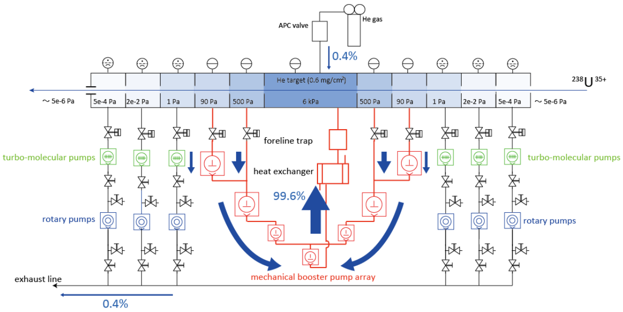

Figure 6: Schematic of He gas recirculation system.

Figure 6 shows a schematic of the actual recirculating system. We used the multistage mechanical booster pumps (MBPs) array consisting of 7 MBPs. The total nominal pumping speed is 12, 000 m^3/h. The maximum recycling rate is 99.6%. The replacement of the target gas is necessary to reduce the accumulation of impurities and target activations.

The maximum mean charge state obtained with the He stripper is 65+. The value is significantly higher than the value around 56+ obtained with a higher-Z gas stripper like nitrogen or argon. We also found the fraction of 64+ (~25%) is enhanced due to the atomic shell effect. The obtained energy spread with He gas was half of that obtained with fixed carbon foils [17].

One concern for using the He gas stripper is that powerful uranium beams may make a hole even in gas strippers. Such target thinning effects will determine the application limit of the He gas stripper. To check this effect, we measured the time of flight (TOF) of uranium beams after the stripper as a function of the beam intensities pathing through the stripper. The mean temperature rise of the He gas along the beam path can be estimated from the TOF data. The obtained temperature rises are plotted in Fig. 7.

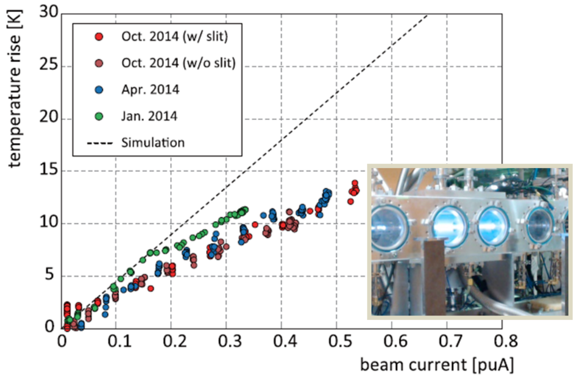

Figure 7: Temperature rises of He gas along the beam path as a function of beam current and picture of glowing He stripper.

Compared with CFD calculations (dotted line), the experimental data is significantly lower, which imply the heating efficiency of uranium beams to the He gas is not so high (~50%). Emissions of vacuum ultraviolet lights from excited helium atoms or molecules are possible processes to explain the low heating efficiency. The target thinning is not so serious problem at the present intensities at RIBF.

N2 Gas-jet Curtain

The present intensity of uranium beams injected into the stripper is reaching to ~10^{13}/s at RIBF. With increasing injection intensities, various difficulties for the operation of the He gas stripper are emerged. Small fraction of beam loss in the He gas stripper causes serious hardware troubles or radioactivites. The qualities of beams injected to the He stripper become worse in high-intensity operations due tospace charge effects in the pre-accelerators. It is required to enlarge the diameter of the orifices in the He stripper for the efficient transmission of high-intensity beams.

On the other hand, small leak of He gas to the RRC, placed ~7-m upstream of the stripper, becomes serious problem at high-intensity operation. The RRC has only cryopumps (total pumping speed is ~120 m^3/s for N2). Because they have almost no pumping power for He gas, the leaked He gas is accumulated in the RRC gradually. Collisions between U ions and He atoms in the RRC can easily change their charges and cause the beam loss. For the acceleration of the high-intensity uranium beams, such beam loss induces further losses by the local pressure rise due to the gas desorption.

To overcome these difficulties, we invented the N2 gas-jet curtain method. By using curtain-like nitrogen gas-jet separating two rooms (Fig. 8), we can block the helium flow to the low-pressure side and the leaked gas is exchanged to N2 from He.

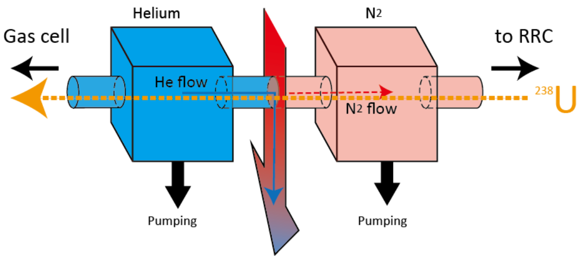

Figure 8: Concept of N2-jet curtain.

Based on the concept, we designed and developed the actual device to make N2 gas-jet curtain optimizing with CFD calculations. The device was installed in the He stripper and tested. Figure 9 shows the demonstrated performance of the N2 gas-jet curtain method. The sealing abilities are drastically increased. The gas leaked to downstream was successfully exchanged to nitrogen as we desired. Also, we found N2 gas-jet curtain works as a pre-stripper. Initial rapid stripping in N2 gas-jet curtain (~30 μg/cm^2) reduces the required pressure of He gas with ~ 15%.

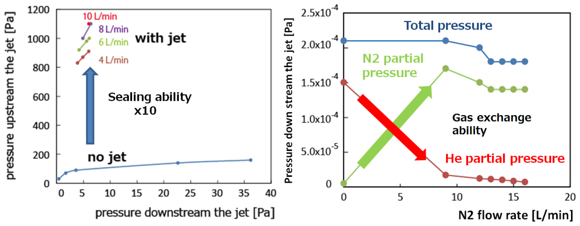

Figure 9: Performance of N2-jet curtain.

By using the gas-jet curtain, we enhanced the minimum orifice diameter from 10 mm to 12 mm as shown in Fig. 10. The 4-D acceptance of the system is 1.5 times higher than that of the previous system.

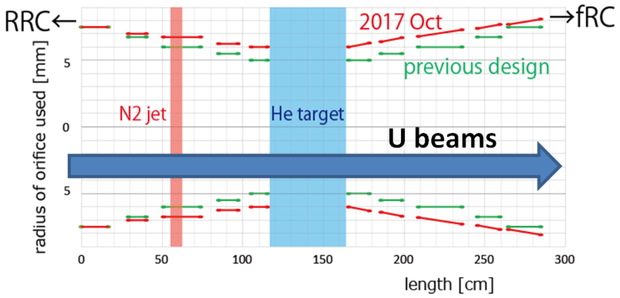

Figure 10: Enlargement of orifice diameters in the He stripper.

The improved system was actually applied in the user runs in 2017. The output intensities were increased with 25% due to the increasing transmission efficiencies. No serious pressure rise in the RRC was observed. The N2 gas-jet curtain method was greatly contributed the new world record of the output intensity (71 pnA at 345 MeV/u) achieved in 2017

Plasma Windows

As an advanced method for the pressurised gas confinement, we have developed the plasma windows (PWs) since 2011 [19]. The PW is firstly developed by Dr. Ady Hershcovich at BNL [20]. The PW are used to make large pressure difference between a high-pressure side and a low-pressure side. A high-temperature wall stabilized arc plasma compensates the high density on the high-pressure side. Furthermore, the viscosity of the flowing gas in the plasma is increased. Because of them, the gas flow to low-pressure side is restricted. In our group, diameters of orifice up to Φ6mm are tested so far. The achieved conduction reduction factor for He at Φ6mm is around 8. We are developing a new PW with larger apertures more than 1cm. Also, spectroscopies of arc plasma to know the temperature and the density are undergoing.

Rotating Graphite Carbon Stripper

As the second stripper, we have developed rotating disk stripper [21]. The module of the rotating stripper can provide the rotation speed up to ~1000 rpm. The disk diameter is about 11 cm. The system can provide the irradiation area more than 60 times of the beam spots. As a material of the disk, Be was used during 2012-2014. It worked quite well [22]. Since 2015, we used new material, which is the highly oriented graphite sheet (GS) produced by the Japanese company KANEKA Corporation [23]. The structure is like layered graphene. A prominent feature of the KANEKA GS is its very high thermal conductivity of 1500 W/mK in the planar direction. The temperature increase at the beam spot is expected to be suppressed. High density and uniform thickness are also preferable features. In addition, it is mechanically strong and can be handled easily.

The performance of the rotating GS stripper is outstanding [24]. For the Be stripper, when it was irradiated with ~10^{18} uranium ions in total, we found it became cracked and heavily deformed due to the heat cycle. On the other hand, irradiation of ~$2\text{x}10^{18}$ uranium ions caused only a slight deformation to the rotating GS stripper. Although the lifetime is under investigation (more than 40 days at the present intensities), we can increase the beam intensities without serious problem.

Charge Stripper Ring

As described above, two charge strippers are used for uranium acceleration at RIBF. In this acceleration scheme, the total stripping efficiency is ~6% at most. On the other hand, FRIB will use multi-charge acceleration method. They will accelerate 5 charge states at the same time by using the superconducting linac. The aiming effective efficiency of the stripper is ~85%. Unfortunately the method cannot be applied to the acceleration scheme with ring accelerators such as cyclotrons.

The charge stripper ring is a new concept to improve the effective stripping efficiency of the strippers for the ring accelerators [25]. Figure 11 shows an optimized ring for the second stripper at the RIBF. The U^{64+} beams are injected into the ring with a charge exchange injection scheme. The beams other than the selected charge state (86+) are circulated recovering the energies and re-entered to the stripper. The beams with U^{86+} are extracted simultaneously by using extractors with static magnetic or electric fields. The ring is isometric for all charge states to hold bunch structure. In the present design, the magnetic field is 1.8 T and the size is about 15 m x 5 m. Specially-designed quadrupole magnets are placed for orbits of all charge states independently at the dispersive region, where the orbit separation between two adjacent charge states is ~10 cm. The expected heat load on the stripper (3 mg/cm^2) is ~900W. The rotating GS stripper is a possible candidate.

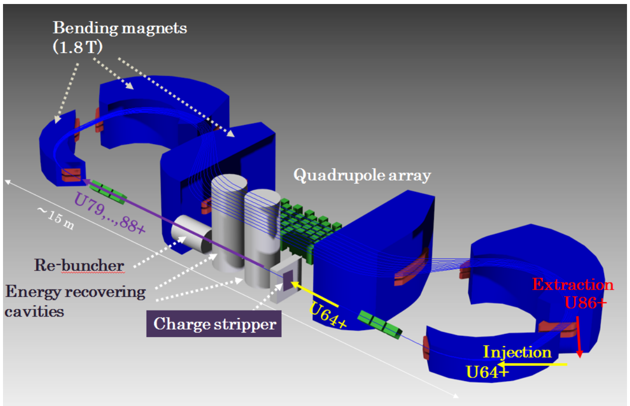

Figure 11: A design of the charge stripper ring for the second stripper at RIBF.

SUMMARY

Various non-traditional strippers for world's in-flight RI beam facilities are being developed. The H2 gas-cell stripper at GSI is almost ready for FAIR. FRIB finished the principle verification of the liquid Li stripper and developing actual machines matching to the actual operations. He gas stripper and rotating GS-disk stripper have been developed at RIBF and are working well. Studies for further advanced strippers and techniques, plasma strippers, gas-jet curtain, plasma windows and stripper rings are also undergoing and will become strong tools in near future

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