ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-THPME067

AIR STRIPPER FOR INTENSE HEAVY ION BEAMS

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Abstract

Intensity upgrade of very heavy ions such as uranium or xenon beams is one of the main concerns at the RIKEN Radioactive Isotope Beam Factory (RIBF). The lifetime problem of carbon-foil strippers due to the high energy deposition of beams was a principal bottleneck for the intensity upgrade. Our group have pursued gas strippers as an alternative to carbon foils. We have already developed and successfully operated a re-circulating He-gas stripper for 11-MeV/nucleon uranium beams. Recently, the second gas stripper with air dedicated for 51-MeV/nucleon ^{124}Xe beams was developed. We confined a very thick gas target, up to 20 mg/cm^2 of air, in a 0.5-m target chamber. One good feature of using air is that it can be inexhaustible for our use. The stripper was stably operated in user runs performed in June 2013. The maximum beam intensity reached 38 pnA and the average intensity provided to users becomes approximately four times higher than it was in 2012. The down time-free gas strippers substantially contributed to the successful intensity upgrade.

INTRODUCTION

Intensity upgrade of very-heavy ions such as U and Xe beams towards our goal intensity of 1 pμA is one of the main concerns at the RIKEN Radioactive Isotope Beam Factory (RIBF). A new injector, RILAC2 [1, 2], which includes a 28-GHz superconducting electron cyclotron resonance ion source [3, 4], has been successfully developed and became fully operational in the fiscal year 2011. In the present multi-stage acceleration scheme with RILAC2 and four ring cyclotrons (RRC, fRC, IRC and SRC) (Fig. 1), the charge state of ions converted twice before and after the fRC with charge strippers. The injection energy E$_i$ for the first stripper is 10.8 MeV/nucleon and E$_i$ for the second stripper is 50.7 MeV/nucleon. Carbon-foil strippers, which are the most widely used in world's hadron accelerators [5–7], have been used at the RIBF for acceleration of all ion spices [8,9]. The major problem for such solid-state strippers with very-heavy ions is the serious damage caused by the huge energy deposition. The previously measured lifetime of a static carbon-foil stripper was as short as 15 h when it was irradiated by uranium beams at 10.8 MeV/nucleon with intensities of up to 20 pnA, which is still several hundreds times lower than our goal intensity [10]. This fact means that the possible output intensities for very-heavy ion beams are principally limited by the short lifetime problem when we uses the carbon foil strippers. The emittance growth due to the intrinsic thickness ununiformity of carbon-foil strippers is also serious problem for the multi-stage acceleration with four cyclotrons at the RIBF.

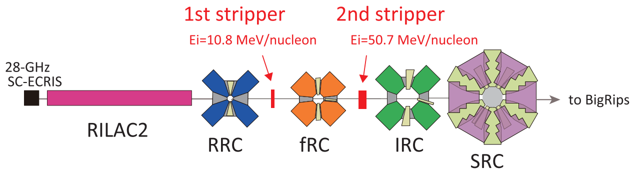

Figure 1: Acceleration scheme with RILAC2 and four ring cyclotrons (RRC, fRC, IRC and SRC) for very-heavy ions. The charge state of ions converted twice before and after the fRC.

Our group have pursued gas strippers for fast very-heavy ions as an alternative to carbon foils to solve the problems [11–14]. Gas strippers have great advantages in the durability and the thickness uniformity. The recently developed recirculating helium gas stripper successfully solved the lifetime problem of the first-stage carbon foil stripper in the use with U beams at 10.8 MeV/nucleon [15]. However, the lifetime problem was an issue for the second-stage stripper as well. In the previous runs with Xe beams in 2012, it was necessary to replace the second-stage carbon-foil stripper every 8 h because of the decreasing thickness.

In the present study, we developed a very-thick air stripper as a second-stage stripper applicable for ^{124}Xe beams at 50.7 MeV/nucleon. We also tried Xe-beam acceleration only with gas strippers (the first stripper is N_2 gas and the second one is air) for the first time in the RIBF user runs.

AIR STRIPPER

One of the difficulties for realizing gas strippers is the lower charge state equilibrium compared with that for the solid-state stripper due to the lack of the density effects. The reachable charge states for various gas for ^{238}U and ^{124}Xe beams at the injection energy of 51 MeV/nucleon were investigated in the previous work [16]. We found that our desired charge state can be obtained with air targets as well as carbon-foil strippers for ^{124}Xe beams, although the reachable charge state with air targets for ^{238}U beams was significantly lower than that for carbon-foil strippers. Air is the best choice for the gaseous media of the second stripper for ^{124}Xe because it is very common and easy to use.

Other difficulty for realizing gas strippers is the windowless confinement of large amount of gas in the beamline vacuum around 10^{-6} Pa. The thickness required to obtain the charge state equilibrium of the beams increases significantly at higher beam injection energies. To obtain the equilibrium charge state 52+ for 50.7-MeV/nucleon ^{124}Xe beams with the air stripper, the thickness of 5 mg/cm^2 is sufficient.

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In the present case, however, the second-stage stripper also functions as an energy degrader that changes the output energy of the fRC which is approximately 51 MeV/nucleon, to the injection energy of the subsequent cyclotron IRC which is approximately 46 MeV/nucleon.

The required thickness of the second air stripper (more than 18 mg/cm^2) is about 30 times higher than the thickness for the first-stage helium stripper (~0.6 mg/cm^2). Although the air is quite easier to confine compared to the helium gas, it is a challenge to achieve the required pressure around 25 kPa at the target region, which is more than four times higher than that for the helium stripper.

The new charge stripping system was constructed in the E1 room after the fRC. The similar technology of differential pumping for windowless gas confinement as the prototype He gas stripper [14], where tube-separated three-stage differential pumping systems were used, was applied to the new system. The new stripper consists of two tube-separated five-stage differential pumping systems with 17 pumps (Fig. 2).

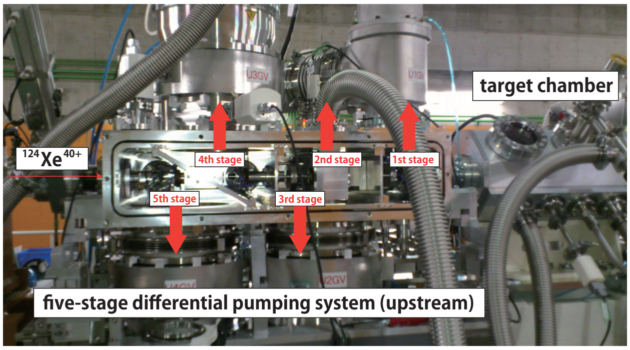

Figure 2: Five-stage differential pumping system of upstream side for the air stripper. All stage-separating walls with tubes can be slided and removed easily when we do not use the air stripper.

The monolithic chamber for the five-stage differential pumping is very compact (880 mm in length). Such compactness is important for the easy transmission of beams. Stage 1 and stage 2 are evacuated powerful mechanical booster pumps with backing rotary oil pumps. High throughput turbomolecular pumps are used in stage 3-5. Flow-disturbing plates [14, 17] are placed in stage 1-3. All stage-separating walls and attached parts can be removed easily when we accelerate other ions with the carbon-foil stripper.

To make a very thick air target, up to 20 mg/cm^2 in thickness, air in the E1 room was continuously compressed (Fig. 3). The inlet pressure of a pressure regulator was kept at 0.7 MPa with a relief valve. The regulator's secondary pressure was set to 0.4 MPa to deliver a steady flow to the target via a mass-flow controller. High-flow air up to 400 STL/min can be stably introduced to the target chamber in this system. The evacuated air in the differential pumping systems is sent to a gas disposal line to outside the room. Because we used air in the room, which could be inexhaustible, we did not need any recirculation system in the air stripper even at high-flow operations.

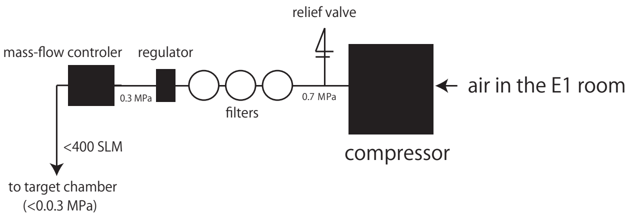

Figure 3: A schematic diagram of the compressed air supplying system. Up to 400 STL/min of air in the E1 room can be sent to the target chamber via the flow controller.

OPERATION

The stripper construction was completed in March 2013 and stably operated as the second stripper in user runs performed in June 2013. The compressed air with the flow rate of 225 STL/min was introduced continuously in the target chamber in user runs during 2 weeks (fig. 4). The target pressure was kept at 23 kPa, which corresponds to the thickness of 19 mg/cm^2.

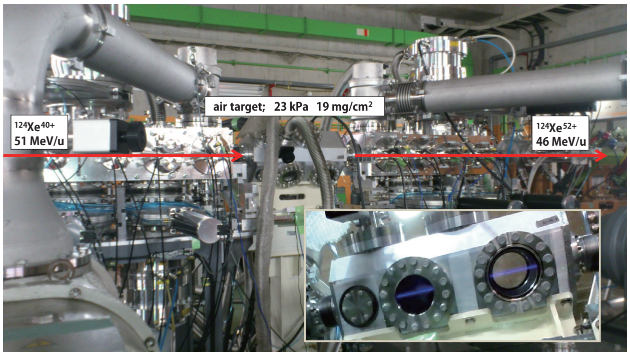

Figure 4: Pictures of the air stripper and glowing xenon beams (~ 100 pnA). The ^{124}Xe^{40+} beams with 51 MeV/nucleon from the fRC pass through the air stripper. The subsequent cyclotron IRC recieves the ^{124}Xe^{52+} beams with 46 MeV/nucleon. The beams passing through the air stripper emits visible blue lights.

We also used thin nitrogen gas (0.2 mg/cm^2), which is confined in the same system of the recirculating helium gas stripper [15], as the first stripper before the fRC in the user runs. In this operation, the target pressure was kept at 300 Pa without gas recirculation.

In the user runs, the ^{124}Xe^{19+} beams extracted from a 28GHz-ECR ion source are accelerated to 0.68 MeV/nucleon by RILAC2 and then go into RRC. The beams are accelerated up to 10.8 MeV/nucleon in RRC and then go through the first nitrogen stripper. The charge state 40+ is selected with the stripping efficiency of approximately 20% [11]. After the acceleration to 50.7 MeV/nucleon by using fRC, the ^{124}Xe^{40+} beams are injected to the air stripper. The Xe^{52+} beams, whose frac-

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tion is approximately 50%, are subsequently accelerated up to the energy of 345 MeV/nucleon with IRC and SRC.

The availability (actual beam service time/scheduled beam service time) of Xe beams at 345 MeV/nucleon in the user runs reached 91% [18]. The maximum beam intensity reached 38 pnA, and the average intensity provided to users becomes approximately four times higher than it was in 2012. The new down time-free gas stripper contributed substantially to these improvements.

DISSCUSSIONS

In the user runs, $^{124}\mathrm{Xe}^{19+}$ beams up to 1.3 sμA at 10.8 MeV/nucleon were actually injected to the first nitrogen stripper. Such beams generate an energy loss of approximately 16 W. It would easily heat up the nitrogen gas because of the low flow rate of nitrogen (~ 2.6 STL/min).

We observed the dependence of the output energy of the $^{124}\mathrm{Xe}^{40+}$ beams after the first nitrogen gas stripper on the injected beam currents. In this measurement, induced signals at the phase probe placed at the downstream of the nitrogen stripper are measured for various injection currents. The timing shifts of zero crossing showed a clear increase of the output velocity with increasing beam currents (Fig. 5). The estimated density reduction of nitrogen gas by 1.3-pμA xenon beams is about 25%. Figure 5 also shows the shift of the horizontal position of the beams after the 90-degree bending when the current is changed from 0.26 pμA to 1.3 pμA. We compensated the sizable density reduction depending on the beam intensities by increasing the gas pressure of nitrogen gas in the target chamber.

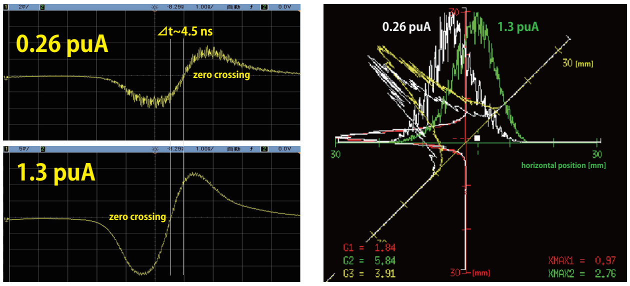

Figure 5: The timing shift of $^{124}\mathrm{Xe}^{40+}$ beams measured with the phase probes downstream the nitrogen stripper for different beam currents (left) and the shift of the horizontal position of the beams after the 90-degree bending from the current of 0.26 pμA to 1.3 pμA (right).

At the second stripper, $^{124}\mathrm{Xe}^{40+}$ beams up to 160 pnA at 51 MeV/nucleon were actually injected in the present user runs. We can see a clear beam trajectory inside the air target as shown in Fig. 3. They generate an energy loss of approximately 80 W.

One concern about air stripper is the production of radiolytic noxious gases, such as ozone and nitrogen compounds, due to the huge energy deposition of $^{124}\mathrm{Xe}$ beams. A dominant radiolytic compound would be nitric acid, which would cause various negative effects on the system because of its strong oxidation power. At the present intensities, however, we did not detect any serious indication of the production of nitric acid.

CONCLUSION

In conclusion, we successfully developed and operated the air stripper, which removed a primary bottleneck in the high-intensity Xe-beam acceleration. We note that this is the first observation of successful of the acceleration only with gas strippers at the RIBF, which is an important cornerstone for next-generation high-intensity heavy ion accelerators.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the cyclotron crews for providing high quality beam and for their help during the preparation and the measurements.

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