BNL-94057-2010-CP

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Presented at the 46th ICFA Advanced Beam Dynamics Workshop
Morschach, Switzerland
September 27 – October 1, 2010

Collider-Accelerator Department

Brookhaven National Laboratory

**U.S. Department of Energy
DOE Office of Science**

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A NEW POSSIBILITY OF LOW-Z GAS STRIPPER FOR HIGH POWER URANIUM BEAM ACCELERATION ALTERNATIVE TO C-FOIL

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Abstract

The RIKEN accelerator complex started feeding the next-generation exotic beam facility RIBF (RadioIsotope Beam Factory) with heavy ion beams from 2007 after the successful commissioning at the end of 2006. Many elaborating improvements increased the intensity of the various heavy ion beams from 2007 to 2010. However, the available beam intensity especially of uranium beam is far below our goal of 1 pμA (6 x 10^{12} particle/s). In order to achieve it, upgrade programs are well in progress, including constructions of a new 28 GHz superconducting ECR ion source and a new injector linac. However, the most serious problem of the charge stripper for uranium beam is still open although many elaborating R&D works for the problems. Equilibrium charge state in gas generally is much lower than that in carbon foil due to its density-effect. But gas stripper is free from the problems originated from its lifetime and uniformity in thickness. Such merits pushed us think about low-Z gas stripper to get higher equilibrium charge state even in gas. Electron loss and capture cross section of U ion beams in He gas were measured as a function of their charge state at 11, 14 and 15 MeV/u. The extracted equilibrium charge states from the cross point of the two lines of the cross sections were promisingly higher than those in N_2 gas by more than 10. The plasma window is expected to be a key technology to solve the difficulty in accumulation of such thick as about 1 mg/cm^2 of low-Z gas.

INTRODUCTION OF RI BEAM FACTORY

RIKEN Nishina center has constructed an RI Beam Factory (RIBF) [1] aiming to realize a next generation facility that is capable of providing the world's most intense RI beams at energies of several hundred MeV/nucleon over the whole range of atomic masses. The RIBF requires an accelerator complex which would accelerate the full mass range of ions and deliver 80 kW of uranium beam at an energy of 345 MeV/nucleon. Figure 1 shows a bird's eye view of RIBF. The left part is the old facility completed in 1990. Using the four-sector K540-MeV ring cyclotron (RRC) [2] with the two injectors, RILAC (RIken Linear ACcelerator) [3] and AVF cyclotron [4], many experiments were carried with RI beams of light ions because RRC can accelerate relatively light ions up to 100 MeV/u, which is the lower limit for the RI-beam production. In order to expand the mass range for RI beam production up to uranium, the three ring cyclotrons, fRC (a fixed-frequency Ring Cyclotron) [5], IRC (Intermediate Ring Cyclotron) [6] and SRC (Superconducting Ring Cyclotron) [7] were designed and constructed as energy boosters for the RRC. The SRC is the world's first ring cyclotron using superconducting sector magnets with the largest bending power.

The design and construction of the RIBF accelerators started from 1997 and the accelerator building was completed at the end of March 2003. In November 2005, we reached a big milestone that the superconducting sector magnets for SRC were successfully excited at the maximum field level. The first beam was obtained at December 28, 2006 [8, 9]. Many elaborating improvements were carried out to increase the beam intensity and to commission the new beam species to meet with requirements from the experiments. Table 1 is a list of the beam accelerated so far. They realized many nuclear experiments, such as the discovery of 45 new isotopes [10] and the study of halo structure and large deformation of extremely neutron-rich Ne isotopes [11, 12]. Our goal is 1 pμA for the whole atomic range. We reached the goal intensity for He and O and about one fourth of the goal for Ca. However, the beam intensity of U beam is still very low, suggesting that we need drastic measures.

Table 1: A list of the beam accelerated so far with its intensity and date.

Ion	**Energy** (MeV/u)	**Intensity** (pnA)	**Date**
pol-d	250	120	May 2009
^{4}He	320	1000	Oct. 2009
^{14}N	250	80	May 2009
^{18}O	345	1000	June 2010
^{48}Ca	345	230	May 2010
^{86}Kr	345	30	Nov. 2007
^{238}U	345	0.8	Dec. 2009

INTENSITY UPGRADE FOR URANIUM BEAM

From the operational experience mentioned in the previous section, key issues to increase the intensity of uranium ion beams can be clearly pointed out as follows. First, more beams are necessary from the ion source. Now Nakagawa et al. are developing a new 28 GHz superconduct-

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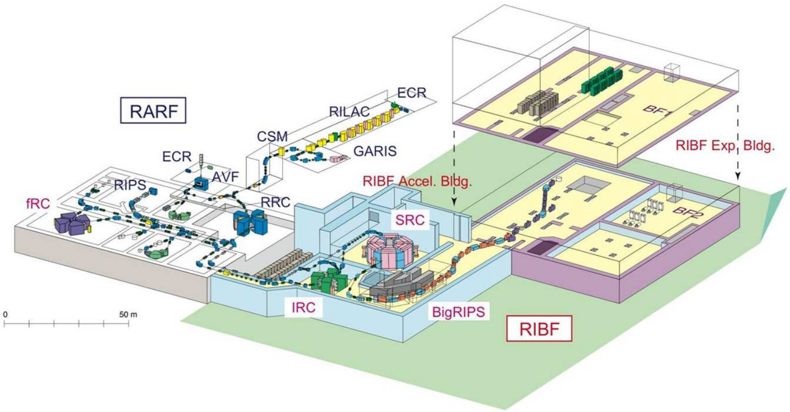

Figure 1: A bird's eye view of RI Beam Factory.

ing ECR ion source which is designed to have as large plasma volume as 1100 cm^3 [13, 14]. An important point of the source is that the coil system is designed to make the magnetic field distribution flat in this central region, by exciting the solenoids independently. This ion source is expected to produce U^{35+} ions at an intensity of more than 15 pμA, which is necessary to obtain 1 pμA beams from the SRC. The coil was successfully excited to the designed level in October 2008. Test of the ECR source started from April 2009 with 18 GHz mode because we didn't have 28 GHz source at that time. The intensity of uranium reached 10 eμA which is about five times of those from the ion source used formerly. The ion source will be moved to the upstream of a new injector mentioned later and will be test with 28 GHz mode in this year.

Next, a new injector is necessary in order to avoid the emittance growths due to their space charge forces in acceleration of ion beams from the new powerful ion source. The new injector is designed to efficiently accelerate ions with a mass-to-charge ratio of 7, aiming at heavy ions such as ^{84}Kr^{13+}, ^{136}Xe^{20+} and ^{238}U^{35+}, up to energy of 680 keV/nucleon [15]. It mainly consists of an RFQ linac based on the four rod structure and three drift-tube linac (DTL) based on the quarter-wavelength resonator (QWR). Installation of all the main componentts has already been finished and excitation test of all the tanks were finished to start beam commissioning from the middle of the next December.

The last key issue is to make charge stripper with long life time, which is a still open problem.

CHARGE STRIPPER PROBLEM FOR URANIUM ACCLERATION

Figure 2 shows the acceleration scheme for uranium acceleration with the two strippers. The first stripper is located after RRC at 11 MeV/u and the second one is located after FRC at 51 MeV/u. Now carbon foils are used for both ones and the typical thicknesses for the first and second strippers are 300 μg/cm^2 and 14 mg/cm^2, respectively. The problem about the first stripper will be more serious. Carbon foils commercially available from ACF-metal [16] are used for the first stripper. Their typical lifetime is about 12 hours with 1 eμA. We are also developing carbon foils of the same thickness in RIKEN, and the quality is getting closer to those of the commercially available ones [17]. There is no problem for the intensities available right now. But it will be surely serious problem because intensity of uranium beam is ready to be increased by more than 100 with the upgrade programs mentioned before, requiring much stronger strippers. Therefore we started intense R&D programs about the first stripper from 2008.

Firstly we started irradiation tests using a large foil on rotating cylinder developed by Ryuto et al. [18] to expand irradiation area, expecting long lifetimes. A foil of 100 mm in diameter was put on the cylinder which can rotate in beam vacuum. The first sample tested two years ago died quite as shortly as in about 15min. Some tests were carried out to know why the rotating foils shortly broke. And we found that a very slowly (0.05 rpm) rotating foil can survive for more than 38 hours with 1.7 eμA. However, we also found that beam intensity behind the stripper changes periodically so much that we could not tune the succeeding accelerator, suggesting that uniformity of the foil is not sufficiently good. We might need a feedback system to compensate the fluctuation of its thickness if we use it in real operations.

Secondary, we started to develop gas strippers. Gas stripper is free from lifetime although lower equilibrium charge state than that in carbon foil because of density effect. At that time we did not have data about equilibrium charge state in N$_2$ gas and there is no available empirical formulas enough to predict it correctly. Therefore we measured that at 11 MeV/u using a gas target system with differential pumping system which was formerly used for nuclear experiments [19]. The measured equilibrium charge state in N$_2$ was 56 which is far below that in carbon foil, 71, suggesting that the gas stripper cannot used for the uranium because the acceptable charge state for the fRC is larger than 69.

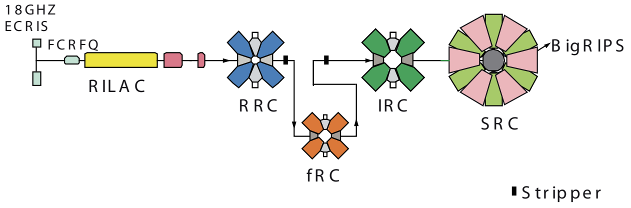

Figure 2: Acceleration scheme for uranium acceleration with two strippers.

LOW-Z GAS STRIPPER

The merit of gas stripper is that it is free from lifetime and its thickness is completely uniform. Such merits pushed us to think about what we can do to get higher charge state in gas. The first solution is increase of stripping energy because generally equilibrium charge state increases as a function of projectile energy. The equilibrium charge states were additionally measured at 14 MeV/u and 15 MeV/u using N_2 gas stripper which was described in the previous section. They are 61 and 62 at 14 MeV/u and 15 MeV/u, respectively [20]. Extrapolation of the results suggests that the stripping energy should be increased to 22 MeV/u to get 69+ as a equilibrium charge state which is the lowest acceptable charge state for FRC. To realize that, we need additional acceleration before the stripper and decelerator behind the stripper or making its injection radius larger by more than 50 cm. Such huge remodeling will cost more than $10 M. The second solution is expected to be change of the stripping material to low-Z gas (He and H_2).

Background

Equilibrium charge state is determined by competition of e-loss and e-capture processes of the ion. the capture cross sections depend strongly on the ion velocity V_p compared with that of the target electrons. In particular, the capture phenomenon is very suppressed because of bad kinematical matching when the ion velocity significantly exceeds that of 1s electrons V_{1s} which are the fastest target electrons. Such suppression of the capture is expected to be appeared in the case of lower-Z of targets or higher ion velocity because V_{1s} is approximately expressed to be Z/137, resulting in higher equilibrium charge state. Actually a substantial increase in equilibrium charge state is observed in some experimental data about equilibrium charge state or effective charge at intermediate energies in lower-Z region [21, 22, 23]. Table 2 summarizes the reaction conditions which shows charge enhancement of equilibrium charge state in low-Z region with the V_p/V_{1s} parameter from the references with those in the reactions where the cross section measurements were carried out in He, showing that charge enhancement in low-Z region can be expected. The table also lists the parameters in the reactions where equilibrium charge states were measured in N_2, showing lower charge states due to the density effect.

Table 2: Reactions where enhancement of equilibrium charge are observed in low-Z target region. The definition of V_p/V_{1s} is shown in the text. The lower part of the table lists the reactions where measurements about equilibrium charge states were carried out in this work and the work in the references of [19, 20].

Reaction	**Energy (MeV/u)**	**V_p/V_{1s}**	**Ref.**
Ar + H_2	4.25	8	[21]
U + He	22	15	[22]
U + N_2	50	76	[23]
U + He	11	10.5	
U + He	14	11.9	
U + He	15	12.3	
U + N_2	11	3.0	
U + N_2	14	3.4	
U + N_2	15	3.5	

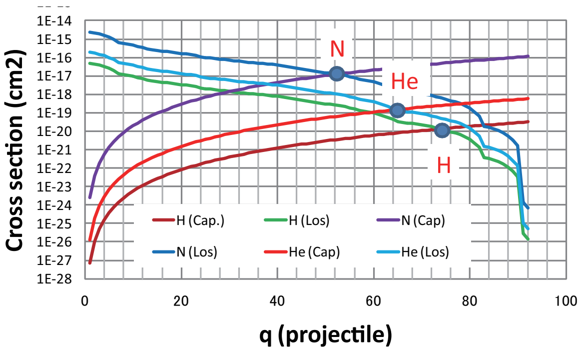

Figure 3: A simple estimation for cross sections of e-loss and capture in N_2, He and H_2.

Figure 3 shows e-loss and capture cross sections simply calculated by binary encounter model [24] and Schlachter's formula [25] as a function of it's charge state for H_2, He and N_2. the two lines for each case cross at the equilibrium charge state. They clearly show higher charge stats in low Z gas than that in N_2 gas. There are no data about equilibrium charge state of uranium in low-Z gas at this energy region mainly because of difficulty in accumulating low-Z gas without window. For example our gas stripper system mentioned in the last section can accumulate only 0.015 mg/cm^2 of He where U ion does not reach at its equilibrium at 11 MeV/u, while 1.1 mg/cm^2 of N_2 can be accumulated. So we measured cross sections of 1 electron loss and capture as a function of charge state of uranium ion to extract equilibrium charge from their cross point.

Experiment

The experiment was conducted at RIBF using RILAC and RRC. A schematic of the experimental setup is presented in Fig. 4. Beams of 11 MeV/u $^{238}U^{35+}$, 14 MeV/u $^{238}U^{41+}$, and 15 MeV/u $^{238}U^{41+}$ were extracted from RRC. The incoming ions passed through a carbon foil located in front of a bending magnet, which was used to select individual projectile charge state, Q_i. Thickness of the carbon foils was optimized so as to get the max intensity of the charge state. Each beam was directed through a windowless, differentially pumped He gas cell. After emerging from the gas cell, the beams passed through a second bending magnet into a Faraday Cup (FC) at a point of F41. FC at F41measured intensity of the beam current of the charge state for e-loss (Q_i+1), e-capture (Q_i-1) and no reaction (Q_i). The pressure of the He target gas was monitored by a Baratron pressure transducer and the gas flow was regulated by means of an automated control valve and flow controller. Additional details of the experimental setup are described in the reference of [19]. The cross section of e-loss σ_{loss} and e-capture $\sigma_{capture}$ was extracted from the following equation.

$$\sigma_{loss} = \frac{1}{t}\frac{I(Q_i+1)}{\sum I(Q_m)} \tag{1}$$

$$\sigma_{capture} = \frac{1}{t}\frac{I(Q_i-1)}{\sum I(Q_m)} \tag{2}$$

The intensity at F41 was normalized by the intensity at a FC located at the upstream of the gas cell to cancel the fluctuation of beam intensity from the RRC. In the measurement Cell pressure is 0.51 kPa. At this pressure thickness of the gas stripper was measured to be 13.27±1.81 μg/cm^2 using α-ray from Am.

Figure 5 shows measured cross sections as functions of charge number of the uranium ion at 11, 14 and 15 MeV/u. The absolute values of the cross sections in Fig. 5 have ambiguity by 13.6 % though their relative values of the cross sections keep accurate because the cross section were extracted assuming that thickness is the center value of the measurement described above. The data shows that cross section of the electron capture largely depends on the energy while the e-loss cross section does not depend so much on the energy. Because contribution of multiple electron transfer in He is very small [26], it is good approximation that the cross point of two line gives the equilibrium charge state. The cross points are extracted to be 66, 73 and 75 at 11, 14 and 15 MeV/u. Table 3 shows equilibrium charge state in He, N_2 and C. Those in He are obviously larger than those in N_2 by more than ten and are close to those in Carbon.

Table 3: Equilibrium Charge state in He, N_2 and C at 11, 14 and 15 MeV/u. The data for N_2 and C were taken from the reference of [19, 20].

Material	**Q_e@11 (MeV/u)**	**Q_e@14 (MeV/u)**	**Q_e@15 (MeV/u)**
He	66	73	75
N_2	56	61	62
C	72	76	77

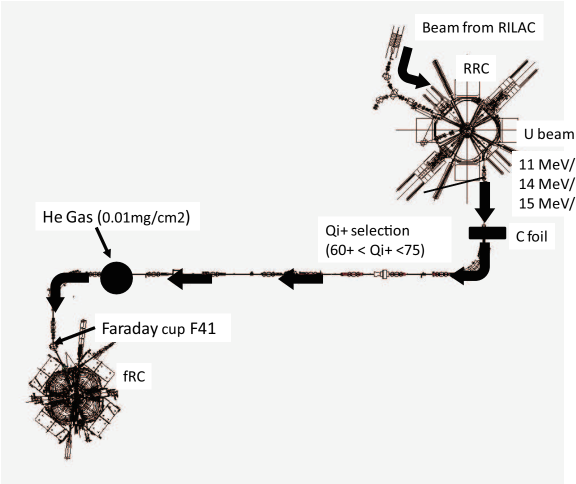

Figure 4: A schematic sketch how to measure the cross sections of e-loss and e-capture in the RIBF beam lines.

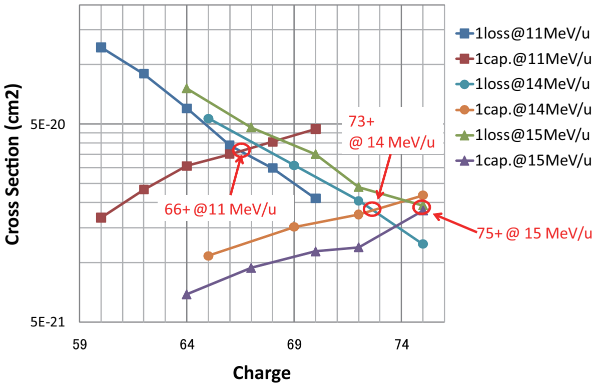

Figure 5: Measured cross sections of e-loss and e-capture as a function of the charge state of uranium ion at 11, 14 and 15 MeV/u in He gas. The cross sections were extracted assuming that thickness of the gas cell is 13.27 μg/cm^2.

Gas stripper with plasma windows

The measurement results are very promising to realize low-Z gas stripper for higher charge state of uranium. However, one problem of difficulty in accumulation of low-Z gas is still remained. As mentioned in the previous subsection, the existing gas stripper can accumulated only 0.015 mg/cm^2 (0.5 kPa) of He while it can 1.1 mg/cm^2 of N_2. From simple estimation, about 1 mg/cm^2 of He or H_2 is necessary to be accumulated to get higher charge state, suggesting a necessity of a new device to solve this problem. The new device is expected to be Plasma Window invented by Ady Hershcovitch in 1995 [27]. The Plasma Window is a wall-stabilized plasma arc used as an interface between accelerator vacuum and pressurized targets. There is no solid material introduced into the beam and thus it is also capable of transmitting a charged particle beam with low loss. It mainly consists of 3 cathodes, anode and some cooling plates to cool-down the plasma arc as shown in

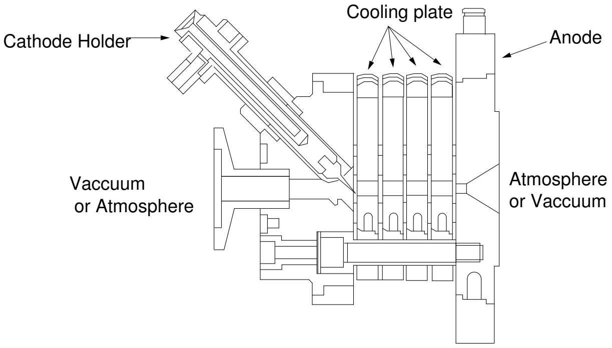

Figure 6: A schematic sketch of a plasma window.

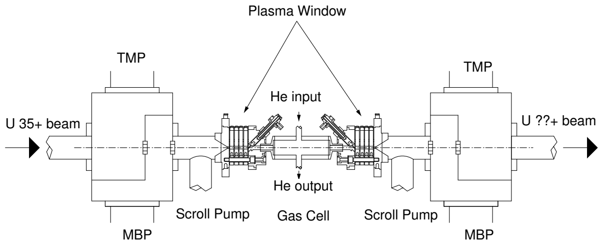

Figure 7: A conceptual sketch of low-Z gas stripper with two plasma windows.

Fig. 6. The arc in the plasma window can generate pressure difference between it's ends by a factor of 600. So it can keep the pressure inside of the gas cell keeping the outside vacuum. Figure 7 shows a schematic sketch of the low-Z gas stripper using plasma window. The low-Z gas is accumulated in the cell which is sandwiched by the two plasma windows.

We are starting R&D programs with tests of a plasma window in a test stand with help from Ady Hershcovitch. As the first step, Ar gas will be used and a diameter of the window is 2 mm in the test. We like to have the first ignition until the end of March 2011. From 2011 we will study performance of the Plasma Window with He or H_2 instead of Ar and with extended diameter of 6 mm. From 2012 we will start to make gas stripper with the two plasma window which I show in the previous slide for off-line test.

SUMMARY

The operation of RIBF from 2007 to 2010 was very successful after the first beam. The new 28 GHz superconducting ECR ion source and the new injector are ready to be operated to increase intensity of uranium beam. Stripper problem for uranium beam is still open though we did may elaborating R&D works about rotational cylinder foils and N_2 gas stripper. Recently we found that the low-Z gas stripper would be one of the candidate from the measurement results, showing that equilibrium charge state is higher than that in N_2 by more than 10. We believe that difficulty in accumulation of low-Z gas can be overcome by the plasma window.

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