CHARGE STRIPPERS FOR ACCELERATION OF URANIUM BEAM AT RIKEN RI-BEAM FACTORY

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Abstract

A uranium beam was accelerated to 345 MeV/nucleon using two or three stages of charge strippers at the RIKEN RI-beam factory. The dependence of the charge state distribution of uranium on the carbon foil thickness was measured at 0.67, 0.87, 11, and 51 MeV/nucleon. Rotating charge strippers were constructed to strip high-intensity beams.

INTRODUCTION

Charge strippers play an essential role in a heavy-ion accelerator complex, because a high-charge state enables the acceleration of heavy-ion beams to a high energy using small accelerators. The equilibrium charge state of ions is determined by the velocity of the ions, and a higher equilibrium charge state can be obtained when the ions are charge-stripped at a higher velocity. Therefore, charge strippers placed between accelerators realize the efficient acceleration of heavy-ion beams in a heavy-ion accelerator complex in which heavy ions are accelerated using sequentially connected accelerators. The RIKEN RI-beam factory (RIBF) is such a heavy-ion accelerator complex [1]. At the RIBF, three stripper sections are used to accelerate ions from hydrogen to uranium [2]. Figure 1 shows a schematic view of the RIBF. Ions are accelerated successively by the RIKEN heavy-ion linac (RILAC), the RIKEN ring cyclotron (RRC), a fixed-frequency ring cyclotron (fRC), an intermediate-stage ring cyclotron (IRC), and a superconducting ring cyclotron (SRC). The latter three ring cyclotrons, the fRC, the IRC, and the SRC, are newly constructed. The three stripper sections are placed downstream of the first three accelerators, the RILAC, the RRC, and the fRC. The beam energies incident on the strippers are 0.67, 11, and 51 MeV/nucleon, respectively.

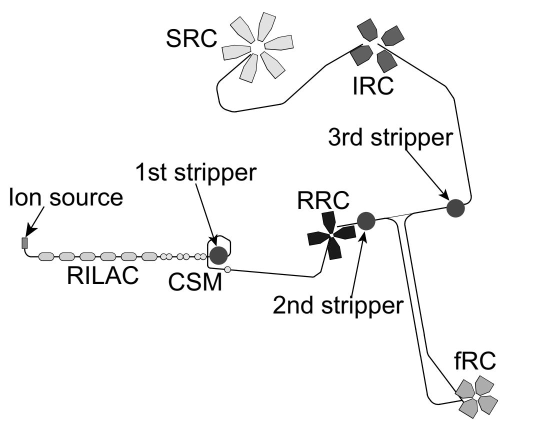

Figure 1: Schematic view of RIBF showing accelerators and charge strippers. The abbreviations of the accelerators are explained in the text.

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A uranium beam was accelerated to 345 MeV/nucleon using two or three charge strippers. The design process of the newly constructed ring cyclotrons required the charge state distribution and equilibrium thickness of the charge strippers. However, we could not obtain sufficient data, particularly on the third stripper placed between the fRC and the IRC. Thus, the charge state distribution and the equilibrium thickness were estimated by calculations [3, 4]. The validity of the calculations was checked by comparison with the measured charge state distributions of ions lighter than uranium at the same energy region. The GLOBAL calculation [3] accurately reproduced the charge state distributions of Kr and Xe at equilibrium [2]. In this paper, the charge state distributions of uranium measured at 0.67, 0.87, 11, and 51 MeV/nucleon are presented, and the structure of one of the two rotating strippers is described.

FIRST STRIPPER

The first stripper was used to strip the $^{238}U^{14+}$ ions accelerated using the RILAC to 35+ in the early stage of the commissioning of the RIBF. Figure 2 shows the charge state distributions of uranium stripped using a 20-μg/cm^2-thick carbon foil at 0.67 and 0.87 MeV/nucleon. Charge state distributions obtained from Shima et al. [5] are accurately reproduced the measured data. The $^{238}U^{35+}$ ions extracted from the ion source are now directly sent to the RRC after acceleration by the RILAC without charge stripping.

SECOND STRIPPER

The second stripper strips $^{238}U^{35+}$ ions extracted from the RRC at 11 MeV/nucleon to a charge state that can be accelerated using the fRC. The $^{238}U^{35+}$ ions were planned to be stripped to 72+ using a 0.5-mg/cm^2-thick carbon foil. In the early stage of the commissioning of the RIBF, 0.6-mg/cm^2-thick carbon foils were used to strip uranium ions

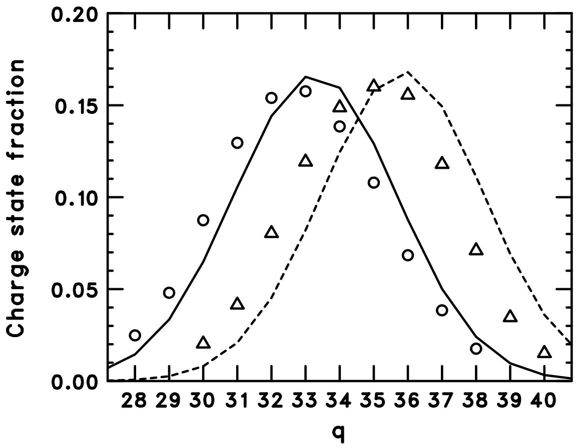

Figure 2: Charge state distributions of uranium at 0.67 and 0.87 MeV/nucleon behind a 20-μg/cm^2-thick carbon foil. The horizontal and vertical axes indicate the charge state and charge state fraction of uranium ions, respectively. Circles and triangles represent the data measured at 0.67 and 0.87 MeV/nucleon, respectively. Solid and dashed lines represent the values from the table in ref. [5] at 0.67 and 0.87 MeV/nucleon, respectively.

to 72+, because the injection energy of the fRC was designed to be lower than the energy behind a 0.5-mg/cm^2-thick carbon foil as a margin to allow the use of thicker foil. Figure 3 shows the carbon-foil-thickness dependence

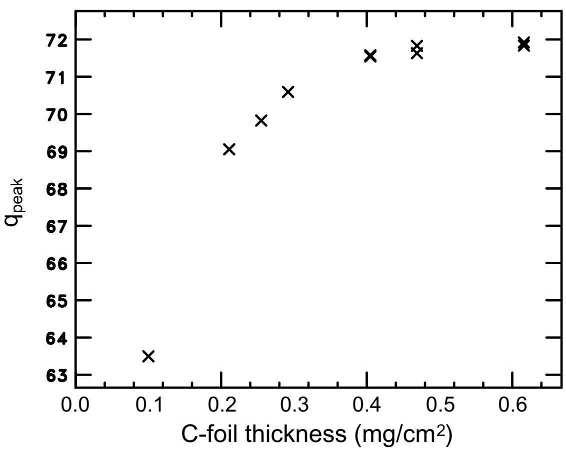

Figure 3: Carbon-foil-thickness dependence of peak position of charge state distribution. The horizontal axis indicates the thickness of the carbon foil. The vertical axis indicates the charge state at the peak of the charge state distribution.

of the charge state at the peak of the charge state distribution. The peak position of the charge state distribution approaches 72+, the equilibrium charge state, when carbon foils thicker than 0.5 mg/cm^2 are used. At the second stripper section, 0.3-mg/cm^2-thick carbon foils are now used to strip $^{238}U^{35+}$ ions at 11 MeV/nucleon to 71+, because the energy broadening caused by a 0.6-mg/cm^2-thick car-

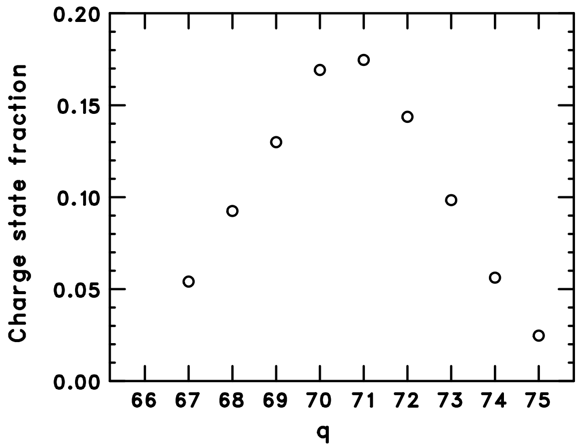

Figure 4: Charge state distribution of uranium at 11 MeV/nucleon stripped by 0.3-mg/cm^2-thick carbon foil. The horizontal and vertical axes indicate the charge state and charge state fraction of uranium ions, respectively.

bon foil was larger than the expected value obtained from energy straggling. Figure 4 shows the charge state distribution of uranium at 11 MeV/nucleon stripped by a 0.3-mg/cm^2-thick carbon foil.

The beam load deposited on the carbon stripper foil increases linearly with the beam intensity. A rotating-cylinder charge stripper was constructed to strip an intense uranium beam [6]. Figure 5 shows a schematic view of

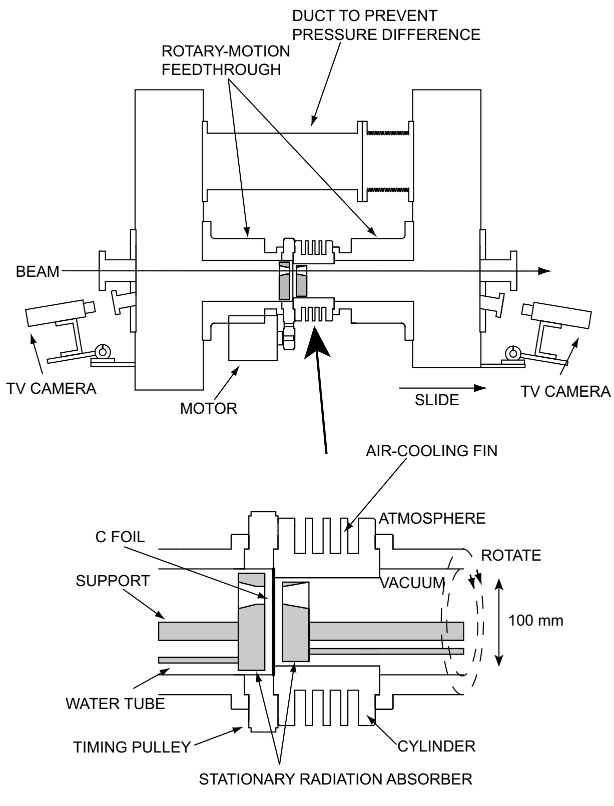

Figure 5: Schematic view of rotating-cylinder stripper showing side view and close-up view around carbon foil.

the rotating-cylinder stripper. A carbon foil is attached to an aluminum cylinder. The inner diameter and length of the cylinder are 100 and 120 mm, respectively. The outer surface of the cylinder is shaped into air-cooling fins. Both ends of the cylinder are connected to hollow-shaft ferrofluid-sealed rotary-motion feedthroughs. The feedthroughs are placed on the sidewalls of the rectangular vacuum chambers. The beam passes through the vacuum duct formed by the cylinder and the feedthroughs. A motor placed outside the vacuum chambers rotates the cylinder. The distance between the beam spot and the rotation axis is 30 mm. The maximum rotation frequency is 1000 rpm. The thermal radiation emitted by the foil is absorbed by water-cooled Al disks whose surfaces facing the rotating foil are coated with thermally sprayed alumina to increase emissivity. The Al disks are stable and have holes to allow the beams to pass through. The rectangular vacuum chambers are connected with a 165-mm-diameter duct to avoid a pressure difference while evacuating the chambers. Typically, it takes 40 minutes to change the foil as well as some time for the evacuation. The speeding up of the foil change is a subject of future development. The operation of the rotating-cylinder charge stripper was examined by rotating a 0.5-mg/cm^2-thick carbon foil at 500 rpm. The foil was rotated stably without breakage.

THIRD STRIPPER

The third stripper strips ^{238}U^{71+} ions extracted from the fRC at 51 MeV/nucleon to a charge state that can be accelerated by the IRC and the SRC, and also decreases the beam energy to the injection energy of the IRC. In the planning stage of the RIBF, we could not obtain data on the charge state distribution of uranium at 51 MeV/nucleon; thus, the equilibrium charge and stripper thickness were estimated using the GLOBAL calculation. The plan was that ^{238}U^{72+} ions would be charge-exchanged to 88+ using a 14-mg/cm^2-thick carbon foil. Figure 6 shows the charge state distributions of uranium at 51 MeV/nucleon stripped by a 14-mg/cm^2-thick carbon foil. The GLOBAL and ETACHA [4] calculations are shown along with the result of measurement. Both calculations overestimated the equilibrium charge state. The peak position of the charge state distribution was measured behind carbon foils of thicknesses from 4 to 17 mg/cm^2. The peak position approached 86+ when the ions were stripped by carbon foils thicker than 10 mg/cm^2; thus, we decided to accelerate ^{238}U^{86+} ions using the IRC and the SRC. A 14-mg/cm^2-thick carbon foil attached to a foil changer with an energy adjuster function (FCEA) [7] was tilted at 33° to decrease the beam energy to the injection energy of the IRC, because the extraction energy of the fRC was designed to be high as a margin to allow the use of thicker stripper. We plan to strip a high intensity beam using a rotating-shaft charge stripper [6], also using the FCEA as an energy adjuster.

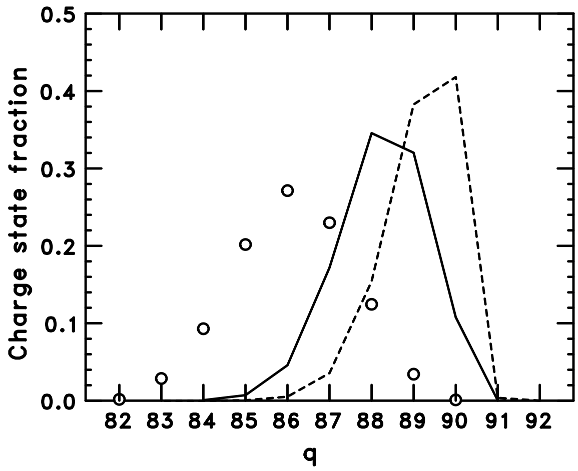

Figure 6: Charge state distributions of uranium at 51 MeV/nucleon stripped by 14-mg/cm^2-thick carbon foil. The horizontal and vertical axes indicate the charge state and charge state fraction, respectively. The circles, solid line, and dashed line represent the measured data, GLOBAL calculation, and ETACHA calculation, respectively.

SUMMARY

A uranium beam was accelerated to 345 MeV/nucleon using two or three charge strippers. The dependences of the charge state distributions on the carbon foil thickness were measured at three stripper sections, and the thicknesses of the carbon stripper foils and the charge states to be accelerated were determined. Rotating strippers were constructed to strip high-intensity beams.

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