New developments in low-Z gas stripper system at RIKEN Radioactive Isotope Beam Factory (RIBF)

Hiroki Okuno, Nobuhisa Fukunishi, Hiroo Hasebe, Hiroshi Imao, Osamu Kamigaito, Masayuki Kase, Hironori Kuboki
(RIKEN Nishina Center, Wako)
Introduction to RIBF and charge strippers for U acceleration in the world

Problems with the charge strippers at RIBF

R&D results on low-Z gas stripper

Commissioning status of an actual machine for He gas stripping
Introduction to RIKEN RI Beam Factory (RIBF)

The old facility (1975 to 1990)

RIBF (1997 to 2012)

BigRIPS (Fragment separator)

SRC -- World’s First!
History of RIBF

1997- Project started.
2006 28th Dec: The first beam from SRC.
2007-2012: Improvement, improvement...
2011 Oct.-: New injection system for intensity upgrade of U beam

New injection system (SC-ECRIS+RILAC2)

U\textsuperscript{35} is extracted from SC-ECRIS.
Achieved Beam Intensities (Goal 1 $1 \mu\text{A} = 6 \times 10^{12} \#/s$)

Problems w.r.t. charge strippers will be more severe!!
Function of charge stripper

Equation of motion for accelerators

\[ \frac{dv}{dt} = \frac{Q}{M} \left( E + v \times B \right) \]

Sensitivity to E and B
Acceleration
Bending or focusing

Charge equilibrium
Electron loss = Electron capture

(a) Solid

Equilibrium charge state vs. Energy (MeV/nucleon)

- Solid data
- Leon
- Baron
- Schwietz (solid)
- GLOBAL (carbon)
General requirements on charge strippers

• **High charge state**
  – Reduction total accelerating voltage and cost
  – Density effect in solid/liquid => ~20% higher charge states compared to gas

• **High stripping efficiency**
  – Typical stripping efficiency = 10%-30%
  – Using too many strippers decreases beam intensity to zero.

• **Long lifetime**
  – Lifetime of carbon foil is inversely proportional to beam intensity.
  – Lifetime-related problems are critical to high-power beam operation.

• **Good stability**
  – Contributes to stable operation of the acceleration complex.

• **Uniform thickness**
  – Energy spread after the stripper, emittance growth in the longitudinal direction

Uranium accelerators: FAIR@GSI, FRIB@MSU, RIBF@RIKEN
<table>
<thead>
<tr>
<th>FAIR@GSI</th>
</tr>
</thead>
</table>

### Chart (a) Solid

- Equilibrium charge state vs. energy (MeV/nucleon)
- Data points for Leon, Baron, Schiwietz (solid), GLOBAL (carbon)

### Table

<table>
<thead>
<tr>
<th><strong>Final energy of U</strong></th>
<th><strong>1000</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type of accelerator</strong></td>
<td>Synchrotron</td>
</tr>
<tr>
<td><strong>Number of strippers</strong></td>
<td>1</td>
</tr>
<tr>
<td><strong>Stripping energy</strong> (MeV/nucleon)</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Charge state</strong></td>
<td>4+ → 28+</td>
</tr>
<tr>
<td><strong>Stripping efficiency</strong></td>
<td>~14%</td>
</tr>
<tr>
<td><strong>Beam power at stripper (kW)</strong></td>
<td>300 (pulsed)</td>
</tr>
<tr>
<td><strong>Type of stripper</strong></td>
<td>N$_2$ gas (supersonic gas jet)</td>
</tr>
<tr>
<td><strong>Technical challenge</strong></td>
<td>Dynamic Vacuum</td>
</tr>
</tbody>
</table>
Dynamic Vacuum

- adsorbed residual gas
- dipole
- electron capture
- desorption
- electron loss
- desorption
- beam loss
- collimator / ion catcher
- further charge exchange
<table>
<thead>
<tr>
<th><strong>FRIB</strong></th>
<th><strong>Final energy of U (MeV/nucleon)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>200</td>
</tr>
<tr>
<td><strong>Type of accelerator</strong></td>
<td>SRF linac</td>
</tr>
<tr>
<td><strong>Number of strippers</strong></td>
<td>1</td>
</tr>
<tr>
<td><strong>Stripping energy (MeV/nucleon)</strong></td>
<td>16.3</td>
</tr>
<tr>
<td><strong>Charge state</strong></td>
<td>33+, 34+ =&gt; 76+, 77+, 78+, 79+, 80+</td>
</tr>
<tr>
<td><strong>Stripping efficiency</strong></td>
<td>~80%</td>
</tr>
<tr>
<td><strong>Beam power at stripper (kW)</strong></td>
<td>40</td>
</tr>
<tr>
<td><strong>Type of stripper</strong></td>
<td>Liquid Li film (baseline) He gas with Plasma Windows (alternative)</td>
</tr>
<tr>
<td><strong>Technical challenge</strong></td>
<td>Liquid Li film Plasma Window</td>
</tr>
</tbody>
</table>
Liquid lithium stripper
J. Nolen, C. Reed and Y. Momozaki (ANL)

Development of a liquid lithium thin film for use as a heavy ion beam stripper

JInst. 4 (2009) P04005

Y. Momozaki, J. Nolen, C. Reed, V. Novick and J. Specht

F. Marti, May 7 2012, RISP Workshop, Slide 20
Plasma Window Contained Gas Stripper
Hershcovitch, Thieberger et al (BNL)

Conduction reduction factor ~ 20
We need to increase beam aperture (2 mm → 6 mm)
### RIBF@RIKEN

#### Technical challenge

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final energy of U (MeV/nucleon)</td>
<td>345</td>
</tr>
<tr>
<td>Type of accelerator</td>
<td>Cyclotron</td>
</tr>
<tr>
<td>Number of strippers</td>
<td>2</td>
</tr>
<tr>
<td>Stripping energy (MeV/nucleon)</td>
<td>11 and 51</td>
</tr>
<tr>
<td>Charge state</td>
<td>$35^+ \rightarrow 71^+/65^+ \rightarrow 86^+$</td>
</tr>
<tr>
<td>Stripping efficiency</td>
<td>$\sim 5%$ [Invention!]</td>
</tr>
<tr>
<td>Beam power at stripper (kW)</td>
<td>7.5</td>
</tr>
<tr>
<td>Type of stripper</td>
<td>$1^{st}$ stripper C-foil $\rightarrow$ He gas $2^{nd}$ stripper C-foil $\rightarrow$ Wheel?</td>
</tr>
<tr>
<td>Technical challenge</td>
<td>He gas confinement</td>
</tr>
</tbody>
</table>
Uranium Acceleration at RIBF

Before Aper

We should think about the first stripper more seriously.

Momentum spread after the stripper

Before

After

Wider!
## Requirements on the first stripper

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Effect on the cyclotron-based complex (RIBF)</th>
<th>Fixed C-foil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge state</td>
<td>&gt;69</td>
<td>Output energy: constant</td>
<td>71+</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sector field: increased</td>
<td></td>
</tr>
<tr>
<td>Lifetime</td>
<td>&gt; 1 week (100 eµA)</td>
<td>Replacement of foil requires careful tuning</td>
<td>12 h (1.4 eµA)</td>
</tr>
<tr>
<td>Uniformity</td>
<td>&lt;10%</td>
<td>Extraction efficiency</td>
<td>~10%</td>
</tr>
</tbody>
</table>

## R&D programs for the first stripper (2008-)

1: Large carbon foil on a rotating cylinder
2: N₂ gas stripper
Large C-foil on a rotating cylinder

Lifetime 60 times longer than that of the fixed foil.
The first test for the rotating stripper (May 2008)

A rotating foil was tested in May 2008 => Broke shortly, 15 min
Rotation speed ~ 100 rpm
Very slowly rotating CNT-based foils can survive for 3 - 4 days (10 e\(\mu\)A).

Video of the irradiation on the rotating foil though it is very difficult to recognize its rotation. Some foil sections were missing after 3-4 days when the foil should be replaced.

This stripping system was successfully used in a U beam campaign last year, when the new injector system (RILAC2) started operation as an actual injector.
R&D programs for N\textsubscript{2} gas stripper

Gas stripper (N\textsubscript{2}):  
1. Free from lifetime-related problems.  
2. Lower equilibrium charge state $Q_e$.  
   (absence of density effect)  
A set of test results about gas stripper (Feb./March 2009)

- U beam: The average charge state with the gas stripper is far below the acceptable charge state for the fRC, 69+.
# Summary of the R&D studies

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Fixed C-foil</th>
<th>Large C-foil on a rotating cylinder</th>
<th>N₂ gas</th>
<th>Low-Z gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge state</td>
<td>&gt;69</td>
<td>71+</td>
<td>71+</td>
<td>56+</td>
<td>Higher?</td>
</tr>
<tr>
<td>Lifetime</td>
<td>&gt;1 week (100 eµA)</td>
<td>12 h (1.4 eµA)</td>
<td>4-5 days (10 eµA)</td>
<td>Sufficiently long</td>
<td>Sufficiently long</td>
</tr>
<tr>
<td>Uniformity</td>
<td>&lt;10%</td>
<td>~10%</td>
<td>&gt;10%</td>
<td>~0%</td>
<td>~0%</td>
</tr>
</tbody>
</table>
Example of charge state of U in He (22 MeV/u)

Effective charge

Enhancement of the effective charge in the low-Z gas region
← suppression of electron capture process

Stripping energy at RIBF: 11 MeV/u
Can we expect higher charge states in the low-Z gas for our gas stripping?

NIMB 107 (1996) 9
A simple estimation of cross sections for 1e-loss and 1e-capture

Loss: M. Gryzinski, Phys. Rev. 138 (1965) A305. (Binary Encounter Model)
Experimental Method

- The beams passed through a carbon foil located in front of a bending magnet, which was used to select the individual projectile charge states.
- Several carbon foils were prepared to select projectile charge states from 60 to 75.
- Each beam was directed through a windowless He gas cell of 15 µg/cm² in thickness to exchange charge again.
- After emerging from the gas cell, the beams passed through a second bending magnet into a FC to analyze the electron captured and stripped ions.

![Diagram of Experimental Setup]

- He Gas (15 µg/cm²)
- Qi⁺ selection (60⁺ < Qi⁺ < 75)
- Bending Mag.
- U beam
  - 11 MeV/u 35⁺
  - 14 MeV/u 41⁺
  - 15 MeV/u 41⁺
- C foil
- Bending Mag.

![Graphs showing fraction of lower than equilibrium, equilibrium, and higher than equilibrium]

- \( \sigma_{\text{cap}} < \sigma_{\text{ion}} \)
- \( \sigma_{\text{cap}} = \sigma_{\text{ion}} \)
- \( \sigma_{\text{cap}} > \sigma_{\text{ion}} \)
Electron capture and loss cross sections of U in He-gas were measured to estimate the equilibrium charge state.

Measured Results

- Electron capture and loss cross sections of U in He-gas were measured to estimate the equilibrium charge state.


- Eq. Charge state in N₂: 56+ @ 11 MeV/u

- Acceptable with fRC: 69+.

- Charge: 66+ @ 11 MeV/u

- Charge: 73+ @ 14 MeV/u

- Charge: 75+ @ 15 MeV/u
Difficulty in accumulation of low-Z gas

The existing gas stripper: He $\sim 15 \mu g/cm^2$ (0.7 kPa)
  (cf. $N_2$ 1.3 mg/cm$^2$)

About 1 mg/cm$^2$ of low-Z gas is necessary to be accumulated to obtain higher charge states.

$\rightarrow$ A new device to make it possible ...

Two options

1. Plasma Windows
   $\rightarrow$ special techniques to design and operate them.
   $\rightarrow$ We began the R&D works on the PW with A. Herschcovith.

2. big Mechanical Booster Pumps (MBP)
   $\rightarrow$ They are big but commercially available.
   $\rightarrow$ We initiated He gas accumulation of about 1 mg/cm$^2$ to measure charge distribution and energy spread using them.
Two He gas targets with differential pumping system

1: 8-m He gas target

2: 0.5-m He gas target
Results (U(11 MeV/u) +He) (Sept. 2010, June, 2011)

Charge state

Energy Spread

\[ \frac{\Delta E}{E} (4\sigma) \approx 0.4\% \text{ (preliminary)} \]

Charge-exchange straggling:

H. Weick et al.,

(cf. \( \approx 0.7\% \text{ (preliminary)} \)
in C-foil (300 \( \mu g/cm^2 \))

We decided to make an actual machine for the He gas stripping.

But there are some issues to be solved.

1. Impurity
2. Thermal issue
3. He gas recycling system
Actual machine development

He circulating vol.: 300m³/day (unique recycling system)
5 stage diff. pumping: 21 pumps
Large beam aperture: >Φ10 mm
8 order pres. Reduction: 7 kPa⇒10⁻⁵ Pa

He gas region
- 7 kPa
- 50 cm
- 0.7 mg/cm²

2012 Jan.  Installation OK!
Mar.  Offline test OK!
Apr.- May  Test w/ U beams
Tests using U beams are in progress for the next U campaign scheduled in the next autumn.

Beam intensity: 13 eµA

Achieved beam intensity after He gas stripper

Checklists: No problems could be found thus far!!

• Impurity: oil, water, N₂, or O₂ (Increase capture cross section)
  => Low level (No change in the charge state distribution)

• High power beam easily makes a “hole” in gas due to heat generation?
  => No sign in the charge distribution and energy spread thus far

• He gas recycling system
  => 98%: recycled + 2%: to recovery line in the laboratory. No loss of He gas
Summary

- The RIBF has been successfully operated from 2007 to 2012 after the first beam.
- The new injector system began operation in October 2011 to increase the U ion beam intensity.
- The stripper problem is still unresolved.
- However, the low-Z gas stripper is an important candidate.
- In the process of testing the low-Z gas stripper,
  - The electron capture and loss cross section were measured.
  - The charge evolution and energy spread were measured using a thick He gas target with the big MBP system.
- We decided to make an actual machine for the He gas stripping.
- We are testing the machine for the next U campaign in the coming autumn.
- We should do battle with the second stripper in the near future.