Realization of New Charge-state Stripper for High-power Uranium Ion Beams

Hiroshi Imao

ACFA/IPAC’13 Prize

238U
Outline

1. Uranium acceleration
   • Problem in charge stripper

2. He stripper development
   • Technical issues & prototype tests
   • Practical system development

3. Highlight data
   • Performance and highlight data

4. Summary and future prospects
Riken RI Beam Factory (RIBF)

Cyclotron-based heavy-ion accelerator complex

goal intensity; \textbf{1 puA} (= 6.24 \times 10^{12} /s)

Upgrading of $^{238}$U intensity

RI beams via in-flight fission

Expansion of nuclear chart

$\Rightarrow$ create a thousand of new RI

Key factor
Charge stripper
Charge stripping in inflight-RI facilities

Heavy ion accelerator $\rightarrow$ flexibility of charge state controlled by Ion source & Charge-state stripper

- **FAIR**(Synchrotron, PLS)
  Low charge state to avoid space charge

- **RIBF**(Cyclotron, DC), **FRIB**(SRF linac, DC)
  Highly charged ions
  Charge stripping at intermediate energies $\Rightarrow$ outstanding issue!!
  $\Rightarrow$ No established ways for high-power beams

(Low-Z gas, liq-Li, plasma strippers etc.)
Original acceleration scheme at RIBF

1. U acceleration

**dE/dx ∝ Z₁² • Z₂/A**

- **48 Ca**
  - Cfoil (40 μg/cm²)
  - 10+ → 16+ (35%)
  - 2.7 MeV/u

- **238 U**
  - Cfoil (1.4 μg/cm²)
  - 16+ → 20+ (96%)
  - 46 MeV/u

**max. 410 puA**

**max. 3.5 puA**

11 MeV/u 10 puA **238 U ~ 400 MeV 500 mA** proton!!!
1. U acceleration

**1st. Stripper at 11 MeV/u**
- foil thickness less than 1 \( \text{um} \)
- fragile, thickness non-uniformity, poor thermal conductivity

**Bottleneck of }^{238}\text{U acceleration at RIBF**

<table>
<thead>
<tr>
<th>C-foil: &lt;0.02 puA</th>
<th>Rotating CNT-foil: &lt;\sim0.3 \text{ puA}</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="before" alt="C-foil before and after" /> <img src="after" alt="C-foil after" /></td>
<td><img src="rotating_cnf_foil" alt="Rotating CNT-foil" /></td>
</tr>
</tbody>
</table>

Goal: 10 puA \( \Rightarrow \) New stripper is required

H. Hasebe et al.
Low-Z (Z; atomic number) gas (e.g., H₂ • He)

• Non destructive & uniform thickness
• High charge state equilibrium

slow velocity of electrons \( (v_{1s} \propto Z_{c}/137) \)

⇒ suppression of e- capture

Calculation

\[ \text{H. Okuno et al., PRST-AB 14, 033503 (2011)} \]
Technical challenge
Windowless confinement
- Diffusiveness ($\propto \sqrt{m}$)
- Slow equilibrium

Prototype systems
Feasibility of gas confinement
- Diff. pumpings w/ huge pumps
- Gas flow-disturber
  $\Rightarrow$ conductance suppression

Fundamental data
- Charge distribution
- Energy spread
- Beam transmission
Gas was directly confined within **beamline** (H$_2$ 1 mg/cm$^2$, He 3 mg/cm$^2$)
He gas with thickness of 2 mg/cm² was confined in 0.5-m target region

He; 2 mg/cm²
N₂; 30 mg/cm²
2. He stripper development

**Fundamental data and strategy**

- **Charge evolution**
  - mean charge state $65^+$ for H$_2$ and He
  - acceptable state of fRC $69^+$ (C $71^+$, N$_2$~$56^+$)

- **Energy spread**
  - Time distribution measured w/ scinti.
  - Half of spread for C-foil (thickness uniformity)

- **Transmission**
  - 50cm target, φ6mm aperture $\Rightarrow$ 70%

*H. Imao et al., PRST-AB 15, 123501 (2012)*

**Strategies for practical system**

- acceleration for 64+ w/ fRC modification
- target thickness reduced (0.5-0.7 mg/cm$^2$)
- beam orifice enlarged (Φ6mm⇒Φ10mm)
2. He stripper development

Design of He gas stripper

RIKEN Recirculating He-Gas Charge-State Stripper

- 5-stage diff. pumping; 22 pumps
- Large beam aperture; >Φ10 mm
- 8 order pres. reduction; 7 kPa⇒10⁻⁵ Pa
- He gas flow; 300 m³/day

Charge exchange here

He gas; 7 kPa * 50 cm ⇒ 0.7 mg/cm²

U⁶⁺
to fRC

from RRC

U³⁵⁺
Gas recirculation w/ rotary pumps

Gas recirculation with MBP

Only w/
Mechanical booster pumps

Reduced complexity of purification system

- Cost reduction
- Stable target and reliable system
Design of recirculation system

- **Multi-stage MBP array** (7 units, 12000 m³/h)
- Recycling rate < **99.6%**
- Target refilling rate > 0.4% (impurity, activation)
- Auto pressure control for gas supply
2. He stripper development

High duty line & limited time!

R&D works in 2012

2012 Jan. Installation

Mar. Offline tests
thickness <1 mg/cm²
Recycle rate <99.6%

Apr.-Oct. Online tests
fRC upgrade
new beam dump

Nov.-Dec. User runs
Effect of impurity (Air, H₂O, HC) on charge state

$\sigma_{\text{cap}} \propto Z^{4.2}$ (less than 100 ppm of impurity is required)

Charge state distribution is the most sensitive test!

mean charge state 64+ w/ recycling rate of 99.6% (equivalent to the value 64+ w/o recycling)
3. Highlight data

### Beam intensities after strippers

**Beam after SRC**

<table>
<thead>
<tr>
<th></th>
<th>2011</th>
<th>2012</th>
<th>[\sim 10^{11} /s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak intensity [pnA]</td>
<td>3.6</td>
<td>15.1</td>
<td></td>
</tr>
<tr>
<td>Service rate [%]</td>
<td>56.7</td>
<td>80.3</td>
<td></td>
</tr>
<tr>
<td>Mean intensity [pnA]</td>
<td>1.6</td>
<td>10.2</td>
<td></td>
</tr>
</tbody>
</table>

Stably operated!

User runs w/ He stripper

2011: w/ rot. C-foil

2012: w/ He stripper
3. Highlight data

Glow of uranium beams
4. Summary and future prospect

New acceleration scheme for high-power $^{238}$U with recirculating He gas stripper is realized

Tenfold increase of average output intensity of $^{238}$U in 2012

- He stripper removed primary bottleneck
  (Operated without any deterioration w/ $^{238}$U beams during 1.5 months)
- Success of some other remarkable accelerator upgrades
  (Ion source, K700-fRC, high-power beam dump, 2nd Be disk stripper etc.)
Acknowledgement

MUSASHI ASACUSA group
(positron accumulator for antihydrogen production)
Y. Yamazaki, K. Michishio, M. Tarek, T. Shimoyama,
Y. Kanai, Y. Enomoto, N. Kuroda, Y. Nagata, H.A. Torii,
H. Higaki, C.H. Kim, H. Toyoda, K. Fujii, M. Ohtsuka,
K. Tanaka, Y. Nagashima, Y. Matsuda, B. Juhász,
A. Hohri, M. Corradini, M. Leali, E. Lodi-Rizzini,
V. Mascagna, L. Venturelli, N. Zurlo and many others.

RNC Accelerator group (He gas stripper)
O. Kamigaito, T. Aihara, N. Fukunishi, S. Fukuzawa, M. Fujimaki, T. Fujinawa, A. Goto, M. Hamanaka,
H. Hasebe, Y. Higurashi, E. Ikezawa, S. Ishikawa, T. Kageyama, M. Kase, M. Kidera, K. Kobayashi,
M. Komiyama, Y. Kotaka, R. Koyama, H. Kuboki, K. Kumagai, T. Maie, M. Nagase, T. Nakagawa,
M. Nakamura, T. Nakamura, M. Nishida, M. Nishimura, E. Ohki, J. Ohnishi, Y. Ohshiro, H. Okuno,
N. Sakamoto, K. Sakuma, J. Shibata, K. Suda, K. Tamura, N. Tsukiori, H. Uchiyama, Y. Uwamino,
T. Watanabe, Y. Watanabe, K. Yadomi, T. Yamauchi, Y. Yano, K. Yamada, H. Yamasawa, S. Yokouchi and
many others.

Other facilities and companies
K. Nagamine, K. Hosoyama, A. Hershcovich, F.Marti, J. Akiba, T. Kobayashi, M. Kumashiro,
D. Nakamura, S.Niwa, T. Sakurai, A. Yamamoto and many others
New addition is born to my family
(4 days ago during conference reception!!)
Thank you very much!
Let’s discuss in poster session today THPW0038