Operating Experience with the RIKEN Radioactive Isotope Beam Factory


Nishina Center for Accelerator-Based Science, RIKEN
RI Beam Factory Project aims

(1) to produce the world-most-intense RI beam
(2) to make systematic studies on unstable nuclei far from stability

Nucleosynthesis in universe (r-process)

Search for unstable nuclei with novel structure

(from a pamphlet of Nishina center for Accelerator-Based Science)
Layout of RI Beam Factory

Old facility (1986~)

Charge-State Multiplier (CSM)

RRC = Riken Ring Cyclotron (1986~)
fRC = fixed-frequency Ring Cyclotron (2006~)
IRC = Intermediate-stage Ring Cyclotron (2006~)
SRC = Superconducting Ring Cyclotron (2006~)

New facility (2006)

18 GHz ECRIS
RIKEN heavy-ion linac (RILAC)

BigRIPS

RRC = Riken Ring Cyclotron (1986~)
fRC = fixed-frequency Ring Cyclotron (2006~)
IRC = Intermediate-stage Ring Cyclotron (2006~)
SRC = Superconducting Ring Cyclotron (2006~)
## Specifications of RIBF ring cyclotrons

<table>
<thead>
<tr>
<th></th>
<th>fRC</th>
<th>IRC</th>
<th>SRC</th>
<th>RRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-number (MeV)</td>
<td>570</td>
<td>980</td>
<td>2600</td>
<td>540</td>
</tr>
<tr>
<td>number of sector magnets</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>velocity gain</td>
<td>2.1</td>
<td>1.5</td>
<td>1.5</td>
<td>4.0</td>
</tr>
<tr>
<td>number of trim coils ( / sector magnet)</td>
<td>10</td>
<td>20</td>
<td>4(SC)</td>
<td>26</td>
</tr>
<tr>
<td>RF resonators</td>
<td>2+FT</td>
<td>2+FT</td>
<td>4+FT</td>
<td>2</td>
</tr>
<tr>
<td>frequency range (MHz)</td>
<td>54.75</td>
<td>18~38</td>
<td>18~38</td>
<td>18~38</td>
</tr>
</tbody>
</table>

SC = superconducting  
NC = normal conducting  
FT = flat-top resonator
Acceleration modes in RIBF

(1) Variable-energy mode

\( ^{27} \text{Al}, ^{48} \text{Ca}, ^{86} \text{Kr} \)

\( \sim 400 \text{ MeV/u @ SRC} \)

(2) Fixed-energy mode

\( ^{238} \text{U} 345 \text{ MeV/u @ SRC} \)

(3) AVF-injection mode

Polarized deuteron, \( ^{14} \text{N} \)

\( 250 \sim 440 \text{ MeV/u @ SRC} \)
Operation history

(Does not include experiments using RRC beams.)

<table>
<thead>
<tr>
<th>Year</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>U</td>
<td>U</td>
<td>Kr</td>
<td>U</td>
<td>U</td>
<td>U</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2007</td>
<td>U</td>
<td>U</td>
<td></td>
<td>U</td>
<td>Ca</td>
<td>U</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>N</td>
<td>U</td>
<td>Xe</td>
<td>N</td>
<td>Pol.-d</td>
<td>U</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

BigRIPS

125\(^{\text{Pd}}\) & 126\(^{\text{Pd}}\) (T. Ohnishi et al.)

1st beam

upto RRC

upto fRC

upto IRC

upto SRC

Zero-degree spectrometer

~20 New Isotopes

SHARAQ, Zero-degree spectrometer = Experimental instrumentation installed downstream the BigRIPS
Polarized deuteron beam (April, 2009)

$\vec{d} - \vec{p}$ at 250 MeV/A

$A_y$

$A_yy$

$A_x$

Analyzing power measurements with single-turn extracted beams
## Operation statistics

### Operation-time statistics (hours)

<table>
<thead>
<tr>
<th>year</th>
<th>2008</th>
<th>2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRC operation</td>
<td>3961</td>
<td>3757</td>
</tr>
<tr>
<td>RRC experiment</td>
<td>1165</td>
<td>687</td>
</tr>
<tr>
<td>RIBF operation</td>
<td>2051</td>
<td>1845</td>
</tr>
<tr>
<td>RIBF experiment</td>
<td>685</td>
<td>414</td>
</tr>
</tbody>
</table>

5 months operation approved
50% used for RIBF
30% of RIBF operation used for experiments
Oil contamination in He refrigerator of SRC

He refrigerator of SRC was contaminated with oil from He compressor. (Feb. 2008)

HX1~7, T1~4 etc cleaned up.

Oil separator of He compressor
4 steps → 6 steps

Cooling power 1410 W → 1378 W
SRC performance as an isochronous cyclotron

Isochronous Magnetic Field
(2008, Dec. 17th 06:09)

Voltage and Phase Deviation of RF system

Voltage deviation [%]

Phase drift [deg.]

Elapsed time [h]

ΔV/V ~ 0.01%  Δψ ~ ±0.1° RF

damaged by flat-top rf fields

13 degree RF
Present performance of RIBF

Present status
~90% transmission efficiency in variable-energy mode
~200 pnA operation is available for light ions ($^{48}$Ca).

<table>
<thead>
<tr>
<th>Maximum Beam Intensity</th>
<th>Extraction efficiency of ring cyclotrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>ion</td>
<td>(nA)</td>
</tr>
<tr>
<td>$^{238}\text{U}^{86+}$ (07/07/03)</td>
<td>4</td>
</tr>
<tr>
<td>$^{86}\text{Kr}^{34+}$ (07/11/04)</td>
<td>1100</td>
</tr>
<tr>
<td>$^{238}\text{U}^{86+}$ (08/11/16)</td>
<td>35</td>
</tr>
<tr>
<td>$^{48}\text{Ca}^{20+}$ (08/12/21)</td>
<td>3500</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ion</th>
<th>$^{48}\text{Ca}$ (08/12/21)</th>
<th>$^{238}\text{U}$ (08/11/16)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRC</td>
<td>95%</td>
<td>86%</td>
</tr>
<tr>
<td>fRC</td>
<td></td>
<td>117%*</td>
</tr>
<tr>
<td>IRC</td>
<td>93%</td>
<td>86%</td>
</tr>
<tr>
<td>SRC</td>
<td>82%</td>
<td>66%</td>
</tr>
</tbody>
</table>

* may include 20~30% errors

(yy/mm/dd)
Transmission efficiency problem ($^{238}$U)

Transmission efficiency from ion source to each accelerator
(Charge stripping efficiencies are not included)

Charge stripping efficiencies
- $^{48}$Ca: 30%
- $^{86}$Kr: 12%
- $^{238}$U: 4 ~ 5%

$^{238}$U 2% (2007) → 16% (2008)
$^{86}$Kr 9% (2007) → $^{48}$Ca 35% (2008)
To obtain good transmission efficiency ($^{238}$U beam)

Thick carbon foil strippers
Long beam lines

Good thickness uniformity
Phase adjustments of flat-top resonators
Highly-stabilized system
Effect of secondary electrons

Turn pattern of IRC-MDP1 (07/05/22)

positive current (ion dominated)

Zero current

negative current (electron dominated)

Injection

Extraction

Modification of SRC-MDP

Front View

Top View
Precise phase adjustment of flattop resonators

**FT phase precisely tuned**

**FT phase -1 degree shifted**

**FT phase +1 degree shifted**

$^{48}$Ca beam, IRC (08/06/05)
Charge stripper problem

(1) $^{238}\text{U}^{35+} \rightarrow ^{238}\text{U}^{71+}$ @ 10.75 MeV/nucleon (0.5 ~ 0.6 μA)

Longitudinal beam profile (@ 38 m below the stripper)

(a) 300μg/cm$^2$
    FWHM=1.35 nsec

(b) 300 μg/cm$^2$ used for 15 hours
    FWHM=2.45 nsec

(c) 219 μg/cm$^2$
    FWHM=1.02 nsec

Commercial carbon foil (Arizona)

(1) Energy spread @ A01 stripper (1.4% energy loss) = ~ 0.5 %
(2) Lifetime < 10 hours for 600 nA $^{238}\text{U}$ beam
(3) multi-layer carbon, diamond-like carbon were also tested.
Stability of injector (RILAC)

allowable limit = ±0.1 degree in phase & ±0.1% in voltage

Voltage fluctuation (%)

Time (hour)

Phase (6/7 9:00 - 6/8 9:00)

Voltage (6/7 9:00 - 6/8 9:00)

Time (hour)

RILAC

18 GHz ECRIS

RFQ

Stripper

CSM

#1

#2

#3

#4

#5

#6
Correlation between fluctuations of RF voltages and commercial electricity

No. 1 cavity  
C. C. = 0.04

No. 2 cavity  
C. C. = 0.18

No. 3 cavity  
C. C. = 0.69

No. 4 cavity  
C. C. = 0.42

No. 5 cavity  
C. C. = 0.01

No. 6 cavity  
C. C. = -0.06

Automatic gain controllers (AGC) were upgraded in 2002.
Emittance analysis of $^{48}$Ca beam (08/12/21)

Utilizing the data of beam widths obtained by beam profile monitors, we estimated beam emittances based on the first order ion optics.

(1) Emittance (IRC-injected beam) = $2.2 \sim 2.3 \pi$ mm mrad (unnormalized, within $4\sigma$ region)
(2) Emittance (SRC-injected beam) = $\sim 1.7 \pi$ mm mrad (unnormalized, within $4\sigma$ region)
(3) No notable emittance growth was observed.
(4) Corresponding normalized-RMS emittance is $0.19 \pi$ mm mrad.
Emittance analysis for $^{238}\text{U}$ beam (08/11/16)

Emittance estimation based on 1st order optics 
($\pi$ mm mrad, unnormalized, within $4\sigma$ region)

<table>
<thead>
<tr>
<th></th>
<th>vertical</th>
<th>horizontal</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRC extraction</td>
<td>2.6</td>
<td>~ 2.4</td>
</tr>
<tr>
<td>fRC extraction</td>
<td>1.4</td>
<td>5</td>
</tr>
<tr>
<td>IRC injection</td>
<td>2.1</td>
<td>5 ~ 6</td>
</tr>
<tr>
<td>SRC injection</td>
<td>1.4</td>
<td>~ 4</td>
</tr>
</tbody>
</table>

Vertical direction: no problem
Horizontal direction: Large emittance growth
Emittance Growth during fRC acceleration

$EIC = electrostatic\ inflection\ channel$

**horizontal @ fRC-EIC**

- $\pm 3 \sigma$ eigen ellipse

**vertical @ fRC-EIC**

(1) Emittance growth in horizontal direction = 1.7
   Horizontally over-focused

(2) Vertically, beam was strongly defocused.
   Second-order aberration
Other improvements (2007~2008)

(1) Upgrade of vacuum pumps for low-energy region of the injector linac.
(2) RF contacts introduced for the radial probes to suppress leakage RF fields from flat-top resonators (TE01 mode).
(3) Interference filters were introduced to the phase probe of fRC to obtain high S/N ratio.
(4) Beam-phase and RF-fields monitoring system using lock-in amplifiers (SR844) was developed.
(5) Beam interlock system to protect hardwares started its operation.
(6) Type-E thermocouple gauges installed to SRC-EDC to measure heat load caused by beam loss.
(7) Water-cooling thermal baffles were introduced to decrease temperature of a RF shield in front of cryopumps. (SRC)
(8) Faraday cups were modified to suppress effectively secondary electrons.
(9) High-Temperature Superconducting SQUID beam monitor started its operation.
(10) Ion-beam core monitor operating with 50 KHz has been developed.
(11) Beam line bypassing IRC was constructed and commissioned.
To obtain high-intensity uranium beam
28 GHz-ECRIS + RILAC2

28GHz SC-ECRIS
T. Nakagawa et al.
Tests @ RILAC (2009)
Installation (2010)

Prebucnher
18.25 MHz

RFQ
Four-Rod, 36.5 MHz

DTLs QWR, 36.5 MHz

RILAC2
0.7 MeV/nucleon for M/q = 7 ion
Fabrication (FY2009)
Beam commissioning (FY2010)
Summary

• Oil contamination problem of He refrigerator of SRC was solved.
• SRC works well as a good isochronous cyclotron.
• Transmission efficiency was improved.
• 200-pnA $^{48}$Ca beam & 0.4-pnA $^{238}$U beam are now available.
• A series of experiments were performed in these 6 months.

• Charge strippers used in $^{238}$U acceleration are most important problem.
• Stability of RILAC should be improved.

• New superconducting ECRIS will start its operation in 2009.
• Construction of a new injector linac was started.
Beam monitors in beam lines

<table>
<thead>
<tr>
<th>BT</th>
<th>length (m)</th>
<th>PF</th>
<th>FC</th>
<th>P.S.</th>
</tr>
</thead>
<tbody>
<tr>
<td>RRC - fRC</td>
<td>78</td>
<td>12</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>fRC - M04</td>
<td>60</td>
<td>9</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>M04 - IRC</td>
<td>59</td>
<td>15</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>IRC - SRC</td>
<td>62</td>
<td>11</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

P.S. = plastic scintillator (longitudinal, TOF)

PF = beam profile monitor (wire-scanner type)

FC = Faraday cup used in 2007

Permanent magnet (3 kG)

Suppressor (1 kV)
Modification of Faraday cup

Sizable beam loss disappeared with new FCs.

Faraday cup used in 2007

Permanent magnet (3 kG)
Suppressor electrode (1 kV)

Faraday cup used in 2008

ICF 152 frange
cooling water

SHV-R
Feedthrough

~30 V
~900 V

Stroke 65
Emittance analysis of $^{238}$U beam (08/11/7)

Results of beam-size fitting

- **fRC injection** horizontal (sol090224v1, 08/11/07)
- **fRC to M04 stripper** horizontal (F01a~MB0, dp/p=0.076% 08/11/07)
- **M04 stripper to IRC** horizontal (M05~IRC dp/p=0.20% 08/11/07)
- **SRC injection** horizontal (K00~G50 dp/p=0.08% 08/11/07)
Emittance Growth @ D-rebuncher

Before D-rebuncher (D15)

After D-rebuncher (D18)

Horizontal emittance growth @ D-rebuncher

x 1.5 (design value)

x 2.0 (observed)
Turn Patterns

fRC turn pattern ($^{238}$U, 08/11/26)

effect of secondary electrons

IRC turn pattern ($^{238}$U, 08/11/26)

SRC turn pattern ($^{48}$Ca, 08/12/07)

Single-turn extraction was failed

Single-turn extraction was succeeded
Reasons of low transmission efficiency especially in $^{238}\text{U}$ acceleration

(1) Beam monitors were not suited for uranium acceleration. Suppression of secondary electrons was insufficient.

(2) Beam quality itself was bad due to the existence of thick carbon foils.
   \[ \text{Eloss} = 1.4\% \text{ for } (^{238}\text{U}^{35+} \rightarrow ^{238}\text{U}^{71+}) / \text{thickness uniformity} = 30\% \]
   \[ \text{Eloss} = 9\% \text{ for } (^{238}\text{U}^{71+} \rightarrow ^{238}\text{U}^{86+}) / \text{thickness uniformity} = \sim 7\% \]

(3) Stability of the old injector linac was insufficient.
Charge stripper problem

\(^{86}\text{Kr}^{18+} @ 2.3 \text{ MeV/nucleon}\)

Beam phase monitored by the phase-pickup probe / 25 m below the stripper (X51)

No. 9 X51 = 14\(\mu\)A (full beam)
full beam (14 \(\mu\)A)
lifetime ~ 20 min.

Just after RILAC

No. 10 e04-wide, X51 = 7.59\(\mu\)A

full beam with enlarged beam image
lifetime ~ 80 min.

No. 28 X51 = 1.43\(\mu\)A (ATT 1/10)

beam intensity attenuated (1.4 \(\mu\)A)
lifetime ~ 1000 min.

(PCC071019, 20 \(\mu\)g/cm\(^2\))
Lifetime of various carbon foils

$^{86}\text{Kr}^{18+}$ @ 2.3 MeV/nucleon

- Lifetime before breakdown: 4 hours

- Polymer coating carbon foil

- Commercial

- No polymer coating

$\text{Polymer} = \text{Poly(monochloro-para-xylylene)}, \text{Parylene}$
## Charge stripper status

<table>
<thead>
<tr>
<th>Ion</th>
<th>E (MeV/u)</th>
<th>Intensity (μA)</th>
<th>Quality</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}\text{Ca}^{10+}$</td>
<td>2.7</td>
<td>30</td>
<td>O.K.</td>
<td>O.K.</td>
</tr>
<tr>
<td>$^{48}\text{Ca}^{16+}$</td>
<td>45</td>
<td>3</td>
<td>O.K.</td>
<td>O.K.</td>
</tr>
<tr>
<td>$^{86}\text{Kr}^{18+}$</td>
<td>2.3</td>
<td>25</td>
<td></td>
<td>&lt; 2 hours</td>
</tr>
<tr>
<td>$^{136}\text{Xe}^{20+}$</td>
<td>11</td>
<td></td>
<td>O.K. (gas stripper will be used)</td>
<td></td>
</tr>
<tr>
<td>$^{136}\text{Xe}^{41+}$</td>
<td>50</td>
<td></td>
<td>Not tested</td>
<td></td>
</tr>
<tr>
<td>$^{238}\text{U}^{35+}$</td>
<td>11</td>
<td>0.6</td>
<td>Not so good</td>
<td>&lt; 15 hours</td>
</tr>
<tr>
<td>$^{238}\text{U}^{71+}$</td>
<td>50</td>
<td>0.2</td>
<td>Not so good</td>
<td>O.K.</td>
</tr>
</tbody>
</table>
Charge stripper problem

\[ ^{238}\text{U}^{35+} \rightarrow ^{238}\text{U}^{71+} \text{ @ 10.75 MeV/nucleon (0.6 \, \mu A)} \]

0.3 mg/cm\(^2\) multi-layer PCC foil

very short lifetime without oven-conditioning

more than 24 hours oven (523K) for several hours

rotating carbon foil stripper
0.3 mg/cm\(^2\) multi-layer PCC foil

broken, within 25 minutes
Electron Probe Micro-Analysis

0.5 mg/cm$^2$ PCC foil

Ta (from a slit)

non-irradiated part

irradiated part
Fig. 2. AFM images of surface of the substrate side of the 300 μg/cm²-thick multi-layer PCC-foil: (a) non-irradiated part and (b) irradiated part.

Fig. 3. AFM images of surface of the evaporating source side of the 300 μg/cm²-thick multi-layer PCC-foil: (a) non-irradiated part and (b) irradiated part.

H. Hasebe et al., RIKEN Accel. Prog. Rep. 42
## Voltage fluctuation of No.2 resonator of RILAC

<table>
<thead>
<tr>
<th>Time</th>
<th>V (mV, VVM)</th>
<th>I @ A01 (nA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15:17:20</td>
<td>62.9</td>
<td>562</td>
</tr>
<tr>
<td>15:18:00</td>
<td>63.0</td>
<td>519</td>
</tr>
<tr>
<td>15:18:35</td>
<td>63.2</td>
<td>416</td>
</tr>
<tr>
<td>15:19:30</td>
<td>62.9</td>
<td>570</td>
</tr>
</tbody>
</table>

## Longitudinal beam profile vs Voltage of No.2 resonator

The graph shows the longitudinal beam profile vs voltage at e04. The RILAC2 tank voltage was varied slightly in the e04 region, with beam time profiles presented (Background off, normalized).
Effects of A01 stripper
($^{238}$U$^{35+}$, 10.75 MeV/nucleon, 2007, Oct. 2nd)
Stability of magnetic fields

$^{238}$U acceleration

RRC

NMR measurement

fRC

Estimated by coil currents

$B \sim 1.7 \text{ Tesla}$
Turn pattern obtained by old MDP

observed

Com070628_T2
12 mrad injection

simulation
fRC Turn Pattern

08/11/17 00:33

observed

simulation

Sol090224v1

Sol090225v1
Turn pattern comparison

$^{238}\text{U}^{86+}$ @ IRC-MDP2

observed

simulation

dp/p = 0.20%

dp/p = 0.22%
Comparison of Beam Profile

$^{48}$Ca beam on IRC-injection line