RI Beam Factory
and
Other Radioactive Isotope Beam Facilities

(1) report the present status of RIBF
(2) outline the worldwide RI beam facilities in the near future

N. Fukunishi
Nishina Center for Accelerator-Based Science, RIKEN
Radioactive Isotope Beam

Discovery science
Nuclear Structure
halo, skin, super-heavy elements
Nuclear Astrophysics
r-process, neutron star, supernovae
Fundamental symmetries
electric dipole moment search in RI

Application
Nuclear energy
neutron cross section relevant to ATW
Medicine and Biology
imaging, targeted therapy, radiotracer
Industry
RI as in-situ detectors
National Security

Exotic nuclei?
OECD report (1999)

$^{11}$Li neutron halo
Pioneering work,

Big Bang nucleosynthesis
H, He, 7Li, 7Be

Fusion reaction in stars
up to iron

rp-process
up to U

s-process
up to Bi

r-process
up to Pb

Pioneering work,
**ISOL technique**

\[(1^+ \rightarrow n^+ \text{ scheme})\]

- **Driver beam** \((p,d)\)
- **Production target**
- **Ion Source**
  - Surface IS
  - Plasma IS
  - Laser IS
- **Analyzer magnet**
- **Charge state breeder**
  - ECR
  - EBIT
- **Post accelerator**

**In-flight separation**

- **Driver beam** (high-energy heavy ion)
- **Production target**
- **Fragment separator**
  - \(B_{\rho}\)
  - TOF
  - \(\Delta E\)

T. M. J. Symons, 4th Int. Conf. on Nuclei far from Stability, CERN 81-09 (1981) 668.

## ISOL vs in-flight
thought to be complementary

<table>
<thead>
<tr>
<th></th>
<th>ISOL</th>
<th>In-flight</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Driver ion</strong></td>
<td>light ions (p, d)</td>
<td>heavy ion</td>
</tr>
<tr>
<td><strong>Origin of RI</strong></td>
<td>target ion</td>
<td>projectile ion</td>
</tr>
<tr>
<td><strong>Target</strong></td>
<td>thick target</td>
<td>thin target</td>
</tr>
<tr>
<td><strong>In-target yield</strong></td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td><strong>RI separation</strong></td>
<td>sensitive to chemical properties</td>
<td>physical</td>
</tr>
<tr>
<td><strong>Time scale</strong></td>
<td>&gt; 50 ms</td>
<td>&gt; 1 μs</td>
</tr>
<tr>
<td><strong>Instrumentation</strong></td>
<td>post accelerator</td>
<td>fragment separator</td>
</tr>
<tr>
<td><strong>Beam quality</strong></td>
<td>good</td>
<td>poor</td>
</tr>
<tr>
<td><strong>Experiments</strong></td>
<td>spectroscopy</td>
<td>reaction scheme</td>
</tr>
</tbody>
</table>
First-generation RI beam facilities

- **Red** = synchrotron-based
- **Blue** = cyclotron-based
- **Green** = linac-based

**Facilities:**
- GANIL/SPIRAL
- REX-ISOLDE
- CERN
- EXCYT
- INFN Catania
- GSI
- ISAC/TRIUMF
- CCF-NSCL
- ATLAS
- ANL
- HRIBF
- ORNL
- IMP CAS
- Lanzhou
- RARF
- RIKEN

*Note: Colors indicate the type of facility.*
RIKEN RI Beam Factory
The first of the second-generation in-flight facilities

Old facility (1986~)
- RILAC = RIKEN Heavy-ion linac (1980~)
- CSM = Charge-State Multiplier (2001~)
- 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
- RILAC
- CSM
- AVF
- RRC
- fRC
- IRC
- BigRIPS (fragment separator)
- ZDS
- SHARAQ
- GARIS

RILAC = RIKEN Heavy-ion linac (1980~)
CSM = Charge-State Multiplier (2001~)
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><strong>K-number (MeV)</strong></td>
<td>570</td>
<td>980</td>
<td>2600</td>
<td>540</td>
</tr>
<tr>
<td><strong>Number of sector magnets</strong></td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td><strong>Velocity gain</strong></td>
<td>2.1</td>
<td>1.5</td>
<td>1.5</td>
<td>4.0</td>
</tr>
<tr>
<td><strong>Number of trim coils ( / sector magnet)</strong></td>
<td>10</td>
<td>20</td>
<td>4(SC)</td>
<td>22(NC)</td>
</tr>
<tr>
<td><strong>RF resonators</strong></td>
<td>2+FT</td>
<td>2+FT</td>
<td>4+FT</td>
<td>2</td>
</tr>
<tr>
<td><strong>Frequency range (MHz)</strong></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 = flattop resonator  

\[ *K = (M/q)^2 \times E_{\text{max}} \text{ (MeV/nucleon)} \]
SRC works as a good isochronous cyclotron

**Isocronous magnetic field**

- SRC (10/05/09)
- IRC (10/05/07)

**Stability of RF resonators**

- ΔV/V ~ 0.01%
- Δψ ~ ±0.1° RF
Acceleration modes in RIBF

(1) Variable-energy mode
   \(^{27}\text{Al, }^{48}\text{Ca, }^{86}\text{Kr}\)
   \(~400 \text{ MeV/u @ SRC}\)

(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 statistics / Stability

<table>
<thead>
<tr>
<th>Year</th>
<th>Beam service to users (h)</th>
<th>All RIBF operation (h)</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>414</td>
<td>1845</td>
<td>/</td>
</tr>
<tr>
<td>2008</td>
<td>496</td>
<td>2051</td>
<td>0.68</td>
</tr>
<tr>
<td>2009</td>
<td>1129</td>
<td>3036</td>
<td>0.68</td>
</tr>
<tr>
<td>2010*</td>
<td>907</td>
<td>1820</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Reliability = \( \frac{\text{actual beam service time}}{\text{scheduled beam service time}} \)

“All RIBF operation” include beam tuning, beam commissioning etc in addition to beam service to users.

*First half of 2010

**2010/5/21 ~ 6/11**

\(^{48}\text{Ca} 345\text{ MeV/nucleon}\)

(a) Beam intensity measured with Faraday Cup G01

User required low-intensity beams

(b) Voltage of PP signals

Beam bunch signals measured by a phase-pickup electromode
## RIBF performance

### Beam intensity

<table>
<thead>
<tr>
<th>ion (date)</th>
<th>(pnA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}\text{U}^{86+}$ (07/07/03)</td>
<td>0.05</td>
</tr>
<tr>
<td>$^{86}\text{Kr}^{34+}$ (07/11/04)</td>
<td>33</td>
</tr>
<tr>
<td>$^{238}\text{U}^{86+}$ (08/11/16)</td>
<td>0.4</td>
</tr>
<tr>
<td>$^{48}\text{Ca}^{20+}$ (08/12/21)</td>
<td>175</td>
</tr>
<tr>
<td>$^{4}\text{He}^{2+}$ (09/10/31)</td>
<td>1000</td>
</tr>
<tr>
<td>$^{238}\text{U}^{86+}$ (09/12/19)</td>
<td>0.8</td>
</tr>
<tr>
<td>$^{48}\text{Ca}^{20+}$ (10/5/31)</td>
<td>230</td>
</tr>
<tr>
<td>$^{18}\text{O}^{8+}$ (10/6/17)</td>
<td>1000</td>
</tr>
</tbody>
</table>

*Charge stripping efficiencies are excluded*

### Transmission efficiency*

#### Variable-energy mode

- $^{48}\text{Ca}$ (08/12/08)
- $^{48}\text{Ca}$ (10/06/06)
- $^{18}\text{O}$ (10/06/22)

#### Fixed-energy mode

- $^{238}\text{U}$ (07/07/03)
- $^{238}\text{U}$ (08/11/16)
RILAC2

Intensity upgrade of uranium beams

Y. Higurashi et al.; Proc. IPAC10, THPEC060

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

RILAC2
0.7 MeV/nucleon for M/q = 7 ion
Fabrication (FY2009)
Beam commissioning (FY2010)
## New RI beam facilities worldwide

### ISOL facilities

<table>
<thead>
<tr>
<th>Facility</th>
<th>Location</th>
<th>Driver</th>
<th>Power (kW)</th>
<th>Post accel.</th>
<th>Fission rate</th>
<th>RI yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spiral2 (2012)</td>
<td>France</td>
<td>d, sc-linac</td>
<td>200</td>
<td>K265 cyclo.</td>
<td>$10^{14}$ (pps)</td>
<td>$10^{10}$ (pps)</td>
</tr>
<tr>
<td>SPES (2013)</td>
<td>Italy</td>
<td>p, cyclotron</td>
<td>8</td>
<td>sc-linac</td>
<td>$10^{13}$ (pps)</td>
<td>$10^{9}$ (pps)</td>
</tr>
<tr>
<td>HIE-ISOLDE (2015)</td>
<td>Swiss</td>
<td>p, synchrotron</td>
<td>10</td>
<td>sc-linac</td>
<td>$10^{13}$ (pps)</td>
<td>$10^{9}$ (pps)</td>
</tr>
<tr>
<td>ARIEL (2015)</td>
<td>Canada</td>
<td>p, cyclotron e-linac</td>
<td>100 / 100</td>
<td>sc-linac</td>
<td>$\sim 10^{14}$ (pps)</td>
<td></td>
</tr>
<tr>
<td>EURISOL (&gt; 2020)</td>
<td>EU</td>
<td>p, sc-linac</td>
<td>5000</td>
<td>sc-linac</td>
<td>$10^{16}$ (pps)</td>
<td>$10^{12}$ (pps)</td>
</tr>
</tbody>
</table>

### In-flight facilities

<table>
<thead>
<tr>
<th>Facility</th>
<th>Location</th>
<th>Driver</th>
<th>Energy (MeV/A)</th>
<th>Intensity (uranium)</th>
<th>Fragment separator</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAIR (2016)</td>
<td>Germany</td>
<td>synchrotron</td>
<td>1500</td>
<td>$2 \times 10^{11}$ pps</td>
<td>Super-FRS</td>
</tr>
<tr>
<td>FRIB (2017)</td>
<td>USA</td>
<td>sc-linac</td>
<td>200</td>
<td>$5 \times 10^{13}$ pps</td>
<td>3-stage separation</td>
</tr>
</tbody>
</table>
Next (intermediate) generation ISOL facilities

**SC-linacs**
- Higher energy post-accelerator
  - PIAVE-ALPI, SPES
  - REX upgrade, HIE-ISOLDE
  - ISAC upgrade, ARIEL
- High intensity driver
  - 200-kW driver (SPIRAL2)
  - 5-MW driver (EURISOL)
  - 100-kW electron driver (ARIEL/ISAC)

**Target technology**
- Neutron converter
  - Carbon, SPIRAL2
  - Hg, EURISOL
- UCx target with a fast release time
  - SPES, SPIRAL2, EURISOL

**Multi-user capability**
- 5 experimental ports (GANIL/SPIRAL/SPIRAL2)
- Two new target stations (ARIEL)
- 6 UCx targets (EURISOL)

**RI beam intensity**
- $10^9$ pps (SPES, HIE-ISOLDE)
- $10^{10}$ pps (ARIEL, SPIRAL2)
- $10^{12}$ pps (EURISOL)
Asian activities in RI beam science

**South Korea**

Heavy-ion Accelerator for RIB (KoRIA)

- Multi-purpose
- Both ISOL and In-flight
- In-flight fragmentation after ISOL
- SC linac
  - 10-μA 200-MeV/nucleon U beam
- K = 100 MeV high-intensity cyclotron
- Budget = 0.4 B US$, Schedule = 2016 construction complete

**VEC-RIB Facility**

VECC Kolkata, India

Four RF systems have been successfully commissioned
- RFQ
- Pre-buncher
- IH-linac

**HIRFL-CSR**

IMP Lanzhou, China

Beam commissioning of cooler storage rings

Figure 8-a): Momentum spread before and after cooling.

J. W. Xia et al.; Proc. of IPAC’10, THYMHO1

H. K. Pandey et al.; Proc. of IPAC’10, THPEA002
FAIR
(Facility for Antiproton and Ion Research)
The next generation in-flight facility in Europe

- Synchrotron-based multipurpose facility
  APPA (Atomic and Plasma Physics, and Applied Science)
  CBM (Hadron and quarks in compressed nuclear matter)
  NuSTAR (Nuclear and Nuclear Astrophysics)
  PANDA (Antiproton)

- Main Accelerator SIS100
  Ultra-high vacuum under the control with dynamic pressure rise
  Rapid cycling superconducting magnets (4 T/s)
  High RF voltage

- Advanced Ring technologies
  CR - fast stochastic cooling and isochronous mass measurements
  NESR - precise mass measurements, e-RI scattering, internal-target experiments

- Stripper-problem free facility

- Construction will be completed in 2015 - 2016

GSI (Germany and State Hesse) and 15 partner countries promote FAIR project.

O. Boine-Frankenheim et al.; Proc. of IPAC10, WEYRA01
FIAR Baseline Technical Report (March 2006)
FRIB

(Facility for Rare Isotope Beams)
The power-front in-flight facility

Front-end ( < 0.3 MeV/nucleon)
High-intensity ECR ion source (33+ & 34+, 6 pμA each)

Driver Linac (Sc-linac)
Segment 1 ( < 17.5 MeV/nucleon for uranium)
2 types (β = 0.041 & 0.085) of QWRs at 80.5 MHz
14 cryomodule

Charge stripping at 17.5 MeV/nucleon for uranium

Segment 2
2 types (β = 0.285 & 0.53) of HWRs at 322 MHz
31 cryomodule

400 kW beam power for all ions
200 MeV/nucleon for uranium → 8 pμA
610 MeV for protons

• High-acceptance & high-resolution 3-stage fragment separator
• MSU contribution

• First beam ~ 2017
• Future upgrade - 400 MeV/nucleon uranium

R. C. Yoke et al.; Proc. of SRF2009, FR0AAU02
<table>
<thead>
<tr>
<th></th>
<th>RIBF</th>
<th>FRIB</th>
<th>FAIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV/A)</td>
<td>345</td>
<td>200 (400)</td>
<td>1500</td>
</tr>
<tr>
<td>Driver beam intensity (pps)</td>
<td>$1.5 \times 10^{12}$ \ ($6 \times 10^{12}$, goal)</td>
<td>$5 \times 10^{13}$</td>
<td>$2 \times 10^{11}$</td>
</tr>
<tr>
<td>RI beam intensity for very exotic RIs*</td>
<td>0.11 \ (0.47)</td>
<td>1 \ (~10, after upgrade)</td>
<td>0.62</td>
</tr>
<tr>
<td>Driver</td>
<td>Cyclotron</td>
<td>SC-linac</td>
<td>Synchrotron</td>
</tr>
<tr>
<td>Charge stripper</td>
<td>11 MeV/A 50 MeV/A</td>
<td>17.5 MeV/A</td>
<td>1.4 MeV/A gas stripper OK</td>
</tr>
</tbody>
</table>
| pro                | ●Simple  
                   ●Compact  
                   ●Few RF resonators  
                   ●cost effective CW machine | ●Large acceptance  
                   ●Multi-charge-state acceleration possible  
                   ●High energy upgrade is straight forward | ●High energy  
                   ●Free from stripper problem  
                   ●Cooler & storage ring experiments |
| con                | ●No design universality for large scale cyclotron  
                   ●Small longitudinal acceptance  
                   ●Beam loss at extraction is critical | ●Not compact  
                   ●Large cryogenic facility | ●Not compact  
                   ●High vacuum required  
                   ●Low beam intensity |

*E^{2.5} dependence is assumed, E (MeV/A) - under discussion
Uranium Beam Intensity

**FRIB vs RIBF**

**RIBF**

two-step charge-stripping scheme is adopted.
0.27 \( \mu \text{A} \) uranium beam is expected after RILAC2 upgrade.
10 \( \mu \text{A} \) \(^{238}\text{U}^{35+}\) ion at ECR-IS
60% transmission efficiency in total (does not include charge stripping efficiency)

**FRIB**

A innovative multi-charge-state acceleration is proposed.
8 \( \mu \text{A} \) uranium beam is expected with 6 \( \mu \text{A} \) each for \(^{238}\text{U}^{33+}\) and \(^{238}\text{U}^{34+}\)

---

### RIBF

<table>
<thead>
<tr>
<th>Charge State</th>
<th>Component</th>
<th>Trans. Efficiency</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>35+</td>
<td>ECR-IS</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>linac</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RRC</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>fRC</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>IRC</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SRC</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>16%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>27%</td>
<td></td>
</tr>
<tr>
<td>33+ &amp; 34+</td>
<td></td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>

### FRIB

<table>
<thead>
<tr>
<th>Charge State</th>
<th>Component</th>
<th>Trans. Efficiency</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>77+ ~ 81+</td>
<td></td>
<td></td>
<td>80%</td>
</tr>
<tr>
<td>80%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From R. C. Yoke et al.; Proc. of SRF2009, FR0AAU02
Intensity upgrade strategy in RIBF

Introduction of K=2300 MeV superconducting fixed-frequency cyclotron in stead of fRC

K=2300 MeV Superconducting fRC

Harmonic number = 10 (challenging)
12 (modest)

Rinj = 2 m / 2.4 m
Rext = 4.05 m / 4.9 m
K = 2300 MeV
Weight = 3300 tons / 5700 tons

Design of the injection system is very challenging with a small injection radius of 2 m.
Energy upgrade toward 1 A GeV?

A geometrical consideration indicates that RIBF Dream Machine is not crazy.

<table>
<thead>
<tr>
<th></th>
<th>SRC</th>
<th>PSI-DM</th>
<th>SRC-booster</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eext</td>
<td>0.35 A GeV</td>
<td>1 GeV</td>
<td>0.9 A GeV</td>
</tr>
<tr>
<td>Einj</td>
<td>0.12 A GeV</td>
<td>0.12 GeV</td>
<td>0.35 A GeV</td>
</tr>
<tr>
<td>Magnets</td>
<td>6 (3.8 T)</td>
<td>12 (2.1 T)</td>
<td>12 (4 T)</td>
</tr>
<tr>
<td>Cavity</td>
<td>4 (0.6 MV)</td>
<td>8 (1 MV)</td>
<td>7 (1 MV)</td>
</tr>
<tr>
<td>Rinj</td>
<td>3.56 m</td>
<td>2.9 m</td>
<td>7.15 m</td>
</tr>
<tr>
<td>Rext</td>
<td>5.36 m</td>
<td>5.7 m</td>
<td>9.0 m</td>
</tr>
<tr>
<td>Velocity gain</td>
<td>1.5</td>
<td>2.0</td>
<td>1.26</td>
</tr>
<tr>
<td>Energy gain (extraction)</td>
<td>0.8 A MeV</td>
<td>6.3 MeV</td>
<td>2.9 A MeV</td>
</tr>
<tr>
<td>DR/dn (centering)</td>
<td>2.5 mm</td>
<td>5.6 mm</td>
<td>4.3 mm</td>
</tr>
<tr>
<td>K value</td>
<td>2.6 GeV</td>
<td>1 GeV</td>
<td>6.9 GeV</td>
</tr>
<tr>
<td>Total Acc. Voltage</td>
<td>0.64 GeV</td>
<td>0.88 GeV</td>
<td>1.54 GeV</td>
</tr>
</tbody>
</table>

Summary

Radioactive Isotope beam facilities worldwide

- RI beam intensities obtained by the first-generation RI beam facilities are not sufficient to access nuclei far from the stability of the nuclear chart.
- Many next-generation RIB facilities are under construction and planned including both ISOL and in-flight facilities.
- SC-linacs will be widely used for these new facilities.
- Activities of Asian countries in this research field has been increasing.

RIBF

- Design goal intensity was established for light ions (He and O)
- $^{48}$Ca - 23% of design goal
- Uranium beam intensities should be increased.
  
  A new injector RILAC2 will be commissioned in 2010.

  Very-short life time of charge stripper is another important issue.

- Reliability has been improved.

Next generation in-flight facilities (FRIB and FAIR)

- RI beam intensities expected in FRIB and FAIR are higher than RIBF.

Intensity-upgrade and/or energy-upgrade of RIBF is necessary.