Rare-Isotope Beam Facilities in Asia

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"A new generation of high-intensity RNB facilities of each of the two basic types, ISOL and In-Flight, should be built on a regional basis."

(The OECD Megascience Forum Report of the Working Group on Nuclear Physics, 1999)
RIB facilities in Asia

- RIKEN / RIBF
- KEK / KISS
- IMP / HIRFL
- IUAC
- VECC
- CIAE / BRIF
- IBS / RISP
- RIKEN / RIBF
- KEK / KISS
RIKEN RIBF, Japan

3 Injectors & 4 Booster cyclotrons
In-flight fragmentation / fission

Y. Yano, NIM B261 (2007) 1009
(RIBF=Radioactive Isotope Beam Factory)
RILAC2 Layout

Operation started in Dec 2010

To RRC @ 670 keV/u (M/q<6.8)

Pre-buncher

DTL1

RFQ

DTL2

DTL3

Rebuncher

High-Energy Beam Transport

Thin & Strong Quadrupoles

Low-Energy Beam Transport

28GHz SC-ECRIS

K. Yamada, IPAC2012
Achieved beam intensities at RIBF

- pol-d (250 MeV/u) 120 pnA
- d (250 MeV/u) 1000 pnA
- $^4$He (320 MeV/u) 1000 pnA
- $^{14}$N (250 MeV/u) 400 pnA
- $^{18}$O (345 MeV/u) 1000 pnA
- $^{48}$Ca (345 MeV/u) 415 pnA
- $^{86}$Kr (345 MeV/u) 30 pnA

- $^{124}$Xe (345 MeV/u) 15 pnA
- $^{238}$U (345 MeV/u) 3.5 pnA

=> $2 \times 10^{10}$ pps
R&Ds:
• Charge stripper
  => (Dr. Okuno’s talk)
• Upgrade of fRC
  => Waiting for beam test
• UO₂ oven
  => in progress
• Stabilization of temperature
• Dated components
Recent results from RIBF

New $T_{1/2}$ measured!

S. Nishimura et al., PRL 106 (2011) 052502

5 PRL, 3 PLB, 2 PRC, 2 JPSJ ..
New experimental apparatus & Collaboration

EUROBALL-RIKEN Cluster Array (EURICA)

Superconducting Analyser for Multi-particle from Radio Isotope beam (SAMURAI)

Rare-RI ring Budget approved!

KISS / KEK (former TRIAC group)
KISS project by KEK at RIKEN

Argon-gas catcher cell
+ Laser resonant ionization ($Z$)
+ Mass separation ($A$)
+ Low-background det. system

E3-room

Decay measurement stations

E2-room

Mass separator

J3-room

Laser light

GAs-cell system

Xe, U @10 MeV/u
From RILAC2-RRC

High purity Argon gas

$\varepsilon_{\text{tot.}} \sim 7\%$ ($t_{1/2}=500\text{ ms}$)
$R_Z \sim 1000$, $R_A \sim 840$
$T_{\text{extr.}} \sim 240\text{ ms}$

~3 day machine time for $^{200}\text{W}$

Courtesy of Prof. Miyatake (KEK)
(KISS : KEK Isotope Separation System)
Argon-gas catcher cell
+ Laser resonant ionization ($Z$)
+ Mass separation ($A$)
+ Low-background det. system

Decay measurement stations

E3-room

E2-room

J3-room

Mass separator

Laser light

Xe, U @10 M
From RILAC2

High purity Argon gas

GAs-cell system

High Voltage Cage

Courtesy of Prof. Miyatake (KEK)

(KISS : KEK Isotope Separation System)

E2-room

Mass-, Atomic-number Separated Beams

Primary Beams

Gas Cell (inside)
IMP-CAS HIRFL, China

2 Cyclotrons + 2 Cooler-ring Synchrotron
In-flight fragmentation

SSC(1988) K450MeV

SFC(1987) K69MeV

Mass measurement ToF target

E-cooler

PISSA

8.4 Tm C=128.8 m

CSRm(2006)
10.64 Tm C=161 m

CSR(2007)

Cancer therapy

Internal target

External target

Medial energy Exp. area

Low energy Exp. area

LHC (Large Hadron Collider)

Courtesy of Prof. Zhao (IMP)

(HIRFL = Heavy Ion Research Facility in Lanzhou)
New beams in HIRFL

$\text{H}_2^+\, 400\text{MeV/u}$

$\text{Bi}^{36+}\, 170\text{MeV/u}$

$\text{U}^{32+}\, 100\text{MeV/u}, \, 10^7\text{ppp}$
Long pulse slow extraction in CSRm: 10,000 s

- 1/3 resonance slow extraction
- RF-Knockout exciting
- Feedback of extraction rates with fast Qs

240 ± 50 ions

Courtesy of Prof. Zhao (IMP)
Recent results from HIRFL

Mass measured for drip-line nuclei $^{63}$Ge, $^{65}$As, $^{67}$Se, $^{71}$Kr

X. L. Tu, PRL 106 (2011) 112501
Near-future plan (next 2~3 years): SSC-Linac

1. 1 MeV/u beam for SSC
2. Beam intensity: >0.5 puA for 238U at Linac.
3. Parallel operation with SFC and Linac-SSC.

Courtesy of Prof. Zhao (IMP)
1. 1 MeV/u beam for SSC
2. Beam intensity: >0.5 puA for 238U at Linac.
3. Parallel operation with SFC and Linac - SSC.

Near-future plan (next 2~3 years): SSC-Linac

Aluminum prototype of IH-DTL tank1

Cavity coated with copper in inner surface

Courtesy of Prof. Zhao (IMP)
Near-future plan (next 3~5 years): CSR-Linac

1. 10 MeV/u beam for CSRm.
2. Beam intensity: >5 euA for 238U.
3. Parallel operation with SFC, SFC+SSC and Linac-CSR.

<table>
<thead>
<tr>
<th>Element</th>
<th>Length [cm]</th>
<th>Frequency [MHz]</th>
<th>Energy [MeV/u]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEBT</td>
<td>920</td>
<td>0→13.4167</td>
<td>0.00373</td>
</tr>
<tr>
<td>RFQ</td>
<td>252</td>
<td>53.6667</td>
<td>0.143</td>
</tr>
<tr>
<td>MEBT1</td>
<td>175</td>
<td>53.6667</td>
<td>0.143</td>
</tr>
<tr>
<td>DTL1</td>
<td>480</td>
<td>53.6667</td>
<td>1.025</td>
</tr>
<tr>
<td>MEBT2</td>
<td>400</td>
<td>161</td>
<td>1.025</td>
</tr>
<tr>
<td>DTL2</td>
<td>3000</td>
<td>161</td>
<td>10</td>
</tr>
<tr>
<td>HEBT</td>
<td>3300</td>
<td>161</td>
<td>10</td>
</tr>
</tbody>
</table>
CIAE BRIF, China

- ISOL / Driver = 100 MeV 200 µA compact H⁻ cyclotron
- 20000 mass resolution ISOL => Tandem => 2 MeV/q super-conducting LINAC

- Civil engineering started in 2011 / Cyclotron fabrication completed in 2011

Courtesy of Prof. Liu (CIAE)
(BRIF = Beijing Rare Ion beam Facility)
H- compact cyclotron (CYCIAE-100)

Courtesy of Prof. Liu (CIAE)
H- compact cyclotron (CYCIAE-100)

Courtesy of Prof. Liu (CIAE)
Superconducting linac in fabrication

- BRIF will be commissioned in 2014.

Courtesy of Prof. Liu (CIAE)
Future plan: CARIF project at CIAE

- ISOL + PF scheme

**CARIF (China Advanced Rare Ion-beam Facility)**

- Reactor
- Target/Ion source
  - He-jet/In-pile
- CARR
  - $5 \text{ g}^{235}\text{U}$
  - $2 \times 10^{15}$ fis./s
  - 60 MW, Max. $8 \times 10^{14} n_{th}/c/cm^2$

- ISOL
  - $10 \mu\text{A}$

- ECR
- Stable IS

- LINAC
  - 10 MeV/u
  - LINAC
  - 150 MeV/u

- Decay Spec.
- Nucl. Data
- Basic Sym.

- Nucl. Astro.
- SHE
- RI reac. Sepr.

- Cancer The.
- Single Part. Eve.

- Production target
  - 5 mg/cm$^2$$^9\text{Be}$
  - Ca. 1.8 B RMB, commission ca. 2020

- Drip line search
- New magic No.
- $\beta x n$ decay

- Exp. Term.
- HI, $n$, $\gamma$, $\beta$

- Unstable Data
- Nucl. Effects

- Explore extreme
- Extend application
- Combine ISOL and PF
- Using mature technology
- Aiming world class facility

- $^{78}\text{Ni}$ 250 pps
- $^{120}\text{Sr}$ 2x10$^{-4}$ pps
- $^{132}\text{Sn}$ 5x10$^{10}$ pps
- $^{91}\text{Kr}$ 4x10$^{11}$ pps
- $^{142}\text{Xe}$ 9x10$^{9}$ pps

- Courtesy of Prof. Liu (CIAE)
Linac3 is placed here for the time-being.

RIB project – VECC, India

Courtesy of Prof. Chakrabarti (VECC)
RIB project – VECC, India

Linac3 is placed here for the time-being

Linac3

LINAC2

LINAC1

RFQ1

RFQ2

ECR

HR cave-1

1.3 MeV/u RIB

100 keV/u

289 keV/u

415 keV/u

2011

2008

2005

2011

Target-IS

K130 Cyclotron beam

K130 vault

Courtesy of Prof. Chakrabarti (VECC)
Linac3 is placed here for the time-being.

RIB project – VECC, India

Courtesy of Prof. Chakrabarti (VECC)
Linac3 is placed here for the time-being

Linac2

Linac1

RFQ1

RFQ2

LINAC3

100 keV/u 2008

289 keV/u 2010

415 keV/u 2011

HR cave-1

K130 vault

Target-IS

K130 Cyclotron beam

Linac3 is placed here for the time-being

Courtesy of Prof. Chakrabarti (VECC)
RIB project – VECC, India

Linac3 is placed here for the time-being.

Multiple target chamber

Courtesy of Prof. Chakrabarti (VECC)
Measured RIB decay-spectra before RFQ2

<table>
<thead>
<tr>
<th>RIB</th>
<th>Prod. route</th>
<th>T1/2</th>
<th>pps @ FC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{14}$O</td>
<td>$^{14}$N(p,n)</td>
<td>71 s</td>
<td>$4.4 \times 10^3$</td>
</tr>
<tr>
<td>$^{42}$K</td>
<td>$^{40}$Ar(α,pn)</td>
<td>12.36 hr</td>
<td>$2.7 \times 10^3$</td>
</tr>
<tr>
<td>$^{41}$Ar</td>
<td>$^{40}$Ar(α,2pn)</td>
<td>109 min</td>
<td>$1.3 \times 10^3$</td>
</tr>
</tbody>
</table>

Gamma-ray spectrum at FC2 (before RFQ)
50 MeV superconducting e-linac (VECC-TRIUMF collaboration)

Courtesy of Prof. Chakrabarti (VECC)

Injector
300 keV to 10 MeV

Accelerator
10 MeV to 50 MeV

Phase-1: 2009 – 2013
Phase-2: 2013 – 2017
Future plan: ANURIB facility

A National Facility for Unstable and Rare Isotope Beams

Phase-1

12th Plan
2012-17

High freq., high current ECR Ion Source

Material Science with stable & RIBs

1.0 MeV/u

1.5 keV/u

0.1 MeV/u

7 MeV/u

100 MeV/u

Sc electron LINAC
50 MeV, 100 kW

e- n

Actinide Target

Radioactive Atoms

1+ RIB

ECR Ion Source

Stable isotope injection

RFQ

Transfer line for nuclear astrophysics

NEutron beam-line for nuclear astrophysics

Material Science with stable & RIBs

Spectroscopy of r-process, n-rich exotic nuclei

Nuclear Astrophysics

Nuclear structure, Elastic/ Inelastic scattering, Coulomb barrier physics, Super Heavy Elements

Studies on drip line & near drip line nuclei

Positron beam-line

Studies on drip line & near drip line nuclei

Positron beam-line

Future plan: ANURIB facility

Courtesy of Prof. Chakrabarti (VECC)
Production of low energy $^7$Be radioactive ion beam at IUAC using HIRA

($HIRA$: Heavy-Ion Reaction Analyzer)

$^7$Be radioactive ion beam (RIB) has been optimised

Energy range of $^7$Be RIB: 17 to 22 MeV
Production reactions: $(p,n),(d,n)$ type of reactions in inverse kinematics
Filter + transporter: existing RMS, HIRA operated in new ion optics

Typical RIB parameters
Size $\sim 4$ mm (fwhm), $\varphi$ & $\varphi \varphi = +/- 30$ mrad, $\varphi E = +/- 0.5$ MeV
Purity $> 99\%$, Intensity $\sim 10^4$ pps
HYbrid Recoil mass Analyzer - **Unique dual-mode, dual-stage spectrometer with large acceptances and rigidity at IUAC, New Delhi**
(to fully exploit ECR + LINAC beams of higher energy and intensity)

Useful to access heavy fusion evaporation residues with large efficiency along beam direction in **gas-filled mode** rejecting beam-like particles, target-like recoils and fission fragments – **First stage only**
(similar to Dubna, RIKEN, LBL, JYFL facilities but unique in design)

Useful to produce secondary radioactive beams (similar to $^7$Be in HIRA but with higher energies and lesser purity) in **momentum achromatic (vacuum) mode** – **First stage only**
Nuclei: $^7$Be, $^{13}$N, $^{17,18}$F

Energy Range: 20-50 MeV

Expected flux: $10^3$-$10^4$/s
IBS – RISP project, Korea

Science Business Belt

(RISP=Rare-Isotope Science Project)
Concept of the Accelerator Complex

IF Linac

200 MeV/u (U), 8 µA

Nuclear data

Medical science
Material science

Medical Research

Fragment Separator

Gas Catcher, Gas cell

High Energy Experiments

Atomic Trap Experiments

Nuclear Physics

Material science

Bio science
Medical science

IBS – RISP project, Korea

Courtesy of Prof. Kim (SNU/IBS)
Summary

- R&Ds of RI-Beam facilities are very active in Asia.
- New facilities are planned to start in coming 10 years.
- Regional and international collaborations are important in various technical challenges.
Many thanks to

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H. Miyatake
Accelerator Group
Nuclear Landscape

- Neutron halo & skin
- Proton halo
- New excitation mode
- rp-process
- Evolution of Shell structure
- r-process
- Super-Heavy Element

Stable (Stability line)

O Synthesis

Ni, 28
Ca, 40
He, 2
O, 8
World’s first superconducting RING cyclotron
$B_{\text{max}} = 3.8 \, \text{T}$, Total weight = 8300 tons

First beam: Dec. 2006
Achieved Intensity=> $^4\text{He}: 1000 \, \text{pnA}$, $^{48}\text{Ca}: 415 \, \text{pnA}$, $^{238}\text{U}$: 3.5 pnA etc.
2007 BT

2008 BT

2009 BT

2010 BT