Review of Heavy-ion Cyclotrons

The present review includes
• brief summary of basic features of heavy-ion cyclotrons
• important achievements of HI cyclotron facilities
• recent developments of HI cyclotron facilities

but cannot include
• medical cyclotrons
• innovative design studies
• novel applications
• ............

Nishina Center for Accelerator-based Science, RIKEN
N. Fukunishi
The Beginning

According to Livingston, the first heavy-ion beam was a 50-MeV $^{12}\text{C}$ beam accelerated by the Berkeley 37-inch cyclotron in 1940.

Table 1. EARLIEST HEAVY ION ACCELERATORS

<table>
<thead>
<tr>
<th>Date</th>
<th>Machine</th>
<th>Location</th>
<th>Typical particle</th>
<th>Energy</th>
<th>Extracted beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>1940</td>
<td>37-in. Cyclotron</td>
<td>Berkeley</td>
<td>$^{12}\text{C}^{2+},6^+$</td>
<td>50 MeV</td>
<td>8/s*</td>
</tr>
<tr>
<td>1950</td>
<td>60-in. Cyclotron</td>
<td>Berkeley</td>
<td>$^{12}\text{C}^{2+},6^+$</td>
<td>100 MeV</td>
<td>$10^5$/s</td>
</tr>
<tr>
<td>1953</td>
<td>225-cm Cyclotron</td>
<td>Stockholm</td>
<td>$^{12}\text{C}^{2+},4^+$</td>
<td>130 MeV</td>
<td>$10^{11}$/s*</td>
</tr>
<tr>
<td>1953</td>
<td>63-in. Cyclotron</td>
<td>Oak Ridge</td>
<td>$^{14}\text{N}^{3+}$</td>
<td>28 MeV</td>
<td>2µA</td>
</tr>
<tr>
<td>1953</td>
<td>156-cm Cyclotron</td>
<td>Birmingham</td>
<td>$^{12}\text{C}^{2+},6^+$</td>
<td>120 MeV</td>
<td></td>
</tr>
<tr>
<td>1955</td>
<td>180-cm Cyclotron</td>
<td>Saclay</td>
<td>$^{12}\text{C}^{2+},6^+$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1956</td>
<td>120-cm Cyclotron</td>
<td>Leningrad</td>
<td>$^{14}\text{N}^{3+}$</td>
<td>16 MeV</td>
<td>0.5 µA</td>
</tr>
</tbody>
</table>

* Internal beam

75 years have passed!
Heavy-ion Cyclotrons Worldwide

✓ Commissioning rush (1980 ~ 2000)

✓ Two trends in 1980 ~ 2000
  • Compact superconducting cyclotrons
    MSU, Chalk River, INFN-LNS, KVI, Texas A&M
  • Separate-sector cyclotrons
    GANIL, Lanzhou, RIKEN, RCNP, iThemba LABS

✓ Many compact cyclotron have been commissioned.

✓ Continuous upgrades

These data are taken from “List of Cyclotrons”, compiled in “Cyclotrons and their Applications 2004”, edited by A. Goto and Y. Yano. Newly commissioned cyclotrons or upgrades are also added based on later individual reports.
Three Type of Heavy-ion Cyclotrons Widely Used

Compact (AVF)

Proposed by Thomas

Demonstrated by Richardson

Compact, Superconducting (compact SC)

Pioneered by Chalk River and MSU
H. Blosser et al., 7th ICCA* (1975) p. 584.

Separate Sector (SS)

Proposed by Willax
H. A. Willax, 3rd Int. Conf. on Sector-Focused Cyclotrons (1963) p. 386.

\[ K_B = 8 \sim 625 \text{ MeV} \]

\[ K_B = 500 \sim 1200 \text{ MeV} \]

\[ K_B = 130 \sim 2600 \text{ MeV} \]

*ICCA = International Conference on Cyclotrons and their Applications
Bending and Focusing Limits

$E$: Total Kinetic Energy
$A$: Mass Number
$q$: Charge Number

✓ Bending limit

$$E/A \leq K_B \left(\frac{q}{A}\right)^2$$

✓ Vertical focusing limit

$$E/A \leq K_F \left(\frac{q}{A}\right) \text{ for compact SC}$$

$$E/A \leq K_F \text{ for others}$$

✓ RF frequency

✓ Resonances

✓ Injection

RIBF SRC

$^{238}U^{86+}$ 345 AMeV (Bρ = 8.06 Tm)

$K_B = 2640$ MeV

$^{238}U^{44+}$ 100 AMeV (Bρ = 7.99 Tm)

$K_B = 2930$ MeV

![Graphs showing working regions for compact SC and normal conducting magnets.](image)
Basic Features of Compact HI Cyclotrons

ECR-IS

$V_{\text{ext}} \approx 20 \sim 30 \text{ kV}$

$B_{\text{max}} = 1.5 \sim 2.1 \text{ T}$

$V_{\text{dee}} = 50 \sim 100 \text{ kV}$

Beam injection
- electrostatic inflector (mirror, spiral, hyperboloid)

Beam extraction
- electrostatic deflector (ESD)
- charge stripping

Axial injection line

Resonator

Cyclotron

Field correction
- radial trim coils
- harmonic coils

Valley
- Low $B$, large gap

Hill
- (High $B$, small gap)

yoke

orbit

main coil

pole

resonator
## Example of Compact HI Cyclotrons

ESD : Electrostatic Deflector / CS : Charge-stripping extraction / * : for negative ions

<table>
<thead>
<tr>
<th>Facility</th>
<th>Name</th>
<th>$K_B$ (MeV)</th>
<th>No. of sectors</th>
<th>Spiral angle (deg.)</th>
<th>Gap hill/valley (cm)</th>
<th>No. of Dee</th>
<th>$V_{acc}$ (kV)</th>
<th>$F$ (MHz)</th>
<th>Extraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>JYFL</td>
<td>K130</td>
<td>130</td>
<td>3</td>
<td>58</td>
<td>17.4/33.0</td>
<td>2</td>
<td>50</td>
<td>10 ~ 21</td>
<td>ESD / CS*</td>
</tr>
<tr>
<td>JAEA-Takasaki</td>
<td>K110</td>
<td>110</td>
<td>4</td>
<td>53</td>
<td>16.6/40.5</td>
<td>2</td>
<td>60</td>
<td>10.6 ~ 22</td>
<td>ESD</td>
</tr>
<tr>
<td>CYRIC</td>
<td>K110</td>
<td>110</td>
<td>4</td>
<td>53</td>
<td>16.6/40.5</td>
<td>2</td>
<td>60</td>
<td>10.6 - 22</td>
<td>ESD / CS*</td>
</tr>
<tr>
<td>LBNL</td>
<td>88-inch</td>
<td>160</td>
<td>3</td>
<td>55</td>
<td>19.0/30.0</td>
<td>1</td>
<td>50</td>
<td>5.5 - 16</td>
<td>ESD</td>
</tr>
<tr>
<td>Warsaw</td>
<td>U-200P</td>
<td>160</td>
<td>4</td>
<td>0</td>
<td>2.6/15.0</td>
<td>2</td>
<td>70</td>
<td>12 - 18</td>
<td>CS</td>
</tr>
<tr>
<td>FLNR JINR</td>
<td>U-400</td>
<td>625</td>
<td>4</td>
<td>0</td>
<td>4.2/30.0</td>
<td>2</td>
<td>100</td>
<td>5.5 - 12</td>
<td>CS</td>
</tr>
<tr>
<td></td>
<td>U-400M</td>
<td>550</td>
<td>4</td>
<td>43</td>
<td>10.0/50.0</td>
<td>4</td>
<td>170</td>
<td>11.5 - 24</td>
<td>CS</td>
</tr>
<tr>
<td>VECC</td>
<td>K130</td>
<td>130</td>
<td>3</td>
<td>55</td>
<td>19.0/30.0</td>
<td>1</td>
<td>60</td>
<td>5.5 - 15.5</td>
<td>ESD</td>
</tr>
<tr>
<td>GANIL</td>
<td>CIME</td>
<td>265</td>
<td>4</td>
<td>0</td>
<td>12.0/30.0</td>
<td>2</td>
<td>100</td>
<td>9.6 - 14.5</td>
<td>ESD</td>
</tr>
</tbody>
</table>

Major part of the data are from “List of Cyclotrons”, compiled in “Cyclotrons and their Applications 2004”, edited by A. Goto and Y. Yano. Newly commissioned cyclotrons are recent upgrades are included based on their individual reports.
Recent Activities @ JYFL

Example of K130 performance ¹⁰⁴Ar 4.3 µA at 5 A MeV

MCC30/15  
(K_B = 30 MeV, H⁺, D⁺, 2009–)

K130  
(Scanditronix, K_B = 130 MeV, 1992–)

IGISOL  
(Trap, Laser)

RITU (Gas-filled recoil spectrometer)
MARA (Vacuum recoil spectrometer)
RADEF (Irradiation)

New experimental hall (50 × 13.5 m²)

Detailed studies on ECRIS Beams

V. Toivanen et al., ICCA 2010, p. 153.

ECR (14.5 GHz)  
V_ext ~ 20 kV

Annual use of K130  
7500 hours

P. Heikkinen., ICCA 2013, p. 43.

40Ar 4.3 µA at 5 MeV
Intensity Upgrade of LBNL 88-inch Cyclotron

- Highly charged ions for microchip testing: Xe\(^{43+}\)
- High-intensity beams for nuclear physics: \(^{48}\text{Ca}\)

**VENUS**

- \(V_{\text{ext}} \sim 30\) kV

**AECR-U**

- \(V_{\text{ext}} < 14 \rightarrow > 25\) kV

Axial Injection line
B\(R\) upgrade

88-inch Cyclotron (1962~)

- \(K_B = 160\) MeV

Spiral inflector for high-intensity beams
Median plane correction by unbalancing excitation currents of trim coils

New spiral inflector

<table>
<thead>
<tr>
<th>Height</th>
<th>25 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>(R_{\text{mag}})</td>
<td>32 mm</td>
</tr>
<tr>
<td>Gap</td>
<td>10 mm</td>
</tr>
<tr>
<td>(E)</td>
<td>20 kV/cm</td>
</tr>
</tbody>
</table>

250-MeV \(^{48}\text{Ca}\) beam

- Peak intensity: 2.05 \(\mu\)A \(\leftarrow\) 0.6 \(\mu\)A
- Average: 1.1 \(\sim\) 1.5 \(\mu\)A (8-week-long experiment)
- Material consumption rate: 0.27 mg/h

D.S. Todd et al., ICCA 2013, p. 19.
K. Yoshiki Franzen et al., ICCA 2013, p. 186.
Activities @ FLNR JINR

U-300
(classical, 1959~)

U-400M\(^{(1)}\)
\((K_B = 550\text{ MeV, 1991~})\)

U-400
\((K_B = 625\text{ MeV, 1978~})\)

ECR\(^{(2)}\)
Axial Injection
(Spiral, 1996)

Modernization to
U-400R\(^{(4)}\)

DC-280
\((^{48}\text{Ca, >1 p\text{\mu A}})\)

Super Heavy
DRIBs post-accel.

RI beams \((^{6,8}\text{He etc})\)
triton \((6 \times 10^{10}\text{ pps})\)
DRIBs driver

U-200
\((K_B = 145\text{ MeV, 1968~})\)

IC-100
\((DC-40)\)
\((radial, K_B = 40\text{ MeV, 1985})\)

ECR\(^{(2)}\)
Axial Injection

SC-ECR\(^{(3)}\)
Axial Injection
ESD extraction
(2004)

DC-110\(^{(5)}\)
\((radial, K_B = 110\text{ MeV, 2012})\)

Industrial Applications
- nuclear track membrane
- surface modification

DC-60\(^{(6)}\)
\((radial, K_B = 60\text{ MeV, 2006})\)
to Astana
(Kazakhstan)

U-400M
\((K_B = 625\text{ MeV, 1991~})\)

ECR\(^{(2)}\)
Axial Injection
(Mirror, 1995)

U-400
\((K_B = 625\text{ MeV, 1978~})\)

Modernization to
U-400R\(^{(4)}\)

RI beams \((^{6,8}\text{He etc})\)
triton \((6 \times 10^{10}\text{ pps})\)
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Axial Injection
ESD extraction
(2004)

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\((radial, K_B = 110\text{ MeV, 2012})\)

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- surface modification

DC-60\(^{(6)}\)
\((radial, K_B = 60\text{ MeV, 2006})\)
to Astana
(Kazakhstan)

(1)G. Gulbekyan et al., 13th ICCA (1992) p.11.
(3)B. Gikal et al., ICCA 2007, p. 27.
(4)G. Gulbekyan et al., IPAC2011, p. 2700.
(5)B.N. Gikal et al., RuPAC2014, p. 146.
(6)B.N.Gikal et al., ICCA 2004, p. 205.
High Intensity HI Beams @ FLNR JINR

**U-400**

before upgrade (~1996)

PIG + CS extraction

<table>
<thead>
<tr>
<th>Ion</th>
<th>E (MeV)</th>
<th>$I_{\text{external}}$ ($\times 10^{12}$ pps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}\text{O}^{2+}$</td>
<td>8.8</td>
<td>15</td>
</tr>
<tr>
<td>$^{20}\text{Ne}^{2+}$</td>
<td>5.6</td>
<td>10</td>
</tr>
<tr>
<td>$^{40}\text{Ar}^{4+}$</td>
<td>7.0</td>
<td>7</td>
</tr>
<tr>
<td>$^{48}\text{Ti}^{5+}$</td>
<td>5.5</td>
<td>7</td>
</tr>
<tr>
<td>$^{55}\text{Mn}^{6+}$</td>
<td>6.0</td>
<td>6</td>
</tr>
</tbody>
</table>

PIG: $\sim$10 mg/h


**U-400**

after upgrade (1996~)

High intensity $^{48}\text{Ca}$ beams

Low material consumption rate

- ECR Ion Source
- Axial Injection
- Charge stripping extraction

1.4 $\mu$A $^{48}\text{Ca}^{5+}$ beam

with material consumption of 0.4 mg/h

B. N. Gikal et al., ICCA 2004, p. 100.

**DC-280**

(under construction)

$> 10$-$\mu$A $^{48}\text{Ca}$ beams

- ECR Ion Source (25 kV)
- High-voltage terminal (75 kV)
- Axial Injection (spiral)
- Multi-harmonic buncher
- High vacuum ($\sim$5 $\times 10^{-6}$ Pa)
- Flat-top cavities

CIME : Post-accelerator of ISOL Facility

Dedicated to RI beams obtained by ISOL method.
- $K_B = 265$ MeV
- wide energy range: 1.7 (1)* $\sim$ 25 AMeV
- RF harmonic: 2 $\sim$ 5 (6)* with two inflectors
  $H = 2, 3$: Müller, $R_{mag} = 34 \text{ mm} / H = 4, 5$: Spiral, $R_{mag} = 45 \text{ mm}$
- high vacuum: $5 \times 10^{-6}$ Pa
- large acceptance: $\sim 80 \pi \text{ mm-mrad}$
- nuclear probes for faint RI beams
  silicon and scintillator detectors on radial probes

Design made by 3D electric (CHA3D) and magnetic (TOSCA) field calculations

High $A/q$ resolution ($10^{-4}$)

F. Chautard et al., ICCA 2007, p. 99.

F. Varenne et al., ICCA 2001, p. 74.
* : later upgraded.
Compact Superconducting Cyclotrons

- Purpose: mainly nuclear physics
- Ion species: p (H\(_2^+\)) ~ U
- Energy: a few AMeV ~ 100 AMeV or higher
- Beam intensity: 10\(^9\) ~ 10\(^{12}\) pps

<table>
<thead>
<tr>
<th>Facility</th>
<th>Name</th>
<th>(K_B) (MeV)</th>
<th>First beam</th>
<th>(R_{ext}) (m)</th>
<th>Iron weight (ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chalk River*</td>
<td>K520</td>
<td>520</td>
<td>1985</td>
<td>0.65</td>
<td>170</td>
</tr>
<tr>
<td>INFN-LNS</td>
<td>LNS-SC</td>
<td>800</td>
<td>1994</td>
<td>0.87</td>
<td>176</td>
</tr>
<tr>
<td>KVI</td>
<td>AGOR</td>
<td>600</td>
<td>1994</td>
<td>0.90</td>
<td>100</td>
</tr>
<tr>
<td>NSCL MSU</td>
<td>K500</td>
<td>500</td>
<td>1982</td>
<td>0.66</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>K1200</td>
<td>1200</td>
<td>1988</td>
<td>1.0</td>
<td>240</td>
</tr>
<tr>
<td>Texas A&amp;M</td>
<td>K500</td>
<td>520</td>
<td>1988</td>
<td>0.67</td>
<td>100</td>
</tr>
<tr>
<td>VECC</td>
<td>K500</td>
<td>520</td>
<td>2009(^#)</td>
<td>0.67</td>
<td>?</td>
</tr>
</tbody>
</table>

* 1996 shutdown / \(^#\) internal beam

Isochronism of Compact SC Cyclotrons

Magnet: Compact type
• fully saturated iron poles
• circular SC main coils
• $B_{\text{max}} \sim 5$ T

Coarse isochronism
split main coils, individually excitable

Fine isochronism
RT trim coils or trim rods (Chalk River)

Magnetic fields of split main coils

Trim coils (MSU K500)

Trim-rods distribution (Chalk River)
Betatron Motion in Compact SC Cyclotrons

Various ion species for a wide energy range
✓ vertical focusing ← flutter fields produced by iron poles
✓ azimuthally symmetric field ← SC main coils
✓ weak vertical focusing at higher excitation level
✓ tight resonance conditions especially for 3 sector machines

Resonances are crossed at
\[ \nu_r = 2\nu_z \]
\[ \nu_z = 1 \]
\[ \nu_r = 1 \]
(precessional extraction)

F. Resmini et al., 8th ICCA (1978) p. 2078.
Beam Extraction from Compact SC Cyclotrons

- small $R_{\text{ext}} \leftarrow$ High B
- low $V_{\text{acc}} \leftarrow$ conventional dees
- electrostatic deflector
- orbit geometry change

**MSU K1200**

$2 \times \text{ESD} + 8 \times \text{PMC} + \text{CBs}$

M : Passive Magnetic Channel (PMC)
C : Compensation Bar (CB)

**KVI AGOR**

$\text{EMC1}$
$J = 140 \ A/\text{mm}^2$

$\text{EMC2}$ (SC)

$\text{ESD}$ (3 parts)


# Magnet Specifications of Compact SC Cyclotrons


<table>
<thead>
<tr>
<th>Facility</th>
<th>Name</th>
<th>$K_B$ (MeV)</th>
<th>$K_F$ (MeV)</th>
<th>$R_{ext}$ (m)</th>
<th>Hill / Valley gap (cm)</th>
<th>No. of sector</th>
<th>Total ampere turn ($10^6$ A)</th>
<th>$J_{ave}$ (A/mm$^2$)</th>
<th>Stored Energy (MJ)</th>
<th>Cryo-stability</th>
<th>$B_{ave}$ (T)</th>
<th>No of Trim coil / pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chalk River*</td>
<td>K520</td>
<td>520</td>
<td>100</td>
<td>0.65</td>
<td>3.7 / 65</td>
<td>4</td>
<td>6.2</td>
<td>25</td>
<td>22</td>
<td>yes</td>
<td>1.7 - 5.0</td>
<td>13 rods</td>
</tr>
<tr>
<td>INFN-LNS-SC</td>
<td></td>
<td>800</td>
<td>200</td>
<td>0.87</td>
<td>8.6 / 91.6</td>
<td>3</td>
<td>6.55</td>
<td>35</td>
<td>45</td>
<td>yes</td>
<td>2.2 - 4.8</td>
<td>20</td>
</tr>
<tr>
<td>KVI AGOR</td>
<td></td>
<td>600</td>
<td>220</td>
<td>0.9</td>
<td>7.0 / 168</td>
<td>3</td>
<td>6.6</td>
<td>43/33</td>
<td>56</td>
<td>no</td>
<td>1.7 - 4.1</td>
<td>15</td>
</tr>
<tr>
<td>NSCL MSU</td>
<td>K500</td>
<td>500</td>
<td>160</td>
<td>0.66</td>
<td>6.35 / 91.4</td>
<td>3</td>
<td>5</td>
<td>36</td>
<td>18</td>
<td>yes</td>
<td>3.0 - 5.0</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>K1200</td>
<td>1200</td>
<td>400</td>
<td>1.0</td>
<td>7.6 / 91.4</td>
<td>3</td>
<td>7</td>
<td>36/40</td>
<td>60</td>
<td>yes</td>
<td>3.0 - 5.3</td>
<td>21</td>
</tr>
<tr>
<td>Texas A&amp;M</td>
<td>K500</td>
<td>520</td>
<td>160</td>
<td>0.67</td>
<td>6.35 / 91.4</td>
<td>3</td>
<td>5</td>
<td>36</td>
<td>16.9</td>
<td>yes</td>
<td>3.1 - 4.9</td>
<td>13</td>
</tr>
<tr>
<td>VECC*</td>
<td>K500</td>
<td>520</td>
<td>160</td>
<td>0.67</td>
<td>6.35 / 91.4</td>
<td>3</td>
<td>5</td>
<td>36</td>
<td>22</td>
<td>yes</td>
<td>-4.9</td>
<td>13</td>
</tr>
</tbody>
</table>

* 1996 shutdown / # internal beam
Achievements of Compact SC Cyclotrons

The design operating diagrams were successfully covered by these compact cyclotrons!

KVI AGOR

NSCL MSU K1200
(stand-alone operation)

INFN-LNS K800

E/A (MeV)

up to 1999

$E_{max} = 80$ AMeV for $q/A = 0.5$

L. Calabretta and D. Rifuggiato, ICCA 2001, p. 79.

D. Rifuggiato et al., ICCA 2013, p. 52.

F. Marti et al., ICCA 2001, p. 64.

# Upgrades towards RI Beam Facilities

<table>
<thead>
<tr>
<th>Before upgrade</th>
<th>After upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acceleration Scheme</strong></td>
<td><strong>Upgrade</strong></td>
</tr>
<tr>
<td><strong>Typical Performance</strong></td>
<td></td>
</tr>
<tr>
<td><strong>INFN-LNS EXCYT(^{(1)}), 1995~</strong></td>
<td>15-MV Tandem + K800 (CS inj.)</td>
</tr>
<tr>
<td><strong>Acceleration Scheme</strong></td>
<td>Post Accel. : Tandem (ISOL facility)</td>
</tr>
<tr>
<td><strong>INFN-LNS EXCYT(^{(1)}), 1995~</strong></td>
<td></td>
</tr>
<tr>
<td><strong>KVI TRIμP(^{(2)}), 2003~</strong></td>
<td>ECR + AGOR</td>
</tr>
<tr>
<td><strong>NSCL MSU CCF(^{(3)}), 1996~</strong></td>
<td></td>
</tr>
<tr>
<td><strong>NSCL MSU CCF(^{(3)}), 1996~</strong></td>
<td>K500 / K1200 stand-alone</td>
</tr>
<tr>
<td><strong>Texas A&amp;M(^{(4)}) IG, 2005~</strong></td>
<td>K500 stand-alone</td>
</tr>
</tbody>
</table>

Achievements of Upgrades

KVI AGOR
10^{13} pps for 20 ~ 30 AMeV, <^{40}\text{Ar} \rightarrow 1 \text{ kW}
Extraction efficiency : ~ 90%

NSCL MSU CCF
4 \times 10^{12} pps for 150-AMeV, ^{16}\text{O} \rightarrow > 1 \text{ kW}
Extraction efficiency : ~ 90%

INFN-LNS EXCYT
1.6 \times 10^{12} pps for 45-AMeV ^{13}\text{C}^{4+}
A proposal for 20-kW light ion beams based on charge-stripping extraction scheme
L. Calabretta and D. Rifuggiato, ICCA 2001, p. 79.

NSCL MSU
More than 1000 RI beams were produced
~ 900 RI beams were used in experiments

A. Stolz et al., ICCA 2013, p. 7.
Tritron: Separate Orbit Cyclotron Prototype


Specifications

- Injection radius: 0.66 m
- Extraction radius: 1.45 m
- Turn separation: 4 cm
- Max. B of sector channels: 1.7 T
- RF frequency: 170 MHz
- Acc. voltage: 0.53 MV
- Number of turns: 19.8
- Max. energy: 20 AMeV for $^{12}$C
- Beam aperture: 10 mm

Cross-sectional view of SC channels

- AG focusing and phase stability are available
- Compact (no voluminous yoke)

Tritron accelerated $^{32}$S$^{14+}$ ions from 40 to 72 MeV.
Concept of Separate Sector Cyclotron

One magnet $\rightarrow$ piecewise magnets (sector magnets).

Magnet-less valley $\rightarrow$ high flutter magnetic fields & stronger vertical focusing
$\rightarrow$ installation of high-voltage acceleration cavities
$\rightarrow$ useful space for beam probes, future upgrades.....

H. A. Willax, 3rd Int. Conf. on Sector-Focused Cyclotrons (1963) p. 386.
V. P. Dmitrievsky, “Relativistic Cyclotron with Space Variation of Magnetic Field”,
## Separate Sector Cyclotrons

* now dedicated to accelerate a 68-MeV proton beam

<table>
<thead>
<tr>
<th>Facility</th>
<th>Name</th>
<th>$K_B$ (MeV)</th>
<th>No. of sectors</th>
<th>Spiral angle (deg.)</th>
<th>$V_{acc}$ (kV)</th>
<th>$F$ (MHz)</th>
<th>Injector</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIRFL</td>
<td>SSC</td>
<td>450</td>
<td>4</td>
<td>0</td>
<td>200</td>
<td>6.5 - 14</td>
<td>SFC</td>
</tr>
<tr>
<td>GANIL</td>
<td>CSS1</td>
<td>380</td>
<td>4</td>
<td>0</td>
<td>160</td>
<td>7 - 13.45</td>
<td>C01 or C02</td>
</tr>
<tr>
<td></td>
<td>CSS2</td>
<td>380</td>
<td>4</td>
<td>0</td>
<td>250</td>
<td>7 - 13.45</td>
<td>CSS1</td>
</tr>
<tr>
<td>RCNP</td>
<td>RCNP Ring Cyclotron</td>
<td>400</td>
<td>6</td>
<td>30</td>
<td>375</td>
<td>30 - 52</td>
<td>RCNP-AVF ($K_B = 140$ MeV)</td>
</tr>
<tr>
<td>HZB*</td>
<td>K130</td>
<td>132</td>
<td>4</td>
<td>0</td>
<td>140</td>
<td>10 - 20</td>
<td>Tandetron</td>
</tr>
<tr>
<td>iThemba LABS</td>
<td>Separate-Sector Cyclotron</td>
<td>200</td>
<td>4</td>
<td>0</td>
<td>230</td>
<td>6 - 26</td>
<td>SPC1 or SPC2 ($K_B = 11$ MeV)</td>
</tr>
</tbody>
</table>

Major part of the data are from “List of Cyclotrons”, compiled in “Cyclotrons and their Applications 2004”, edited by A. Goto and Y. Yano. Newly commissioned cyclotrons are added based on their individual reports.
GANIL : High Power Cascaded Cyclotron System

“GANIL Scheme”
✓ High transmission efficiency at injector cyclotrons
  High source voltage
  Buncher
  6D matching
  Large turn separation ($R_{ext} = 49$ cm, 25 turns)
✓ Charge stripping only after CSS1
✓ CSS2 → 250kV

<table>
<thead>
<tr>
<th>Beam</th>
<th>$E$ (AMeV)</th>
<th>$I \times 10^{13}$ pps</th>
<th>Power (KW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$C$^{6+}$</td>
<td>95</td>
<td>2*</td>
<td>3.6</td>
</tr>
<tr>
<td>$^{13}$C$^{6+}$</td>
<td>75</td>
<td>2*</td>
<td>2.9</td>
</tr>
<tr>
<td>$^{14}$N$^{7+}$</td>
<td>95</td>
<td>1.6</td>
<td>3.4</td>
</tr>
<tr>
<td>$^{24}$Mg$^{12+}$</td>
<td>95</td>
<td>1</td>
<td>3.8</td>
</tr>
<tr>
<td>$^{36}$Ar$^{18+}$</td>
<td>95</td>
<td>0.8</td>
<td>4.6</td>
</tr>
</tbody>
</table>

* safety limit

F. Chautard and Bd Henri Becquerel, ICCA 2010, p. 16.

IMP-Lanzhou

**SECRLAL**

- **SFC**<sup>(1,2)</sup>
  - compact
  - $K_B = 69$ MeV

- **SSC**<sup>(1,2)</sup>
  - $K_B = 450$ MeV
  - $TE: 25 \sim 50\%$
  - $^{36}Ar^{8+}, 22$ AMeV
  - 3 µA
  - $^{12}C^{4+} > 1.5 \times 10^{13}$ pps

**Cyclotrons as injectors to CS rings**

- Light ions: SFC $\rightarrow$ CSRm
- Heavy ions: SFC + SSC $\rightarrow$ CSRm

**CSRe**<sup>(4)</sup>

- Cooler-Storage Ring
- Internal Target
- Mass measurements (RI)
  - $C = 128.8$ m
  - $Bp < 9.4$ Tm
  - Single-turn injection

**CSRm**<sup>(4)</sup>

- Cooler-Storage Ring
- Acceleration
  - $C = 161$ m
  - $Bp < 11.5$ Tm
- CS / Multiple multi-turn injection
  - $^{12}C^{6+} \sim 600$ AMeV, $7 \times 10^9$ ppp
  - $^{36}Ar^{8+} \sim 500$ AMeV, $4 \times 10^8$ ppp

**New linac injector of SSC**

- X.Yin et al., IPAC 2014, p. 3277.

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(2) H.W. Zhao et al., ICCA 2004, p. 121.
(4) W.L. Zhan et al., ICCA 2001, p. 175.
RIKEN RIBF

**Accelerators**
- RILAC: RIKEN Heavy-ion linac (1981~)
- AVF: K70-MeV AVF cyclotron (1989~)
- RRC: RIKEN Ring Cyclotron (1986~)
- SRC: Superconducting Ring Cyclotron (2006~)
- RILAC2: (2011~)

**Research instruments**
- RIPS, BigRIPS: Fragment separator
- GARIS: Gass-filled Recoil Ion Separator
- ZDS: Zero-Degree Spectrometer
- SAMURAI: Superconducting analyzer
- SHARAQ: SHRAQ spectrometer
- RRR: Rare RI Ring

RC: Ring Cyclotron

Recently commissioned! (Y. Yamaguchi, TUM1C04)
# Ring Cyclotrons in RIBF

<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>700</td>
<td>980</td>
<td>2600</td>
<td>540</td>
</tr>
<tr>
<td>$R_{\text{inj}}$ (cm)</td>
<td>156</td>
<td>277</td>
<td>356</td>
<td>89</td>
</tr>
<tr>
<td>$R_{\text{ext}}$ (cm)</td>
<td>330</td>
<td>415</td>
<td>536</td>
<td>356</td>
</tr>
<tr>
<td>Weight (tons)</td>
<td>1300</td>
<td>2900</td>
<td>8300</td>
<td>2400</td>
</tr>
<tr>
<td>Sector magnets</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Number of trim coils / main coil</td>
<td>10</td>
<td>20</td>
<td>4 (SC)</td>
<td>26</td>
</tr>
<tr>
<td>Trim coil currents (A)</td>
<td>200</td>
<td>600</td>
<td>3000 (SC)</td>
<td>600</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$\sim$38</td>
<td>18$\sim$38</td>
<td>18$\sim$38</td>
</tr>
<tr>
<td>Acceleration voltage (MV)</td>
<td>0.8</td>
<td>1.26</td>
<td>2.3</td>
<td>0.3$^*$</td>
</tr>
</tbody>
</table>

SC : superconducting / NC : normal conducting / FT : flattop resonator
* : for uranium acceleration (18.25 MHz)
Acceleration Modes at RIBF

Variable energy mode
Light & medium-heavy ions
\(^{48}\text{Ca}, ^{70}\text{Zn}\)

Fixed energy mode
Heavy ions
\(^{78}\text{Kr}, ^{124}\text{Xe}, ^{238}\text{U}\)

AVF-injection mode
Very light ions
\((\text{pol-d}, ^{4}\text{He}, ^{18}\text{O})\)
Beam energies of the beams without explicitly indicated are 345 AMeV.

**Beam Power**

- **SRC extraction**
  - $^{78}$Kr : 13.1 kW (0.49 pμA)
  - $^{48}$Ca : 8.8 kW (0.53 pμA)
  - $^{238}$U : 3.2 kW (0.04 pμA)

- **RRC extraction**
  - 10.8-AMeV $^{238}$U : 4.0 kW (1.54 pμA)
  - 45.7-AMeV $^{48}$Ca : 1.6 kW (0.74 pμA)

**Beam Availability**

- 92% (2014)
- 93% (1st half, 2015)
Achievements of HI Cyclotrons

Compact & low cost accelerator
→ Many active facilities

Reliable accelerator
→ High reliability
→ Cyclotron cascades work well

Upgradable accelerator
→ LBNL 88-inch

User-friendly accelerator
→ Cocktail beam acceleration

High-intensity accelerator
Future Possibilities?

Toward higher beam energy
→ 0.7 ~ 1.0 GeV/nucleon
“*The last frontier of cyclotrons?*”

Toward higher beam intensity
→ 10 pμA for E ~100 AMeV
→ > 1 pμA for very heavy ions
“Can we utilize fully 3rd generation ECRISs?*

Toward low operational cost
→ High-Tc superconductivity?

New type
→ SOC again?
→ Strong Focusing Cyclotron (SFC)
→ Skelton Cyclotron
Activities of heavy-ion cyclotrons are widely spread worldwide, although construction of new heavy-ion cyclotrons are slowed down.

These heavy-ion cyclotrons have upgraded their performances continuously.

High-intensity beams are now available for various ion species and beam energies.

Further intensity upgrades are possible if we will successfully utilize very high performances obtained in 3rd-generation ECR ion sources.

Good synergetic effects from large SC linac complexes (FRIB, RAON) are expected.