Review of high power-cyclotrons for heavy-ion beams

September 6, 2010
Cyclotrons 2010, Lanzhou

A. Goto
RIKEN Nishina Center
Outline

1. Introduction

2. Overview of facilities worldwide that operate high-power heavy-ion cyclotrons

3. Some technological issues related to high-power heavy-ion beams

4. Summary
Introduction

- Cyclotrons producing a wide range of heavy-ion beams were developed in the 1980s.

- Heavy ions $\rightarrow$ large magnetic rigidity

  Two types of cyclotrons: 1) Superconducting AVF cyclotrons
  2) Separated-sector cyclotrons or Ring cyclotrons

- Requirements for RI beams
  
  The intensities as well as energies of heavy-ion cyclotrons have been remarkably increased.
  Development of ECR ion sources that are able to produce highly-charged heavy ions

- Now several high-power heavy-ion cyclotrons worldwide are operational.
Six facilities that operate high-power heavy-ion cyclotrons

- KVI
- FLNR/JINR
- HIRFL
- GANIL
- RIBF
- NSCL/MSU

Beam power > ~kW
GANIL
(Grand Accelerateur National d’Ion Louds)

1982 First beam from CSS2
Mid-1980 OAE project
1998 First beam from CIME

Beam energy
CSS1: 5.5 ~ 13.7 MeV/u
CSS2: 24 ~ 95 MeV/u

RI beams
ISOL method
Projectile fragmentation
## CSS2 beams

<table>
<thead>
<tr>
<th>Beams</th>
<th>Energy (MeV/u)</th>
<th>Intensity (pnA)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}$C$^{6+}$</td>
<td>95</td>
<td>3,200</td>
<td>3,600</td>
</tr>
<tr>
<td>$^{13}$C$^{6+}$</td>
<td>75</td>
<td>3,000</td>
<td>2,900</td>
</tr>
<tr>
<td>$^{14}$N$^{7+}$</td>
<td>95</td>
<td>2,140</td>
<td>3,400</td>
</tr>
<tr>
<td>$^{16}$O$^{8+}$</td>
<td>95</td>
<td>2,000</td>
<td>3,000</td>
</tr>
<tr>
<td>$^{18}$O$^{8+}$</td>
<td>75</td>
<td>290</td>
<td>400</td>
</tr>
<tr>
<td>$^{20}$Ne$^{10+}$</td>
<td>95</td>
<td>1,570</td>
<td>2,400</td>
</tr>
<tr>
<td>$^{22}$Ne$^{10+}$</td>
<td>80</td>
<td>1,500</td>
<td>2,600</td>
</tr>
<tr>
<td>$^{24}$Mg$^{12+}$</td>
<td>95</td>
<td>1,670</td>
<td>3,800</td>
</tr>
<tr>
<td>$^{36}$S$^{16+}$</td>
<td>78</td>
<td>690</td>
<td>1,900</td>
</tr>
<tr>
<td>$^{36}$Ar$^{18+}$</td>
<td>95</td>
<td>1,330</td>
<td>4,600</td>
</tr>
<tr>
<td>$^{48}$Ca$^{19+}$</td>
<td>60</td>
<td>240</td>
<td>700</td>
</tr>
<tr>
<td>$^{58}$Ni$^{56+}$</td>
<td>75</td>
<td>150</td>
<td>700</td>
</tr>
<tr>
<td>$^{76}$Ge$^{30+}$</td>
<td>61</td>
<td>120</td>
<td>500</td>
</tr>
<tr>
<td>$^{78}$Kr$^{34+}$</td>
<td>70</td>
<td>210</td>
<td>1,200</td>
</tr>
<tr>
<td>$^{124}$Xe$^{44+}$</td>
<td>50</td>
<td>50</td>
<td>300</td>
</tr>
</tbody>
</table>

**GANIL**

- **K-value**: 380 MeV
- **No. of sectors**: 4
- **Extraction radius**: 3.0 m
- **Max. mag. field**: 1.6 T
- **No. of resonators**: 2
- **Magnet weight**: 1,700 t

**CSS1 & 2**

- **CSS1 beams**
- **CSS2 beams**
NSCL/MSU
(National Superconducting Cyclotrons Laboratory)

1982  First beam from K500
1988  First beam from K1200
2000  First beam from the coupled cyclotrons

Beam energy
K1200: 20 ~ 200 MeV/u
### K1200 beams

<table>
<thead>
<tr>
<th>Beams</th>
<th>Energy (MeV/u)</th>
<th>Intensity (pnA)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{16}$O</td>
<td>150</td>
<td>500</td>
<td>1,200</td>
</tr>
<tr>
<td>$^{18}$O</td>
<td>120</td>
<td>500</td>
<td>1,080</td>
</tr>
<tr>
<td>$^{22}$Ne</td>
<td>150</td>
<td>220</td>
<td>730</td>
</tr>
<tr>
<td>$^{24}$Mg</td>
<td>170</td>
<td>200</td>
<td>820</td>
</tr>
<tr>
<td>$^{36}$Ar</td>
<td>150</td>
<td>150</td>
<td>810</td>
</tr>
<tr>
<td>$^{40}$Ar</td>
<td>140</td>
<td>200</td>
<td>1,120</td>
</tr>
<tr>
<td>$^{40}$Ca</td>
<td>140</td>
<td>70</td>
<td>390</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>140</td>
<td>140</td>
<td>940</td>
</tr>
<tr>
<td>$^{58}$Ni</td>
<td>160</td>
<td>40</td>
<td>370</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>130</td>
<td>50</td>
<td>490</td>
</tr>
<tr>
<td>$^{78}$Kr</td>
<td>150</td>
<td>100</td>
<td>1,170</td>
</tr>
<tr>
<td>$^{112}$Sn</td>
<td>120</td>
<td>10</td>
<td>120</td>
</tr>
<tr>
<td>$^{124}$Xe</td>
<td>140</td>
<td>25</td>
<td>430</td>
</tr>
<tr>
<td>$^{208}$Pb</td>
<td>85</td>
<td>4</td>
<td>70</td>
</tr>
<tr>
<td>$^{238}$U</td>
<td>80</td>
<td>0.3</td>
<td>6</td>
</tr>
</tbody>
</table>

- **K-value**: 1,200 MeV
- **No. of sectors**: 3
- **Extraction radius**: 1.01 m
- **Max. mag. field**: 6.1 T
- **No. of resonators**: 3
- **Magnet weight**: 260 t

---

**NSCL**
FLNR/JINR
(Flerov Laboratory of Nuclear Reactions)

- 1978  First beam from U400
- 1991  First beam from U400M
- 2002~ DRIBs project

**Beam energy**
- U400: 3 ~ 20 MeV/u
- U400M: 30 ~ 50 MeV/u

**RI beams**
- ISOL method
About 66% of the total operation is used for the acceleration of $^{48}$Ca ions to synthesize new super-heavy elements.

Upgrade project of the U400 is underway: to increase the beam intensity up to 2.5 ~ 3 p μA and to increase the energy variation for $^{48}$Ca, $^{50}$Ti, etc.
HIRFL
(Heavy Ion Research Facility in Lanzhou)

1988    First beam from SSC
Early-2000 Refurbishment of SFC & upgrade of SSC
2007    First beam from CSRm

Beam energy
SFC:    < 10 MeV/u
SSC:    < 100 MeV/u
CSRm:   1,100 MeV/u for C ions
        520 MeV/u for U^{72+} ions

RI beams
  In-flight fission of U ions
  Projectile fragmentation
**HIRFL**

<table>
<thead>
<tr>
<th>Beams</th>
<th>Energy (MeV/u)</th>
<th>Intensity (pnA)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}\text{C}^{4+}$</td>
<td>7.0</td>
<td>3,750</td>
<td>320</td>
</tr>
<tr>
<td>$^{16}\text{O}^{6+}$</td>
<td>8.0</td>
<td>3,000</td>
<td>260</td>
</tr>
<tr>
<td>$^{20}\text{Ne}^{7+}$</td>
<td>7.2</td>
<td>1,710</td>
<td>250</td>
</tr>
<tr>
<td>$^{26}\text{Mg}^{8+}$</td>
<td>6.5</td>
<td>250</td>
<td>43</td>
</tr>
<tr>
<td>$^{40}\text{Ar}^{8+}$</td>
<td>2.4</td>
<td>1,880</td>
<td>180</td>
</tr>
<tr>
<td>$^{78}\text{Kr}^{19+}$</td>
<td>4.0</td>
<td>470</td>
<td>150</td>
</tr>
<tr>
<td>$^{129}\text{Xe}^{27+}$</td>
<td>3.0</td>
<td>260</td>
<td>100</td>
</tr>
<tr>
<td>$^{238}\text{U}^{26+}$</td>
<td>0.8</td>
<td>13</td>
<td>2.5</td>
</tr>
</tbody>
</table>

**K-value** 450 MeV  
**No. of sectors** 4  
**Extraction radius** 3.21 m  
**Max. mag. field** 1.6 T  
**No. of resonators** 2  
**Magnet weight** 2,000 t  

**SSC beams**

<table>
<thead>
<tr>
<th>Beams</th>
<th>Energy (MeV/u)</th>
<th>Intensity (pnA)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}\text{C}^{6+}$</td>
<td>100</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>$^{22}\text{Ne}^{10+}$</td>
<td>70</td>
<td>50</td>
<td>77</td>
</tr>
<tr>
<td>$^{36}\text{Ar}^{8+}$</td>
<td>7.2</td>
<td>440</td>
<td>350</td>
</tr>
<tr>
<td>$^{58}\text{Ni}^{22+}$</td>
<td>6.5</td>
<td>9</td>
<td>26</td>
</tr>
<tr>
<td>$^{129}\text{Xe}^{27+}$</td>
<td>2.4</td>
<td>28</td>
<td>70</td>
</tr>
<tr>
<td>$^{209}\text{Bi}^{31+}$</td>
<td>5.8</td>
<td>10</td>
<td>20</td>
</tr>
</tbody>
</table>
1996 First beam from AGOR

Beam energy

AGOR: $35 \sim 90$ MeV/u for $Q/A=0.5$
$10 \sim 30$ MeV/u for $Q/A=0.25$
$6$ MeV/u for $Q/A=0.1$

RI beams
Inverse kinematics method
Upgrade project of the AGOR is underway to increase the beam intensity in order to obtain a beam power of ~1 kW for all beams up to Pb.

<table>
<thead>
<tr>
<th>Beams</th>
<th>Energy (MeV/u)</th>
<th>Intensity (pnA)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{11}\text{B}^{3+}$</td>
<td>19</td>
<td>160</td>
<td>30</td>
</tr>
<tr>
<td>$^{12}\text{C}^{4+}$</td>
<td>23</td>
<td>1,000</td>
<td>280</td>
</tr>
<tr>
<td>$^{19}\text{F}^{4+}$</td>
<td>11</td>
<td>330</td>
<td>70</td>
</tr>
<tr>
<td>$^{20}\text{Ne}^{6+}$</td>
<td>23</td>
<td>2,200</td>
<td>1,000</td>
</tr>
<tr>
<td>$^{36}\text{Ar}^{10+}$</td>
<td>30</td>
<td>500</td>
<td>540</td>
</tr>
<tr>
<td>$^{40}\text{Ca}^{14+}$</td>
<td>45</td>
<td>160</td>
<td>290</td>
</tr>
<tr>
<td>$^{82}\text{Kr}^{19+}$</td>
<td>25</td>
<td>160</td>
<td>330</td>
</tr>
<tr>
<td>$^{208}\text{Pb}^{27+}$</td>
<td>9.2</td>
<td>40</td>
<td>80</td>
</tr>
</tbody>
</table>
RIBF
(RI Beam Factory, RIKEN Nishina Center)

1986    First beam from RRC
Mid-1990 Upgrade of the pre-injector of RILAC
2006    First beam from SRC

Beam energy

RRC:  7 ~ 135 MeV/u for heavy ions
SRC:  345 MeV/u for all heavy ions
      < 400 MeV/u for 0.4<Q/A<0.5
      < 440 MeV for Q/A=0.5

RI beams
In-flight fission of U ions
Projectile fragmentation

New injector linac, RILAC2, will be ready for commissioning by the end of 2010.
**RIBF**

- **K-value**: 2,600 MeV
- **No. of sectors**: 6
- **Extraction radius**: 5.36 m
- **Max. mag. field**: 3.8 T
- **No. of resonators**: 4
- **Magnet weight**: 8,100 t

**Superconducting**

**Goal**: 1p μA for 345 MeV/u 
**238U** ions 
(80 kW)

---

**RRC beams**

<table>
<thead>
<tr>
<th>Beams</th>
<th>Energy (MeV/u)</th>
<th>Intensity (pnA)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12C⁶⁺</td>
<td>135</td>
<td>770</td>
<td>1,250</td>
</tr>
<tr>
<td>14N⁷⁺</td>
<td>135</td>
<td>710</td>
<td>1,340</td>
</tr>
<tr>
<td>18O⁸⁺</td>
<td>100</td>
<td>590</td>
<td>1,060</td>
</tr>
<tr>
<td>22Ne¹⁰⁺</td>
<td>110</td>
<td>360</td>
<td>870</td>
</tr>
<tr>
<td>36Ar¹⁷⁺</td>
<td>115</td>
<td>80</td>
<td>330</td>
</tr>
<tr>
<td>40Ar¹⁵⁺</td>
<td>63</td>
<td>800</td>
<td>2,020</td>
</tr>
<tr>
<td>48Ca¹⁷⁺</td>
<td>63</td>
<td>140</td>
<td>420</td>
</tr>
<tr>
<td>56Fe²⁴⁺</td>
<td>90</td>
<td>8</td>
<td>40</td>
</tr>
<tr>
<td>86Kr³⁰⁺</td>
<td>63</td>
<td>80</td>
<td>430</td>
</tr>
<tr>
<td>136Xe²⁰⁺</td>
<td>11</td>
<td>15</td>
<td>22</td>
</tr>
</tbody>
</table>

**SRC beams**

<table>
<thead>
<tr>
<th>Beams</th>
<th>Energy (MeV/u)</th>
<th>Intensity (pnA)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18O⁸⁺</td>
<td>345</td>
<td>1,000</td>
<td>6,210</td>
</tr>
<tr>
<td>48Ca²⁰⁺</td>
<td>345</td>
<td>230</td>
<td>3,810</td>
</tr>
<tr>
<td>86Kr³⁰⁺</td>
<td>345</td>
<td>33</td>
<td>980</td>
</tr>
<tr>
<td>238U⁶⁺</td>
<td>345</td>
<td>0.8</td>
<td>66</td>
</tr>
</tbody>
</table>
Statistics for the beam power of heavy-ion beams obtained from high-power cyclotrons so far
Some technological issues related to high-power heavy-ion beams

- ECR ion sources
- LEBT
- Extraction
- Charge strippers
- Beam diagnostics/safety system/stability
- Availability
- Space charge effect
ECR ion sources

- At RIBF
  Goal: 1 $\mu$A 345 MeV/u uranium beam
  > 500 $e \mu A$ $^{25+}$ from the ion source is required.

- VENUS and SECRAL of 3rd generation ECR ion sources have achieved good performance.
  Ex.: 180 $e \mu A$ $^{35+}$ from VENUS

- RIKEN 28 GHz SC-ECRIS has been newly constructed and expected to produce such 500 $e \mu A$ $^{35+}$ ions.
  - Large ECR-zone size
  - Gentle field gradient
LEBT

- To control the quality of beams in the LEBT is very important to obtain good net transmission efficiency.

- At NSCL
  - Study has been carried out intensively using BaF₂-coated viewing plates and an Allison-type emittance scanner.
    
    To deal with hollow beams
    - A solenoid lens was replaced with an electrostatic lens.
  - The net beam transmission efficiency was improved by 400% from 2003 to 2006.

- A more detailed study involving both simulations and experiments still has to be carried out to further elucidate the mechanism of beam motion.
  
  Unknown factor: neutralization
  
  initial condition at the extraction of the ion source
Extraction

- **Beam loss at electrostatic deflectors**
  - limits cyclotron output beam intensity

- **At RIBF**
  - Beam loss at the SRC-EDC is monitored by measuring:
    - *temperature* of the septum electrode
    - *radiation* with an ionization chamber
  - Heat load limit: **300 W**
    (corresponds to 10% of the total power for 345 MeV/u $^{48}$Ca beam)

- **How to deal with the problem:**
  - increase of RF voltage
  - use of flattop resonator
  - collimation of the beam
  - development of a deflector that endures higher values of beam loss, say 1 kW
Charge strippers

- Charge stripper problems are very serious for very heavy ions like U.
- At RIBF
  - For the acceleration of a U beam, two carbon-foil charge strippers are used.
  - A problem occurs with the first stripper.

*Acceleration scheme of a uranium beam at RIBF*
Charge strippers

- At RIBF (cont’d)
  - Lifetime: ~ 10 h with a beam intensity of 80 pnA (3 W loss)
  - The lifetime is determined by the decrease of beam intensity due to energy spread after irradiation. (The foils are not necessarily broken.)
  - Non-uniformity of thickness is 30 %.
  - The target intensity of 1 pμA is about 1,000 times higher than what is currently available.

Development of other types of charge strippers such as a gas stripper or a liquid stripper are essential for higher intensity beams.

**TOF signal measured downstream the charge stripper**

(a) 300μg/cm² FWHM=1.35 nsec

(b) 300 μg/cm² used for 15 hours FWHM=2.45 nsec
Charge strippers

- At NSCL
  - Experiment performed in the K1200 with a Pb beam
  - Significant decay observed at $10^{14}$ ions in 4 mm$^2$ in the cyclotron
  - Not practical to use at the present time

*SEM photographs of Pb irradiated foil*

*Accumulated current dependency of beam transmission efficiency*
Beam diagnostics/safety system/stability

- **Non-destructive beam diagnostic devices** are indispensable for high-intensity operations.

- **At GANIL**
  - The machine is tuned step-by-step by reducing the beam-chopping rate.
  - Interceptive diaphragms and **current transformers**
  - The beam loss is continuously monitored and if it exceeds a threshold, the safety system works.

- **At RIBF**
  - A monitoring system of beam phases and RF fields using **lock-in amplifiers (LIAs)** has recently been developed.

- **An automated beam alignment system using inductive beam position monitors (BPMs)** is also useful.
Availability

- Availability = \(\frac{\text{Delivered beam time}}{\text{Scheduled beam time}}\)

- The availability is now as high as \(\sim 90\%\) at every facility.
Space charge effect

- Little study on the space charge effects in heavy-ion cyclotrons; cf. considerable research has been devoted to those in high-intensity proton cyclotrons such as PSI cyclotrons.
- However, it has become necessary to take these effects into account in simulations even for heavy-ion cyclotrons.
- In the PSI proton cyclotron, “round beam” formation was observed and has been studied intensively.

“Round beam” formation in the PSI Injector II

Beam patterns in the PSI Ring cyclotron

[ Calculation by S. Adam ]

[ Calculation by Y. J. Bi and A. Adelmann ]
Space charge effect

- “Round beam” formation and the matching condition for it are studied for heavy ion beams.
  [ P. Bertran et al., Cyclotrons 2001 (2001) 379 ]

- Some simulations for RIBF cyclotrons
  - “Round beam” in the RRC
  - Intensity limit due to the longitudinal space charge effect in the SRC

“Round beam” formation in the RRC at 0.5 mA for a U\(^{35+}\) beam

[ Calculation by S. Vorozhtsov ]

Intensity dependence of beam clearance in the SRC

[ Calculation by H. Okuno ]
Summary

- High-power cyclotrons for heavy-ion beams have played essential role in RI beam sciences.

- Six facilities worldwide that operate high-power heavy-ion cyclotrons were overviewed.
  
  The beam power of up to several kW have been obtained for ions lighter than around Ar.

- Some technological issues related to high-power heavy-ion beams were discussed on the basis of the experiences of the above cyclotrons.
  
  There are still challenging technological issues to be solved to meet great targets.

- High-power heavy-ion cyclotrons are expected to be more and more useful for RI beam sciences.
Acknowledgement

I do appreciate the following colleagues who sent me their slides:

Stefan Adam, Sytze Brandenburg, Frederic Chautard, Boris Gikal, Daniela Leitner, Felix Marti, Mike Seidel, Jeffry Stetson, Sergey Vorozhtsov and Hongwei Zhao

Thanks for members of the Accelerator Group, RIKEN Nishina Center.
Thank you for your attention!
Three acceleration modes

- Fixed-energy mode (345 MeV/u)
- Variable-energy mode (< 400 MeV/u)
- AVF-injection mode (< 440 MeV/u)
Acceleration of $^{238}$U beam

- ECRIS
- RILAC
  - 11 MeV/u
  - $^{35+} \Rightarrow ^{71+}$
  - 18%
- RRC
- SRC
  - 0.67 MeV/u
  - $^{U35+}$
  - 2 eµA
- IRC
  - 0.40 pnA ($2.5 \times 10^9$ pps)
  - @345 MeV/u ($\beta = 0.68$)
- 50 MeV/u
  - $^{71+} \Rightarrow ^{86+}$
  - 28%
- 114 MeV/u
Acceleration of $^{48}$Ca beam

RILAC
2.7 MeV/u
10+ $\Rightarrow$ 16+
35%

ECRIS

Ca10+
20 eμA

IRC

SRC

170 pnA ($1.0 \times 10^{12}$ pps)
@345 MeV/u ($\beta = 0.68$)

45 MeV/u
16+ $\Rightarrow$ 20+
87%

114 MeV/u
Beam transmission efficiency

Ex.: Beam transmission efficiencies at RIBF

- 85 % in variable-energy mode (three cyclotrons: RRC-IRC-SRC)
- 40 % in fixed-energy mode (four cyclotrons: RRC-fRC-IRC-SRC)

Note: charge stripping efficiencies (30% for $^{48}$Ca and 4.4% for $^{238}$U) are excluded.
Charge strippers in RIBF

18 GHz ECRIS

FCRFO

RILAC

RRC

IRC

SRC

BigRIPS

345 MeV/u

U

35+ --> 71+ 300 μg/cm²

71+ --> 86+ 1.4 mg/cm²

345 MeV/u

Ca/Kr

18 GHz ECRIS

FCRFO

RILAC

RRC

IRC

SRC

BigRIPS

345 MeV/u

40/20 μg/cm²

1,000/200 μg/cm²
Stability

- At RIBF
  
  - Drift of the magnetic field of the RRC: 1 ppm/h for the first 600 h

\[ S. \text{Okumura et al., Cyclotrons 2001 (2001) 330} \]
An electric power cogeneration system (CGS) with the output electric power of 6.5 MW is operated at RIBF.

To increase the reliability and overall energy efficiency of the power supply of the entire facility.

It powers apparatus requiring continuous operation such as the He refrigerator of the SRC.

When the CGS stops, the equipment is immediately switched over to the commercial power grid.