Commissioning of HIRFL-CSR and its Electron Coolers

Institute of Modern Physics
Chinese Academy Of Sciences

Xiaodong Yang

September 22 2005
Function of Cooler in HIRFL-CSR

Main Ring

Heavy Ion Beam
Accumulation

Experimental Ring

High Precision
High Resolution
Physics Program of CSR

RIB physics
(With Radioactive Ion Beams)

Researches of hot nuclei
(With high-energy beams)

Atomic physics
(With highly charged heavy ions)

Related applications
<table>
<thead>
<tr>
<th>Parameter</th>
<th>CSRm</th>
<th>CSRe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference (m)</td>
<td>161.0014</td>
<td>128.8011</td>
</tr>
<tr>
<td>Average radius (m)</td>
<td>8R_{SSC}=34R_{SFC}=25.62416</td>
<td>4/5R_{CSRm}=20.499328</td>
</tr>
<tr>
<td>Geometry</td>
<td>Race-track</td>
<td>Race-track</td>
</tr>
<tr>
<td>Max. energy (MeV/u)</td>
<td>2800 (p)</td>
<td>2000 (p)</td>
</tr>
<tr>
<td></td>
<td>1100 (C^{6+})</td>
<td>750 (C^{6+})</td>
</tr>
<tr>
<td></td>
<td>500 (U^{22+})</td>
<td>500 (U^{92+})</td>
</tr>
<tr>
<td>B_{p} (Tm)</td>
<td>0.81/12.05</td>
<td>0.50/9.40</td>
</tr>
<tr>
<td>B(T)</td>
<td>0.10/1.60</td>
<td>0.08/1.60</td>
</tr>
<tr>
<td>Ramping rate (T/s)</td>
<td>0.05 ~ 0.4</td>
<td>-0.1 ~ -0.2</td>
</tr>
<tr>
<td>Repeating circle (s)</td>
<td>~17 (~10s for Accumulation)</td>
<td></td>
</tr>
<tr>
<td>Acceptance</td>
<td>Fast-extraction mode</td>
<td>Normal mode</td>
</tr>
<tr>
<td>A_{h} (π mm-mrad)</td>
<td>200 (Δp/p = ±0.3 %)</td>
<td>150 (Δp/p =±0.5%)</td>
</tr>
<tr>
<td>A_{v} (π mm-mrad)</td>
<td>40</td>
<td>75</td>
</tr>
<tr>
<td>Δp/p (%)</td>
<td>1.4 ( (ς_{h} = 50 \pi \ \text{mm-mrad}) )</td>
<td>2.6 ( (ς_{h} = 10 \pi \ \text{mm-mrad}) )</td>
</tr>
</tbody>
</table>

### CSR major parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CSRm</th>
<th>CSRe</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-cooler</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron energy (KeV)</td>
<td>35</td>
<td>300</td>
</tr>
<tr>
<td>Eff. cooling length (m)</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>RF system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harmonic number</td>
<td>1</td>
<td>16, 32,64</td>
</tr>
<tr>
<td>f_{min}/f_{max} (MHz)</td>
<td>0.24/1.81</td>
<td>6.0 / 14.0</td>
</tr>
<tr>
<td>Voltages (n x kV)</td>
<td>1 x 7.0</td>
<td>1 x 20.0</td>
</tr>
<tr>
<td>Vacuum (mbar)</td>
<td></td>
<td>(3.0 x 10^{-11})</td>
</tr>
</tbody>
</table>
W = 41.8855 m
L = 55.7101 m
C = 161.0014 m

CSRm Lattice Layout
<table>
<thead>
<tr>
<th>Main Parameters Table of HIRFL-CSR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td><strong>Ion Energy/MeV/u</strong></td>
</tr>
<tr>
<td>8-50</td>
</tr>
<tr>
<td><strong>Electron Energy/keV</strong></td>
</tr>
<tr>
<td><strong>Ring Length/m</strong></td>
</tr>
<tr>
<td><strong>Cooling section Length/m</strong></td>
</tr>
<tr>
<td><strong>β Function/m</strong></td>
</tr>
<tr>
<td>Horizontal $\beta_h$</td>
</tr>
<tr>
<td>Vertical $\beta_h$</td>
</tr>
<tr>
<td><strong>Dispersion/m</strong></td>
</tr>
<tr>
<td><strong>Magnetic Strength/T</strong></td>
</tr>
<tr>
<td><strong>Max Electron Current/A</strong></td>
</tr>
<tr>
<td><strong>Initial Emittance (πmmmrad)</strong></td>
</tr>
<tr>
<td>Horizontal $\varepsilon_h$</td>
</tr>
<tr>
<td>Vertical $\varepsilon_v$</td>
</tr>
<tr>
<td><strong>Initial Momentum Spread $\Delta P/P$</strong></td>
</tr>
<tr>
<td><strong>Final Emittance (πmmmrad)</strong></td>
</tr>
<tr>
<td>Horizontal $\varepsilon_h$</td>
</tr>
<tr>
<td>Vertical $\varepsilon_v$</td>
</tr>
<tr>
<td><strong>Final Momentum Spread $\Delta P/P$</strong></td>
</tr>
</tbody>
</table>
Some topics discussed

• Collection of electron beam
• Adiabatic expansion of electron beam
• Influence of magnetic field imperfection
• Motion of electron beam in toroid
Parameters related to the cooling time
---lattice function

- $\beta$Function
- Dispersion
- Initial Emittance and Momentum Spread
Parameters related to cooling time

---Ion beam

- Ion Energy
- Species of Ion
- Charge State
- Ion Beam Current
Parameters related to Cooling Time

---Electron Beam

- Density of Electron
- Electron Beam Current
- Radius of Electron Beam
- Transverse Temperature of Electron Beam
Parameters related to Cooling Time
---Electron cooling Device

• Effective Cooling Length
• Magnetic Field Strength
• Parallelism of Magnetic Field in Cooling section
Cooling time as a function of Betatron function
Cooling time as a function of dispersion in the cooler location
Cooling time as a function of initial emittance

$\tau / s$

$\varepsilon_{h} / \pi \text{mm mrad}$

$^{16}\text{O}^{8+}$ 25 MeV/u
$\varepsilon_{h} = 20 \pi \text{mm mrad}$
$\beta_{h} = 10 \text{m} \quad \beta_{v} = 17 \text{m}$
$B = 0.1 \text{T} \quad \Delta B / B = 1 \times 10^{-4}$
$\Delta p / p = 5 \times 10^{-3}$
Cooling time as a function of initial momentum spread

$^{16}\text{O}^{8+}$ 25 MeV/u
$\varepsilon_h=150 \, \mu\text{m mm rad}$
$\varepsilon_v=20 \, \mu\text{m mm rad}$
$\beta_h=10 \, \text{m} \quad \beta_v=17 \, \text{m}$
$B=0.1 \, \text{T} \quad \Delta B/B=1\times10^{-4}$
Cooling time as a function of ion energy
Cooling time as a function of charge state
Cooling time as a function of injection ion beam current.

- $^{16}\text{O}^8$ 25 MeV/u
- $\varepsilon_h = 150 \, \text{mm mrad}$
- $\varepsilon_v = 20 \, \text{mm mrad}$
- $\beta_h = 10 \, \text{m}$
- $\beta_v = 17 \, \text{m}$
- $B = 0.1 \, \text{T}$
- $\Delta B/B = 1 \times 10^{-4}$
- $\Delta P/P = 5 \times 10^{-3}$

Graph shows the cooling time ($\tau$) in seconds ($\text{s}$) as a function of the injection ion beam current ($I_{\text{ion}}$) in milliamperes (mA) per $10^{-3}$.
Cooling time as a function of electron density at different radius
Cooling time as a function of electron beam current at fixed radius

\[ \frac{238\text{U}^{91+}}{E=219.44\text{ keV}} \]
\[ E_I = 0.1\text{ eV} \]
\[ \Delta B/B = 1.0 \times 10^{-4} \]
\[ R = 0.025\text{ M} \]
\[ B = 0.15\text{ T} \]
\[ \beta_T = 14.9\text{ M} \]
Cooling time as a function of radius of electron beam at fixed density

- $B_{\text{cooling}} = 0.10T$
- $B_{\text{cooling}} = 0.15T$

- $^{238}\text{U}^{91+}$
- $E_0 = 219.44$ keV
- $j_e = 0.42$ A/cm$^2$
- $E_r = 0.1$ eV
- $\Delta B/B = 1.0 \times 10^{-4}$
- $\beta = 14.9$ M
Cooling time as a function of transverse energy of electron

$^{238}\text{U}^{91+}$

$E_e = 219.44 \text{ keV}$

$I = 3 \text{ A}$

$R = 0.0225 \text{ M}$

$\Delta B/B = 1.0 \times 10^{-4}$

$\beta = 7.5 \text{ M}$

$L_c = 4 \text{ M}$

Cooling time $\tau / \text{ sec}$

Transverse energy of electron $E_r / \text{ eV}$
Cooling time as a function of length of cooling section

\[ \text{Cooling time } \tau \text{ sec} \]

\[ \text{Length of cooling section } L_{\text{cooling}} / \text{M} \]

- \( B_{\text{cooling}} = 0.15 \text{T} \)
- \( B_{\text{cooling}} = 0.10 \text{T} \)

\[ ^{238} \text{U}^{91+} \]

\[ E_e = 219.44 \text{ keV} \]

\[ I = 3 \text{ A} \]

\[ R = 0.0225 \text{ M} \]

\[ E_f = 0.1 \text{ eV} \]

\[ \Delta B/B = 1.0 \times 10^{-4} \]

\[ \beta = 7.5 \text{ M} \]
Cooling time as a function of magnetic inductive strength in cooler

- $^{238}\text{U}^{91+}$
- $E_e = 219.44$ keV
- $E_f = 0.1$ eV
- $\Delta B/B = 1.0 \times 10^{-4}$
- $\beta = 14.9 \text{ M}$

- $I = 3.0 \text{ A} \ R = 0.015 \text{ M}$
- $I = 5.3 \text{ A} \ R = 0.020 \text{ M}$
Cooling time as a function of magnetic field parallelism

$^{238}\text{U}^{91+}$

$E_e = 219.44 \text{ keV}$

$I = 3 \text{ A}$

$R = 0.0225 \text{ M}$

$E_r = 0.1 \text{ eV}$

$\beta = 7.5 \text{ M}$

$L_c = 4 \text{ M}$

$B = 0.15 \text{ T}$

$B = 0.10 \text{ T}$
Previous results of commissioning

- Hollow beam
- High parallelism magnetic field in cooling section
- Electrostatic bending
Angle of Magnetic force line with respect to geometric center before adjustment
Angle of Magnetic force line with respect to geometric center after adjustment
Electron beam profile
Comparison of different bending
Noise at different bending
## Results of commissioning

<table>
<thead>
<tr>
<th></th>
<th>CSRm</th>
<th>CSRe</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electron energy (keV)</strong></td>
<td>Design</td>
<td>test</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td><strong>Beam current (A)</strong></td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td><strong>parallelism</strong></td>
<td>horizontal</td>
<td>&lt;1×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>vertical</td>
<td>&lt;1×10⁻⁴</td>
</tr>
<tr>
<td><strong>Beam loss rate</strong></td>
<td>&lt;1×10⁻⁴</td>
<td>&lt;1×10⁻⁴</td>
</tr>
<tr>
<td><strong>Vacuum (mbar)</strong></td>
<td>3×10⁻¹¹</td>
<td>1×10⁻¹¹</td>
</tr>
<tr>
<td><strong>Stability of HVPS</strong></td>
<td>1×10⁻⁴</td>
<td>1×10⁻⁴</td>
</tr>
</tbody>
</table>
Stability of magnetic field power supply

<table>
<thead>
<tr>
<th></th>
<th>CSRm</th>
<th>CSRe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>design</td>
<td>test</td>
</tr>
<tr>
<td>200A PS</td>
<td>1.0×10^{-3}</td>
<td>5.9×10^{-4}</td>
</tr>
<tr>
<td>780A PS</td>
<td>1.0×10^{-3}</td>
<td>2.4×10^{-4}</td>
</tr>
<tr>
<td>1200A PS</td>
<td>1.0×10^{-3}</td>
<td>3.8×10^{-4}</td>
</tr>
<tr>
<td>Bending PS</td>
<td>1.0×10^{-3}</td>
<td>5.0×10^{-4}</td>
</tr>
<tr>
<td>CX6 Correction coil PS</td>
<td>1.0×10^{-3}</td>
<td>1.3×10^{-4}</td>
</tr>
<tr>
<td>CY6 Correction coil PS</td>
<td>1.0×10^{-3}</td>
<td>1.1×10^{-2}</td>
</tr>
</tbody>
</table>
Conclusion

1. lattice parameters of HIRFL---CSR lie in the optimal range for electron cooling
2. In the CSRm, the ion with higher charge state and lower energy should be chose as injection so that the ion beam will be cooled to required emittance in the shorter time
3. Electron cooling is more powerful when the injected ion beam has smaller initial emittance and momentum spread.
Conclusion

4. If introduce positive dispersion in the cooling section, the cooling time will become shorter than zero dispersion.

5. Electron density should approach optimal value in the case of low energy, and as big as possible in the case of high energy.

6. The magnetic field should be strong enough and parallelism is better than $1 \times 10^{-4}$. 
Previous Commission of CSR

- From September 2004, the injection line was tuned with 7 Mev/u C^4+ beam, the ion beam intensity is about 3 microamperes. The transmission efficiency is about 70%. Three cycles beam were observed in the main ring.
We would like to acknowledge our Russian colleagues.

Sincere honor and respect to the members of international advisory committee.

Thanks!