HIAF Electron Cooling System &
Space Charge Effects of Cooled Intense Heavy-ion Beams

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OUTLINE

- **HISTORY:** The High Intensity heavy-ion Accelerator Facility (HIAF) at IMP Lanzhou

- **MOTIVATION:** Electron Cooling System for HIAF

- **STATUS:** Cooling Effects Simulation Results

- **CHALLENGES:** Instabilities of High Intensity Heavy-ion Beams with Electron Cooling

- **FUTURE:** Questions and Outlook
High Intensity heavy-ion Accelerator Facility, HIAF

---12th five-year plan of science and technology in China (2011-2015)
High Intensity heavy-ion Accelerator Facility, HIAF

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High Intensity heavy-ion Accelerator Facility, HIAF

---12th five-year plan of science and technology in China (2011-2015)
Ions provided by iLinac: 28puA (U\(^{34+}\) at the injection energy 17 MeV/u)

Expected particle number in the BRing: \(10^{11}\) (U\(^{34+}\) at the injection energy 17 MeV/u)

Gain of accumulation: \(\sim 70\)

- Beam accumulation by the combination of E-cooling & two phase painting injection
- Make short bunch at the extraction energy
Ion Charge State=34
Mass Number=238
Kinetic Energy (Initial)=17 MeV/u
Kinetic Energy (Final)=800 MeV/u
Electron energy=9.326 keV (@injection energy), 438.871 keV (@ extraction energy)
Electron density=2.0*10^7 cm^-3
dp/p (Initial momentum spread, uniform distribution, RMS value)=±2*10^-3
Initial emittance (uniform distribution, RMS value)= 60 pi.mm.mrad
Beta-function @ the cooling section=15m
Magnetic field @ the cooling section = 0.2 T
Particle number=5*10^{10}
Ring circumference=500m
Cooler length=10 m (2% of ring circumference)
COOLING at INJECTION ENERGY

0 sec
x\times vx plane

1 sec
x\times vx plane

3 sec
x\times vx plane

\begin{align*}
\mathcal{H}^{(0)} &\quad \text{H_{\text{norm}}} \\
x &\quad \text{particle number}
\end{align*}
\[ \delta_{j+1} = \delta_j \exp\left(-\frac{1}{\text{dec}}\right) + \frac{Z \cdot U_{RF}}{A \gamma \beta^2 E_0 10^6} (\sin \varphi_j - \sin \varphi_0) + \sqrt{\text{dec} \cdot \delta_0} \cdot 24 (\text{rnd}(1) - 0.5) \]

\[ \varphi_{j+1} = \varphi_j + 2\pi \hbar \eta \delta_{j+1} \]
COOLING at EXTRACTION ENERGY

Evolution of Bunch Shape (red) & Space charge potential (Green)

---Dr. T. Katayama
200 MeV/u C\textsuperscript{6+} ions @ CSRe
RF voltage = 1.0 kV,
RF frequency = 1.319 MHz
Ie=300 mA with a expansion factor = 3.0

\[ U_{RF}(s) = U_0 \sin\left(\frac{S}{R}\right) \]
\[ \Omega_s^2 = \frac{\partial(U_{RF}(s) + U_{sp}(S))}{\partial s} \bigg|_{s=0} \]
\[ \sigma_b^3 - \sigma_b \sigma_{b0}^2 = kN \]
7.0 MeV/u C⁶⁺ ions was injected with e-cooling continually, particle loss directly around 2.5 mA and the intensity of the beam is limited $10^{10}$. 

![Graph showing time (sec) vs. current (μA)](image)

2007/09/10
7.0 MeV/u C^6+ ions was injected with e-cooling continually, particle loss directly around 2.5 mA and the intensity of the beam is limited $10^{10}$. 

**INSTABILITIES of COOLED BEAM**

- Longitudinal
- Transverse

[Graph showing timebase and frequency]
## INSTABILITIES of COOLED BEAM

Overview of intensities of cooled ion beams around the world

<table>
<thead>
<tr>
<th>Ring</th>
<th>Ion</th>
<th>Energy (MeV/u)</th>
<th>I_ion (mA)</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIS</td>
<td>Kr$^{34+}$</td>
<td>11</td>
<td>5</td>
<td>5E09</td>
</tr>
<tr>
<td>CELSIUS</td>
<td>H$^+$</td>
<td>45</td>
<td>1</td>
<td>6E09</td>
</tr>
<tr>
<td>TSR</td>
<td>C$^{6+}$</td>
<td>73.3</td>
<td>18</td>
<td>3.0E10</td>
</tr>
<tr>
<td>TSR</td>
<td>H$^+$</td>
<td>21</td>
<td>2.4</td>
<td>1.4E10</td>
</tr>
<tr>
<td>TSR</td>
<td>Au$^{50+}$</td>
<td>695</td>
<td>0.003</td>
<td>1.0E06</td>
</tr>
<tr>
<td>CSRm</td>
<td>C$^{6+}$</td>
<td>7</td>
<td>6.5</td>
<td>3.0E10</td>
</tr>
<tr>
<td>CSRm</td>
<td>Xe$^{27+}$</td>
<td>2.9</td>
<td>0.5</td>
<td>1.0E08</td>
</tr>
<tr>
<td>CSRe</td>
<td>C$^{6+}$</td>
<td>660</td>
<td>15</td>
<td>1.0E10</td>
</tr>
<tr>
<td>COSY</td>
<td>H$^+$</td>
<td>45</td>
<td>9.2</td>
<td>1.2E11</td>
</tr>
</tbody>
</table>
Space Charge Limitation of an electron-cooled proton beam

Stability of cooled beams
J. Bosser, C. Carli, M. Chanel, N. Madsen, S. Maury, D. Möhl*, G. Tranquille
CERN, CH 1211 Genève 23, Switzerland

TRANSVERSE FEEDBACK SYSTEM
FOR THE COOLER SYNCHROTRON COSY-JÜLICH – FIRST RESULTS
V. Kamedzhiev, J. Dietrich, I. Mohos, Forschungszentrum Jülich GmbH, Germany

Electron drift instability in storage rings with electron cooling
A. Burov

Resonances driven by the Electric Field of the Electron Cooler
V. Ziemann
The Svedberg Laboratory
Linear tune shift due to the space charge effect of e-beam

\[ I_e = \rho \pi r_e^2 \beta c \]

\[ r_e = 30\text{mm} \]

\[ E_k = 17\text{MeV/u} \quad \text{U}^{34+} \text{ ions} \]

\[ \gamma = 1.018, \beta = 0.188 \]

\[ I_e = 1.0\text{A} \]

\[ \rho = 6.3 \times 10^{-6}\text{C/m}^3 \]

\[ E(r) = \frac{\rho r}{2\varepsilon_0} = 3.5 \times 10^5 \frac{r(\text{mm})}{\text{m}} \frac{\text{mV}}{\text{m}} \]

\[ \Delta pc = ZeE(r)L_{\text{cooler}} / \beta \]

\[ \Delta x' = \frac{\Delta p}{p_0} = \frac{r}{f} \]

\[ \Delta v = \frac{\beta_x}{4\pi f} = 0.012 I_e / A \]
Electron beam distribution written by error function

\[ \psi(r) = \text{erfc}\left( \frac{r - b}{a} \right) \]

\[ \frac{d^2 \eta}{d \theta^2} + \nu^2 \eta = -4\pi \nu \xi S(\eta) \delta_p(\theta) \]

\[ \Delta v_x(\varepsilon) = \frac{2\xi}{\sqrt{\varepsilon x \beta_x}} \int_0^{2\pi} d\phi \cos\phi S(\sqrt{\varepsilon x \beta_x} \cos\phi) \]
Space Charge Effect of E-Beam

Electron beam distribution written by error function

\[ \psi(r) = \text{erfc}\left( \frac{r}{a} \right) \]

\[ \frac{d^2 \eta}{d \theta^2} + \nu^2 \eta = - \]

\[ \cos \phi \delta \left( \sqrt{\varepsilon \beta_x \cos \phi} \right) \]

\[ l_e = 0.5 \, \text{A} \]
\[ L_{\text{cool}} = 10 \, \text{m} \]
\[ b = 30 \, \text{mm} \]
\[ ^{238}\text{U}^{34} \, 17 \, \text{MeV} \]
\[ \xi = 0.0087 \]

\[ I_e = 0.5 \, \text{A} \]
\[ L_{\text{cool}} = 10 \, \text{m} \]
\[ b = 30 \, \text{mm} \]
\[ \sigma = b / \sqrt{2} \]
\[ ^{238}\text{U}^{34} \, 17 \, \text{MeV} \]
Single particle tracking

\[ dd = 4\pi \frac{\xi}{N} E(x_i) \quad \text{Kick of space charge field of e-beam} \]

\[ dx_i = dx_i \exp\left(-\frac{1}{\text{damping}}\right)-dd \quad \text{Damping (cooling) turn by turn} \]

\[ x_{i+1} = \cos(2\pi v_x)x_i + \beta_x \sin(2\pi v_x)dx_i \quad \text{Betatron motion in the ring} \]

\[ dx_{i+1} = -x_i \frac{\sin(2\pi v_x)}{\beta_x} + \cos(2\pi v_x)dx_i \]

\[ \xi = 0.01 \quad x_0 = 4.5cm \quad \nu = 0.625 \]
**SPACE CHARGE EFFECT of E-BEAM**

**Single particle tracking**

\[ dd = 4\pi \frac{\xi}{N} E(x_i) \]

Kick of space charge field of e-beam

\[ dx_i = dx_i \exp\left(-\frac{1}{\text{damping}}\right) - dd \]

Damping (cooling) turn by turn

\[ \xi = 0.01 \quad x_0 = 4.5cm \quad \nu = 0.625 \]
Dependences on the e-beam current

\[ \xi = 0.05 \]

\[ \xi = 0.01 \]

\[ \xi = 0.005 \]

\[ \xi = 0.001 \]
Dependences on the tune value
Incoherent tune shift (Laslett tune shift)

\[ F(r) = (1 - \beta^2)\rho e^2 \frac{r}{2\varepsilon_0} \]

\[ N = B_f \frac{A}{Z^2} \frac{2\pi}{r_p} \gamma^3 \beta^2 \varepsilon_x (-\Delta Q) \]
**SPACE CHARGE EFFECT of ION-BEAM**

Single particle tracking

\[ dx_{i+1} = dx_i - dec \cdot dx_i + \sqrt{dec \cdot dx_0^2 \cdot (\text{rnd} - 0.5)} \]

Cooling & heating

\[ dd = 4\pi \frac{\xi}{N} E(x_i) \]

Kick of space charge field of ion beam

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** Without space charge effect **

** N=10^{10} **

** N=5 \times 10^{10} **

** N=10^{11} **
From Parkhomchuk’s idea, the cooling force limitation by intensity beams is:

\[ n_i n_e < \frac{\beta^4 \gamma^6}{l_{cool}^4 (4\pi)^2 \gamma r_e L_c} \approx 2.5 \times 10^{10} \text{(1/cm}^6) \]

\[ n_i \approx 10^3 - 10^4 \text{(1/cm}^3) \]

\[ l_{cool} = 10m \quad Ring = 500m \quad L_c \approx 10 \]

\( ^{34+} \text{U} \) at the injection energy of 17 MeV/u, stored particle number:

\[ n_i \approx 3 \times 10^{10} \]

For ion beam emittance (total) is about 10 pi.mm.mrad
An e-cooling system is considered to install in the booster ring of the HIAF project, in order to increase the accumulation gain factor at the injection energy, and make a short bunch at the extraction energy.

A classical magnetized electron cooler can provide a fast beam cooling effect at the injection energy.

A short bunch length is achieved by using the RF and E-cooling system. The final bunch length is determined by RF voltage and space charge effect.

The space charge field of the e-beam can make a linear tune shift, a non-linear tune spread and resonance islands for the beam with large size.

The space charge effect of ion beam is to limit the final emittance of cooled intense beams.

According to Parkhomchuk’s formula, the cooling force is limited by the ion beam density.
Thanks for your attention!