Design of a Compact Electron Gun for the HV Electron Cooler for the NICA Collider

Andrey Denisov

Budker Institute of Nuclear Physics
Electron cooling system for the NICA collider

- Ion energy: 1-4.5 GeV/u
- e⁻-beam energy: 0.2 – 2.5 MeV

Experiments with colliding Au^{79+} beams
Increase beam life-time using electron cooling
Increase experiment luminosity

Heavy ion Linac
Nuclotron
Booster
Collider
MPD (Detector)
E-cooling

Design of a Compact Electron Gun for the HV Electron Cooler for the NICA Collider
The concept of electron cooling

Cooling efficiency depends on the electron beam momentum spread and current density.

* The process actually takes much more iterations to cool the ion beam.

Design of a Compact Electron Gun for the HV Electron Cooler for the NICA Collider
Electron oscillations

Coherent electron oscillations in the electron beam

For efficient electron cooling the amplitude of these oscillations must be low

Electrical field of the gun has axial symmetry

$T_\perp \approx 0.1 \text{ eV (1000 } ^\circ \text{C) } \ll E_\perp$
Electrons oscillations energy tolerance

For efficient electron cooling the amplitude of electron oscillations must be low

$$r_L = \frac{p_\perp c}{e B}$$

$$E_\perp = \frac{p_\perp^2}{2 m_e}$$

Electrons of the beam oscillate with the same phase (at the beginning)

Beam radius changes due to coherent oscillations of the electrons

We can use BPMs to measure these oscillations
Electrons oscillations energy tolerance

For efficient electron cooling the amplitude of electron oscillations must be low

* Guiding magnetic field in the cooling section \( B \) is about 1-2 kG

\[
E_\perp = \frac{p_\perp^2}{2 m_e} \quad r_L = \frac{p_\perp c}{e B}
\]

BPMs sensitivity: 10-30 μm

\[
E_\perp = 1 \text{ eV} \quad \leftrightarrow \quad r_L \approx 20 \text{ μm} \\
(B = 1.5 \text{ kG})
\]

We don’t aim at oscillations energy lower than 1 eV, as we don’t have means to measure it
Required electron beam current density

Electron beam density is yet another factor that affects the cooling time

Empirical formula for the electron cooling force (beam reference system)

\[
\frac{d\vec{p}_i}{dt'} = \frac{4Z^2 e^4 n_e' \Lambda}{m_e} \cdot \frac{-\vec{v}_i}{\left[\vec{v}_i'^2 + v_{eff}^2\right]^{3/2}}
\]

Estimation for the cooling decrement (observational reference frame):

\[
\tau^{-1} \sim j_e \cdot \frac{Z^2}{A} \cdot \frac{4e^3 \Lambda}{\gamma^5 m_e m_p v_0^4} \cdot \frac{1}{x'^3}
\]

\(x'\) - the maximum angle in the ion beam

* The decrement grows as the transverse temperature decreases, therefore this formula estimates the upper bound for the cooling time
Required electron beam current density

Parameters of the NICA collider

<table>
<thead>
<tr>
<th>Parameter</th>
<th>79 / 197</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z / A$</td>
<td>1.0</td>
</tr>
<tr>
<td>Ion energy, Gev/u</td>
<td>3.0</td>
</tr>
<tr>
<td>Hor / ver rms beam emittance (unnormalized), $\pi \text{mm mrad}$</td>
<td>1.1 / 0.95</td>
</tr>
<tr>
<td>Ion energy, Gev/u</td>
<td>1.1 / 0.85</td>
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<tr>
<td>IBS growth time, s</td>
<td>1.1 / 0.75</td>
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<tr>
<td>IBS growth time, s</td>
<td>1.1 / 0.75</td>
</tr>
<tr>
<td>Beta function at the cooling section, m</td>
<td>10</td>
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<tr>
<td>Circumference of the collider ($L_p$), m</td>
<td>503</td>
</tr>
<tr>
<td>Length of the cooling section ($L_C$), m</td>
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<tr>
<td>$t_{\text{Cool}}$, s</td>
<td>16</td>
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<tr>
<td>$j_e$, A/cm$^2$</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>180</td>
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</table>

$$t_{\text{Cool}} \approx \frac{x^3}{j_e} \cdot \left( \frac{Z^2}{A} \cdot \frac{4e^3 \Lambda}{\gamma^5 m_e m_p v_0^4} \right)^{-1} \cdot \frac{L_p}{L_C}$$

Necessary electron current density $j_e \approx 1\text{A/cm}^2$
Electron gun has a control electron to vary a beam profile (COSY, NICA Booster) Using a four-sector control electrode

Electron gun

Electron cooling systems produced in BINP

Energy of an electron beam

<table>
<thead>
<tr>
<th>Energy of an electron beam</th>
<th>LEIR</th>
<th>SIS</th>
<th>CSRe</th>
<th>COSY</th>
<th>NAP-M</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 keV</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>10 keV</td>
<td></td>
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<tr>
<td>100 keV</td>
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<tr>
<td>1 MeV</td>
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<tr>
<td>10 MeV</td>
<td></td>
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</tbody>
</table>

Control electrode

Anode
Four-sector control electrode

Variable electron beam current density

Regime | $U_{\text{anode}}$ V | $U_{\text{control}}$ V
---|---|---
1: Hollow | 500 | 300
2: Flat | 500 | 100
3: Thin | 500 | −100

* Red curve is measured current density, and the blue curve is calculated.
Four-sector control electrode

* Voltage is applied to a single sector.

* Varying magnetic field.

Measuring the position of the modulated beam part using BPM

We can measure beam position, size and rotation
Towards higher electron current density

Why not to reuse the existing electron gun?

- The electron current density is not enough for the electron cooler for the NICA collider
- The electron beam is unnecessarily large.

Ion beam diameter (rms) for the NICA collider is just about **0.6 cm**

Using the smaller beam we can achieve greater current density at the same overall current

We designed a new gun, which can provide a **1 cm** diameter beam with current up to **1 A**

<table>
<thead>
<tr>
<th>$U_{\text{anode}}$</th>
<th>$U_{\text{control}}$</th>
<th>$R_{\text{beam}}$</th>
<th>$J_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 kV</td>
<td>2 kV</td>
<td>3 cm</td>
<td>0.56 A/cm$^2$</td>
</tr>
</tbody>
</table>

The perveance of the electron gun for the COSY electron cooler.

![Graph showing measured and calculated perveance](graph.png)
Electron gun with a convex cathode

Using a convex cathode to get more current
Electron gun with a flat cathode

Using Pierce optics to get a beam with minimal transverse momentum spread
Resonant behavior of the electron beam

The resulting momentum spread depends on the configuration of the electrical fields and the guiding magnetic field.

![Graph showing the relationship between the electron beam's momentum spread and the magnetic field strength](image)

- For different magnetic field strengths (700 G, 800 G, 900 G, 1000 G), the electron beam's momentum spread is shown as a function of the z-coordinate.
- The graph illustrates how the momentum spread changes with varying magnetic field strengths and z-coordinates.
A convex cathode has a larger emissive surface and higher electrical field strength due to its curvature, therefore its perveance is higher.

In case of a gun with a flat cathode, the momentum spread can be diminished using an electrostatic lens, while a gun with a convex cathode has a more complex velocities distribution.
Comparison of the two electron guns

Varying beam current density (B = 900 G)

- Flat cathode
  - $U_A = 20 \text{ kV}, U_C = 2.5 \text{ kV}$
  - $U_A = 15 \text{ kV}, U_C = 1.3 \text{ kV}$
  - $U_A = 10 \text{ kV}, U_C = 4 \text{ kV}$
  - $U_A = 10 \text{ kV}, U_C = 2 \text{ kV}$

- Convex cathode
  - $U_A = 11 \text{ kV}, U_C = -3 \text{ kV}$
  - $U_A = 18 \text{ kV}, U_C = -2.5 \text{ kV}$
  - $U_A = 11 \text{ kV}, U_C = -3 \text{ kV}$

Flat beam
Hollow beam
Thin beam
Electron beam bending

Ions caught into acceleration tube can hit the cathode and damage it.

To ensure the safety of the cathode, the gun is shifted from the axis of the acceleration tube.

We use magnetic bending to hide the cathode from the line of incident ions.

Additional corrector magnet is used to compensate the electrons drift in the magnetic bend.

Bullet points:
- Gun
- Corrector magnet
- Electrostatic lens
- B_{LONG}
- e^{-}
- i^{+}

Explanation:
- The electron beam is bent using magnetic fields.
- The gun is shifted to prevent ions from hitting the cathode.
- An additional corrector magnet is used to compensate for electron drift.

Text:
- To ensure the safety of the cathode, the gun is shifted from the axis of the acceleration tube.
- We use magnetic bending to hide the cathode from the line of incident ions.
- Additional corrector magnet is used to compensate the electrons drift in the magnetic bend.

Diagram details:
- Gun
- Corrector magnet
- Electrostatic lens
- B_{LONG}
- e^{-}
- i^{+}
Electron beam bending

Using test particles to estimate the beam momentum spread after the magnetic bending

\[ V_x, \text{cm/s} \cdot 10^8 \]

\[ V_Z, \text{cm/s} \cdot 10^7 \]

Angle between the force lines and the acceleration tube axis

\[ E_{\perp}^{\text{in}} \approx 0 \text{ eV} \]
\[ E_{\perp}^{\text{out}} \approx 0.04 \text{eV} \]

Разработка электронной пушки для электронного охладителя коллайдера NICA
The lens can suppress oscillations with energy up to 1.5 eV.

The lens force is slightly non-linear with the radial coordinate.
Thank you for your attention!