Application of cooling methods at NICA project

G.Trubnikov
JINR, Dubna
1. NICA scheme, modes of operation, working cycles;

2. Booster scheme, parameters, beam requirements;

3. Status of the electron cooler for booster;

4. Collider scheme, parameters, beam requirements;

5. Beam cooling scenario at the collider: numerical simulations, choice of energy range for optimal operation of beam cooling systems to provide required luminosity life-time for the experiment;

6. Conceptual design of the stochastic cooling system for collider;

7. Conceptual design of the HV electron cooler for collider;

8. Experiment on stochastic cooling at Nuclotron in the NICA energies
NICA complex

Electron cooling

Stochastic cooling

HV electron cooling

G. Trubnikov, COOL-2011, Alushta, Ukraine
Booster synchrotron

G.Trubnikov, COOL-2011, Alushta, Ukraine
### Booster electron cooling system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Booster electron cooling system</td>
<td></td>
</tr>
<tr>
<td>Ions</td>
<td>$^{197}$Au$^{31+}$ (65+)</td>
</tr>
<tr>
<td>Booster circumference, m</td>
<td>211.2</td>
</tr>
<tr>
<td>Injection/extraction energy, MeV/u</td>
<td>3/600</td>
</tr>
<tr>
<td>Max. dipole field, T</td>
<td>1.8</td>
</tr>
<tr>
<td>Ion number</td>
<td>$2 \times 10^9$</td>
</tr>
<tr>
<td>Beta functions in cooling section, m</td>
<td>8 / 8</td>
</tr>
<tr>
<td>Dispersion in cooling section, m</td>
<td>0.6</td>
</tr>
<tr>
<td>Maximum electron energy, keV</td>
<td>50.0</td>
</tr>
<tr>
<td>Electron beam current, A</td>
<td>0 ÷ 1.0</td>
</tr>
<tr>
<td>Cooler overall length, m</td>
<td>4.0</td>
</tr>
<tr>
<td>Eff. length of the cooling section, m</td>
<td>2.5</td>
</tr>
<tr>
<td>Magnetic field in the e-cooler, kG</td>
<td>1.5</td>
</tr>
<tr>
<td>Magnetic field inhomogeneity in the cooling section, $\Delta B/B$</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>Electron beam radius, cm</td>
<td>2.5</td>
</tr>
<tr>
<td>Transverse electron temperature, meV</td>
<td>200</td>
</tr>
<tr>
<td>Longitudinal electron temperature, meV</td>
<td>0.5</td>
</tr>
<tr>
<td>Cooling time, s</td>
<td>1</td>
</tr>
<tr>
<td>Residual gas pressure, Torr</td>
<td>$10^{-11}$</td>
</tr>
</tbody>
</table>

**Poster session: A. Rudakov**

G. Trubnikov, COOL-2011, Alushta, Ukraine
Simulation of cooling process with BETACOOL

Evolution of the bunched ion beam parameters during the cooling process

The dependence of the cooling time and transverse emittance after cooling process on misalignment angle between electron and ion beams axes

Initial parameters of the cooling

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion energy, MeV</td>
<td>100</td>
</tr>
<tr>
<td>Ion kind</td>
<td>$^{197}\text{Au}^{31+}$</td>
</tr>
<tr>
<td>Particle number</td>
<td>$2 \times 10^9$</td>
</tr>
<tr>
<td>Initial Tr_emittance, $\pi$ mm mrad</td>
<td>1.5</td>
</tr>
<tr>
<td>Initial momentum spread</td>
<td>$5 \times 10^{-4}$</td>
</tr>
<tr>
<td>RF voltage, kV</td>
<td>10</td>
</tr>
<tr>
<td>Initial bunch length, m</td>
<td>14</td>
</tr>
<tr>
<td>Electron beam current, A</td>
<td>1.0</td>
</tr>
<tr>
<td>Electron beam temp. long/trans, meV</td>
<td>200 / 0.5</td>
</tr>
<tr>
<td>Misalignment of ion and electron beams axes</td>
<td>$5 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Poster session: A.Rudakov

G.Trubnikov, COOL-2011, Alushta, Ukraine
NICA collider
Lattice choice

<table>
<thead>
<tr>
<th>Optics</th>
<th>Ring circumference, m</th>
<th>$E_{\text{t}}$, GeV/u ($\gamma_{\text{t}}$)</th>
<th>Slip-factor, $\eta$ at 4.5 GeV/u</th>
<th>VRF-max, kV</th>
<th>Number of the dipoles in the ring</th>
<th>Length of the dipole magnet, m</th>
<th>$T_{\text{IBS,s}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FODO-12 cells</td>
<td>497</td>
<td>5.68 (7.05)</td>
<td>0.010</td>
<td>804</td>
<td>80</td>
<td>1.94</td>
<td>1240</td>
</tr>
<tr>
<td>FODO-11 cells</td>
<td>489</td>
<td>5.10 (6.43)</td>
<td>0.006</td>
<td>702</td>
<td>72</td>
<td>2.16</td>
<td>1110</td>
</tr>
<tr>
<td>FODO-10 cells</td>
<td>503</td>
<td>4.54 (5.89)</td>
<td>0.0006</td>
<td>666</td>
<td>96</td>
<td>1.62</td>
<td>980</td>
</tr>
<tr>
<td>Triplets 8 cells</td>
<td>529</td>
<td>4.66 (5.96)</td>
<td>0.002</td>
<td>720</td>
<td>84</td>
<td>1.85</td>
<td>1200</td>
</tr>
<tr>
<td>Triplets 10 cells</td>
<td>576</td>
<td>6.16 (7.56)</td>
<td>0.012</td>
<td>995</td>
<td>108</td>
<td>1.44</td>
<td>1610</td>
</tr>
</tbody>
</table>

Key issue: injection
Collider parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring circumference, m</td>
<td>503.04</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>23</td>
</tr>
<tr>
<td>Rms bunch length, m</td>
<td>0.6</td>
</tr>
<tr>
<td>Beta-function in the IP, m</td>
<td>0.35</td>
</tr>
<tr>
<td>Ring acceptance (FF lenses)</td>
<td>40π mm mrad</td>
</tr>
<tr>
<td>Long. acceptance, dp/p</td>
<td>±0.010</td>
</tr>
<tr>
<td>Gamma-transition, $\gamma_{tr}$</td>
<td>7.091</td>
</tr>
<tr>
<td>Ion energy, GeV/u</td>
<td>1.0, 3.0, 4.5</td>
</tr>
<tr>
<td>Ion number per bunch</td>
<td>2.75$\cdot$10$^8$, 2.4$\cdot$10$^9$, 2.2$\cdot$10$^9$</td>
</tr>
<tr>
<td>Rms momentum spread, 10$^{-3}$</td>
<td>0.6, 1.25, 1.65</td>
</tr>
<tr>
<td>Rms beam emittance, h/v, (unnormalized), π-mm-mrad</td>
<td>1.1, 1.1, 1.1</td>
</tr>
<tr>
<td>Luminosity, cm$^{-2}$s$^{-1}$</td>
<td>1.1e25, 1e27, 1e27</td>
</tr>
<tr>
<td>IBS growth time, sec</td>
<td>186, 702, 2540</td>
</tr>
</tbody>
</table>

Peak luminosity can be estimated as:

$$L = \frac{N_b^2}{4\pi\varepsilon\beta^*} F_{coll} f_{HG} \left( \frac{\sigma_s}{\beta^*} \right)$$

The collision repetition rate:

$$F_{coll} = \frac{\beta c}{l_{bb}}, \quad l_{bb} = \frac{C_{Ring}}{n_{bunch}}$$

Hour-glass effect ~ 1 (because in our case $\sigma_s << \beta$):

$$f_{HG} \left( \frac{\sigma_s}{\beta^*} \right) = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} \exp(-u^2)du \left[ 1 + \left( \frac{u\sigma_s}{\beta^*} \right)^2 \right]$$

Maximum luminosity is reached when the bunch phase volume corresponds to the ring acceptance.
Lattice requirements and limitations

To reach maximum peak luminosity one needs to meet the following evident requirements:
• minimum beta function in the IP;
• maximum collision repetition rate (that corresponds to bunch number in rings as maximum as possible);
• maximum bunch intensity;
• minimum beam emittance;
• minimum bunch length.

FF lenses aperture (radius) : 40mm

Proposed chromaticity correction scheme provides the transverse dynamic aperture of about 120 π-mm-mrad and dynamic aperture on the relative momentum deviation of about ±1%
**IBS calculations**

**Strategy:**
1. $\varepsilon_x = 1.1 \text{ pi mm mrad (due to } 6\sigma_x = 40)$
2. Equal heating rates of all degrees
3. $dP/P \sim (1-1.5)e^{-3}$ is acceptable
   (from bunch coherent stability condition)
4. $L \leq 1e27$

**Luminosity**

$$L \propto \beta^5 \gamma^6$$

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**“IBS dominated regime”:**

bunch parameters are determined by equilibrium between IBS and beam cooling.

$$L = 8\pi^2 \beta^5 \gamma^6 \Delta Q^2 \frac{A^2}{Z^4} \cdot \frac{\varepsilon c}{r_p \beta^* l_{bb}} \cdot \left(\frac{\sigma_s}{C_{Ring}}\right)^2 \cdot f_{HG}$$
Different regimes of operation

Conclusions: when Energy > 3 GeV/u we can allow $T_{\text{cool}} = T_{\text{ibs}}$.
when $E < 3$ GeV/u we need $T_{\text{cool}} \ll T_{\text{ibs}}$ (at least by one order)

IBS heating times at maximal luminosity for two arc optics.

When emittance and $dP/P$ are strongly bound (dependent) – IBS dominated regime
When emittance and $dP/P$ are independent – space charged (SC) dominated
At low energy range IBS DR we can increase Luminosity increasing emittance.
But as soon as $\varepsilon_x$ is limited by aperture FF lenses, we should increase beta-function at IP.
It can give additional 50% for Luminosity

\[ A \approx \frac{a^2}{\beta_{\text{max}}} \quad \beta_{\text{max}} \approx \beta^* + \frac{l_{tr}^2}{\beta^*} \]

\[ L \sim \frac{\varepsilon}{\beta^*} \cdot f_{HG} \left( \frac{\sigma_s}{\beta^*} \right) \sim \frac{a^2}{\left( \beta^* + \frac{l_{tr}^2}{\beta^*} \right) \beta^*} f_{HG} \]
Stochastic cooling

\[
\frac{1}{\tau} = \frac{W}{N} \left(1 - \frac{1}{M_{pk}^2}\right)^2 \quad N_{eq} = N \frac{C}{\sqrt{2\pi}\sigma_e} \quad M_{pk} = \frac{1}{2(f_{\text{max}} + f_{\text{min}})\eta_{pk} T_{pk} \frac{\Delta\rho}{p}} \quad f_{\text{max}} \leq \frac{1}{2\eta_{pk} T_{pk} \frac{\Delta\rho}{p}} \quad M_{kp} = \frac{1}{2(f_{\text{max}} - f_{\text{min}})\eta_{kp} T_{kp} \frac{\Delta\rho}{p}}
\]

At such position of the kicker the condition gives for the acceptable upper frequency of the band the value of about 20 GHz (at the momentum spread equal to the ring dynamic aperture ±0.01). The luminosity of \(1 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}\) corresponds to about \(2.3 \times 10^9\) ions per bunch, the effective ion number is about \(8 \times 10^{11}\). To provide required cooling time the cooling bandwidth can be chosen from 3 to 6 GHz.

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Kicker - 48 meters upstream the IP-point
PU - 132 meters upstream the Kicker
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Total and partial slip-factors of the ring as the function of ion energy.

"Slice" overlapping (by D.Moehl)

3..6 GHz: Tsc≈0.5Tibs
2..4 GHz: Tsc≈Tibs
Beam emittances @ equilibrium state. Rates ($\tau_\varepsilon_x=\tau_\varepsilon_y=\tau_\sigma_P$) - from IBS calculations for lattice.

Luminosity is fitted to $1e27$, $\varepsilon_x$ is fitted to $1.1 \pi$ mm mrad

$$\vec{F} = -\vec{V} \frac{4Z^2 e^4 n_e L_p}{m} \left( \frac{1}{V^2 + \Delta_{e,\text{eff}}^2} \right)^{3/2}$$

$$L_p = \ln \left( \frac{\rho_{\text{max}} + \rho_{\text{min}} + \rho_\perp}{\rho_{\text{min}} + \rho_\perp} \right)$$

$$\rho_{\text{max}} = \frac{v_i}{1/\tau_{\text{flight}} + \omega_p}$$

$$\rho_{\text{min}} = \frac{Ze^2}{m} \frac{1}{V^2 + \Delta_{e,\text{eff}}^2}$$

$$\Delta_{e,\text{eff}} = 0.0046 \text{ eV}$$

Angular spread [rad] = 2e-5

Parkhomchuk model. $\beta_x = \beta_y \approx 20$ m @ cooling section, L = 6 m, B=1T (required mainly to provide adiabatic transport of the electron beam from HV source to the cooling section), I_{electron} = 0.5 A. T_{tr_e} - chosen at all energies to the value in order to have $\tau_{\text{life}}$ (due_to_recombination)$\geq$10 hours (36000 seconds: recombination rate limit = 2.7E-5.

Radius_{electron_beam} chosen to have T_{ecool} = min (same at all energies)

The cooling rate is determined mainly by longitudinal electron temperature (that is dominated by HV generator stability) and logarithmically depends on the transverse one
Electron cooling

Dependence of the cooling times for transverse and longitudinal degrees of freedom

Recombination suppression:
- a) Increasing $T_{tr\_e}$
- b) "Shift" of electron energy
  (Talk A. Philippov)

Conclusions: $T_{ecool} \sim 0.05$ Tibs at 1 GeV/u
HV electron cooling system
HV electron cooling system

Electron beam energy, MeV | 0,5 ÷ 2,5
Collector potential vs to cathode, kV | 0,5 ÷ 2,0
Electron beam current | 0,1 ÷ 1,0
Electron beam current losses, mA | < 0,1
Radiated power from cathodes, W | 2×100
Max. radiated power at collectors, kW | 2×2
Electron cathode diameter, cm | 3,0
Long. Magnetic field, T | 0,1 ÷ 2,0
Electron energy stability | 1×10⁻⁴

Poster session: S.Yakovenko
Circumference, m 251.5
Ions up to A=56
Energy, GeV 3.5
Rev.frequency, MHz 1.2
Vacuum, Torr 10^-10
Intensity 10^11(p)-10^9(C12)
Ring slippage factor 0.0322
dp/p 10^-3
Simulations of stochastic cooling

Expected evolution of particle distribution function and rms value of \( dP/P \) for protons.

Expected evolution of particle distribution function and rms value of \( dP/P \) for carbon ions (C6+).
We plan to assemble and TEST stochastic cooling system prototype at Nuclotron in the end of 2011 (depends on electronics delivery)
Thank you for your attention!

Many thanks to my colleagues for fruitful discussions and unvaluable help:
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