Application of cooling methods at NICA project

G.Trubnikov on behalf of team

RUPAC-12 conference
St.Petersburg, 25 September 2012
NICA complex

Electron cooling

Stochastic cooling

HV electron cooling
Booster synchrotron

**Injector**
3MeV/nucleon
Au^{31+} RFQ

4 large straight sections
1. Injection
2. Two RF-cavity
3. One turn extraction
4. E-cooler
Booster electron cooling system

Ions

197Au^{31+ (65+)}

Booster circumference, m

211.2

Injection/extraction energy, MeV/u

3/600

Max. dipole field, T

1.8

Ion number

2 × 10^9

Beta functions in cooling section, m

10-6 / 6-10

Dispersion in cooling section, m

0.6

Maximum electron energy, keV

50.0

Electron beam current, A

0 ÷ 1.0

Cooler overall length, m

5.7

Eff. length of the cooling section, m

2.5

Magnetic field in the e-cooler, kG

1.5

Magnetic field inhomogeneity in the cooling section, ΔB/B

1 × 10^{-4}

Electron beam radius, cm

2.5

Trans.electron temperature, meV

200

Long. electron temperature, meV

0.5

Cooling time, s (I_e=0.05A)

0.4

Residual gas pressure, Torr

10^{-11}

Zero dispersion in the large stright section
Simulation of cooling process with BETACOOL

Evolution of the bunched ion beam parameters during the cooling process (Ion energy = 3 MeV/u).

Initial parameters of the cooling

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion energy, MeV</td>
<td>3</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, $\pi \text{ mm mrad}$ (rms)</td>
<td>1.5</td>
</tr>
<tr>
<td>Initial momentum spread</td>
<td>$1 \times 10^{-3}$</td>
</tr>
<tr>
<td>RF voltage, kV</td>
<td>10</td>
</tr>
<tr>
<td>Electron beam current, A</td>
<td>0.05</td>
</tr>
<tr>
<td>Electron beam temp. long/trans, meV</td>
<td>200 / 0.5</td>
</tr>
</tbody>
</table>

Horizontal and vertical emittances

Phase space diagrams

ion momentum spread
Transverse emittance evolution in the collider injection chain

From HILac $6\sigma \leq 10 \pi\cdot\text{mm}\cdot\text{mrad}$ (upper limit for vertical emittance)

Horizontal Booster acceptance $\sim 120 \pi\cdot\text{mm}\cdot\text{mrad}$
(upper limit for the horizontal $6\sigma$ emittance in the case of multturn injection)

In Booster: Kinematic decrease + Electron cooling (if necessary)

At 65 MeV/u rms $\varepsilon_h \leq 4.21 \pi\cdot\text{mm}\cdot\text{mrad}$ $\varepsilon_v \leq 0.35 \pi\cdot\text{mm}\cdot\text{mrad}$

At 600 MeV/u (without cooling) rms $\varepsilon_h \leq 1.23 \pi\cdot\text{mm}\cdot\text{mrad}$ $\varepsilon_v \leq 0.102 \pi\cdot\text{mm}\cdot\text{mrad}$

Increase in transfer line from Booster to Nuclotron:
- Stripper
- Coupling
- Mismatch

If $\varepsilon_h >> \varepsilon_v$, $\varepsilon_h \sim$ constant, $\varepsilon_v$ increases by about 3 times

At injection into Nuclotron rms $\varepsilon_h \leq 1.23 \pi\cdot\text{mm}\cdot\text{mrad}$ $\varepsilon_v \leq 0.3 \pi\cdot\text{mm}\cdot\text{mrad}$
NICA collider
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>$40\pi$ mm mrad</td>
</tr>
<tr>
<td>Long. acceptance, dp/p</td>
<td>$\pm 0.010$</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>$2.75\cdot10^8$, $2.4\cdot10^9$, $2.2\cdot10^9$</td>
</tr>
<tr>
<td>Rms momentum spread, $10^{-3}$</td>
<td>0.62, 1.25, 1.65</td>
</tr>
<tr>
<td>Rms beam emittance, h/v, (unnormalized), $\pi$-mm-mrad</td>
<td>1.1/1.01, 1.1/0.89, 1.1/0.76</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:

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

The collision repetition rate:

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

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

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

Maximum luminosity is reached when the bunch phase volume corresponds to the ring acceptance.
Collider parameters

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.

Proposed chromaticity correction scheme provides the transverse dynamic aperture of about 120 \( \pi \cdot \text{mm} \cdot \text{mrad} \) and dynamic aperture on the relative momentum deviation of about ±1%.

Hour-glass effect is reached when the bunch phase volume corresponds to the ring acceptance

\[
L = \frac{N_b^2}{4\pi\varepsilon\beta^*} F_{\text{coll}} \int_{\text{HG}} \left( \frac{\sigma_s}{\beta^*} \right)
\]

\[
C_{\text{Ring}} = \frac{\beta c}{l_{bb}} \frac{n_{\text{bunch}}}{F}
\]

\[
\int_{\text{HG}} \left( \frac{\sigma_s}{\beta^*} \right) = \frac{1}{\sqrt{\pi}} \int_0^\infty \exp(-u^2)du
\]

\[
1 + \left( u\sigma_s \right)^2 \left( \frac{\beta^*}{\beta} \right)^2
\]

FF lenses aperture (radius): 40mm

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The problems we have met and the solutions

<table>
<thead>
<tr>
<th>The problems:</th>
<th>The solutions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓ Beam space charge effects</td>
<td>✓ Electron cooling application</td>
</tr>
<tr>
<td>✓ Beam-beam effects</td>
<td>✓ Stochastic cooling application</td>
</tr>
<tr>
<td>✓ IntraBeam scattering (IBS) [\Rightarrow] luminosity degradation</td>
<td>✓ Beam parameters choice</td>
</tr>
<tr>
<td>✓ Recombination in e-cooler</td>
<td>✓ Operation scenario optimisation</td>
</tr>
<tr>
<td>✓ Bunch halo formation [\Rightarrow] parasitic collisions, background growth</td>
<td>✓ Scrappers and collimators</td>
</tr>
</tbody>
</table>
Role of beam cooling

1. Beam stacking using BB system:
   Injection repetition is 10 sec, the cooling times has to be short enough

2. Longitudinal cooling during beam bunching

3. During experiment:
   - in IBS dominated mode - Suppression of IBS;
   - in SC dominated mode – providing optimum phase volume

MAC meeting Dubna June 2012
Beam stacking with BB system and cooling

E > 3 GeV/u:
stacking with Stochastic cooling
The cooling time is proportional to the bunching factor
for “almost” coasting beam in BB the cooling times ~ 10 sec
(T.Katayama previous MAC)

E < 3 GeV/u:
Stacking with Electron cooling
Problem – cooling time strongly depends on energy
and does not depend on bunching factor

The cooling power sufficient for experiment can be insufficient for effective stacking
T. Katayama, October 2011, 3.5 GeV/u

Beam stacking with electron cooling

Stacking efficiency (A. Smirnov)

E = 1.5 GeV/u
Stacking efficiency 86%

E_Init = 1π-mm-mrad

Distribution over momentum

E = 1.5 GeV/u

E = 2.5 GeV/u

E = 3.5 GeV/u
Stacking with electron cooling and beam bunching

Effective stacking can be realized below ~ 2 GeV/u
Possible solution:
- Stacking at 1 GeV/u with efficiency closed to 100%
- Slow acceleration to the experiment energy

At constant longitudinal emittance ($\sigma_p \times \sigma_s = \text{const}$) minimum threshold current of microwave instability corresponds to coasting beam

$$I_{th} \sim \sigma_p^2$$

the momentum spread is inversely proportional to bunching factor

**Formation of required long emittance by a few steps:**
- At storage of coasting beam formation $\sigma_p$ required for the stability
  (long emit. is larger than required at collisions by about bunching factor $\sim 13$)

- Bunching at 24 harmonics + cooling of long emittance by about 6 times,
  Formation of the bunch of about 1.2 m, required to recapture in $h=72$

- Bunching + cooling at $h = 72$,
  formation of required bunch length and momentum spread
IBS calculations

**Strategy:**
1. $\varepsilon_x = 1.1$ 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**

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

"IBS dominated regime": bunch parameters are determined by equilibrium between IBS and beam cooling.

$dQ > 0.05$ (max @ 1 GeV/u: 0.471)
IBS calculations

Strategy:
1. $\epsilon_x = 1.1 \, \text{pi mm mrad (due to } 6\sigma_x = 40)\)
2. Equal heating rates of all degrees
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4. $L \leq 1e27$

"IBS dominated regime":
bunch parameters are determined by equilibrium between IBS and beam cooling.

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

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

When emittance and $dP/P$ are strongly bound (dependent) – IBS dominated regime

When emittance and $dP/P$ are independent – space charged (SC) dominated

$dQ \leq 0.05$
Stochastic cooling

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

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 1-10^{27} cm^{-2}s^{-1} corresponds to about 2.3\cdot10^9 ions per bunch, the effective ion number is about 8\cdot10^{11}. To provide required cooling time the cooling bandwidth can be chosen from 3 to 6 GHz.

"Slice" overlapping (by D.Moehl)

3..6 GHz: Tsc ~ 0.5Tibs

2..4 GHz: Tsc ~ Tibs
Beam emittances @ equillibrium state. Rates (τ _ε_\_x=τ _ε_\_y = τ _σ_P ) - from IBS calculations for lattice.
Luminosity is fitted to 1e27, ε_x is fitted to 1.1 π mm mrad

\[
\rho = -\sqrt{N} \frac{4Z^2e^4n_e L_p}{m} \frac{1}{(V^2 + \Delta^2_{e,\text{eff}})^{3/2}}
\]

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

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

\[
\rho_{\text{min}} = \frac{Ze^2}{m} \frac{1}{V^2 + \Delta^2_{e,\text{eff}}}
\]

\[
\Delta_{e,\text{eff}} = 0.0046 \text{ eV}
\]

Angular spread [rad] = 2e-5

Parkhomchuk model. \( \beta_x = \beta_y \approx 20m @ cooling section, L = 6m, B=1T \)
(required mainly to provide adiabatic transport of the electron beam from HV source to the cooling section), \( I_{\text{electron}} = 0.5A. \) \( T_{\text{tr}_e} \) - chosen at all energies to the value in order to have \( \tau_{\text{life}} \) (due_to_recombination)\( >=10 \) hours (36000 seconds: recombination rate limit = 2,7E-5.
Radius_electron_beam chosen to have \( T_{\text{ecool}} = \text{min} \) (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 $T_{\text{tr\_e}}$
- b) “Shift” of electron energy

Conclusions: $T_{\text{ecool}} \sim 0.05$ Tibs at 1 GeV/u
Summary final

The graph shows the relationship between time and energy for different cooling scenarios: IBS DR and SC DR. The time is plotted on a logarithmic scale, and the energy is plotted on a linear scale. The curves indicate how the time required for cooling varies with energy for each scenario.

- **IBS DR**: The red line represents the time required for IBS DR cooling. The time increases significantly with energy.
- **SC DR**: The blue line represents the time required for SC DR cooling. The time also increases with energy, but at a slower rate compared to IBS DR.

The graph includes additional lines for specific conditions and scenarios, such as:

- **T_ibs@dQ<=0.05 & L=1E2**
- **T_ecool_tr**
- **T_ecool_long**
- **T_stoch_Mohl**

These conditions are likely related to different cooling strategies or parameters that affect the time-to-energy relationship.
HV electron cooling system
HV electron cooling system

Electron beam energy, MeV | 0.5 ÷ 2.5
Collector potential vs 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. rad. 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

HV Generator prototype U=250 kV, I=1 mA

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SC experiment at Nuclotron

Circumference, m 251.5
Ions up to $A=56$
Energy, GeV 3.5
Rev. frequency, MHz 1.2
Vacuum, Torr $10^{-10}$
Intensity $10^{11}(p)$-$10^9(C_{12})$
Ring slippage factor 0.0322
dp/p $10^{-3}$

NICA

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Nuclotron-NICA
Stochastic cooling system prototype at Nuclotron

Slot-coupler structures, manufactured at IKP FZJ

Vacuum chamber for pick-up

Vacuum chamber for kicker

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Experimental set-up:

- Ring slot coupler, 16 rings (produced in COSY)
- Kicker side (filter and other electronics are in the box)
- PU in cryostat with preamps and combine

45-й сеанс
1000 сек
1.2 Тл
d 5 \times 10^9
Experimental results:

Schottky noise measurements

Notch filter rejects revolution frequencies

Energy range 0.5-4.0 GeV/u
Deutrons, C6+
During 2 runs in 2011 and 2012

Beam BTF d, 2 GeV/u
Conclusions

1. Electron cooling at Booster is required to have wide machine possibilities at beam injection from HILAC and to perform applied research

2. Stochastic cooling at NICA collider is sufficient for IBS suppression and for beam stacking also

3. Electron cooling can be used for cooling at experiment in the total energy range

4. Electron cooling can provide effective stacking at small energy only

5. At energy larger than 3 GeV/u the experiment can be provided using electron cooling as well as stochastic, or combination of both methods

5. At energy below 3 GeV/u the experiment is provided using electron cooling. Possibility to increase of luminosity at minimum energy is related with space charge dominated mode

6. Slow acceleration of the beam is presumed for the case when effective stacking (or injection) is complicated at the experiment energy
Thank you for your attention!

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