Electron Cooling at the Relativistic Heavy Ion Collider

Ilan Ben-Zvi
Collider-Accelerator Department
Instrumentation Division and IEEE LI/NY NPSS seminar
## RHIC II luminosities

<table>
<thead>
<tr>
<th>Parameter</th>
<th>unit</th>
<th>Enhanced design</th>
<th>RHIC II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Au-Au operation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>GeV/n</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>No of bunches</td>
<td>...</td>
<td>111</td>
<td>111</td>
</tr>
<tr>
<td>Bunch intensity</td>
<td>$10^9$</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Average $\mathcal{L}$</strong></td>
<td>$10^{26}$cm$^{-2}$s$^{-1}$</td>
<td>8</td>
<td>70</td>
</tr>
<tr>
<td><strong>p↑- p↑ operation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>GeV</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>No of bunches</td>
<td>...</td>
<td>111</td>
<td>111</td>
</tr>
<tr>
<td>Bunch intensity</td>
<td>$10^{11}$</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Average $\mathcal{L}$</strong></td>
<td>$10^{30}$cm$^{-2}$s$^{-1}$</td>
<td>150</td>
<td>500</td>
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<tr>
<td><strong>Polarization $P$</strong></td>
<td>%</td>
<td>70</td>
<td>70</td>
</tr>
</tbody>
</table>

Courtesy Wolfram Fischer

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**Office of Science**
U.S. DEPARTMENT OF ENERGY

**RHIC**

**Brookhaven National Laboratory**
What is Luminosity?

A rate of collisions for a given cross sectional area ("target size").

\[
\text{Luminosity} = \frac{(\text{Number of ions per bunch})^2 \times \text{Collision frequency}}{\text{Area}}
\]
Luminosity and Temperature

• Luminosity is inversely proportional to the size of the beams.
• The size of the beams is related to their temperature.
• A cooler beam is smaller (intuitive).
• Hence the desire to cool the beams.
What is the ion’s temperature?

- The average gold ion kinetic energy in RHIC is about 20,000,000 MeV.
- The temperature (random motion) for gold ions in RHIC is about 0.8 MeV, or about $10^{10}$ degrees.
- We cannot prepare the ion beams to be much colder (and they heat up in the accelerator – see next).
- We must make the electrons much colder, and even this is not easy.
Intra-Beam Scattering (IBS)

- IBS heats the ion beam in the storage ring.
- The heat flow comes from ion collisions and their interaction with the accelerator’s fields.
- IBS leads to luminosity decline through an increase in the ion temperature and particle loss.
- IBS can be opposed only by cooling.
Intra-Beam Scattering

Ions in the storage ring are confined by guiding Fields, bending and focusing.

Due to relativistic effects, in the beam reference frame they move much more transversely than longitudinally, by a factor of $\gamma$.

The ions collide with each other, leading to accumulation of longitudinal random energy. The longitudinal motion couples to the transverse motion through dispersion.
The Solution: Electron Cooling

- Cold electron beam is merged with ion beam.
- Heat is transferred from hot ions to cold electrons.
- Electron beam is renewed.
- The ions are cooled repeatedly.
Ion-electron collisions

Two charged particles interact by Rutherford scattering. The moving particle loses energy.
Problem: Catch up with the train…

The ions are moving around the RHIC ring at an enormous speed.

In order to allow the electrons to cool the ions, they must be moving at the same speed.

The cooling takes place “on the train”, where the ions and electrons experience only their relative motion.
Cooling time

\[ \text{Cooling time} \propto \left( \frac{\gamma \varepsilon_n}{\beta^c} \right)^{3/2} \frac{\beta^c}{I} \frac{\text{Mass}}{\text{Charge}} e^2 \gamma^2 \frac{\text{Circumference}}{\text{Cooler length}} \]

\( \theta \) is the ions angular spread, \( I \) is the electron current.

\( \gamma = \frac{\text{Energy}}{\text{Rest mass}} \)

\( \gamma \) enters in part due to special relativity: Time dilation of the cooling time and Lorentz contraction of the electron charge density. Other part is from ion velocity.

The expected cooling time is about ½ an hour.

In this time, the ions circumnavigate RHIC 150 million times.
Classical Electron Cooling Setup

G. I. Budker, the inventor of electron cooling.

Electron gun

Solenoid magnets for guiding electrons

Electron dump

Ion beam in

First electron cooler: NAP-M, 1974
68 MeV protons
35 keV electrons

Ion beam out

Typical voltage: 100kV to 300 kV.
Electrons are guided by solenoid magnetic fields.
Beams are continuous streams, not bunched.
Need for New Technologies

• To match speed with the RHIC beam, the electron energy must be 54 MeV, about 10 times higher than any existing cooler.
• The electron beam needs to be “cold” (low emittance), and at a high current (0.1 A). That requires a special source.
R&D issues

• Understanding the cooling physics in a new regime to reduce uncertainty
  – cooling dynamics simulations with some precision
    • IBS, recombination, disintegration
    • benchmarking experiments
    • stability issues

• Developing a high current, energetic, low emittance electron beam
  – Photoinjector (gun, cathode, laser…) 5 nC, 3μm
  – Energy Recovery Linac, x5 of state-of-the-art current
    • Preservation of high-charge, low emittance beam
    • Wakes, CSR, space-charge
IBS in RHIC – measurements (noisy curves) vs. theory (smooth curves) Example of 2005 data with Cu ions. Simulations – Martini’s model of IBS for exact designed lattice of RHIC, including derivatives of the lattice functions.

Growth of 95% normalized emittance $[\mu m]$ for bunch with intensity $N=2.9 \cdot 10^9$

FWHM [ns] bunch length growth for intensities $N=2.9 \cdot 10^9$ and $1.4 \cdot 10^9$

Courtesy Alexei Fedotov
The cooling “friction” force and dynamics of cooling

\[ F = -\frac{4\pi m_e e^4 Z^2}{m} \int L \frac{\vec{V}_i - \vec{V}_e}{|\vec{V}_i - \vec{V}_e|} f(v_e) d^3v_e \]

BETACOOL (JINR, Dubna) and VORPAL (Tech-X, Colorado)

Formula integration in BETACOOL compared with VORPAL simulation from first principles.

rms electron velocities

\[ \Delta|| = 1.0\text{e}5 \text{ m/s} \]
\[ \Delta\perp = 4.2\text{e}5 \text{ m/s} \]

Courtesy Alexei Fedotov
Experimental benchmarking: using Recycler (FNAL) E-cooling

FNAL uses classical electron cooling (the weak solenoid is used practically only for guiding the electron beam)

FNAL e-cooling allows us to:
1. Benchmark the models for the friction force
2. Study evolution of ion distribution under cooling

Presently the highest energy cooler (~4.5 MeV electrons). Closest example to RHIC cooler.
Benchmarking at FNAL, longitudinal

V [m/s] (PRF)

F[eV/m]

Courtesy Alexei Fedotov
Hardware development

- Photocathodes, including diamond amplified photocathodes
- Superconducting RF gun
- Energy Recovery Linac (ERL) cavity
- New optical elements (merger)
- Full ERL demonstration
Energy Recovery in a Linac

Energy recovery is possible also in a linac. The microwave cavity of the linac acts like a flywheel, storing energy in its electromagnetic field. This energy is borrowed and then returned by the beam, depending on its time of arrival at the cavity.

Beam gaining energy from cavity

Beam returning energy to cavity
Ampere SRF ERL cavity

“Single mode”:
All HOMs damped.
Multi ampere rating.

Courtesy Andrew Burrill
Ampere superconducting RF gun
Measured gain of a diamond amplifier

Courtesy Xiangyun Chang
Some of the installed equipment
Optimization, laser shaping (5 nC)

Courtesy Jorg Kewisch
E-cooler: 2 passes ERL layout

1. SRF Gun,
2. Injection merger line
3. SRF Linac two 5-cell cavities and 3$^{rd}$ harmonic cavity
4, 4’. 180° achromatic turns
5, 6. Transport lines to and from RHIC,
7. Ejection line and beam dump
8. Short-cut for independent run of the ERL.

54 MeV, 5 nC at 9.4 MHz. RF 703.75 MHz. Gun 5 MeV
Gold luminosity in RHIC II

Average luminosity (with cooling) over the run $8.5 \times 10^{27}$

BETACOOL simulation Alexei Fedotov
Technically Driven Schedule

- CD – 0: Approve Mission Need – 3QFY2007
- CD – 2a: Approve Long Lead Procurement – 3QFY2008
- CD – 2b: Approve Performance Baseline – 3QFY2009
- CD – 3a: Start of Long Lead Procurements – 3QFY2009
- CD – 3b: Approve Start of Construction – 4QFY2009
- CD – 4: Approve Start of Operations – 4QFY2013
## Schedule of Project Costs

(dollars in thousands)

<table>
<thead>
<tr>
<th>Prior Years</th>
<th>FY 2008</th>
<th>FY 2009</th>
<th>FY 2010</th>
<th>FY 2011</th>
<th>FY 2012</th>
<th>Outyears</th>
<th>Total</th>
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<tbody>
<tr>
<td>TEC(Design)</td>
<td>0</td>
<td>7,500</td>
<td>10,500</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>TEC (Construction)</td>
<td>0</td>
<td>0</td>
<td>500</td>
<td>24,250</td>
<td>27,250</td>
<td>12,250</td>
<td>7,750</td>
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<tr>
<td>OPC Other than D&amp;D</td>
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<td>2,000</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3,000</td>
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<tr>
<td>Offsetting D&amp;D Costs</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td><strong>Total, Project Costs</strong></td>
<td><strong>0</strong></td>
<td><strong>2,000</strong></td>
<td><strong>8,000</strong></td>
<td><strong>34,750</strong></td>
<td><strong>27,250</strong></td>
<td><strong>12,250</strong></td>
<td><strong>10,750</strong></td>
</tr>
</tbody>
</table>
Other applications of high-brightness, high-power e beams

- ERL Light-sources
- Megawatt FELs
- eRHIC
- Compton X-ray sources
- Terahertz sources.
Conclusions

• Electron cooling will be the next major upgrade of RHIC.

• With electron cooling, an experiment (colliding gold on gold) of ten months running time will take just one month.

• The technology developed for cooling will benefit also future BNL facilities, such as a light source and electron ion collider.

• This is a very challenging and exciting area in accelerator science.

Many BNL’ers are working on this subject.
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• John Smedley

SM Division
• Animesh Jain

C-AD
• Thomas Roser

+ Many others…

Thank you!