(RHIC low energy operation)
RHIC II, and eRHIC

Wolfram Fischer
C-A Department

RHIC and AGS Annual User’s Meeting
22 June 2007
Outline

1. Status, Enhanced Design, EBIS

2. (Low energy operation) → covered by George Stephans, MIT

3. RHIC II → electron cooling

4. Other ideas → stochastic cooling, IR modifications, electron lenses

5. eRHIC
Relativistic Heavy Ion Collider

- 2 superconducting rings
- 3.8 km length
- operation since 2000
- 6 experiments so far

- only operating ion collider (up to gold 100 GeV/n)
- only operating polarized proton collider
RHIC running modes

- Au–Au  4.6, 10, 28, 31, 65, 100 GeV/nucleon
- d–Au   100 GeV/nucleon
- Cu–Cu  11, 31, 100 GeV/nucleon
- Polarized p–p  11, 31, 100, 205, 250 GeV

Some modes only for days – fast machine setup essential.
Delivered luminosity increased by >2 orders of magnitude in 7 years.

Delivered to PHENIX, one of RHIC’s high-luminosity experiments.

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Show nucleon-pair luminosity for ions: $\mathcal{L}_{NN}(t) = A_1 A_2 \mathcal{L}(t)$
(can compare different ion species, including protons)
Calendar time in store after setup

Setbacks in last 2 years
- set-up times decreased in Run-7 (~1 h/store)
- but failure hours increased significantly

Failures modes are under intense scrutiny

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### Enhanced Design Parameters (~2009)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>unit</th>
<th>Achieved</th>
<th>Enhanced design</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>103</td>
<td>111</td>
</tr>
<tr>
<td>Bunch intensity</td>
<td>$10^9$</td>
<td>1.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Average $\mathcal{L}$</td>
<td>$10^{26}$cm$^{-2}$s$^{-1}$</td>
<td>14</td>
<td>8</td>
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<tr>
<td><strong>p↑- p↑ operation</strong></td>
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<td></td>
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<tr>
<td>Energy</td>
<td>GeV</td>
<td>100</td>
<td>250</td>
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<tr>
<td>No of bunches</td>
<td>…</td>
<td>111</td>
<td>111</td>
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<tr>
<td>Bunch intensity</td>
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<tr>
<td>Average $\mathcal{L}$</td>
<td>$10^{30}$cm$^{-2}$s$^{-1}$</td>
<td>20</td>
<td>150</td>
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<tr>
<td>Polarization $\mathcal{P}$</td>
<td>%</td>
<td>60</td>
<td>70</td>
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</tbody>
</table>
Electron Beam Ion Source (EBIS)

- Current ion pre-injector: upgraded Model MP Tandem (electrostatic)
- Plan to replace with: Electron Beam Ion Source, RFQ, and short linac

→ Can avoid reliability upgrade of Tandem
→ Expect improved reliability at lower cost
→ New species: \( ^{235}\text{U} \), \( ^{3}\text{He} \)
→ Under construction

→ Expect commissioning to begin in 2009
Low energy Au-Au operation (1)

Demonstrated Au-Au collisions at $\sqrt{s} = 9.2$ GeV/nucleon

T. Satogata et al.

Luminosity not yet analyzed quantitatively.
Low energy Au-Au operation (2)

Event seen by the STAR detector.

Low energy operation in principle possible.
Luminosity of this year’s test (1/2 normal injection energy) not yet analyzed quantitatively.

→ Working on e-cooling in AGS for luminosity increase at even lower energies (down to 1/4 or normal injection).
## RHIC II – electron cooling (≥ 2013)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>unit</th>
<th>Enhanced design (achieved)</th>
<th>RHIC II</th>
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<tr>
<td><strong>Au-Au operation</strong></td>
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</tr>
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<td>...</td>
<td>111 (103)</td>
<td>111</td>
</tr>
<tr>
<td>Bunch intensity</td>
<td>$10^9$</td>
<td>1.0 (1.1)</td>
<td>1.0</td>
</tr>
<tr>
<td>Average $\mathcal{L}$</td>
<td>$10^{26}\text{cm}^{-2}\text{s}^{-1}$</td>
<td>8 (14)</td>
<td>70</td>
</tr>
<tr>
<td><strong>p$\uparrow$- p$\uparrow$ operation</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Energy</td>
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<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>
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<tr>
<td>Average $\mathcal{L}$</td>
<td>$10^{30}\text{cm}^{-2}\text{s}^{-1}$</td>
<td>150</td>
<td>400</td>
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<tr>
<td>Polarization $P$</td>
<td>%</td>
<td>70</td>
<td>70</td>
</tr>
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</table>
RHIC II – electron cooling (≥ 2013)

Hadron collider luminosities

- LHC p-p (design)
- RHIC p-p (design)
- RHIC p-p (design)
- RHIC a-A (design)
- RHIC a-A (design)
- LHC a-a (design)
- Tevatron II p-p
- RHIC Enhanced (design)
- eRHIC e↑p↑/A (design)

proton-proton (p-p) and proton-antiproton (p-\bar{p}) collisions
ion-ion collisions (A-A)
lepton-proton (e-p) and lepton-ion (e-A) collisions (e^- and e^+)
spin polarized beams
RHIC II – electron cooling ($\geq 2013$)

Use non-magnetized cooling (no solenoidal field)
(demonstrated with 8.9 GeV antiprotons in Fermilab Recycler – Nagaitsev et al.)

For 100 GeV/nucleon Au beams need:
• 54 MeV electron beam
• 5 nC per bunch
• rms emittance $< 4 \, \mu m$
• rms $\Delta p/p < 5 \times 10^{-4}$

$\rightarrow$ 2.7 MW beam power
$\rightarrow$ need Energy Recovery Linac (ERL)

Courtesy D. Kayran
RHIC II – electron cooling (≥ 2013)

Cooling section:
110m long, $\beta_{x,y} \approx 400m$
Electron beam first cools ions in Yellow ring, then the same beam cools ions in Blue ring of RHIC.
Simulated luminosities (A. Fedotov)

For:
- Beam-loss only from burn-off (luminosity)
- Constant emittance (cooling)

\[ \mathcal{L}(t) = \frac{\mathcal{L}(0)}{(1 + t / \tau)^2} \]

→ \( \tau \approx 5 \) h for Au-Au

Store length limited by burn-off
RHIC II – electron cooling (≥ 2013)

Bunch length with electron cooling

Can maintain 20 cm rms bunch length.

Shaping of longitudinal distribution is possible.
RHIC II – electron cooling (≥ 2013)

E-cooling system under development allows

• Cooling of all species at high bunch intensities (stochastic cooling slows down rapidly for $N_b > 10^9$)

• Cooling down to transition energy

• Pre-cooling of protons at lower energies (30 GeV) (to emittances corresponding to beam-beam limit $\xi_{\text{max}}$)

• Limited cooling of protons at 100 GeV
Other ideas: transverse stochastic cooling (HI)

Longitudinal stochastic cooling operational in Yellow.

→ 15-20% increase in delivered luminosity.
Expect same improvement with heavy ions in Blue.

M. Brennan
M. Blaskiewicz
Other ideas: transverse stochastic cooling (HI)

Transverse stochastic cooling appears also possible for heavy ions.

Calculations by M. Blaskiewicz

Frequency: 5-9 GHz
Cooling time: ~ 1 hour
Other ideas: lower $\beta^*$ (pp)

D. Trbojevic et al.

- Polarized proton luminosity not limited by burn-off $\rightarrow$ reduction in $\beta^*$ useful

- Some options:
  - Squeeze more with existing magnets
  - Quadrupole first IR
  - Slim magnets within detectors
Other ideas: lower $\beta^*$ (pp)

Recent test with Au beams (F. Pilat et al.)

$\beta^*$ lowered from 0.80m to 0.75m to 0.70m
Other ideas: lower $\beta^*$ (pp)

Quadrupole first IR (S. Peggs, S. Tepikian)

$l^* = 10 \text{ m}$ and maximum $\beta$ maintained, $\beta^* = 0.20 \text{ m}$

However, problems with asymmetric species.
Other ideas: electron lenses (pp)

Why an electron lens?

Y. Luo et al.

This tune spread can only be reduced by an electron lens, not by magnets

Polarized proton luminosity limited by beam-beam induced tune spread.

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Other ideas: electron lenses (pp)

Beam-beam effects cannot be corrected with magnets

beam-beam kick

magnet kicks

2 e-lenses operate in Tevatron (not for head-on compensation)
Other ideas: electron lenses (pp)

Simulation by Y. Luo

Tune diffusion w/o e-lens

Tune diffusion w/ e-lens

Electron lens studies under way (~1 year),
Hardware construction (~1 year) only after benefit established.
E-lens technology is similar to EBIS technology.
Main features:

- High-luminosity electron-ion collider
  - \(10^{32-33} \text{cm}^{-2}\text{s}^{-1}\) average for e\(\uparrow\)-p\(\uparrow\)
  - \(10^{30-31} \text{cm}^{-2}\text{s}^{-1}\) average for e\(\uparrow\)-A(\(\uparrow\))

- 10 GeV electron beam (upgrade to 20 GeV)
- Longitudinally polarized electrons, protons, possibly light ions

- 2 versions developed
  - Ring-ring option (B-factory like e-ring)
  - Linac-ring option (higher luminosity potential)
eRHIC ($\geq$ 2015)

Hadron collider luminosities

- proton-proton (p-p) and proton-antiproton (p-\bar{p}) collisions
- ion-ion collisions (A-A)
- lepton-proton (e-p) and lepton-ion (e-A) collisions ($e^-$ and $e^+$)
- $e^+, p^+$ spin polarized beams

Last update: 21 June 2007
eRHIC ($\geq$ 2015)

- eRHIC detector
- e-cooling
- beam dump
- Place for doubling energy linac
- ERL (5-10 GeV $e^-$)
- AGS
- BOOSTER
- LINAC
- RF
- PHENIX
- STAR
- Compact recirculation loop magnets

For multiple passes: vertical separation of the arcs
## ERL-based eRHIC parameters

<table>
<thead>
<tr>
<th></th>
<th>Electron-Proton Collisions</th>
<th>Electron-Au Collisions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High energy setup</td>
<td>Low energy setup</td>
</tr>
<tr>
<td>Energy, GeV</td>
<td>250</td>
<td>10</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>166</td>
<td>166</td>
</tr>
<tr>
<td>Bunch intensity, $10^{11}$ (or $10^9$ for Au)</td>
<td>2.0</td>
<td>1.2</td>
</tr>
<tr>
<td>95% normalized emittance, $\pi\mu$m</td>
<td>6</td>
<td>115</td>
</tr>
<tr>
<td>Rms emittance, nm</td>
<td>3.8</td>
<td>1.0</td>
</tr>
<tr>
<td>$\beta^*$, x/y, cm</td>
<td>26</td>
<td>100</td>
</tr>
<tr>
<td>Beam-beam parameters, x/y</td>
<td>0.015</td>
<td>2.3</td>
</tr>
<tr>
<td>Rms bunch length, cm</td>
<td>20</td>
<td>1.0</td>
</tr>
<tr>
<td>Polarization, %</td>
<td>70</td>
<td>80</td>
</tr>
<tr>
<td>Peak Luminosity/n, $1.e33$ cm$^{-2}$s$^{-1}$</td>
<td>2.6</td>
<td>0.53</td>
</tr>
<tr>
<td>Aver. Luminosity/n, $1.e33$ cm$^{-2}$s$^{-1}$</td>
<td>0.87</td>
<td>0.18</td>
</tr>
<tr>
<td>Luminosity integral /week, pb$^{-1}$</td>
<td>530</td>
<td>105</td>
</tr>
</tbody>
</table>

Luminosity of ring-ring version 10× lower
eRHIC interaction region design

- Yellow ion ring makes 3m vertical excursion.
- Design incorporates both normal and superconducting magnets.
- Fast beam separation. Besides the interaction point no electron-ion collisions allowed.
- Synchrotron radiation emitted by electrons does not hit surfaces of cold magnets.
## IR Design Schemes

<table>
<thead>
<tr>
<th>Scheme Type</th>
<th>Distance to nearest magnet from IP</th>
<th>Beam separation</th>
<th>Magnets used</th>
<th>Hor/Ver beam size ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring-ring, $l^*=1m$</td>
<td>1m</td>
<td>Combined field quadrupoles</td>
<td>Warm and cold</td>
<td>0.5</td>
</tr>
<tr>
<td>Ring-ring, $l^*=3m$</td>
<td>3m</td>
<td>Detector integrated dipole</td>
<td>Warm and cold</td>
<td>0.5</td>
</tr>
<tr>
<td>Linac-ring</td>
<td>5m</td>
<td>Detector integrated dipole</td>
<td>Warm</td>
<td>1</td>
</tr>
</tbody>
</table>

- No crossing angle at the IP
- Linac-ring: larger electron beta*; relaxed aperture limits; allows round beam collision geometry (the luminosity gains by a factor of 2.5).
- Detector integrated dipole: dipole field superimposed on detector solenoid.
ERL-based eRHIC R&D items

- High intensity polarized electron source
  → larger cathode surface with existing densities ~50mA/cm², good lifetime

- ERL technology for high energy, high current beams
  → R&D ERL under construction at BNL

- Development of compact recirculation loop magnets
  → Design, build and test small gap magnet and vacuum chamber

- Electron-ion beam-beam effects
  → instability and break-up of electron-beam
  → realistic simulations, possibly tests with e-lens

- Polarized $^3$He production and acceleration
  → EBIS as ionizer of polarized $^3$He gas
  → depolarizing resonance with anomalous magnetic moment diff. from p
Summary RHIC

- Exceeded Enhanced Design goal for Au-Au luminosity in Run-7
  - Time in store only 46% compared to 53% in Run-4 and 60% goal
  - No progress demonstrated with proton $L$ and $P$ (no running)

- Demonstrated feasibility of Au-Au operation at $E = 9.2$ GeV/nucleon cm
  - e-cooling in AGS under investigation for even lower $E$

- EBIS commissioning expected to begin in 2009 (U, $^3$He↑)

- RHIC II (based on e-cooling at store)
  - Order of magnitude higher heavy ion luminosity
  - 2-3x higher proton luminosity

- Other ideas under study
  - Transverse stochastic cooling (HI), IR optics (pp), e-lenses (pp)

- eRHIC
  - High luminosity $e\uparrow-p\uparrow$, $e\uparrow-A(\uparrow)$ collider (ERL-based $L_{avg} = 10^{33} \text{cm}^{-2}\text{s}^{-1}$)
  - Several R&D items for ERL version need to be pursued