Recent RHIC Performance and Upgrade Plans

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For the RHIC Operations and Upgrade Teams
EPAC 2004 July 6 2004

- RHIC Run-4 Performance: Au-Au and p↑+p↑
- RHIC Performance Limitations and Near-Term Plans
- RHIC Beam Cooling and eRHIC
RHIC Layout
More flexibility than at other hadron colliders
- Variation in particle species, including asymmetric operations
  - So far Au+Au, d+Au, p+p, p↑+p↑ (light ions planned in 2005)
- Variation in energy, energy scans
  - Au+Au at 10, 31, 65, 100 GeV/u
  - p↑+p↑ at 100 GeV (250 GeV planned in 2006)
- Variation in lattice
  - Low $\beta^*$ in most cases (1-3 m)
  - Large $\beta^*$ for small angle scattering experiment ($\geq 10$ m)
  - Polarity change in experimental magnets ~ every 2 weeks

Short runs (~30 weeks/year), with multiple modes
- Significant amount of set-up time required

Four experiments (2 large, 2 small)
- Work to avoid single-experiment bottlenecks

Short luminosity lifetime with heavy ions (IBS, ~ few hours)
- Fast refills essential
## RHIC Achieved and Planned Parameters

<table>
<thead>
<tr>
<th>Mode</th>
<th>No of bunches</th>
<th>Ions/bunch $[10^9]$</th>
<th>$\beta^*$ [m]</th>
<th>Emittance $[\pi \mu m]$</th>
<th>$L_{\text{peak}}$ $[\text{cm}^{-2}\text{s}^{-1}]$</th>
<th>$L_{\text{store ave}}$ $[\text{cm}^{-2}\text{s}^{-1}]$</th>
<th>$L_{\text{week}}$</th>
<th>Time in Store</th>
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<tr>
<td>Au-Au design</td>
<td>56</td>
<td>1</td>
<td>2</td>
<td>15-40</td>
<td>$9 \times 10^{26}$</td>
<td>$2 \times 10^{26}$</td>
<td>$50 \mu b^{-1}$</td>
<td></td>
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<td>Au-Au [Run-2]</td>
<td>55</td>
<td>0.7</td>
<td>1</td>
<td>15-40</td>
<td>$6 \times 10^{26}$</td>
<td>$1 \times 10^{26}$</td>
<td>$15 \mu b^{-1}$</td>
<td>26%</td>
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<td>Au-Au [Run-4]</td>
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* Achieved polarization performance in p↑-p↑ Run-4 was 40-45% in store

* Planned polarization performance by p↑-p↑ enhanced is 70% in store

[best store or week]

[incl. beam studies and maintenance]
RHIC Run-4 Au-Au Achievements

- Start-up/ramp-up in 4 weeks
  - 1 week less than planned
- Consistent high bunch intensity from injector
  - > design of $10^9$ Au/bunch, not yet single-bunch limited
- Time in store increased to 53%
  - 65% in low-energy 9-day 31.2 GeV/u run
- Reliable, near-complete rebucketing into 196 MHz storage RF
- Steering/collimation reduced to 10 min
- Best 7 days delivered 179 $\mu$b$^{-1}$ to PHENIX
  - Nearly 2x all of Run-2 delivered luminosity
- Set-up for 31.2 GeV/u run in less than 2 days
  - Optics/model predictability improvements

W. Fischer et al, MOPLT165
J.M Brennan et al, MOPLT159
A. Drees et al, MOPLT163
J. van Zeijts, TUPLT191
RHIC Run-4 Au-Au Luminosity Evolution

- **274 physics stores**
- **150 \( \mu b^{-1}/week \)**

<table>
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<tr>
<th>Experiment</th>
<th>100 GeV/u</th>
<th>Relative to Run-3</th>
<th>31.2 GeV/u (( \mu b ))^{-1}</th>
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<tbody>
<tr>
<td>PHENIX</td>
<td>1370</td>
<td>15x</td>
<td>21.8</td>
</tr>
<tr>
<td>STAR</td>
<td>1270</td>
<td>21x</td>
<td>20.7</td>
</tr>
<tr>
<td>BRAHMS</td>
<td>560</td>
<td>13x</td>
<td>12.2</td>
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<tr>
<td>PHOBOS</td>
<td>540</td>
<td>7x</td>
<td>12.3</td>
</tr>
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Weeks into run (to March 24 2004)

Integrated luminosity (\( \mu b^{-1} \))

- **Physics target**
- **Minimum projection**
- **Maximum projection**
RHIC Run-4: One Week of Au-Au Physics

Week 9 Feb to 17 Feb [66% of calendar time in store]

18x10^{26} \text{ cm}^{-2} \text{ s}^{-1}

Enhanced luminosity

Design luminosity

60x10^9 \text{ Au intensity}

\tau(\text{lumi}) = 2.5 \text{ hours}

IBS-dominated beam and luminosity lifetimes

Vacuum-dominated beam intensities

Beam experiments

Experiment luminosity

Intensity [x10^9 Au]
**RHIC Polarized Proton Layout**

- **Absolute Polarimeter (H jet)**
- **RHIC pC Polarimeters**
- **BRAHMS & PP2PP (p)**
- **PHOBOS**
- **Siberian Snakes**
- **PHENIX (p)**
- **Spin Rotators**
- **STAR (p)**
- **Siberian Snakes**
- **Spin Rotators**
- **Solenoid Partial Siberian Snake**
- **RHIC pC Polarimeters**
- **200 MeV Polarimeter**
- **Rf Dipole**
- **AGS pC Polarimeters**
- **Helical Partial Siberian Snake**
- **Strong AGS Siberian Snake**

- **RHIC Jet polarimeter/AGS warm snake:** Installed and commissioned during Run-4
- **Spin flipper:** Plan to be commissioned during Run-5
- **Strong AGS cold snake:** Plan to be installed and commissioned during Run-5
**RHIC Run-4 Polarized Protons Accomplishments**

- Commissioned the AGS warm 5% partial helical snake
  - AGS extraction polarization improved to 50%
- Developed ramps to a new working point to optimize
  - Polarization
  - Beam-beam limit
- Commissioned absolute polarimeter using Hydrogen jet target
  - Obtained calibration of analyzing power for CNI polarimeters at RHIC injection, store energies
- Explore the total beam intensity limit with protons
  - Electron cloud formation and pressure rise
AGS Helical Warm Snake

- Successfully commissioned the warm helical 5% partial snake provided by RIKEN (Japan)

- Replaces the AGS solenoidal 5% partial snake
  - improves linear coupling, polarization transfer efficiency

- AGS performance after warm helical snake commissioning:
  - $0.7 \times 10^{11}$ protons per bunch with 45% - 50% polarization
  - $1.1 \times 10^{11}$ protons per bunch with 45% polarization (at run end)
Previous RHIC working area (0.22-0.23) constrained polarized operations

New working point
- Improves polarization transmission/lifetime to effectively 100%
- Improves collision lifetime
- Beam-beam tune spread 0.016 with 2 collisions

Injection infeasible at store tunes due to strong 2/3 resonance
- Move tunes along ramp

R. Tomas et al, MOPLT172
Polarized Proton Ramp Tunes

Machine tunes

- No beam loss while crossing 7th order resonance at 0.717
- Other than the desired tune swing from (0.72, 0.73) to (0.68, 0.69), no significant tunes variations along the ramp
**Polarized H Jet Gas Target Polarimeter**

- Jet polarization very good
  - 95.9% / 95.7% in both states

- Jet thickness ~ $10^{12}$ atoms/cm$^2$
  - no discernable effect on beam

- Jet vacuum rise by factor 5
  - Jet off: 4x$10^{-9}$ Torr
  - Jet on: 2x$10^{-8}$ Torr
  - Beamline vacuum at 6x$10^{-9}$ Torr
  - 1 m from jet

- No observed depolarization from beam wake fields at 56 bunches
Polarized H Jet p-p Elastic Data

Jet profile: FWHM ~ 6 mm
As designed

Hor. pos. of Jet 10000 cts. = 2.5 mm

Number of elastic pp events

Recoil protons elastic pp → pp scattering

CNI peak $A_N$
$1 < E_{REC} < 2$ MeV

prompt events and beam gas
$\alpha$ source calibration

- 100 GeV: ~ 700,000 events at peak of analyzing power (~ $3 \times 10^6$ total useful pp elastic events)
  - CNI calibration to <10%

- 24 GeV: ~ 120,000 events at peak of analyzing power (~ $5 \times 10^5$ total useful pp elastic events)
  - CNI calibration to <20%
  - Goal: CNI calibration to 5%
RHIC Polarization and Luminosity Limitations

- Beam-Beam (pp, lighter ions)
  - Limits number of experiments to 2 (out of 4)
  - New working point
- Instabilities
  - Vulnerable near transition (short bunches, no chrom-jump)
  - Chromaticity, octupoles for transition crossing (transverse)
  - Landau cavities (longitudinal)
- Polarization
  - Strong AGS snake, eliminate polarization losses
- Vacuum (electron clouds, desorption from beam loss)
  - Vacuum instabilities; large experiment backgrounds
  - Use optimized bunch patterns
  - Installation of NEG coated pipes in warm regions
- Intrabeam scattering (Au)
  - Leads to luminosity lifetime of a few hours
  - Ultimately need cooling at full energy (stochastic, electron)
Polarization Upgrade: AGS Cold Snake

Superconducting 20-30% partial snake
- Should give 100% polarization transmission through AGS ramp
- Increase AGS extraction polarization to OPPIS source value (70-75%)

20-30% superconducting helical snake
Installation: Dec. 2004
AGS Spin Matching with Two Snakes

Stable spin vertical component

Spin tune

Injection

First intrinsic resonance (0+Qy)

- Stable spin direction is vertical at injection/extraction
- Maximum vertical tuning area at intrinsic resonances

T. Roser et al, TUPLT190
RHIC Electron Cloud Limitations

86$x 10^{11}$ p$^+$ total, 0.78$x 10^{11}$ p$^+$/bunch, 110 bunches, 108 ns spacing

Electron detector signal
Pressure

Clear connection between e-cloud and pressure at injection

Strongly dependent on bunch pattern

Estimate for $\eta_e$ assuming pressure caused by e-cloud: 0.001-0.02 (large error from multiple sources)

Iriso et al, WEPLT177

Fischer/Iriso, MOPLT164
Intensity Upgrade: NEG Coating

Low Temperature (~200°C) Zr_{30}Ti_{30}V_{40} alloy developed at CERN
To reduce SEY and ESD, and provide linear pumping

- **Q3-Q4 Regions (12cm Φ)**
  - Installed 11 x 5m in Summer 2003 shutdown
  - Installing 50 x 5m NEG coated pipes during Summer 2004 shutdown

- **IR Regions (7cm & 12cm Φ)**
  - BRAHMS: Coated SS sections of 3m x 2, coated Al sleeves in Be-Al pipe
  - PHENIX: Summer 2005
  - PHOBOS: Summer 2005 (3 x 4m Be pipes)
  - STAR: Coated SS sections of 1.5m x 2. NEG Activation an issue!

- **Developing NEG coating at BNL for IR beam pipes**
  - Horizontal cathode with internal permanent magnets
    - Vs. vertical twisted wires and external solenoid at ESRF, SAES, CERN
due to cost of solenoids, building, mounting, schedule, safety...
  - Cathode: Zr and V ribbons wrapped around Ti tube
  - 1m long SS pipe was coated, activated and reached low 10^{-11} Torr
  - Assembly of 6m horizontal cathode for 4m pipes and Al sleeves
Stochastic Bunched Beam Cooling at RHIC

Longitudinal bunched-beam HF Schottky spectra during store:

Protons: persistent coherence (solitons) interferes with cooling

Gold: no persistent coherence due to IBS; debunched beam visible

Microwave stochastic cooling (4-8 GHz) should work for longitudinal cooling and avoid beam debunching due to IBS during store

M. Blaskiewicz et al, THPLT171

Optical stochastic cooling (~ 30 THz) has great potential for the long term.

V. Yakimenko et al, WEPLT185

July 6, 2004 T. Satogata - RHIC Performance and Upgrades
RHIC Electron Cooling

- Au ion energy 100 GeV/u, x100 higher than typical cooler
  - Relativistic factors slow cooling by factor of $\gamma^2$
  - Cooling power a factor of $\gamma^2$ higher than typical
- Bunched electron beam requirements:
  - $E = 54$ MeV, $\langle I \rangle = 100-200$ mA
  - Electron beam power: ~ 5-10 MW!

- Requires high-brightness, high-power, energy recovering superconducting linac
  - Similar to ERL demonstrated by JLab for IR FEL
    (88 MeV, 9 mA)
  - First linac-based, bunched electron beam cooling system used at a collider

L. Merminga, MOYCH02
RHIC Electron Cooler R&D

- Simulation and experimental benchmarking of cooling force for RHIC energies
  - SIMCOOL, BETACOOL, direct numerical calculations [Vorpal, Tech-X, Colorado], e-coolers at GSI, COSY, CELSIUS, collaboration with INTAS
- Demonstrate high precision (<10 ppm) solenoid (5 T design started)
- Demonstrate 20 nC, 100-200 mA 703.8 MHz CW SCRF photocathode electron gun
- Develop 703.8 MHz CW superconducting cavity for high intensity beams
- Build R&D Energy Recovering Linac (ERL)
Initial conceptual design for 703.75 MHz photocathode superconducting gun. Prototype fabrication in 2005. (AES, BNL, Navy)

H. Bluem (AES) et al, MOPLT156
703.8 MHz CW Superconducting Cavity

Niobium prototype delivery next year
Cold Cu model testing Aug 2004
(AES, Navy, JLab, BNL)
Predicted BBU threshold > 1 A!

R. Calaga et al, TUPKF078

July 6, 2004
T. Satogata - RHIC Performance and Upgrades
Integrated testing of major RHIC electron cooling components
Expected to be operational in 2006
RHIC Luminosity With Electron Cooling

Transverse beam profile during store

Also may be able to pre-cool polarized protons at injection energy

Luminosity leveling through continuously adjusted cooling

Store length limited to 4 hours by "burn-off"

Four IRs with two at high luminosity

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Electron-Ion Collider at RHIC: eRHIC

- 10 GeV, 0.5 A e-ring with 1/3 of RHIC circumference
  - similar to PEP II HER
  - $s^{1/2} = 63$ GeV/u for e-Au; $s^{1/2} = 100$ GeV for e$^\uparrow$-p$^\uparrow$
- Luminosity: up to $10^{33}$ cm$^{-2}$ s$^{-1}$
- ZDR completed
  - http://www.agsrhichome.bnl.gov/eRHIC/eRHIC_ZDR.htm

- Electron cooling is a prerequisite for design luminosity
- Design development
  - ring-ring and linac-ring options (with MIT Bates)
- High-intensity polarized He3 source development
- High-current polarized electron source development
  (with Jlab and MIT Bates, mainly for linac-ring option)

V. Ptitsyn et al, MOPLT170
The electron ring of 1/3 of the RHIC ion ring circumference

Full energy injection using polarized electron source and 10 GeV energy linac.

e-ion collisions in one interaction point.
Ion-ion collisions in two other IPs at the same time.

Longitudinal polarization produced by local spin rotators in interaction regions.

Design development in collaboration between BNL, MIT-Bates, BINP and DESY

5-10 GeV static electron ring
recirculating linac injector

50-250 GeV polarized protons
100 GeV/u gold ions

EBIS BOOSTER LINAC AGS

F. Wang et al, MOPLT148
Two alternative designs are presented in the ZDR Appendix A (V. Litvinenko, I. Ben-Zvi, et al).

Electron beam is transported to collision point(s) directly from superconducting ERL.

450mA electron current; 10 GeV energy (extendable).
**Summary**

RHIC Run-4 (Au-Au, p↑-p↑) was a great success
- All program goals achieved or exceeded
- Exceeded Run-3 Au-Au integrated luminosity by 15-20x !!
- Polarized development: jet, AGS warm snake, working point successes

Run-5 will likely be split between light ions and polarized protons

Near-term limitations and required upgrades
- Polarization: AGS cold partial snake (15-20% improvement)
- Vacuum → NEG coated warm beam pipes
- Intrabeam scattering → stochastic cooling, fast refills

Active R&D on beam cooling, design development on eRHIC

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Acknowledgements

Many thanks to...

Wolfram Fischer, Mei Bai, Thomas Roser, Ilan Ben-Zvi


...and of course all RHIC Operations and Upgrade teams