Relativistic Heavy Ion Collider Operations and Performance Evolution

Luminosity and polarization evolution

Plans for luminosity upgrade and 500 GeV running

Low energy RHIC running (Critical point energy scan)

EBIS project status

Accelerator R&D
RHIC – a High Luminosity (Polarized) Hadron Collider

Achieved peak luminosities (100 GeV, nucl.-pair):
- Au–Au  $120 \times 10^{30}$ cm$^{-2}$ s$^{-1}$
- p↑–p↑  $35 \times 10^{30}$ cm$^{-2}$ s$^{-1}$

Other large hadron colliders (scaled to 100 GeV):
- Tevatron (p – pbar)  $32 \times 10^{30}$ cm$^{-2}$ s$^{-1}$
- LHC (p – p, design)  $140 \times 10^{30}$ cm$^{-2}$ s$^{-1}$

Operated modes (beam energies):
- Au–Au  4.6, 10, 32, 65, 100 GeV/n
- d–Au*  100 GeV/n
- Cu–Cu  11, 31, 100 GeV/n
- p↑–p↑  11, 31, 100 GeV

Planned or possible future modes:
- p↑–p↑  250 GeV
- Au – Au  2.5 GeV/n (~ SPS cm energy)
- p↑ – Au*  100 GeV/n  (*asymmetric rigidity)
Gold Ion Collisions at RHIC

Beam Energy = 100 GeV/u

RHIC

9 GeV/u
Q = +79

BOOSTER

AGS

1 MeV/u
Q = +32

TANDEMS
Delivered Integrated Luminosity and Polarization

**Heavy ion runs**

Integrated nucleon-pair luminosity $L_{NN} \text{[pb}^{-1}]$

- d-Au 2007
- Cu-Cu 2005
- d-Au 2003
- Au-Au 2001/02
- Au-Au 2004
- Au-Au 2008

**Polarized proton runs**

Integrated nucleon-pair luminosity $L_{NN} \text{[pb}^{-1}]$

- 2003 P=34%
- 2005 P=46%
- 2008 P=45%
- 2006 P=60%

**Nucleon-pair luminosity**

Luminosity calculated with nucleons of nuclei treated independently; allows comparison of luminosities of different species; appropriate quantity for comparison runs.
Luminosity Limit – Fast Instability Near Transition

- Fast transverse instability (\(~ \text{GHz}\))
- High sensitivity around transition (high peak current, zero chromaticity)
- Effect of broadband impedance and electron clouds
- Cures: octupoles, suppress electron clouds, chromaticity jump, active damper (?)

Tomographic reconstruction of 2D bunch density

Before instability

After instability with \(~ 10 \text{ ms growth rate}\)
RHIC Luminosity Limit – Intra-Beam Scattering (IBS)

- Debunching requires continuous gap cleaning
- Luminosity lifetime requires frequent refills
- Ultimately need cooling at full energy

First successes in addressing IBS:
- Longitudinal stochastic cooling
- Stronger focusing lattice that suppresses 30% of transverse IBS → 20% smaller transverse emittance after 5 hours.
Without Siberian snakes: $\nu_{sp} = G\gamma = 1.79 \text{ E/m} \rightarrow \sim 1000$ depolarizing resonances

With Siberian snakes (local 180° spin rotators): $\nu_{sp} = \frac{1}{2} \rightarrow$ no first order resonances

Two partial Siberian snakes (11° and 27° spin rotators) in AGS
Siberian Snakes

- AGS Siberian Snakes: variable twist helical dipoles, 1.5 T (RT) and 3 T (SC), 2.6 m long
- RHIC Siberian Snakes: 4 SC helical dipoles, 4 T, each 2.4 m long and full 360° twist
Run-7 and Run-8  \( \uparrow-p\uparrow \) operation – polarization

- **Source**
  - \( P = 80 - 82\% \) in Run-8 after \( 85 - 89\% \) in Run-7
  - Aim for \( P = 85\% \) in Run-9

- **AGS**
  - Tested stronger snake and near integer horizontal tune in Run-7
  - Tested injection on the fly (no flat bottom) in Run-8
  - In both cases significant intensity dependent polarization
  - Returned to Run-6 setup with \( P = 55\% \) at extraction vs. \( P = 65\% \) in Run-6
  - (half of the loss due to source, other half due to only 10 days of tuning)
  - For Run-9 use Run-6 set-up with tune jump for horizontal resonances

- **RHIC**
  - About 10\% (absolute) lower \( P \) than in Run-6, more problems in Yellow
  - Learned that horizontal orbit angle through snakes needs better control
  - Need RHIC pC CNI polarimeter upgrade for better reliability
Dual Partial Snake in AGS avoided depolarization from all vertical depolarizing resonances. Strong partial snakes also drive weak horizontal depolarizing resonances. (~ 5-10% polarization loss)

Plan to use tune jump for weak horizontal resonances
Luminosity and Polarization Lifetimes in RHIC at 100 GeV

- Start of acceleration ramp
- Start of collisions
- Collimation complete
- 60% polarization

Graph showing protons, luminosity, and polarization over time from 19:00 to 03:00.
Test of Polarized Proton Acceleration to 250 GeV

45% polarization on first acceleration to 250 GeV!

Loss at strong intrinsic resonance (136 GeV); correctable by adjusting betatron tunes.
Luminosity Limit – Head-on Beam-Beam Interaction

- First strong-strong hadron collider (after ISR)
- Limits high luminosity pp operation (beam-beam tune spread ~ 0.01)
- Cures: Non-linear (chromaticity) corrections, better working point, electron lens

Currently of bunches with 2, 3, or 4 collisions
Tests of $\sqrt{s} = 9$ GeV Au - Au operation in RHIC

- 2008 blue beam lifetime: 3.5 minutes (fast), 50 minutes (slow)
- Sextupole reversal and elimination of octupoles clearly helped beam lifetime
- Injection efficiency and yellow beam lifetime can clearly benefit from further tuning

[T. Satogata, RHIC Retreat 2008]
Luminosity scaling with energy

\[ L \sim \frac{1}{E^3} \quad \text{or} \quad L \sim \frac{1}{E^2} \]

**Graph:**
- Guidance line
- Measured Run-2 to Run-8 data points
- Measured, normalized with number of bunches and bunch intensity

**Axes:**
- Luminosity \[10^{27} \text{ cm}^{-2} \text{ s}^{-1}\]
- Total Au ion energy [GeV/nucleon]
Luminosity scaling with energy

\[ L \sim \frac{1}{\gamma^3} \quad \text{or} \quad L \sim \frac{1}{\gamma^2} \]

- Guidance
- Measured Run-2 to Run-8
- Measured, normalized with no of bunches and bunch intensity
Low energy Au-Au operation – Luminosity upgrade options

E-cooling in RHIC

- Luminosity limited by space charge (space charge limit $\Delta Q_{sc} = 0.05$)
- Expect 3-6 more luminosity when operating at space charge limit
- Electron cooling either with dc beam (Fermilab Pelletron) or with rf beam (56 MHz SRF gun, 703 SRF gun – under construction)

Top-off mode

- Replace 1 - 4 RHIC bunches every AGS cycle, beam stays in RHIC only 3 - 7 min; ~ 2 - 3 more luminosity
- Needs modification of RHIC injection and extraction kickers and experiments need to stay on during continuous refill (likely ok, test desirable)
RHIC Facility Upgrade Plans

- RHIC luminosity upgrade:
  - $0.5 \text{ m } \beta^*$ for Au – Au and p↑ – p↑ operation
  - Stochastic cooling in RHIC of Au beams
  - New storage rf system in RHIC (56 MHz SRF cavity)
  - Electron lens in RHIC for beam-beam compensation (R&D)
- EBIS (low maintenance linac-based pre-injector; all species including U and polarized $^3\text{He}$)
- eRHIC: high luminosity ($\geq 1 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$) eA and pol. ep collider using 10 - 20 GeV electron driver, based on Energy Recovering Linac (ERL), and strong cooling of hadron beams
  Exploring gluons at extreme density!
## RHIC Luminosity and Polarization Goals

<table>
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<th>Parameter</th>
<th>unit</th>
<th>Achieved</th>
<th>Luminosity upgrade</th>
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<td>Energy</td>
<td>GeV/nucleon</td>
<td>100</td>
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<td>No of bunches</td>
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<td>Bunch intensity</td>
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<td>Ave. delivered luminosity**</td>
<td>$10^{26}$ cm$^{-2}$s$^{-1}$</td>
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<td>40*</td>
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<tr>
<td>Energy</td>
<td>GeV</td>
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<td>100 (250)</td>
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<td>No of bunches</td>
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<td>111</td>
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<tr>
<td>Bunch intensity</td>
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<td>Ave. delivered luminosity**</td>
<td>$10^{30}$ cm$^{-2}$s$^{-1}$</td>
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<td>80 (200)</td>
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<tr>
<td>Polarization</td>
<td>%</td>
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<td>70</td>
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</table>

* 5 × ‘enhanced’ luminosity and 20 × design luminosity
* *without vertex cuts*
Stochastic Cooling and 56 MHz SRF cavity

- Longitudinal stochastic cooling of core of bunched beam demonstrated at 100 GeV/n in RHIC counteracting longitudinal IBS.
- Full longitudinal and transverse stochastic cooling under construction

56 MHz SRF storage cavity:
- Avoid rebucketing operation.
- Greatly reduces satellite bunches
- Re-entrant quarter wave resonator
Luminosity Increase with Full Stochastic Cooling

- Transverse stochastic cooling in one plane only
- Second plane cooled through x-y coupling
- 5 – 8 GHz bandwidth split up into 16 frequency bands
- Each frequency has its own cavity kicker

Achieved with longitudinal stochastic cooling in one ring only

3-D stochastic cooling
3-D SC, 56MHz, no 197s
3-D SC, 56MHz, with 197s
longitudinal SC only

Calculation by M. Blaskiewicz.

Transverse kickers
Transverse pickups FO

Fiber optic links

MicroWaveLinks
Electron Lenses for pp Operation

- Polarized proton luminosity is limited by head-on beam-beam tune spread
- Low energy electron beam (similar to EBIS) interacting with proton beam can compensate head-on beam-beam tune spread ($\times 2$ luminosity?)
- Single and multi particle simulation underway
Electron Beam Ion Source (EBIS)

- New high brightness, high charge-state pulsed ion source, ideal as source for RHIC
- Produces beams of all ion species including noble gas ions, uranium (RHIC) and polarized He³ (eRHIC) ($\sim 1-2 \times 10^{11}$ charges/bunch with $\epsilon_{N,\text{rms}} = 1-2 \ \mu\text{m}$)
- Achieved $1.7 \times 10^9$ Au³³⁺ in 20 μs pulse with 8 A electron beam (60% neutralization)
- Construction of EBIS, RFQ and IH Linac complete by 2010

Gold charge state with only 40 ms confinement time.
EBIS Pre-injector Layout

Funding profile:

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**Ion**

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<tr>
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<td>Q/m</td>
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<td>Current</td>
<td>&gt; 1.5 emA (for 1 turn inj)</td>
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<td>Pulse Length</td>
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<tr>
<td>Rep. Rate</td>
<td>5 Hz</td>
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<tr>
<td>Time to switch species</td>
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Electron Beam Ion Source Status

- Construction start (DOE) in FY2007
- Funding:
  - $14.8M DOE TPC ($2.7M in FY2009 completes DOE funding)
  - $4.5M NASA TPC (received in full)
- 6 months delay of construction start and $2.4M reduction in FY2007 due to CR
  - On schedule to meet new CD4 milestone of Q4 FY2010
- All major procurements placed or received:
  - Penetration to Booster completed and tested, BO of building extension
  - High power rf amplifiers, EBIS source hardware, PS, vacuum equipment
  - RFQ (ship 7/08), IH Linac (fab. Starting), large dipole magnets (ship 7/08)
  - 6T solenoid: failed during quench test at ACCEL (Germany); repaired and tested; plan to order spare by 7/08 (no change of CD4)
  - High power electron collector built with constr. funds complete; electron collector built with R&D funds may work after difficulties
- Reprogrammed ~$1.4M AIP and ~$1M ops (no new hires) per year from FY2006 to FY2008; need restoration of reprogrammed funds starting in FY2009
Energy Recovery Linac (ERL) Test Facility

- Test of high current (0.5 A), high brightness ERL operation
- Electron beam for RHIC (coherent) electron cooling (54 MeV, 10 MHz, 5 nC, 4 μm)
- Test for 10 – 20 GeV high intensity ERL for eRHIC.
- Test of high current beam stability issues, highly flexible return loop lattice

1 MW, 703.75 MHz CW Klystron

**SRF Gun**
2MV, 0.5A

**Return loop**

**Beam dump**

5 Cell SRF “single mode” cavity
Q > 10^{10} @20 MV/m CW
ERL – Based Electron-Ion Collider (eRHIC)

- 10 GeV electron design energy. Possible upgrade to 20 GeV by doubling main linac length.
- 5 recirculation passes (4 of them in the RHIC tunnel)
- Multiple electron-hadron interaction points (IPs) and detectors;
- Full polarization transparency at all energies for the electron beam;
- Ability to take full advantage of transverse cooling of the hadron beams;
- Possible options to include polarized positrons at lower luminosity: compact storage ring or ILC-type polarized positron source.
Coherent Electron Cooling

- Idea proposed by Y. Derbenev in 1980, novel scheme with full evaluation developed by V. Litvinenko
- Fast cooling of high energy hadron beams
- Made possible by high brightness electron beams and FEL technology
- ~ 20 minutes cooling time for 250 GeV protons → much reduced electron current, higher eRHIC luminosity
- Proof-of-principle demonstration in RHIC using test ERL.

**Pick-up:** electrostatic imprint of hadron charge distribution onto co-moving electron beam

**Amplifier:** Free Electron Laser (FEL) with gain of 100 - 1000 amplifies density variations of electron beam, energy dependent delay of hadron beam

**Kicker:** electron beam corrects energy error of co-moving hadron beam through electrostatic interaction
## Accelerator Improvement Projects and R&D FY2007-2010

<table>
<thead>
<tr>
<th>Projects</th>
<th>Total ($M)</th>
<th>Completion date</th>
<th>FY2007 Actual</th>
<th>FY2008 Actual</th>
<th>FY2009 President's</th>
<th>FY2010 Proposed</th>
<th>FY2011</th>
<th>FY2012</th>
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<td>eRHIC R&amp;D</td>
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<td>3.00</td>
<td>3.80</td>
<td>3.90</td>
<td>4.10</td>
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### FY2008-FY2013

- AGS MMPS transformer
- RHIC long. stochastic cooling
- RHIC cryo control upgrade
- Main Control Room upgrade
- RHIC SRF 56 MHz
- RHIC trans. stochastic cooling (2nd ring)
- RHIC electron lenses
- RHIC low energy e-cooling
Accelerator R&D

- Build first transverse stochastic cooling plane (FY08, DOE NP)
- Complete test ERL including high brightness, 1 MW SRF photo-cathode gun, high intensity 703 MHz SRF CW cavity, and single return loop. (completion and start of commissioning in FY09 – 10, DOE NP, NAVY)
- eRHIC accelerator R&D:
  - Tests with the high-efficiency energy-recovering superconducting linac (test ERL, DOE NP, NAVY)
  - Design and prototyping of the small aperture magnets and vacuum chambers for eRHIC return loops (BNL LDRD)
  - Development of a polarized $^3$He source (DOE NP)
  - Design of a high-current polarized electron gun (DOE NP, MIT)
  - Development of SRF polarized e gun (LDRD)
  - New HOM damper design for more compact cryo-modules in eRHIC (DOE NP)
  - Crab-crossing schemes for eRHIC (LARP)
  - Develop Coherent Electron Cooling for fast cooling of high energy proton beams (DOE NP)
  - Move test ERL to IP2 for testing coherent and standard electron pre-cooling with 40 GeV/n Au beam (DOE NP)
- Some of these items will be submitted as proposals for R&D related to the RHIC electron-ion collider (eRHIC) when ONP issues a call for proposals for Electron-Ion Collider (EIC) R&D
Summary

Since 2000 RHIC has collided, at many different collision energies,
  • Gold on gold with luminosity exceeding design luminosity by factor of six
  • Asymmetric ions at high luminosity
  • Polarized protons with 60 % average beam polarization

Successful test of Au collisions at very low energy (~ ½ normal injection energy)

Successful operation of longitudinal stochastic cooling

Future runs / upgrade plans:
  • Luminosity upgrade to $40 \times 10^{26}$ cm$^{-2}$ s$^{-1}$ through high energy beam cooling
  • High luminosity 250 x 250 GeV polarized proton run
  • Uranium beams from EBIS
  • High luminosity polarized electron ion collider - eRHIC
Back-up Slides
Spin Flipper (plan)

- Use spin resonance driven by AC dipole(s) to induce spin flip
- Single AC dipole (oscillation) drives two resonances that interfere at $\nu_{sp} = 0.5$, only partial spin flip
- Two AC dipoles with vertical spin precession in between creates rotating drive field