Relativistic Heavy Ion Collider

1 of 2 ion colliders (other is LHC), only polarized p-p collider

2 superconducting 3.8 km rings
2 large experiments
100 GeV/nucleon ions up to U
255 GeV polarized protons

Performance defined by
1. Luminosity $L$
2. Proton polarization $P$
3. Versatility (species, $E$)
Content

Run-12 overview

• Polarized protons, $\sqrt{s} = 200, 510$ GeV
• Uranium-uranium $\sqrt{s_{NN}} = 193$ GeV, copper-gold $\sqrt{s_{NN}} = 200$ GeV

Heavy upgrades and projections

• Luminosity with stochastic cooling & 56 MHz SRF
• Energy scan and low energy cooling

Polarized proton upgrades and projections

• Polarization and luminosity with source upgrade
• Luminosity with RHIC electron lenses
• R&D for polarized $^3$He
2012 RHIC Run (23 weeks of cryo ops) – most varied to date

100 GeV polarized protons
new records for $L_{\text{peak}}, L_{\text{avg}}, P$

255 GeV polarized protons
highest energy polarized proton beam
new records for $L_{\text{peak}}, L_{\text{avg}}, P$

96.4 GeV/nucleon uranium-uranium
heaviest element in collider, shape stochastic cooling: $L_{\text{max}} > L_0$
all ions lost through burn-off
1st time in hadron collider!

100 GeV/nucleon copper-gold
new species combination

possibly 2.5 GeV/nucleon gold-gold test (2 days)
lowest energy to date, 20% of nominal injection $E$

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Run-12 – Polarized protons 100 GeV

Run Coordinator: V. Schoeffer

- $P_{\text{avg,B}} = 61.8\%$ (2009: 56%)
- $P_{\text{avg,Y}} = 56.6\%$ (2009: 57%)

$P_{\text{avg}}$ – average over intensity and time, as measured by H-jet

New: 2 new Landau cavities installed in RHIC; AGS horizontal alignment; 9 MHz system upgraded; AGS horizontal tune jump timing improved; operation from new Main Control Room; down ramp does not stop at injection any more, ramp from park to injection with 2x ramp speed compared to previous runs (saves 2.9 min per ramp)

Polarization details at [www.phy.bnl.gov/cnipol](http://www.phy.bnl.gov/cnipol) (D. Smirnov)
Run-12 – Polarized protons 255 GeV

Run Coordinator: V. Schoeffer

$P_{\text{avg}, B} = 50.3\%$ (2011: 48%)

$P_{\text{avg}, Y} = 53.5\%$ (2011: 48%)

$[P_{\text{avg}}$ – average over intensity and time, as measured by H-jet]

New: same as for 100 GeV; increased store energy to increase polarization lifetime; snakes ramp between 100 GeV and 255 GeV; scan of snake spin rotation axis angle and spin rotation angle; test of longitudinal injection damper; test of Landau phase error compensation (phase error from Booster) compensation

Polarization details at www.phy.bnl.gov/cnipol (D. Smirnov)
Polarization profiles and quantities of interest

- Polarization can be characterized by
  \[ P_0 \quad R = \frac{\sigma_l^2}{\sigma_P^2} \]
  \( P_0 \) center profile value parameter
  (no profile with \( R=0 \), can have \( R_x, R_y, R_s \))

- Polarization \( P_{\text{avg}} \) measured by H-jet is averaged over intensity and time
  \[ P_{\text{avg}} = \frac{P_0}{(1+R_x)(1+R_y)(1+R_s)} \]

- Luminosity-averaged quantities of interest for experiments:
  \[ \langle P_B \rangle, FOM_B = L \langle P_B^2 \rangle \quad \text{single-spin experiments} \]
  \[ \langle P_B \cdot P_Y \rangle, FOM = L \langle P_B^2 \cdot P_Y^2 \rangle \quad \text{double-spin experiments} \]
RHIC Polarization status

2 types of depolarizing resonances
- Imperfection resonances (from vertical closed orbit errors):
  \[ G \gamma = k \]
- Intrinsic resonances (from vertical betatron motion):
  \[ G \gamma = kP \pm Q_v \]
- \( G \) – anomalous magnetic moment (+1.79 for p, −4.18 for \(^3\)He)

Recent improvements (2011-2012)
- 80 horizontal tune jumps in AGS (weak horizontal resonances)
- AGS and RHIC re-alignment
- Operation with 9 MHz rf system (low \( \delta p/p \))
- Acceleration near 2/3 (only 0.006 off; need orbit, tune, coupling feedback on every ramp)
- pC-polarimeter upgrade (rate dependence)

Future improvements
- Polarized source upgrade
- Possibly more RHIC snakes (also for \(^3\)He\(\overline{\text{He}}\))
Beam control improvement – feedbacks on ramp

M. Minty, A. Marusic et al.

Orbit feedback on every ramp allows for
- Smaller $y_{\text{rms}}$ (smaller imperfection resonance strength)
- Ramp reproducibility (have 24 h orbit variation)

Tune/coupling feedback on every ramp allows for
- Acceleration near $Q_y = 2/3$ (better P transmission compared to higher tune)

$x, y_{\text{rms}} \approx 20 \, \mu m (\dagger) \approx 3\% \text{ of rms size}$
Polarization tests during Run-13 (M. Bai et al.)

**Polarization lifetime at store** (0.5-1.0%/h loss at 100 and 250 GeV)
- Energy change from 250 to 255 GeV => no difference
- Depolarization of non-colliding beam on/off the strongest snake resonance (=11/16) => no difference
- Spin tune change ±0.01 => no difference
- Snake spin rotation angle scan ±10 deg => small effect for –10 deg

**Depolarization during energy and rotator ramps**
- Orbit effect of last 2 strong intrinsic resonances => small effect for large orbit error
- Contribution of final $\beta^*$-squeeze => no difference
- Snake spin rotation angle => 5% (absolute) gain in Yellow
- Spin tune change ±0.01 => no difference

**Absolute polarization at injection with H-jet**
- 10 h for measurement in Yellow only (background minimization)
- $P_{\text{avg}} = (63\pm4.4)\%$

=> Unlikely that large polarization gains can be made by further parameter changes (depolarization due to many small effects)
Run-12 – Uranium-uranium 96.4 GeV/nucleon

Run Coordinator: Y. Luo

New: first use of EBIS for RHIC operation; first U-U operation in a collider; used standard lattice to increase off-momentum dynamic aperture; first use of Blue and Yellow horizontal stochastic cooling (resulting in 3D cooling in both rings); due to small beam size need micro-vernier scan every 1/2 h
Electron Beam Ion Source (EBIS)

- Inject single charge ion from primary source (e.g. hollow cathode source)
- 10 A electron beam creates desired charge state in trap (5 T sc solenoid)
- Source for high-charge state, high brightness ion beams
- Accelerated through RFQ and linac, injected into AGS Booster
- All ion species including noble gas, \textit{uranium} and polarized $^3\text{He}$

Operated for NASA Space Radiation Laboratory in 2011-12 with
- $\text{He}^+, \text{He}^{2+}, \text{Ne}^{5+}, \text{Ne}^{8+}, \text{Ar}^{10+}, \text{Kr}^{18+}, \text{Ti}^{18+}, \text{Fe}^{20+}, \text{Ta}^{33+}, \text{Ta}^{38+}$

Operated for RHIC in 2012 with
- $\text{U}^{39+}$ (not possible previously), $\text{Cu}^{11+}, \text{Au}^{31+}$
Preparation of U beams for RHIC

**EBIS out:** $^{39+}$U

- **AGS-to-RHIC transfer line**
  - Stripping foil: $\text{Al}_2\text{O}_3$ (5.2 mg/cm$^2$)
  - $E_{\text{kin}} = 8.51$ GeV/nucleon
  - $^{90+}U$ $\gamma$ $^{92+}U$ (99.9% of intensity)

- **Booster-to-AGS transfer line**
  - Stripping foil: Ni (4.4 mg/cm$^2$) + Al (9.0 mg/cm$^2$)
  - $E_{\text{kin}} = 107$ MeV/nucleon
  - $^{39+}U$ $\gamma$ $^{90+}U$ (35% of intensity)
    (had expected >50% based on GLOBAL)

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P. Thieberger, K. Zeno
Now have full 3D stochastic cooling for heavy ions

- Longitudinal kickers (closed)
- Transverse kickers
- Fibre-optic links
- Microwave links
- Vertical kickers (closed)
- Horizontal kickers (open)
- Horizontal and vertical pickups

5-9 GHz, cooling times ~1 h

M. Brennan, M. Blaskiewicz, F. Severino, PRL 100 174803 (2008); PRSTAB, PAC, EPAC
**U-U store – new mode in 2012**

All beam loss though luminosity (burn-off)!

Cross sections [b]:

<table>
<thead>
<tr>
<th></th>
<th>Au-Au</th>
<th>U-U</th>
</tr>
</thead>
<tbody>
<tr>
<td>BFPP</td>
<td>117</td>
<td>329</td>
</tr>
<tr>
<td>EMD</td>
<td>99</td>
<td>160</td>
</tr>
</tbody>
</table>

3D stochastic cooling leads to new feature in hadron collider:

\[ L_{\text{max}} > L_{\text{initial}} \]
New: first Cu-Au operation in a collider; used standard lattice to increase off-momentum dynamic aperture; first use of Blue and Yellow horizontal stochastic cooling (resulting in 3D cooling in both rings)
Cu-Au store – new mode in 2012

- Intrabeam scattering growth rates ($\sim Z^4 N_b / A^2$)
  
  \[ r_{\text{IBS,Au}} \approx 2x \ r_{\text{IBS,Cu}} \]

- Cooling rates ($\sim 1/N_b$)
  
  \[ r_{\text{SC,Au}} \approx 3x \ r_{\text{SC,Cu}} \]

Optimization of Cu/Au cooling rates:
Overcooling of one beam creates large loss rate in other beam

14 h store length
Time-in-store as fraction of calendar time

- Run-12 with low failure rates in all systems
- Highest time-in-store ratios to date
  (even with increased APEX time during 255 GeV protons compared to Run-11)
RHIC ions – 6 species and 15 energies to date

\[ ^{238}\text{U}^{92+} - ^{238}\text{U}^{92+} \]
\[ \gamma \text{ first time in 2012, 3 weeks physics, complete} \]
\[ 96.4 \text{ GeV/nucleon} \]

\[ ^{197}\text{Au}^{79+} - ^{197}\text{Au}^{79+} \]
\[ 3.85, 4.6, 5.75, 9.8, 13.5, 19.5, 27.9, 31.2, 65.2, 100.0 \text{ GeV/nucleon} \]
\[ ^{63}\text{Cu}^{29+} - ^{197}\text{Au}^{79+} \gamma \text{ first time in 2012, 5 weeks, under way} \]
\[ 99.9/100.0 \text{ GeV/nucleon} \]

\[ ^{63}\text{Cu}^{29+} - ^{63}\text{Cu}^{29+} \]
\[ 11.2, 31.2, 100.0 \text{ GeV/nucleon} \]

\[ d - ^{197}\text{Au}^{79+} \]
\[ 100.7/100.0 \text{ GeV/nucleon} \]

\[ p - p \]
\[ 31.2, 100.2, 204.9, 249.9, 254.9 \text{ GeV} \]

Can collide any species from protons (polarized) to uranium – with each other or with another species
RHIC ions – 6 species and 15 energies to date

2 isotopes: d, p (polarized)

planned: He-3 (polarized)
RHIC heavy ions – luminosity evolution to date

\[ L_{NN} = L N_1 N_2 \] (= luminosity for beam of nucleons, not ions)

\[ <L> = 15x \text{ design in 2011} \]

About 2x increase in \( L_{\text{int}}/\text{week} \) each
- Run-4 to Run-7
- Run-7 to Run10
- Run-10 to Run-11

Rate of progress will slow down – burn off 50% of Au beam in collisions already
• \( \lambda/4 \) Ni resonator common to both beams

• Beam driven

• 56 MHz, 2 MV

Average luminosity vs. vertex size

Calculations by M. Blaskiewicz

56 MHz SRF for heavy ions – under construction (I. Ben-Zvi et al.)

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40 ns Longitudinal profile at end of store

• Even with cooling ions migrate into neighboring buckets

• Can be reduced with increased longitudinal focusing

Demonstrated 2011

Long. + ver. cooling

Full 3D cooling + 56 MHz SRF

Commissioning planned for 2014

40 ns
RHIC – Au-Au energy scan

Energy scan – extends below nominal injection energy in search of critical point in QCD phase diagram

Effects to contend with (#s for 20% nominal (B₀):

- **Large beam sizes** (longitudinal and transverse) controlling losses becomes critical
- **Large magnetic field errors** (b₃ ~ 10, b₅ ~ 6 units from persistent currents in superconducting magnets)
- **Intrabeam scattering** (debunching ~min)
- **Space charge** (ΔQₖaslett ~ 0.1 – new regime for collider)
- **Beam-beam** (ξ/IP ~ 0.003)
- **Low event rates** (~ 1 Hz)

Full energy injection allows for short stores
- At 38% of nominal injection (B₀)
- May operate at 20% of nominal injection (B₀)
Peak and average luminosities fall faster than $1/\gamma^2$ at lowest energies.
Need cooling at low energies to significantly increase luminosities.
e-cooling for low energy collider operation (A. Fedotov et al.)

Fermilab Pelletron (cooled 8 GeV pbar for Tevatron use) usable – scheduled for decommissioning in 3/2012, so far have not requested transfer

Alternative option with e- beam from 112 MHz SRF gun

Cooling into space charge limit
\( \Delta Q_{sc} \sim 0.05 \) (new collider regime)

Expect up to factor 5 more integrated luminosity (depending on energy and \( \Delta Q_{sc} \))

Figure 4. Simulation of luminosity with (blue line) and without (black dots) electron cooling at \( \gamma = 2.7 \).

A. Fedotov, M. Blaskiewicz, BNL C-A/AP/449 (2012)
Low energy operation with cooling AND long bunches

Additional gain by operating with long bunches (at space charge limit)

A. Fedotov, M. Blaskiewicz, BNL C-A/AP/449 (2012)
At 255 GeV in 2012:

- L$_{avg}$ = 105x10$^{30}$cm$^{-2}$s$^{-1}$
- P$_{avg}$ = 52%

L$_{avg}$ +15% relative to 2011
P$_{avg}$ +8% relative to 2011

FOM = $LP^2$
(single spin experiments)

FOM = $LP^4$
(double spin experiments)
Optically Pumped Polarized H⁻ source (OPPIS) – A. Zelenski

Upgraded OPPIS (2013)

Test setup on 10 May 2012

Goals:

1. H⁻ beam current increase to 10mA (order of magnitude)
2. Polarization to 85-90% (~5% increase)

Upgrade components:

1. Atomic hydrogen injector (collaboration with BINP Novosibirsk)
2. Superconducting solenoid (3 T)
3. Beam diagnostics and polarimetry

Source (H⁺)  Neutralizer (H₀)  Ionizer Rb-cell Sona    Na-jet (H⁻)

New Atomic Beam Source (ABS)

New superconducting solenoid

=> 10x intensity from ABS was accelerated through Linac
Motivation

Bunch intensity in 2012 polarized proton physics store

Goal:

Compensate for 1 of 2 beam-beam interactions with electron lenses

Then increase bunch intensity $\Rightarrow$ up to $2\times$ luminosity

Need new polarized proton source – under construction, A. Zelenski

$L \propto N_b^2$
Electron lenses – partial head-on beam-beam compensation

Basic idea:
• 2 beam-beam collisions with **positively** charged beam
• Add collision with a **negatively** charged beam – with matched intensity and same amplitude dependence

Compensation of nonlinear effects:
• e-beam current and shape  
  => reduces tune spread
• $\Delta \psi_{x,y} = k\pi$ between p-p and p-e collision  
  => reduces resonance driving terms

Installation in 2012
Expect up to 2x more luminosity
Workshop program

- $^3\text{He}^{\uparrow}$ source, $^3\text{He}^{\uparrow}$ beams from EBIS
- $^3\text{He}^{\uparrow}$ in Booster/AGS
- $^3\text{He}^{\uparrow}$ in RHIC and EIC
- Polarimetry (low and high energy)
- Physics with $^3\text{He}^{\uparrow}$ beams (theory and experiments)
Development of Polarized $^3$He Ion Source for RHIC
BNL-MIT Collaboration  http://he3.xvm.mit.edu/

R. Milner, C. Epstein, MIT

- Spec.: deliver $^3$He$^{++}$ at \( \approx 3 \times 10^{12} \) atoms/sec with 70% polarization
- Concept: polarize $^3$He gas in glass cell using MEOP in fringe field of \( \approx 5 \) Tesla EBIS solenoid and feed into EBIS
- MEOP technology under development at MIT
  - two Keopsys 10 Watt lasers operational
  - data acquisition system operational
  - 20 liters of $^3$He gas ordered
  - glass systems under construction
- Goal: to test principle of source using spare EBIS solenoid within the next year

Funded by DOE Office of Nuclear Physics
R&D Program for Next Generation Nuclear Physics Accelerator Facilities
Polarized $^3$He in RHIC – plan under development

- Polarized $^3$He source developed at MIT (R. Milner)
- Polarized $^3$He beams from EBIS
- Polarimeter after EBIS linac at 2 MeV/nucleon
- Un-polarized $^3$He from EBIS:
  - Injection into Booster at low rigidity
  - Acceleration in Booster, AGS, RHIC?
  - Test carbon polarimeters
- Acceleration of polarized $^3$He in Booster and transfer to AGS
  - Vertical tune in Booster < 4.19 !!
- Measure polarization at AGS injection energy, no depolarization?
- Accelerate $^3$He in AGS and measure polarization on ramp and extraction
- Calibrate $A_N$ of carbon polarimeter at extraction energy with up/down ramp?
- Transfer to RHIC and calibrate carbon polarimeter in RHIC (which ring?)
- Absolute polarization measurement at RHIC injection with pol. $^3$He jet/cell
- Accelerate in RHIC and measure polarization on ramp and at store energy
  - May need 4 more snakes in Blue ring
- Calibrate $A_N$ of carbon polarimeter at store energy with up/down ramp
- Absolute polarization measurement at RHIC store with pol. $^3$He jet/cell
Possible running modes Run-13 and Run-14 (BUPs)

Run-13

- 500 GeV p-p (STAR, PHENIX) ~10 weeks
- 200 GeV p-p (PHENIX) ~3-4 weeks
- 30 GeV p-p (PHENIX) ~1.5 weeks
- 200 GeV Au-Au (STAR) ~4 weeks

Run-14

- 200 GeV Au-Au (STAR, PHENIX) ~6-8 weeks
- 200 GeV p-p (STAR, PHENIX) ~4 weeks
- 200 GeV d-Au (PHENIX) ~6 weeks
## RHIC luminosity and polarization goals

<table>
<thead>
<tr>
<th>parameter</th>
<th>unit</th>
<th>achieved</th>
<th>goals</th>
</tr>
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<tr>
<td><strong>Au-Au operation</strong></td>
<td></td>
<td>2011</td>
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<tr>
<td>energy</td>
<td>GeV/nucleon</td>
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<td>100</td>
</tr>
<tr>
<td>no colliding bunches</td>
<td>...</td>
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<td>111</td>
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<tr>
<td>bunch intensity</td>
<td>$10^9$</td>
<td>1.3</td>
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<tr>
<td>avg. luminosity</td>
<td>$10^{26}$ cm$^{-2}$s$^{-1}$</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td><strong>p↑-p↑ operation</strong></td>
<td></td>
<td>2012</td>
<td>≥ 2013</td>
</tr>
<tr>
<td>energy</td>
<td>GeV</td>
<td>100 255</td>
<td>100 250</td>
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<tr>
<td>no colliding bunches</td>
<td>...</td>
<td>– 107 –</td>
<td>– 107 –</td>
</tr>
<tr>
<td>bunch intensity</td>
<td>$10^{11}$</td>
<td>1.6 1.7</td>
<td>1.6 2.0</td>
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<tr>
<td>avg. luminosity</td>
<td>$10^{30}$ cm$^{-2}$s$^{-1}$</td>
<td>33 105</td>
<td>30 150</td>
</tr>
<tr>
<td>avg. polarization*</td>
<td>%</td>
<td>58 52</td>
<td>– 60 –</td>
</tr>
</tbody>
</table>

*Intensity and time-averaged polarization as measured by the H-jet. Luminosity-averaged polarizations, relevant in single-spin colliding beam experiments, are higher. For example, for intensity-averaged $P = 48\%$ and $R_x = R_y = 0.2$ (250 GeV, 2011), the luminosity-averaged polarization is $P = 52\%$. 

3D stochastic cooling + 56 MHz SRF

Source + e-lenses
Projections projection for Au-Au

[Note: assume 12 weeks of physics, 8 weeks of ramp-up, start at ¼ of max]

[Note 2: last projections from 14 October 2011 still valid – close to peak performance goals for both polarized protons and heavy ions, will update after Run-12]
Polarized proton projection for Run-13

Polarization (as measured by H-jet): 50-60%

New: lattice (for e-lens, new phase shifter ps), partial or full source upgrade, e-lens (largely commissioning in Run-13)
Projections for polarized protons

[p-p luminosity projections 100 GeV and 250 GeV]

incremental changes
($\varepsilon_{x,y}$, $\varepsilon_s$, $\delta\beta/\beta$, ...)

56 MHz SRF

polarized source upgrade
electron lenses (+ new lattice)

250 GeV

100 GeV

Fiscal year

Integrated luminosity [fb$^{-1}$]

[Note 1: assume 12 weeks of physics, 8 weeks of ramp-up, start at ¼ of max]
[Note 2: last projections from 14 October 2011 still valid – close to peak performance goals for both polarized protons and heavy ions, will update after Run-12]
Run-12
- Polarized protons at $\sqrt{s} = 200, 510$ GeV
  new records for $\sqrt{s}, L_{\text{peak}}, L_{\text{avg}}, P$
- First U-U collisions at $\sqrt{s_{NN}} = 193$
  3D stochastic cooling $\Rightarrow$ 5x $L_{\text{avg}}$ 5x, only burn-off losses
- First Cu-Au collisions $\sqrt{s_{NN}} = 200$ GeV

Run-13 – upgrades mainly for polarized protons
- Polarized source upgrade (partial or full)
  10x intensity, +5% P
- Electron lenses
  requires new lattice, commissioning in Run-13

Run-14 – upgrades mainly for heavy ions
- 56 MHz SRF, +30-50% $L$
- Long. stochastic cooling hardware (pickup, kickers)

Low-energy cooling possible for Au-Au
  up to $\sqrt{s_{NN}} = 20$ GeV with Pelletron; up to $\sim 10x$ $L$;
  $\geq 2017$ – limited by funding, technical resources, personnel