RHIC upgrades and capabilities for the next decade

Wolfram Fischer
Brookhaven National Laboratory
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1. A short history and outlook of RHIC
   species, energies, luminosity, polarization

2. Upgrades for high energy A+A
   bunch intensity + stochastic cooling

3. Upgrades for low energy A+A
   bunch intensity + electron cooling

4. Upgrades for p↑+p↑
   bunch intensity + head-on beam-beam
   compensation, polarization
Relativistic Heavy Ion Collider –
high-luminosity heavy ion and only polarized proton collider

Circumference : 3.8 km
Max dipole field : 3.5 T
Energy, $\sqrt{s_{NN}}$ : 200, 510 GeV p
 : 7.7 – 200 GeV Au
Species : p↑ to U (incl. asymmetric)
Experiments : STAR, PHENIX (→ sPHENIX)
RHIC science programs

1. Creation and study of the Quark Gluon Plasma

- QGP close to perfect liquid
  - The QGP is a strongly coupled nearly “perfect” liquid ($\eta/s$ near the quantum limit $1/4\pi$). RHIC’s cooler QGP is (on average) closer to perfection than the 40% hotter QGP produced at LHC.

2. Origin of the proton spin

- $\frac{1}{2} = \frac{1}{2} + \frac{1}{2} + \frac{1}{2} + \frac{1}{2}$

RHIC result: not zero over some x-range

A short history and outlook of RHIC
RHIC – all running modes to date

2001 to 2016

nominal injection energy

2016

2015

2019/20 BES-II

Species combination

Center-of-mass energy $\sqrt{s_{NN}}$ [GeV] (scale not linear)

nominal injection energy
Delivered Integrated Luminosity – symmetric species

Run-14 Au+Au luminosity exceeds all previous Au+Au runs combined.

Run-13 p+p luminosity exceeds all previous p+p runs combined.
Run-15 all previous 100 GeV runs

Dramatic increase in performance as a result of R&D, capital projects, Accelerator Improvement Projects, and replacement of obsolete technology.

Nucleon-pair luminosity: luminosity calculated with nucleons of nuclei treated independently; allows comparison of luminosities of different species; appropriate quantity for comparison runs.
Delivered Integrated Luminosity – asymmetric species

5 asymmetric combination to date:
- $p^\uparrow + Au$,
- $p^\uparrow + Al$ (never done before)
- $h + Au$
- $d + Au$ (at 4 different energies)
- $Cu + Au$

Asymmetric operation requires:
- sources for two different beams (laser ion source + EBIS; Tandems)
- reliable injector switch-over during RHIC injection (AGS cold snake turn on/off for $p^\uparrow$)
- accommodation of tighter apertures in IRs (DX magnet move for $p^\uparrow + A$, limitations from CeC PoP chamber in Run-16)
- in $p^\uparrow + A$: acceleration of $A$ to plateau near transition for proton injection
- increased experimental protection (PHENIX MPC-EX damage in Run-15)

Best week $d + Au$ Run-16 10x better than Run-8
### RHIC proposed run plan – extents to mid 2020s

<table>
<thead>
<tr>
<th>Years</th>
<th>Beam Species and Energies</th>
<th>Science Goals</th>
<th>New Systems Commissioned</th>
</tr>
</thead>
</table>
| 2016    | High statistics Au+Au d+Au beam energy scan                    | Complete heavy flavor program  
First measurement of $\Lambda_c$  
Collectivity in small systems | Coherent e-cooling test I  
**today**                         |
| 2017    | High statistics Pol. p+p at 510 GeV                            | Transverse size, jet/hadron physics  
PRL submission  
Cooling efficiency | PRL submission  
Cooling efficiency                                      |
| 2018    | $^{96}$Zr+$^{96}$Ru at 200 GeV  
Au+Au at 27 GeV ?       | Establish scaling for $^{96}$Zr+$^{96}$Ru  
Establish scaling for Au+Au  
Cooling efficiency | PRL submission  
Cooling efficiency                                      |
| 2019-20 | 7.7-20 GeV Au+Au (BES-2)                                       | Search for of deconfinement  
Jet, di-jet, v-jet probes of parton  
transport and Color screens | sPHENIX Installation                                      |
| 2021    | TBD                                                            | Contingency for BES-2 extension ?  
sPHENIX installation                                           |
| 2022-?? | 200 GeV Au+Au with upgraded detectors  
Pol. p+p, p+Au at 200 GeV | Jet, di-jet, v-jet probes of parton  
transport and Color screens | sPHENIX installation                                      |
| mid-2020s | Transition to eRHIC ?                                        | Gluon structure  
eRHIC runs                                          | sPHENIX L requests require upgrades |

- **Natural abundance of 3% and 6% respectively**

- **High-energy $p^p+p^p$ and A+A STAR (need leveled L)**

- **Low-energy A+A STAR (L requests require new e-cooler)**

- **High-energy $p^p+p^p$, A+A, $p^p+A$ STAR and sPHENIX (sPHENIX L requests require upgrades)**
## RHIC ultimate luminosity and polarization goals at high energy

<table>
<thead>
<tr>
<th>parameter</th>
<th>unit</th>
<th>achieved</th>
<th>goals</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/nucleon</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>no colliding bunches</td>
<td>...</td>
<td>111</td>
<td>111</td>
</tr>
<tr>
<td>bunch intensity</td>
<td>$10^9$</td>
<td>2.0</td>
<td>2.5 (2.0)</td>
</tr>
<tr>
<td>avg. luminosity</td>
<td>$10^{26}$ cm$^{-2}$s$^{-1}$</td>
<td>87</td>
<td>175 (100)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>44× design</td>
<td>2× achieved</td>
</tr>
<tr>
<td><strong>p↑-p↑ operation</strong></td>
<td></td>
<td>2015</td>
<td>≥ 2021</td>
</tr>
<tr>
<td>energy</td>
<td>GeV</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>no colliding bunches</td>
<td>...</td>
<td>– 111 –</td>
<td>– 111 –</td>
</tr>
<tr>
<td>bunch intensity</td>
<td>$10^{11}$</td>
<td>2.25</td>
<td>3.0</td>
</tr>
<tr>
<td>avg. luminosity</td>
<td>$10^{30}$ cm$^{-2}$s$^{-1}$</td>
<td>63</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td></td>
<td>160</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1× design</td>
<td>2.8× achieved</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.3× design</td>
<td>3.8× achieved</td>
</tr>
<tr>
<td>avg. polarization*</td>
<td>%</td>
<td>55</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>52</td>
<td>55</td>
</tr>
</tbody>
</table>

*Intensity and time-averaged polarization as measured by the H-jet. Luminosity-averaged polarizations are higher.
Physics integration

BES-I and BES-II luminosities

- 4x increase in $L_{\text{avg}}$ with e-cooling
- 3x increase in $L_{\text{avg}}$ without e-cooling

nominal injection energy

initial and avg. luminosity [$10^{24}$ cm$^{-2}$s$^{-1}$]

center-of-mass energy $\sqrt{s}_{\text{NN}}$ [GeV]
RHIC high-energy A+A operation with stochastic cooling
RHIC Run-14

Delivering RHIC-II luminosity

Increase in initial luminosity result of larger bunch intensity

Increase in luminosity lifetime result of 3D cooling, >90% burn-off

2007, Beginning of RHIC-II upgrade

2014, End of RHIC-II upgrade
Au bunch intensity evolution

\[ L(t) = \frac{1}{4\pi} f_0 N \frac{N_b^2(t)}{\varepsilon(t) \beta^*(t)} h(\beta^*, \sigma_s, \theta) \]

- \( \gamma \)-jump, octupoles at transition
- 111 bunches
- scrubbing with protons
- 43 bunches
- EBIS, Booster 4\( \rightarrow \)2\( \rightarrow \)1, AGS 8\( \rightarrow \)4\( \rightarrow \)2 merge
- AGS 12\( \rightarrow \)6\( \rightarrow \)2 merge
- ultimate goal
  (raised from 2.0\( \times \)10\(^9\) this year)

main limits:
- injectors output
- e-cloud in RHIC
- transition instability in RHIC

H. Huang, K. Gardner, K. Zeno, RF, et al.
3D stochastic cooling for heavy ions

M. Brennan, M. Blaskiewicz, F. Severino, PRL 100 174803 (2008); K. Mernick PRSTAB, PAC, EPAC

longitudinal kicker cavity (half side with waveguides)

horizontal kicker (open)

vertical kicker (closed)

longitudinal pickup

transverse pickups, FO

fibre-optic links

microwave links

5-9 GHz, cooling times ~1 h

horizontal and vertical pickups
Run-16 Au+Au at 100 GeV/nucleon

- More collisions in 10 min than in entire 5-week commissioning run in 2001
- $L_{\text{avg}}$ now 44x design

Luminosity

Run Coordinator: Xiaofeng Gu

25% increase in bunch intensity due to AGS bunch merging scheme at injection change from 8→4→2 to 12→6→2 (with minimal increase in longitudinal emittance!)

Maximized $L$ to PHENIX and delivered leveled $L$ to STAR using stochastic cooling and transverse offset at IP

Image of graph showing time evolution of Au+Au with two plateaus: 1st plateau: 2.8 weeks (not good – quench protection diode failure need machine protection upgrade), 2nd plateau: 5.6 weeks (good – switched in and out of d+Au quickly).
RHIC low-energy A+A operation with electron cooling
LEReC Physics integration

RHIC Beam Energy Scan II (BES-II)
for search of critical point in QCD phase diagram

<table>
<thead>
<tr>
<th>center-of-mass energy $\sqrt{s_{NN}}$ GeV</th>
<th>7.7</th>
<th>9.1</th>
<th>11.5</th>
<th>14.6</th>
<th>19.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>events BES-I, actual</td>
<td>M</td>
<td>4.3</td>
<td>11.7</td>
<td>24</td>
<td>36</td>
</tr>
<tr>
<td>events BES-II, min goal</td>
<td>M</td>
<td>80</td>
<td>100</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>events BES-II, full goal</td>
<td>M</td>
<td>100</td>
<td>160</td>
<td>230</td>
<td>300</td>
</tr>
</tbody>
</table>

General strategy to maximize integrated luminosity:

Cooling at the 3 lowest energies (4x gain in $L_{avg}$),
no cooling at the 2 highest energies (3x gain in $L_{avg}$)
=> demonstrated at $\sqrt{s_{NN}} = 19.6$ GeV in Run-16

Start BES-II at highest energies (machine ready w/o cooling)
Interleave cooling commissioning with physics operation
Finish BES-II at lowest energies (largest gain in $L_{avg}$ and time)
Physics integration

BES-I and BES-II luminosities

- 4x increase in $L_{\text{avg}}$ with e-cooling
- 3x increase in $L_{\text{avg}}$ without e-cooling

Initial and average luminosity [10^{24} \text{ cm}^{-2}\text{s}^{-1}]

Center-of-mass energy $\sqrt{s_{\text{NN}}} [\text{GeV}]$

Nominal injection energy

BES-II

BES-I
Low Energy RHIC electron Cooling (LEReC)

A. Fedotov et al.

64 m to IP2

(not to scale)

Energies $E$ : 1.6, 2.0 (2.65) MeV
Avg. current $I_{avg}$ : 27 mA
Momentum $\delta p/p$ : $5 \times 10^{-4}$
Luminosity gain : $4 \times$

1st bunched beam electron cooler
planned operation in 2019/2020
RHIC $p^+ + p^+$ operation with head-on beam-beam compensation
Special devices for polarized protons: source, polarimeters, snakes, rotator, flipper

- Absolute Polarimeter (H jet)
- RHIC pC Polarimeters
- Spin rotators (longitudinal polarization)
- Solenoid Partial Siberian Snake
- RHIC pC Polarimeters
- Spin rotators (longitudinal polarization)
- Siberian Snakes
- Spin flipper
- Strong AGS Snake

Polarimeters need to keep pace with intensity upgrades

- Pol. H⁻ Source
- 200 MeV Polarimeter
- AGS Polarimeter
- AGS Siberian Snake
- Helical Partial Siberian Snake
- Linac Booster

PHENIX (p)

STAR (p)
\[ L(t) = \frac{1}{4\pi} f_0 N \frac{N_b^2(t)}{\varepsilon(t) \beta^*(t)} h(\beta^*, \sigma_s, \theta) \]

**FOM** = \( L P^4 \sim N_b^2 P^4 \) (double spin experiments)

**p bunch intensity and polarization**

- injectors output
- polarization
- e-cloud in RHIC
- beam-beam in RHIC

**AGS warm snake**
- polarized source upgrade with sc solenoid

**AGS cold snake**
- AGS tune jumps, RHIC 9 MHz RF
- polarized source upgrade with Atomic Beam Source
- beam-beam compensation

**Ultimate goal**

**Main limits:**
- injectors output
- polarization
- e-cloud in RHIC
- beam-beam in RHIC

A. Zelenski, H. Huang, K. Gardner, K. Zeno, RF, et al.
Run-15 $p^+ + p^+$ at 100 GeV

First hadron collider with head-on beam-beam compensation: lattice + e-lenses

New lattice (ATS type, S. White) – phase advance $k\pi$ between IP8 and e-lens minimizes beam-beam resonance driving terms

Electron lenses – reduce beam-beam induced tune spread

Tune width measurement: imaginary part of complex beam transfer function (BTF); $p+Al$ – no coherent bb modes

New lattice has larger off-momentum dynamic aperture and accommodates higher beam-beam parameter $\xi$
Transition to an electron-ion collider, mid 2020s

White paper requirements:

- 70% polarized e and p/d/h beams ✔
- Ion beams from d to Pb/U ✔
- $E_{\text{com}}$ from 20 to 100 (150) GeV ✔
- Luminosity $10^{33} - 10^{34}$ cm$^{-2}$s$^{-1}$
- Possibility of more than 1 IR

Jefferson Lab also working on an EIC

Plenary presentation this afternoon:

Abhay Deshpande, Stony Brook

“Science and status of the Electron-Ion Collider in the US”

High-current polarized electron gun (LR)
- R&D at MIT, JLab, and BNL (Gatling gun)

Highly-damped SRF (LR)
- LDRD at BNL

FFAG multi-pass ERL (LR)
- Cβ at Cornell – d

SRF crab cavities (LR+RR)
- R&D at BNL and CERN (HL-LHC)

Strong hadron cooling (LR+RR)
- R&D at BNL and JLab
RHIC for the next decade

Summary

Status

• Au+Au \( L_{\text{avg}} = 8.7 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1} \) (44x design)
• \( p^{\uparrow}+p^{\uparrow} \ L_{\text{avg}} = 1.6 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \) (1.3x design), \( P_{\text{avg}} = 53\% \)
• Au+Au energy range \( \sqrt{s_{\text{NN}}} = 7.7 – 200 \text{ GeV} \)
  (lowest \( E \sim 1/3 \) of nominal injection)
• flexibility to collide any ion with any other ion from \( p^{\uparrow} \) to U
• leveled luminosity for STAR

Upgrades

• Au+Au at \( \sqrt{s_{\text{NN}}} = 200 \text{ GeV} \): \( 2x L_{\text{avg}} \)
  increase in bunch intensity, MPS
• Au+Au at \( \sqrt{s_{\text{NN}}} = 7.7 – 20 \text{ GeV} \): \( 3-4x L_{\text{avg}} \)
  increase in bunch intensity, construction of 1\textsuperscript{st} bunched beam electron cooler
• \( p^{\uparrow}+p^{\uparrow} \): \( 3-4x L_{\text{avg}} \)
  increase in bunch intensity while maintaining polarization
  full use of head-on beam-beam compensation
• maintain flexibility