RHIC Polarized Collider and eRHIC

- Recent performance of RHIC
- Future plans for polarized beams at RHIC
- Accelerator R&D towards eRHIC
- The next machine: eRHIC, a polarized electron-polarized proton collider
RHIC – a High Luminosity Polarized Hadron Collider

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Operated modes (beam energies):
- Au – Au (3.8/4.6/5.8/10/14/32/65/100 GeV/n)
- U – U (96.4 GeV/n)
- Cu – Cu (11/31/100 GeV/n)
- p↑ – p↑ (11/31/100/205/250/255 GeV)
- d – Au* (100 GeV/n)
- Cu – Au* (100 GeV/n)

Achieved peak luminosities:
- Au – Au (100 GeV/n) \(195 \times 10^{30}\) cm\(^{-2}\) s\(^{-1}\)
- p↑ – p↑ (255 GeV) \(165 \times 10^{30}\) cm\(^{-2}\) s\(^{-1}\)

Other large hadron colliders (scaled to 255 GeV):
- Tevatron (p – pbar) \(110 \times 10^{30}\) cm\(^{-2}\) s\(^{-1}\)
- LHC (p – p) \(430 \times 10^{30}\) cm\(^{-2}\) s\(^{-1}\)

Planned or possible future modes:
- Au – Au (2.5 GeV/n)
- p↑ – Au* (100 GeV/n)
- p↑ – \(^3\)He↑* (166 GeV/n)

(*asymmetric rigidity)
RHIC Integrated Luminosity and Polarization (RHIC II performance!)

- **Further upgrades:**
  - 56 MHz SRF system to reduce vertex length
  - Electron lenses to ~ double pp luminosity
  - Polarization goal: 70 %

*Nucleon-pair luminosity*: luminosity calculated with nucleons of nuclei treated independently; allows comparison of luminosities of different species; appropriate quantity for comparison runs.
RHIC Facility Upgrade Plans

- EBIS (2012) (low maintenance linac-based pre-injector; all species including U and polarized $^3$He)
- RHIC luminosity upgrade (RHIC II) ($\geq$ 2012):
  [Au-Au: $40 \times 10^{26}$ cm$^{-2}$ s$^{-1}$; 500 GeV p-p: $1.5 \times 10^{32}$ cm$^{-2}$ s$^{-1}$]
- 0.5 m $\beta^*$ for Au – Au and p↑ - p↑ operation
- Stochastic cooling of Au beams and 56 MHz storage SRF system in RHIC
- Further luminosity upgrade for p↑ - p↑ operation ($\geq$ 2014):
  [500 GeV p-p: $\sim 3 \times 10^{32}$ cm$^{-2}$ s$^{-1}$]
- Electron lens in RHIC for head-on beam-beam compensation ($\times$ 2)
- Low energy ($\sqrt{s} = 5…30$ GeV) Au-Au collisions for critical point search
- $\sim 1…5$ MeV electron cooling of Au beams at injection ($\geq$ 2017)
- eRHIC: high luminosity ($\sim 1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$) eA and pol. ep collider using 5-10 GeV and later up to 30 GeV electron driver, based on an Energy Recovering Linac (ERL), and strong cooling of hadron beams ($> 2020$) Exploring gluons at extreme density!
RHIC Run 12 Performance

- Record luminosities and beam polarizations (61.8% (B); 56.6% (Y)) at 100 GeV
- Record luminosities and beam polarizations (50.3% (B); 53.5% (Y)) at 255 GeV
- First acceleration of $^3$He (unpolarized) in AGS during short test run; Operation of $^3$He-C CNI polarimeter demonstrated

- First U-U collisions; x 5 luminosity from 3-D stochastic cooling
- First Cu-Au collisions; exceeding max. luminosity predictions with record EBIS/injector performance and 3-D stochastic cooling
- 2.5 GeV Au-Au test with decent beam lifetime
- Very short set-up time due to flawless operation of beam-based feed-back system
- First hadron collider with increasing luminosity!

Luminosity in U-U store
Beams cooled to $\varepsilon_{\text{rms, norm}} = 0.4 \, \mu\text{m}$
RHIC – First Polarized Hadron Collider

Spin rotators (longitudinal polarization)

Absolute polarimeter (H↑ jet)

pC polarimeters

Spin flipper

Siberian Snakes

PHENIX

Spin rotators (longitudinal polarization)

STAR

Siberian Snakes

LINAC

POLARIZED H⁻ SOURCE

200 MeV polarimeter

10-25% helical partial Siberian Snakes

5.9% helical partial Siberian Snakes

Int. polarimeter

pC polarimeters

10-25% helical partial Siberian Snakes
Beam control improvement – feedbacks on ramp

- Slow orbit feedback on every ramp allows for
- Smaller $y_{\text{rms}}$ (smaller imperfection resonance strength)
- Ramp reproducibility (have 24 h orbit variation)
- Continues fast 10 Hz orbit feedback eliminates effect of vibrating triplets
- Tune/coupling feedback on every ramp allows for
  - Acceleration near $Q_y = \frac{2}{3}$ with better polarization transmission
Absolute polarimeter (Pol. Hjet)

- Polarized hydrogen jet target allows for absolute beam polarization measurement:
  \[ P_{\text{Beam}} = P_{\text{Target}} \frac{\varepsilon_{\text{Beam}}}{\varepsilon_{\text{Target}}} \]
- Jet target thickness of \( \sim 1 \times 10^{12} \text{ cm}^{-2} \) achieved
- Jet pol. \( 92 \pm 2 \% \) measured with Breit-Rabi polarimeter
- Analyzing power \( A_N \sim 0.044 \) (24 – 255 GeV)

Relative polarimeters (proton-carbon)

- Measure horizontal and vertical polarization profiles
- Fast measurements (~ 2 minutes)

Local polarimeters (forward neutron production)

- Significant asymmetry, calibrated with Hjet
- Used to adjust transverse polarization component to zero
Results from Run 12

100 GeV

- Average store pol. from Hjet
  
  61.8±0.5% (B); 56.6±0.5% (Y)

- Pol. decay from pC polarimeters

255 GeV beam

- Average store pol. from HJet
  
  50.3±0.5% (B); 53.5±0.5% (Y)

- Pol. decay from pC polarimeters
Depolarization in AGS and RHIC

- Polarization loss from intrinsic resonances: polarization lost at edge of beam → polarization profile (A. Bazilevsky, Thu., 5:20 pm)
- Impact of polarization profile on beam polarization at collisions $P_{\text{coll.}}$:

$$ P(x, x', y, y') = P_0 e^{-\frac{x^2 + x'^2}{2\sigma_{x,p}^2}} e^{-\frac{y^2 + y'^2}{2\sigma_{y,p}^2}} ; \quad I(x, x', y, y') = I_0 e^{-\frac{x^2 + x'^2}{2\sigma_{x,I}^2}} e^{-\frac{y^2 + y'^2}{2\sigma_{y,I}^2}} ; \quad R_H = \frac{\sigma_{x,I}}{\sigma_{x,p}} ; \quad R_V = \frac{\sigma_{y,I}}{\sigma_{y,p}} $$

$$ \langle P \rangle = P_0 \frac{1}{(1+R_H)(1+R_V)} ; \quad P_{\text{coll.}} = P_0 \frac{1}{\sqrt{1+\frac{1}{2}R_H}} \frac{1}{\sqrt{1+\frac{1}{2}R_V}} \sqrt{\frac{1+R_H}{1+\frac{1}{2}R_H}} \sqrt{\frac{1+R_V}{1+\frac{1}{2}R_V}} = \langle P \rangle \frac{\sqrt{1+R_H}}{\sqrt{1+\frac{1}{2}R_H}} \frac{\sqrt{1+R_V}}{\sqrt{1+\frac{1}{2}R_V}} $$

- For $R_H \approx R_V$ and small: $P_0 = \langle P \rangle (1+\langle R \rangle)^2 ; \quad P_{\text{coll.}} = \langle P \rangle (1+\frac{1}{2}\langle R \rangle)$
- Note that $P_0$, the polarization of the core particle, should be equal to the maximum achievable polarization.
- Loss of average polarization is compatible with development of polarization profiles → all remaining polarization loss in AGS and RHIC is due to vertical and horizontal intrinsic resonances. (no coherent polarization loss)
Depolarization measurements using up/down ramps

- Asymmetry measurements before acceleration and after identical deceleration determines all sources of depolarization
- AGS up/down measurement gives ~ 10–15 % residual depolarization
- No depolarization up to 100 GeV in RHIC
- RHIC up/down measurements between 100 and 250 GeV give ~ 10–15% depolarization
- Consistent with pol. profiles

AGS up / down ramp w/o jump quads
Suggests 15% loss on up ramp.
Polarization improvements

- New high intensity OPPIS (A. Zelenski, Tue., 3 pm) (+5%)
- 80 horizontal tune jump in AGS operational with high intensity beam
- AGS loss before extraction -> fast, on-the-fly extraction (+ 5%)
- Acceleration near $Q_v = \frac{2}{3}$ in RHIC operational
- Reduce spin tune spread by matching dispersion at the snake locations (+?%)
- 0.5 – 1.0 % polarization loss during 100 and 255 GeV stores: not understood, shorter stores?

With jump quads
\[ \langle P \rangle = 67.6 \pm 1.0 \% \]
\[ R_H = 0.02 \pm 0.02 \]
Jump quads off time
\[ \langle P \rangle = 62.6 \pm 1.5 \% \]
\[ R_H = 0.07 \pm 0.03 \]

Snake resonances:
\[ \nu_y = \frac{2n + 1}{2m} \]
Polarized $^3$He in RHIC

- Polarized $^3$He possible from new EBIS (J. Maxwell, Tue., 3:30 pm)
- Max. energy in RHIC: 170 GeV/n
- Depolarizing res. are stronger, however no depolarization expected with six snakes in RHIC
- Accelerated unpolarized $^3$He from EBIS in AGS
- Relative pol.: $^3$He-C CNI polarimeter; successfully tested with unpolarized $^3$He
- Absolute pol.: $^3$He-$^3$He CNI polarimeter using polarized $^3$He jet?
eRHIC: Electron Ion Collider at BNL
Add an electron accelerator to the existing RHIC

Unpolarized and 80% polarized leptons
5 - 30 GeV

70% polarized protons
50 - 250 (275*) GeV

Light ions (d, Si, Cu)
50 - 100 (110*) GeV/u

Heavy ions (Au, U)
50 - 100 (110*) GeV/u

Pol. light ions ($^3$He)
50 - 167 (184*) GeV/u

Center-of-mass energy range: 30 - 175 GeV
Any polarization direction in lepton-hadrons collisions

* We are exploring a possibility of increasing RHIC ring energy by 10% - 30%
eRHIC design status

- 10 – 30 GeV electron beam accelerated with Energy Recovery Linac (ERL) inside existing RHIC tunnel collides with existing 250 GeV polarized protons and 100 GeV/n HI RHIC beams
- Single pass allows for large collision disruption of electron bunch and high luminosity \( L \sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \) and full electron polarization transparency

Accelerator R&D:
- High current (50 mA) pol. electron gun
- Multi-pass high average current ERL
- Coherent electron cooling of hadron beam
- Polarized \(^3\text{He} \) in RHIC

1\textsuperscript{st} stage: 5-10 GeV electron beam
- Similar to CEBAF 12 GeV upgrade (1 GeV SRF linac + recirculating arcs)

Box area corresponds to the first stage
High CW current (50 mA) polarized electron gun

- Matt Poelker (JLab) achieved 4 mA with good lifetime (Tue., 5:20 pm)
- More current with (effectively) larger cathode area

Single large area cathode
(Development at MIT)

Gatling electron gun: many smaller cathodes
(Development at BNL)

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Energy Recovery Linac (ERL) Test Facility

- Test of high current (0.5 A), high brightness ERL operation
- Highly flexible return loop lattice to test high current beam stability issues
- Allows for addition of a 2\textsuperscript{nd} recirculation loop
- Similar beam current in cavity as for multi-pass eRHIC ERL
- First beam from gun this year

1 MW, 703.75 MHz CW Klystron

SRF Gun
2MV, 0.5A

5 Cell SRF “single mode” cavity
$Q > 10^{10}$ @20 MV/m CW
Coherent electron Cooling (CeC)

- 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 → 10x reduced proton emittance gives high eRHIC luminosity at much reduced electron current
- Proof-of-principle demonstration planned with 40 GeV/n Au beam in RHIC (commissioning during run 15)

**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

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Helical wiggler prototype
CeC for RHIC: High Luminosity with large Piwinski angle

- If head-on collisions are at beam-beam limit, large Piwinski angle collisions with very small emittance can increase luminosity (Super B factory).
- Needs strong cooling: synchrotron rad. or CeC.
- Separate bunches outside high luminosity region to avoid beam-beam from low luminosity region.
- Reducing beam emittance back to beam-beam limit.
- Smaller emittance and shorter overlap region allows for smaller beta-star.
- RHIC: overlap length \(\sim 10\) cm, \(\varepsilon_n\) (95\%) \(\sim 1\ \pi\ \mu m\), \(\beta^* \sim 10\) cm \(\rightarrow \sim x10\) luminosity increase (\(\sim 5 \times 10^{33}\) cm\(^{-2}\) s\(^{-1}\)!)
Summary

- Exceptionally successful RHIC Run-12 with record luminosities and polarization

- Additional upgrades for increased luminosity and polarization (new OPPIS, e-lenses) on track

- Accelerator R&D towards high energy beam cooling and high luminosity electron-ion collider: eRHIC