eRHIC Design Status

Christoph Montag
Collider-Accelerator Department
Brookhaven National Laboratory
The Relativistic Heavy Ion Collider RHIC

- Two superconducting storage rings
- 3833.845 m circumference
- Energy range 25 - 250 GeV polarized protons, or 10 - 100 GeV/n gold
- Virtually all ion species, from (polarized) protons to uranium
- Two collider experiments, STAR and PHENIX
- Siberian snakes to preserve proton polarization on the ramp
- Spin rotators to manipulate spin orientation at IPs
- Operating since 2000
Electron-ion collider physics

- How is the nucleon spin of 1/2 composed of its constituents?
- How are gluons spatially distributed in the nucleon?
- How does the gluon density saturate?

An electron-ion collider (EIC) will provide enhanced access to the nucleon’s “inner landscape”
eRHIC Design Requirements
based on EIC White Paper

- High luminosity, \(10^{33} - 10^{34}\) cm\(^{-2}\)sec\(^{-1}\)
- Large center-of-mass energy range, 20 – 140 GeV
- Longitudinal spin polarization of both beams
- Arbitrary spin patterns in both beams
- Large acceptance for forward scattered protons with \(200\) MeV/c < \(p_\perp\) < 1.3 GeV/c, and a 4 mrad forward neutron cone
Design Concept

- Based on RHIC with 275 GeV polarized protons
- Electron storage ring with 5 - 18 GeV
- 1320 bunches per ring
- Up to 2.7 A electron current
- Very flat normalized proton emittances, 2.4 $\mu$m hor., 0.1 $\mu$m vert., achieved by strong hadron cooling
- Low proton bunch intensities, 0.75 $\cdot$ 10$^{11}$
- Full energy polarized electron injector
Luminosity vs. center-of-mass energy

1.14 \times 10^{34} \text{ cm}^{-2}\text{sec}^{-1} \text{ peak luminosity}
Staged Approach

- Bunched beam electron cooler for eRHIC is very challenging due to high energy and large number of bunches.

- BNL is developing electron cooler for low energy gold beams - first bunched beam electron cooler in the world.

- To mitigate this risk, start with a design that does not need cooling.

- Upgrade to full luminosity performance once cooling becomes available.
Proton Beam Parameters for Initial Phase

<table>
<thead>
<tr>
<th>Parameter</th>
<th>eRHIC</th>
<th>RHIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_b$</td>
<td>330</td>
<td>110</td>
</tr>
<tr>
<td>max. $N_p$</td>
<td>$10^{11}$</td>
<td>1.5</td>
</tr>
<tr>
<td>$\epsilon_N$ hor./vert.</td>
<td>[µm]</td>
<td>4.7/1.8</td>
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<tr>
<td>min. $\sigma_s$</td>
<td>[cm]</td>
<td>8</td>
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<tr>
<td>max. $\Delta p/p$</td>
<td>$10^{-4}$</td>
<td>14</td>
</tr>
<tr>
<td>min. $\beta_p^*$</td>
<td>[cm]</td>
<td>4.4</td>
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<tr>
<td>max. $\beta_p$</td>
<td>[km]</td>
<td>1.2</td>
</tr>
<tr>
<td>min. $\tau_{IBS}$</td>
<td>[h]</td>
<td>7.3</td>
</tr>
<tr>
<td>max. $\mathcal{L}$</td>
<td>[$10^{33}$ cm$^{-2}$sec$^{-1}$]</td>
<td>2.9</td>
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</tbody>
</table>

- Only most extreme parameters are listed - complete list in Backup Slides
- Proton emittances can be achieved by slight shaving (vertical, 25 percent reduction) and noise injection (horizontal) - long IBS growth time requires no cooling whatsoever while ensuring high average luminosity
- Necessary decoupling required for flat beams demonstrated at RHIC during 31.2 GeV d-Au run
• Interleaved arrangement of electron and hadron quadrupoles
• 22 mrad total crossing angle, using crab cavities
• Beam size in crab cavity region independent of energy - crab cavity apertures can be rather small, thus allowing for higher frequency
• Forward spectrometer (B0) and Roman Pots (R1-R4) for full acceptance
Actively shielded electron beampipe through superferric hadron spectrometer B0
Hadron quadrupole Q1 with anti-quadrupole to create field-free region for electrons
Proton $\beta$-Functions at 275 GeV

- Maximum $\beta$ around 1200 m, keeping chromaticities small (10 units horizontally, 12 vertically for half IR - similar to present RHIC)
Electron $\beta$-Functions at 18 GeV

- Small chromaticities (10/15 units) due to early focusing
  - corresponding number for KEKB is 38
## IR Hadron Magnet Parameters

<table>
<thead>
<tr>
<th>$s_{\text{upstream}}$ m</th>
<th>$L$ m</th>
<th>IR cm</th>
<th>OR cm</th>
<th>$B_{\text{pole}}$ T</th>
<th>gradient T/m</th>
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<tbody>
<tr>
<td>B0</td>
<td>3.90</td>
<td>1.20</td>
<td>15.0</td>
<td>40.0</td>
<td>-1.70</td>
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<tr>
<td>Q1</td>
<td>5.70</td>
<td>1.86</td>
<td>3.2</td>
<td>10.1</td>
<td>3.39</td>
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<td>B1</td>
<td>10.20</td>
<td>4.80</td>
<td>8.5</td>
<td>38.5</td>
<td>3.52</td>
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<tr>
<td>Q2</td>
<td>15.60</td>
<td>2.40</td>
<td>12.0</td>
<td>33.0</td>
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<td>Q3</td>
<td>33.12</td>
<td>1.20</td>
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<td>1.35</td>
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<tr>
<td>Q4</td>
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<td>1.59</td>
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<td>B2</td>
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<td>B3</td>
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<td>4.0</td>
<td>34.0</td>
<td>0.0</td>
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<td>Q6</td>
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<td>2.00</td>
<td>4.0</td>
<td>34.0</td>
<td>2.20</td>
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</table>

*: Helical dipoles as RHIC spin rotator
IR Electron Magnet Parameters

\[
\begin{array}{|c|c|c|c|c|c|c|}
\hline
 & s_{\text{upstream}} & L & IR & OR & B_{\text{pole}} & \text{gradient} \\
& \text{m} & \text{m} & \text{cm} & \text{cm} & \text{T} & \text{T/m} \\
\hline
\text{Qe1} & 7.99 & 0.86 & 2.5 & 12.5 & 0.73 & -29.20 \\
\text{Qe2} & 9.11 & 0.67 & 3.2 & 13.2 & 1.06 & 33.20 \\
\text{Qe3} & 19.38 & 0.75 & 3.2 & 23.2 & 0.37 & -11.56 \\
\text{Qe4} & 23.25 & 1.50 & 3.7 & 23.7 & 0.36 & 9.63 \\
\hline
\end{array}
\]

- Inner radii determined by maximum $10\sigma$ proton, $15\sigma$ electron size over entire energy range
- Outer radii determined by space available between beams
- Developed conceptual designs for the most challenging magnets, B0 and Q1
Luminosity vs. $\sqrt{s}$ in Initial Phase

- $2.9 \cdot 10^{33}$ cm$^{-2}$sec$^{-1}$ peak luminosity with 10 GeV electrons, 250 GeV protons, including hourglass, crab crossing, and abort gap
- Electron energy 5 GeV or higher, as suggested by detector designers
Electron polarization

Ramping would destroy electron polarization
Electrons self-polarize at store due to synchrotron radiation:

Self-polarization is not viable except at highest energies
⇒ Need a **full-energy polarized injector**
Advantage of a full-energy polarized injector:

- Electron spin patterns with alternating polarization (as in RHIC proton fills) are required for single-spin physics

- Such fill patterns can be generated by a full-energy polarized injector

- Bunches with the “wrong” (unnatural) polarization direction will slowly flip into the “right” orientation. Time scale given by Sokolov-Ternov self-polarization time

- Bunch-by-bunch replacement at 1 Hz (360 bunches in 6 min) yields sufficient polarization even at full energy with $\tau_{S-T} = 30$ min

- Requires good intensity lifetime $> 1$ h to limit beam-beam effect of electron bunch replacement on proton bunches

- Damping ring to reach 50 nC bunch charge. SLC gun produces 16 nC
1. Recirculating linac injector

- Recirculating linac, based on pulsed 650 MHz cavities

- 3 GeV linac seems feasible in 200 m straight section

- 5 return loops to reach 18 GeV
2. Highly symmetric rapid-cycling (or rapid-ramping) synchrotron (RCS)

- At 20 GeV, electron $G \cdot \gamma = 45.4$
  ($G = 0.00115965219 : \text{anomalous gyromagnetic ratio}$)

- Assume a circular RCS, made up of identical periods

- Superperiodicity $P = 48$ and a tune of $\nu = 48.2$ results in depolarizing resonances at $G\gamma = k \cdot P \pm l \cdot \nu$

- Resonance condition fulfilled at $G\gamma = 2 \cdot P - \nu = 47.8$
  - outside the energy range
• High superperiodicity requires a circular ring, unlike the RHIC tunnel with its six straights

• However, if transfer matrices of straights are unit matrices

\[ M_{\text{straight}} = I, \]

energy range remains resonance free
Polarization in RCS with orbit errors

- Spin tracking confirms validity of RCS concept
- 4000 turns used in simulation
- Faster ramping in only 400 turns technically feasible, further improving polarization preservation
Short, sharp bends to increase damping decrement at low energies, thus allowing high electron beam-beam parameter $\xi = 0.1$
Studies and R&D Items

- Beam-beam simulations
- Electron polarization studies
- Multi-turn off-energy injection to eliminate need for accumulator ring
- Crab cavities
- In-situ beampipe copper coating
Crab Cavity Development

- IR design is based on a 22 mrad crossing angle; separator dipole would severely restrict Physics capabilities
- Need crab cavities to restore luminosity, and avoid synchro-betatron resonances
- Prototypes being developed in collaboration with CERN, needed for LHC luminosity upgrade

Critical R&D effort
In-situ Beampipe Copper Coating

- Resistive wall losses in stainless steel beampipes due to increased number of bunches in ring-ring design and short bunch length in ultimate linac-ring design exceed allowable cryo load

- Need copper coating to increase conductivity

- In-situ beam pipe coating of an entire machine has never been done, but successful coating of 20 m combination of cold-bore RHIC tubing & bellows having room temperature conductivity 85% of solid copper was achieved.

50 cm long cathode magnetron being inserted into a RHIC-type beam pipe
Luminosity Upgrade

- Upgrade requires increased number of bunches - 1320 instead of initial 330 - and hadron cooling.

- Alternatively, if recirculating linac is chosen as full-energy injector, ring-ring scheme can be converted to linac-ring by operating full-energy injector in ERL mode. Requires strong hadron cooling as well, but only 110 bunches.

- Intermediate luminosity upgrade can be achieved at all but the highest electron energies by doubling the initial number of bunches, to 660.

- Proof-of-principle of very strong Coherent electron Cooling (CeC) in progress at RHIC.
Summary

- eRHIC design covers the entire EIC White Paper physics case, with $10^{32} - 10^{33} \text{ cm}^{-2}\text{sec}^{-1}$ luminosities

- Need to carry out critical R&D on crab cavities, in-situ beam pipe coating, and cooling

- Cost effective upgrade to $10^{34} \text{ cm}^{-2}\text{sec}^{-1}$ possible, using strong hadron cooling

- Crucial R&D underway to mitigate risk of strong hadron cooling (CeC Proof-of-Principle)