eRHIC Design Status

Christoph Montag, BNL
May 8, 2018

Electron Ion Collider – eRHIC
RHIC

- Two superconducting storage rings
- 3.8km circumference
- Energy up to 255GeV protons, or 100GeV/n gold
- 110 bunches/beam
- 60% proton polarization – world’s only polarized proton collider
- 6 interaction regions, 2 detectors
- In operation since 2001
EIC Physics Questions

Nuclear Physics Community compiled an EIC WHITE PAPER\(^\ast\) (2014/5):

- How are quarks, gluons & their spins distributed in space & momentum in nucleus?
- How do nucleon properties emerge from quarks and gluons and their interactions?
- How do color-charged quarks, gluons & colorless jets, interact with a nuclear medium
- How do confined hadronic states emerge from quarks & gluons
- How do the quark-gluon interactions create nuclear binding?
- How does dense nuclear environment affect the quarks-gluons correlations & interactions?
- Does gluon density in nuclei saturate @ high energy
  \(\Rightarrow\) gluonic matter with universal properties?

\(^\ast\) A. Accardi et al, Eur Phys J A529:268 (2016)
eRHIC is designed to meet the following requirements:

- **High luminosity**: \( L = (10^{33}-10^{34}) \text{ cm}^{-2}\text{sec}^{-1} \)
- **Large range of center-of-mass energies** \( E_{\text{cm}} = (29-140) \text{ GeV} \)
- **Polarized beams** with flexible spin patterns
- **Favorable condition for detector acceptance** such as \( p_T = 200 \text{ MeV} \)
- **Large range of hadron species**: protons ….Uranium
- **Collisions of electrons with polarized protons and light ions** \( (^3\text{He}, ^1\text{d},…) \)

\[ \Rightarrow \]

eRHIC meets or exceeds the requirements formulated in the White Paper on EIC
Design Concept

- eRHIC is based on the RHIC complex: Storage ring (Yellow Ring), injectors, ion sources, infrastructure; needs only relatively few modifications and upgrades.
- Today's RHIC beam parameters are close to what is required for eRHIC (except number of bunches, 3 times higher beam current, and vertical emittance).
- A (5-18) GeV electron storage ring & its injectors are added to the RHIC complex → $E_{cm} = (29-141)$ GeV.
- Design aims to meet the goals formulated in the EIC WHITE PAPER, in particular the high luminosity of $L = 10^{34} \text{cm}^{-2}\text{s}^{-1}$.
- Design is optimized under the assumption that each beam will have the parameters (in particular beam-beam tune shift) as demonstrated in collisions between equal species (HERA Concept).
- The requirement to store electron beams with a variable spin pattern requires an on-energy, spin transparent injector.
- The total synchrotron radiation power of the electron beam is assumed to be limited to 10 MW. This is a design choice, not a technical limitation.
Facility layout

Electron complex to be installed in existing RHIC tunnel – cost effective
# Maximum Luminosity Parameters

- High beam currents
- Many bunches
- Large beam-beam tune-shift
- Flat beams
- **Need strong hadron cooling**
- Short hadron bunches
- 22 mrad crossing angle with crab cavities
- Large Luminosity

<table>
<thead>
<tr>
<th>Parameter</th>
<th>hadron</th>
<th>electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of Mass Energy [GeV]</td>
<td>104.9</td>
<td></td>
</tr>
<tr>
<td>Energy [GeV]</td>
<td>275</td>
<td>10</td>
</tr>
<tr>
<td>Number of Bunches</td>
<td>1320</td>
<td></td>
</tr>
<tr>
<td>Particles per bunch [$10^{10}$]</td>
<td>6.0</td>
<td>15.1</td>
</tr>
<tr>
<td>Beam Current [A]</td>
<td>1.0</td>
<td>2.5</td>
</tr>
<tr>
<td>Horizontal Emittance [nm]</td>
<td>9.2</td>
<td>20.0</td>
</tr>
<tr>
<td>Vertical Emittance [nm]</td>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td>Hor. beta function at IP $\beta_x^*$ [cm]</td>
<td>90</td>
<td>42</td>
</tr>
<tr>
<td>Vert. beta-function at IP $\beta_y^*$ [cm]</td>
<td>4.0</td>
<td>5.0</td>
</tr>
<tr>
<td>horizontal/vertical fractional betatron tunes</td>
<td>0.08/0.06</td>
<td>0.3/0.31</td>
</tr>
<tr>
<td>Horizontal Divergence $d\sigma_x^*/ds$ [mrad]</td>
<td>0.101</td>
<td>0.219</td>
</tr>
<tr>
<td>Vertical Divergence $d\sigma_y^*/ds$ [mrad]</td>
<td>0.179</td>
<td>0.143</td>
</tr>
<tr>
<td>Horizontal Beam-Beam Parameter $\zeta_x$</td>
<td>0.013</td>
<td>0.064</td>
</tr>
<tr>
<td>Vertical Beam-Beam Parameter $\zeta_y$</td>
<td>0.007</td>
<td>0.10</td>
</tr>
<tr>
<td>IBS Growth Time longitudinal/horizontal [hours]</td>
<td>2.19/2.06</td>
<td>-</td>
</tr>
<tr>
<td>Synchrotron Radiation Power [MW]</td>
<td>-</td>
<td>9.18</td>
</tr>
<tr>
<td>Bunch Length [cm]</td>
<td>5</td>
<td>1.9</td>
</tr>
<tr>
<td>Hourglass and crab reduction factor</td>
<td>0.87</td>
<td></td>
</tr>
<tr>
<td>Luminosity [$10^{34} \text{cm}^{-2}\text{sec}^{-1}$]</td>
<td>1.05</td>
<td></td>
</tr>
</tbody>
</table>

- No problem
- Challenge
- Difficult/R&D required
Luminosity versus Center-of-Mass Energy

![Graph showing luminosity versus center-of-mass energy. The graph illustrates the relationship between luminosity and energy with distinct regions labeled as 'Space-charge limited' and 'Beam-beam limited'. The x-axis represents center-of-mass energy in GeV, while the y-axis represents luminosity in $10^{33} \text{ cm}^{-2} \text{s}^{-1}$. The graph highlights the 10 MW SR limit.]
Beam-Beam Physics

- Operate electron ring just above integer resonance to benefit from dynamic focusing and to stay away from half-integer spin resonance

**Concerns:**
- Slow hadron emittance growth, examined using long term weak-strong simulations
  ➔ No evidence
- Coherent beam-beam instability, examined by strong-strong simulations using several codes
  ➔ Threshold found at twice the design intensities
- No strong dependence of beam-beam parameter on radiation damping decrement found
Dynamic Aperture Assessment

Requirements: Hadrons DA > 5 $\sigma$ (RHIC experience)

Long terms tracking in eRHIC hadron ring
- with beam-beam effect
- with multipole errors

Beam-beam has a strong impact on DA
Systematic multipole errors in the IR should not exceed 2 units of $10^{-4}$ @ 25mm
→ High demand of IR magnet design

No attempts to improve DA by nonlinear corrections yet
No study of random errors yet
Electron Ring Dynamic Aperture

- Requirement: > 10 \( \sigma \) in all three planes (lifetime)
- Main issue: 2\(^{nd}\) order chromaticity (local IR \( \xi_{x,y} = -30 \))
- Off-momentum DA still limited at 0.7% (12\( \sigma \)) by 2nd order vertical chromaticity
- On-momentum DA \( \sim 20 \sigma \), limited by tune shift with amplitude \( \frac{\partial Q_{x,y}}{\partial J_{y,x}} \)
- No results with beam-beam and imperfections yet
- No optimization of non-chromatic sextupoles yet
Dynamic Aperture with 2 IRs

- Naively, one would assume that doubling the IR chromaticity and its correction would deteriorate DA.
- **On-momentum**: Checked that dynamic aperture with 2 IR and 2 family sextupole correction is DA > 20 \( \sigma \)
- **Off-momentum**: IR–IR compensation of IR-off momentum beta beat  
  \[ \Delta \psi_{x,y} = \frac{(2k+1)\pi}{2} \]  
  \( \Rightarrow \) need only 2 sextupole families (one per plane)

This is how HERA-II was operated:

- **Without IR-IR compensation**, no DA at desired working point
- **With IR-IR compensation**  
  \[ \Delta \psi_{x,y} = \frac{(2k+1)\pi}{2} \]  
  \( \Rightarrow \) good on-and off-momentum DA

- Need to confirm with systematic tracking
Collective Effects

Electrons:
- Single bunch instabilities checked with standard code and appear to be stable.
- Transverse coupled bunch modes appear to be stable.
- Might need a longitudinal damper for coupled bunch instabilities.
- We consider the possibility of removing the 3\textsuperscript{rd} harmonic RF system ($$)
- **Fast ion instability** is expected to be present and requires feedback to control.
  - Feedback noise might affect hadrons ➔ still needs to be studied and noise specs need to be defined

Hadrons:
- Electron cloud is most worrisome ➔ Cu and amorphous C coating of stainless steel vacuum chamber needed (prepared and planned)
- IBS: 2 hour emittance growth time horiz. and long. ➔ need **strong hadron cooling**
- Coherent instabilities appear to be absent at top energy
- Might need a narrowband damper to control coupled bunch instabilities at injection.
Electron Storage Ring Polarization

Need to store bunches with 85% initial polarization and spins parallel \( \uparrow \uparrow \) and spins antiparallel \( \uparrow \downarrow \) to guide field in the arc.

\[ \rightarrow \text{Need to replace bunches with parallel spin } \uparrow \uparrow \text{ with a rate of up to } 1/(5 \text{ minutes}) \] because of Sokolov-Ternov depolarization (defines the injection chain)

- Equilibrium polarization \( P_\infty = 50\% \) in eRHIC sufficient to maintain polarization with \( <P> = 63\% \) (spin \( \uparrow \downarrow \rightarrow 80\% \))
- Higher vertical tune better due to easier orbit control (beam-beam feasibility to be checked)
- Spin matching between rotators essential
- Polarization with BB not studied yet (HERA polarization suffered only indirectly from BB: non-colliding bunches pushed to unfavorable tunes by fixing the tunes for colliding bunches (e\textsuperscript{-} - p)

**Conclusion:**
- Polarization ok so far,
- More improvements expected by longitudinal spin matching, harmonic bumps, BBA, etc
IR Layout

IR design requirements:

- Small $\beta^*$ for high luminosity
- Limited IR chromaticity contributions
- Large final focus quadrupole aperture
- Large detector acceptance
  - Large quadrupole aperture, limited beam divergence
- Accommodate dipole spectrometer in the low-$\beta$ optics
- No accelerator magnets +/-4.5 m
- 22 mrad crossing angle, crab crossing, crab cavities 90° from IP
- Avoid synchrotron radiation:
  - no electron bends on the forward side
  - absorb SR far from IP
  - need mask against backscattered SR photons
- Accommodate spin rotators, spin matching
- Space for luminosity monitor, neutron detector, “Roman Pots”

➡️ Design meets all requirements
➡️ Very constrained systems, requires novel types of magnets in the IR
Multi-stage separation:

- Electrons from protons
- Protons from neutrons
- Electrons from Bethe-Heitler photons (luminosity monitor)
IR Vacuum

- Design is still at an early stage
- Impedance assessment has started

➔ 22 kW HOM power deposition in the IR is a challenge for cooling. Cooling design not yet started
Electron Storage Ring

Composed of six FODO arcs with 60° /cell for 5-10 GeV

90° /cell for 18 GeV

Super-bends for 5-10 GeV for emittance control

5 straight sections with simple layout, plus IR straight

Radiate approx. 10 MW for maximum luminosity parameters at 10GeV

→ 11 superconducting 2-cell 563 MHz RF cavities
eRHIC 10 O’clock

D0 to D0 Distance 39.2 m

*Note removal of DX Magnets

RCS 563 MHz NC Cavities Qty 20

e Storage 1690 MHz SRF Cavities Qty 12

e Storage 563 MHz SRF Cavities Qty 11
Super-bend

- Arc dipoles to be split into 3 segments:

  - Above 10 GeV, all segments powered uniformly to reduce SR power
  - At 5 GeV, short center dipole provides a reverse bend to increase damping decrement
SR Vacuum System

Vacuum chamber from **CuCrZr alloy**
Good thermal properties
Weldable
Brazable
Easily available
Reasonable price

Thermal SR power load
ok
Maximum temperature 173°C
well below yield strength limit

**Pumping** based on
integrated NEG Pumps

**RF bellows:**
Critical element of the vacuum system
Improved NSLS-II bellow with outside
CuCr fingers good candidate
Electron Injector Synchrotron

- (5-18) GeV spin polarized electrons are required for injection into the storage ring.
- A comprehensive study resulted in the choice of a spin-transparent rapid cycling synchrotron (RCS) in the RHIC tunnel.
- High lattice quasi-symmetry (achieved by straight sections designed as unity transformations) suppress systematic depolarizing resonance during the ramp.
- A 200 ms ramp is sufficiently fast to cross resonances without loss of polarization.
- Systematic tracking calculations indicate stringent orbit control need; orbits should not deviate by more than 0.5 mm from ideal orbit. While this is a demanding requirement, it is believed feasible using state-of-the-art controls and correction tools.
- Magnetic stray-fields from the injector experienced by the storage ring have been calculated as negligible.
- Electric interference is under study (the power circuit stores the magnetic energy to reduce impact on the grid).
- Bypasses around the detectors are accomplished without distorting the quasi-symmetry.
Rapid-Cycling Synchrotron Polarization

High quasi-symmetry

⇒ Good spin transparency properties

Blue asterisk: 200 ms ramp time
Polarized Electron Source

- Need to provide $10 \text{nC}$ of polarized electrons/second
- SLC Gun with $16 \text{nC}$ $120 \text{ Hz}$ operation is the existence proof
- eRHIC polarized gun is based on the JLAB inverted gun
- Design verified by PIC beam dynamics simulations
- 400 MeV injector linac will be a SLAC type S-band linac.
- Beam transport simulated and found to be ok for eRHIC beams.
- Wien filter, polarimeter design already in fairly large detail
Strong Hadron Cooling

2 hour IBS emittance growth time requires strong hadron cooling

Several methods of strong hadron cooling have been studied.

- Bunched Beam Electron Cooling with an electron storage ring
- Coherent electron cooling with FEL amplifier or micro-bunching amplifier

The most promising approach at this point is micro-bunched electron beam cooling with 2 plasma amplification stages.

Achievable cooling rates with 100 mA electron current and flat beams are in the order of 1 h which would be sufficient for eRHIC.

Analytical calculation of the cooling rate agrees well with simulations within the 1-D model.
A preliminary layout of the cooler facility, based on a 3-turn ERL with 567 MHz cavities
Strong Hadron Cooling

Challenges:
• 100 mA CW electron source is beyond state of the art
• Hadron chicane to compensate for electron delay in the micro-bunching chicanes is a considerable effort (need several Blue ring s.c. RHIC magnets)

Unexplored:
• Short bunches might boost the cooling rate, reduce the electron current and reduce number of amplifications.

To Do:
3-D model
Simulation including space charge and drifts
Optimization of parameters for short bunches
Mitigation of Strong Hadron Cooling Risk

Solution with $L = 0.44 \cdot 10^{34} \text{cm}^{-2} \text{s}^{-1}$ and hor., long IBS growth rates of 10.9 h

Moderate Luminosity Parameters for 10 GeV electrons on 275 GeV hadrons.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>hadron</th>
<th>electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center of Mass Energy [GeV]</td>
<td>105</td>
<td></td>
</tr>
<tr>
<td>Energy [GeV]</td>
<td>275</td>
<td>10</td>
</tr>
<tr>
<td>Number of Bunches</td>
<td>660</td>
<td></td>
</tr>
<tr>
<td>Particles per bunch [$10^{11}$]</td>
<td>1.05</td>
<td>3.</td>
</tr>
<tr>
<td>Beam Current [A]</td>
<td>0.87</td>
<td>2.48</td>
</tr>
<tr>
<td>Horizontal Emittance [nm]</td>
<td>13.9</td>
<td>20</td>
</tr>
<tr>
<td>Vertical Emittance [nm]</td>
<td>8.5</td>
<td>4.9</td>
</tr>
<tr>
<td>horizontal $\beta_x^*$ at IP [cm]</td>
<td>90</td>
<td>63</td>
</tr>
<tr>
<td>Vertical $\beta_y^*$ at IP [cm]</td>
<td>5.9</td>
<td>10.4</td>
</tr>
<tr>
<td>Horizontal Divergence $d\sigma / ds_x^*$ [mrad]</td>
<td>0.124</td>
<td>0.0179</td>
</tr>
<tr>
<td>Vertical Divergence $d\sigma / ds_y^*$ [mrad]</td>
<td>0.380</td>
<td>0.216</td>
</tr>
<tr>
<td>Horizontal Beam-Beam Parameter $\xi_x$</td>
<td>0.015</td>
<td>0.1</td>
</tr>
<tr>
<td>Vertical Beam-Beam Parameter $\xi_y$</td>
<td>0.005</td>
<td>0.083</td>
</tr>
<tr>
<td>IBS Growth Time long/hor [hours]</td>
<td>10.1/9.2</td>
<td>-</td>
</tr>
<tr>
<td>Synchrotron Radiation Power [MW]</td>
<td>-</td>
<td>9.1</td>
</tr>
<tr>
<td>Bunch Length [cm]</td>
<td>7</td>
<td>1.9</td>
</tr>
<tr>
<td>Luminosity [$10^{33} \text{cm}^{-2} \text{sec}^{-1}$]</td>
<td>4.4</td>
<td></td>
</tr>
</tbody>
</table>
eRF, Cold p RF
 Cooling
 Beam dump

6 snakes, polarimeter
 Feedback Diagnostics

Detector
 IR magnets
 Crab Cav.
 Spin rotators

e-Injection
 p-instrumentation

Detector
 IR magnets
 Cab cavities
 Spin rotators

h-warm RF,
 h-injection

Infrastructure
Summary

- eRHIC design reaches a peak luminosity of
  \[ L = 1.05 \cdot 10^{34} \text{cm}^{-2} \text{s}^{-1} \]
- However, this can only be achieved with strong hadron cooling, which is beyond state of the art, and is a topic of ongoing R&D.
- The corresponding design risk is mitigated by R&D, exploring variants for hadron cooling and by a fall-back solution with a respectable luminosity of
  \[ L = 0.44 \cdot 10^{34} \text{cm}^{-2} \text{s}^{-1} \]
- eRHIC design has progressed very well and a tremendous amount of design work was accomplished.
- There are still critical beam dynamic issues which require more effort. They could have an impact on achievable luminosity but do not constitute a risk of missing the EIC White Paper Requirement.
- While a large amount of work is still ahead to arrive at a Conceptual Design, we believe that the present state of the eRHIC design matches well the expectations of a Pre-Conceptual Design.
- Pre-Conceptual Design Report to be published by late June 2018
- ~800 pages, with many subsystems already beyond pre-conceptual stage
- Active R&D program on strong hadron cooling