eRHIC Project

- Performance requirements
- eRHIC design
- R&D for eRHIC
- Cost and schedule
Performance requirements

- Highly polarized (> 70%) electron, proton and neutron (He-3) beams
- Ion beams from deuteron to the heaviest nuclei (uranium)
- Center of mass energy range: ~ 20 GeV to ~ 150 GeV
- Non-zero crossing angle to minimize synchrotron radiation background
- Possibility to have multiple interaction regions
- High luminosity: $10^{33} - 10^{34}$ cm$^{-2}$ s$^{-1}$
- First stage to reach CM energy of $\gtrsim 70$ GeV and luminosity of $10^{32} - 10^{34}$ cm$^{-2}$ s$^{-1}$
RHIC – a High Luminosity (Polarized) Hadron Collider

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

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

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

Other large hadron colliders (scaled to 255 GeV):
- Tevatron (p – pbar) 110×10^{30} cm^{-2} s^{-1}
- LHC (p – p) 430×10^{30} cm^{-2} s^{-1}
RHIC performance supports eRHIC requirements

Further upgrades:
- 56 MHz superconducting storage rf system to reduce vertex length
- Electron lenses to ~ double pp luminosity

Nucleon-pair luminosity: luminosity calculated with nucleons of nuclei treated independently; allows comparison of luminosities of different species; appropriate quantity for comparison runs.
eRHIC: QCD Facility at BNL
Add an electron accelerator to the existing $2B$ RHIC and also using existing RHIC tunnel and cryo facility

Unpolarized and 80% polarized leptons
5 - 30 GeV

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

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

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

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

* It is possible to increase RHIC ring energy by 10%
** positrons-ion collider possible at lower luminosity with extra ring
eRHIC design

- 5 – 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, giving high luminosity (~ $10^{34}$ cm$^{-2}$ s$^{-1}$), and full electron polarization transparency
- Accelerator R&D for highest luminosity:
  - High current (50 mA) pol. electron gun
  - Multi-pass high average current ERL
  - Coherent electron cooling of hadron beam
- 1$^{st}$ 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
Main elements of the concept

- Single pass ERL for electrons allows for large collision disruption of electron bunches, giving high luminosity ($\sim 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$), and full electron polarization transparency

- Small electron beam size allows for small magnets with gaps of 8 mm (and 13 mm at the two lowest energy orbits)

- Linac-ring collider uniquely allows energy change of colliding hadrons from 50 GeV to 250 GeV

- Using recent advances in super-conducting quadrupole technology allows design IR with $\beta^* = 5$ cm

- Crab-crossing with large crossing angle following success at KEK-B

- Need 50 mA of polarized electron beam current for high luminosity

- Strong cooling of hadron beam ($\div 10$ emittance) in both longitudinal and transverse directions using coherent electron cooling

- Together results in eRHIC luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
- Total Linac length: ~ 200 m (70m for 1st stage)
- Warm-to-cold transitions only at the ends
- No quadrupoles in Linac
- Maximum energy gain per pass: 2.45 GeV (0.8 GeV for 1st stage)
- Accelerating gradient: 19.2 MV/m
- Based on BNL SRF cavity with fully suppressed HOMs, critical for high current multi-pass ERL
- eRHIC cavity & cryostat prototypes are under development
eRHIC high-luminosity IR with $\beta^* = 5$ cm

- 10 mrad crossing angle and crab-crossing
- High gradient (200 T/m) large aperture Nb3Sn focusing magnets
- Free-field electron pass through the hadron triplet magnets
- Integration with the detector: efficient beam separation and detection of low angle collision products
- Gentle bending of the electrons to avoid SR
- Simpler solution possible for 1st stage
High acceptance (\(\eta\): \(\pm 5\)) central detector with good PID and vertex resolution
- Tracking and calorimeter with same coverage \(\rightarrow\) good momentum resolution
- Low material density for minimal multiple scattering and bremsstrahlung
- Magnetic field critical for good tracking resolution in forward direction
- Integration of detector into IR design
  - *Roman Pots, ZDC, low e-tagger for very forward electron and proton/neutron detection*
- Very active EIC detector R&D (back-up slide)
Readiness of eRHIC

1\textsuperscript{st} stage eRHIC using existing, demonstrated technology has an initial luminosity of about $10^{32}$ cm$^{-2}$ s$^{-1}$ (2 x max. HERA luminosity) and 80\% e-beam polarization ($\sim$ 2 x HERA e-beam polarization) \rightarrow \textbf{ready to initiate construction}

- 4 mA polarized e beam source demonstrated at Jlab
- High energy ERL demonstrated (CEBAF), multi-pass ERL demonstrated (BINP)
- Performance of existing BNL 704 MHz srf cavity supports eRHIC linac
- Use present RHIC polarized proton beam emittance of $\sim 2$ $\mu$m

Ongoing eRHIC R&D is aimed at increasing eRHIC luminosity to $10^{34}$ cm$^{-2}$ s$^{-1}$:

- Increase of e-beam current to 50 mA using multiple cathodes ($10^{33}$ cm$^{-2}$ s$^{-1}$)
  - \textit{Low risk development; likely available for eRHIC construction; incl. in cost estimate}
- High average current ERL to support operation with high current e beam
  - \textit{Results from test-ERL in 2014}
- Strong cooling of hadron beams to $\sim 0.2$ $\mu$m ($10^{34}$ cm$^{-2}$ s$^{-1}$)
  - \textit{Coherent electron Cooling is best concept and needs R&D; CeC PoP in 2015}
High CW current polarized electron gun

- Matt Poelker (JLab) achieved 4 mA polarized e-beam with good lifetime
- More current with (effectively) larger cathode area
- Gatling gun R&D: twice the current from two cathodes with same lifetime

Single large area cathode

Gatling electron gun: many smaller cathodes

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LDRD, BNL
Energy Recovery Linac (ERL) Test Facility

- Test of high current (0.3 A, 6-passes eRHIC), high brightness ERL operation
- Highly flexible return loop lattice to test high current beam stability issues
- Allows for addition of a 2nd recirculation loop
- Gun rf tested at 2 MV; beam from gun: ~ 4/2013; recirculating beam: 2014
Coherent electron cooling

- 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

**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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**dispersion section**

$E < E_h$

$E > E_h$

**high gain FEL**
Recent developments of eRHIC design

- **External eRHIC design review (8/1-3/2011):**
  - “The committee is highly satisfied with the material presented, covering most of the relevant subjects. The committee did not see any significant holes in the concept.”

- **Numerous external reviews of eRHIC R&D effort (EICAC; C-AD MACs; individual reviews of test-ERL, Gatling Gun, CeC; DOE ONP Accel. R&D review)**

- **Comprehensive simulations of e-beam disruption by proton beam.** Acceptance of deceleration path is larger than disrupted e-beam for 8 mm magnet gap (13 mm at low energy).

- **Studied effect of small gap magnets and surface roughness on impedance and energy loss and spread.**

- **Developed crab cavity design for eRHIC with 6 MV/m deflection gradient and no acceleration gradient.**

- **Large momentum acceptance arcs (FFAG) to replace multiple recirculation arcs.**

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![Figure 4: The phase space distribution of the 5 GeV electron beam](image1.png)

![Figure 5: The beam parameter evolution of the 5 GeV electron beam](image2.png)

![Figure 6: The requirement of the aperture of the energy recovery pathes for various energies (5 GeV, 0.4 GeV and 0.2 GeV) assuming the beta](image3.png)

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<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Crab mode frequency</td>
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<td>Nearest other mode frequency</td>
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<tr>
<td>Cavity length</td>
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<td>Cavity width</td>
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<td>Deflecting voltage*</td>
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<td>Peak surface electric field*</td>
<td>39 MV/m</td>
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<td>Stored energy*</td>
<td>100 Joules</td>
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<td>$R_t/Q$#</td>
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* for peak surface magnetic field of 100 mT.

# circuit definition.
**eRHIC Cost Optimization**

- Bottom-up cost estimation for eRHIC first stage (5 GeV e-beam) has been done during 2012 (full TPC in FY12$ including ~ 33% average contingency, not including detector):
  - Complete cost estimate for the design with two main linacs and 6 recirculating passes in RHIC tunnel: ~ $765M TPC
  - Cost optimization for layout with 4 local recirculation passes for low energy and 2 re-circulating passes in RHIC tunnel: ~ $550M TPC
  - Note: 1st stage eRHIC scope is similar to CEBAF 6 to 12 GeV upgrade (1 GeV CW SRF linac plus 6 upgraded recirculation passes)

- Further value engineering is in progress, which could reduce the cost and/or increase performance:
  - FFAG design of recirculation passes (large momentum acceptance arcs), possibly with permanent magnets, could replace multiple passes with single pass.
  - Could reach 10 GeV electron energy for similar cost.
eRHIC schedule

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Projects/Construction | Operations
Summary

- Linac-ring design of eRHIC reaches high luminosity ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$) over wide CM energy range.

- Uses existing RHIC facility for HI and polarized proton beam ($2B$ replacement value) and existing RHIC tunnel and cryo-facility for e-beam.

- 1st stage eRHIC (5 GeV e-beam with $10^{32} - 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ initial luminosity using existing technology) has preliminary cost estimate of ~ $550M and is ready to initiate construction.

- R&D under way to support highest luminosity ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$) and to achieve cost effective path to 10 GeV e-beam (FFAG arcs).
Back-up slides
Recent Reviews

- **eRHIC design review (8/2011)**
  - J. Delayen (ODU), G. Ganetis (BNL), H.-C. Hseuh (BNL), V. Lebedev (FNAL), M. Poelker (TJNAF), E. Pozdeyev (MSU/NSCL), P. Wanderer (BNL), F. Zimmermann (CERN, chair)

- **DOE ONP C-AD Accelerator R&D review (12/2011)**
  - A. Chao (SLAC), P. Ostrumov (ANL), K. Robinson (LBNL), C. Sinclair (Cornell), J. Delayen (ODU), J. Galayda (SLAC)

- **Gatling Gun Advisory Committee review (6/2012)**
  - K. Aulenbacher (Mainz, Chair), A. Brachtmann (SLAC), H.-C. Hseuh (BNL), M. Poelker (TJNAF)

- **Recent C-AD MAC review of test-ERL (10/2012)**
  - J. Jowett (CERN), G. Krafft (TJNAF), SY Lee (Indiana), K. Ohmi (KEK), V. Shiltsev (FNAL), P. Spiller (GSI), R. Talman (Cornell), F. Zimmermann (CERN, Chair)

- **CeC Proof-of-Principle review (12/2012)**
  - O. Brüning (CERN), H. Padamsee (Cornell), R. Palmer (BNL), V. Lebedev (FNAL, Chair)
**Polarized He-3 in RHIC**

- Recent workshop to review status and R&D needs for polarized He-3 acceleration
- Polarized He-3 from new EBIS; test soon possibly starting with unpolarized He-3
- Polarimetry:
  - Relative: He3-C CNI polarimeter;
  - Absolute: He3-He3 CNI polarimeter using polarized He-3 jet
- Depolarizing res. are stronger; no depolarization expected with six snakes in RHIC
BNL: 1st Detector Design Concept

PID:
-1<\eta<1: DIRC or proximity focusing Aerogel-RICH
1<|\eta|<3: RICH

Lepton-ID:
-3 < \eta < 3: e/p
1<|\eta|<3: in addition Hcal response & \gamma suppression via tracking
|\eta|>3: ECal+Hcal response & \gamma suppression via tracking
-5<\eta<5: Tracking (TPC+GEM+MAPS)
Vibrant Detector R&D Program

- **Calorimetry**
  - W-Scintillator & W-Si
  - compact and high resolution
  - Crystal calorimeters PbW & BGO
  - BNL, Indiana University, Penn State Univ., UCLA, USTC, TAN

- **Pre-Shower**
  - W-Si
  - LYSO pixel array with readout via X-Y WLS fibers
  - Univ. Tecnica Valparaiso

- **PID via Cerenkov**
  - DIRC and timing info
  - Catholic Univ. of America, Old Dominion, South Carolina, JLab, GSI
  - RICH based on GEM readout
  - e-PID: GEM based TRD → eSTAR
  - BNL, Indiana Univ., USTC, VECC, ANL

- **Tracking**
  - BNL, Florida Inst. Of Technology, Iowa State, LBNL, MIT, Stony Brook, Temple, Jlab, Virginia, Yale
  - µ-Vertex: central and forward based on MAPS
  - Central: TPC/HBD provides low mass, good momentum, dE/dx, eID
  - Fast Layer: µ-Megas or PImMS
  - Forward: Planar GEM detectors