Future Electron-Hadron Colliders

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- Forgotten somebody - my apology....
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Content

• Why electron-hadron collider?
• What is expected performance
• Future electron-hadron collider
  • ENC @ FAIR
  • ELIC @ Jlab
  • eRHIC @ BNL
  • LHeC @ CERN
• Accelerator R&D for electron-hadron colliders
• Conclusions

More information at this conference on

• ENC
  MOPEB026  Magnet Design of the ENC Interaction Region
  TUPEB051  IR Design for the Electron-nucleon Collider ENC at FAIR

• ELIC
  TUPEB044  Spin rotator optics for MEIC
  TUPEB045  Chromaticity Correction up to Second Order for ELIC
  TUPEB048  A High-Luminosity Medium Energy Electron-Ion Collider at Jlab
  TUPEC083, Beam-beam effects in the proposed electron-ion collider at Jlab
  WEPECO84, HOM Properties of Superconducting Parallel-Bar Cavities

• eRHIC
  MOPD077, Progress on Analytical Modeling of Coherent Electron Cooling
  MOPEA028, Lattice Design for the ERL Electron Ion Collider in RHIC
  TUPEB035  Preliminary Design of Multi-Cathode DC Electron Gun for eRHIC
  TUPEB040, Small Gap Magnet Prototype Measurements for eRHIC
  TUPEB041, Study of Beam-beam Effects in eRHIC
  TUPEB042, The Transverse Linac Optics Design in Multi-pass ERL
  TUPEC075, Studies of Beam Dynamics for eRHIC
  WEOBRA03  Beam Break-up Estimates for the ERL at BNL, I. Ben-Zvi – talk

• LHeC
  TUPEB034  Interaction Region Design for a Ring Ring Version of the LHeC Study
  TUPEB037  Interaction-Region Design Options for a Linac-Ring LHeC
  TUPEB039  Designs for a Linac-Ring LHeC
  TUPEB043  Deflecting SR from the Interaction Region of a Linac-Ring LHeC
  THPD011  Lattice Design for the LHeC Recirculating Linac
  THPD012  Emittance Growth in the LHeC Recirculating Linac
  THPD071  Electron energy recovery linacs for ultra-high energies

V.N. Litvinenko, IPAC'11, Kyoto, May 26, 2010
Why electron-hadron collider?

- High Energy ep/eA colliders are the perfect instrument for high precision studies. They are the ultimate QCD microscope.

- Over decades they have been the cornerstone of High Energy and High Energy Nuclear Physics

- Next Generation:
  - High energy eA collisions
  - Polarized beams: e↑p↑
  - Substantially higher $\sqrt{s}$ and/or L

- Proposed Facilities
  - LHeC (CERN)
  - EIC (BNL/JLAB)
  - ENC (FAIR)

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The Science of Electron-Hadron Colliders

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- High density parton matter, gluon saturation/non-linear QCD, Color-Glass-Condensate?
- Spin structure of the nucleon
- 3D Spatial Landscape of the nucleon: valence quarks → gluons and sea
- Lepton Flavor Number Violation
- Formation of color neutral hadrons from quarks and gluons
- Higgs physics, Supersymmetry, Beyond the Standard Model, Tera-scale physics, Substructure of quarks and leptons?

V.N. Litvinenko, IPAC’11, Kyoto, May 26, 2010
Energy Reach and Luminosities of future electron-hadron colliders

\[ E_{CM} \equiv \sqrt{4E_e E_h} \]

Luminosity in e-A case is per nucleon, i.e. it is the RHIC style “equivalent e-p luminosity”
ERL or ring for electrons?

- Two main design options for electron-hadron collider
  - Ring-ring: ENC, MEIC/ELIC

\[
L = \left( \frac{4\pi \gamma_h \gamma_e}{r_h r_e} \right) \left( \xi_h \xi_e \right) \left( \sigma_h' \sigma_e' \right) f
\]

\[\xi_e \leq 0.1\]

- Linac-ring: eRHIC

\[
L = \gamma_h f N_h \frac{\xi_h Z_h}{\beta_h^* r_h}
\]

\[\xi_e > 1\]

LHeC still pursuing both ring-ring and linac-ring options
A “simple” idea: ENC@FAIR

idea emerged 08/2008

\[ L > 10^{32} \text{ cm}^{-2}\text{s}^{-1} \]

\[ s^{1/2} > 10\text{GeV} \]

(3.3GeV/c e\(^-\) ↔ 15GeV/c p)

**polarized** e\(^-\) ( > 80%)

↔

**polarized** p / d ( > 80%)

(transversal + longitudinal)

using the PANDA detector

as much as possible

double polarized

Electron Nucleon Collider

Luminosity: 8 × HERA (unpol.)
Preliminary Scheme for ENC at FAIR

ENC@FAIR for electron-proton collisions

© Andreas Lehrach
Sufficient separation at \( s = 1.44\,\text{m} \) for 200 bunches

\[ \theta_{x,y}^* = 0.3\,\text{m} \]
## Beam Equilibria and Luminosities

**Baseline design (protons)**

e-Cooler parameter: $E=8.2$ MeV, $I=3$ A, $B=0.2$ T, $T_T=1$ eV, $T_L=0.5$ meV, $B_r/B < 10^{-5}$, $L=24$ m

RF parameter: $f=52$ MHz, $U=300$ kV

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HESR / 15GeV p</th>
<th>eRing / 3GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$ [ring circumference, m]</td>
<td></td>
<td>~ 575</td>
</tr>
<tr>
<td>$\varepsilon_{\text{norm}} / \varepsilon_{\text{geo}}$ [mm mrad, rms]</td>
<td></td>
<td>$\leq 2.1 / \leq 0.13$</td>
</tr>
<tr>
<td>$\Delta p/p$ (rms)</td>
<td></td>
<td>~ $4 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$\beta_{IP}$ [m]</td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>$r_{IP}$ [mm, rms]</td>
<td></td>
<td>$\leq 0.2$</td>
</tr>
<tr>
<td>$l$ (bunch length) [m]</td>
<td>0.27 - 0.35</td>
<td>0.1</td>
</tr>
<tr>
<td>$n$ (particle / bunch)</td>
<td>$5.4 \cdot 10^{10}$</td>
<td>$23 \cdot 10^{10}$</td>
</tr>
<tr>
<td>$h$ (number of bunches)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>$f_{\text{coll}}$ (collision freq) [MHz]</td>
<td></td>
<td>~ 52</td>
</tr>
<tr>
<td>$l_{\text{coll}}$ (bunch distance) [m]</td>
<td></td>
<td>~ 5.76</td>
</tr>
<tr>
<td>$\Delta Q_{\text{sc}}$ (space charge)</td>
<td>$\geq 0.05$</td>
<td></td>
</tr>
<tr>
<td>$\xi$ (beam-beam parameter)</td>
<td>0.014</td>
<td>0.015</td>
</tr>
<tr>
<td>$L$ (luminosity) [cm$^{-2}$s$^{-1}$]</td>
<td>$\sim 2 \cdot 10^{32}$</td>
<td></td>
</tr>
</tbody>
</table>
# Beam Equilibria and Luminosities

**Advanced design (protons)**

- **e-Cooler parameter:** $E=8.2 \text{ MeV, } I=3 \text{ A, } B=0.2T, \; T_T=1\text{eV, } T_L=0.5\text{meV, } B_r/B < 10^{-5}, \; L=24\text{m}$
- **RF parameter:** $f=104 \text{ MHz, } U=300 \text{kV}$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HESR / 15GeV p</th>
<th>eRing / 3GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$ [ring circumference, m]</td>
<td>~ 575</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_{\text{norm}} / \varepsilon_{\text{geo}}$ [mm mrad, rms]</td>
<td>$\leq 2.3 / \leq 0.14$</td>
<td></td>
</tr>
<tr>
<td>$\Delta p/p$ (rms)</td>
<td>$\sim 4 \cdot 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$\beta_{\text{IP}}$ [m]</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>$r_{\text{IP}}$ [mm, rms]</td>
<td>$\leq 0.1$</td>
<td></td>
</tr>
<tr>
<td>$l$ (bunch length) [m]</td>
<td>0.19 - 0.25</td>
<td>0.1</td>
</tr>
<tr>
<td>$n$ (particle / bunch)</td>
<td>$3.6 \cdot 10^{10}$</td>
<td>$23 \cdot 10^{10}$</td>
</tr>
<tr>
<td>$h$ (number of bunches)</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>$f_{\text{coll}}$ (collision freq) [MHz]</td>
<td>$\sim 104$</td>
<td></td>
</tr>
<tr>
<td>$l_{\text{coll}}$ (bunch distance) [m]</td>
<td>$\sim 2.88$</td>
<td></td>
</tr>
<tr>
<td>$\Delta Q_{\text{sc}}$ (space charge)</td>
<td>$\geq 0.1$</td>
<td></td>
</tr>
<tr>
<td>$\xi$ (beam-beam parameter)</td>
<td>0.014</td>
<td>0.01</td>
</tr>
<tr>
<td>$L$ (luminosity) [cm$^{-2}$s$^{-1}$]</td>
<td>$\sim 6 \cdot 10^{32}$</td>
<td></td>
</tr>
</tbody>
</table>

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BetaCool program
JINR Dubna
### Beam Equilibria and Luminosities

**Baseline design (deuteron)**

- e-Cooler parameter: $E=4.1$ MeV, $I=0.5$ A, $B=0.2$ T, $T_T=1$ eV, $T_L=0.5$ meV, $B_r/B < 10^{-5}$, $L=24$ m
- RF parameter: $f=89$ MHz, $U=300$ kV

<table>
<thead>
<tr>
<th></th>
<th>HESR / 15GeV d</th>
<th>eRing / 3GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$ [ring circumference, m]</td>
<td>~ 576</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_{\text{norm}} / \varepsilon_{\text{geo}}$ [mm mrad, rms]</td>
<td></td>
<td>$\leq 2.4 / \leq 0.15$</td>
</tr>
<tr>
<td>$\Delta p/p$ (rms)</td>
<td>~ $2.4 \cdot 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>$\beta_{\text{IP}}$ [m]</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>$r_{\text{IP}}$ [mm, rms]</td>
<td></td>
<td>$\leq 0.1$</td>
</tr>
<tr>
<td>$l$ (bunch length) [m]</td>
<td>0.17 – 0.19</td>
<td>0.1</td>
</tr>
<tr>
<td>$n$ (particle / bunch)</td>
<td>$1.1 \cdot 10^{10}$</td>
<td>$23 \cdot 10^{10}$</td>
</tr>
<tr>
<td>$h$ (number of bunches)</td>
<td>173</td>
<td>172</td>
</tr>
<tr>
<td>$f_{\text{coll}}$ (collision freq) [MHz]</td>
<td>~ 89.3</td>
<td></td>
</tr>
<tr>
<td>$l_{\text{coll}}$ (bunch distance) [m]</td>
<td>~ 3.3</td>
<td></td>
</tr>
<tr>
<td>$\Delta Q_{\text{sc}}$ (space charge)</td>
<td>$\geq 0.1$</td>
<td></td>
</tr>
<tr>
<td>$\xi$ (beam-beam parameter)</td>
<td>0.014</td>
<td>0.030</td>
</tr>
<tr>
<td>$L$ (luminosity) [cm$^{-2}$s$^{-1}$]</td>
<td>~ $1.8 \cdot 10^{32}$</td>
<td></td>
</tr>
</tbody>
</table>

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BetaCool program
JINR Dubna
Electron-Ion Collider At JLab (ELIC)

ELIC Design Goal

- **Energy**
  - Wide CM energy range between 10 GeV and 100 GeV
  - Low: 3 to 10 GeV e on 3 to 12 GeV/c p (and ion)
  - Medium (**present focus**): up to 11 GeV e on 60 GeV p or 30 GeV/n ion
  - High (**future upgrade**): up to 10 GeV e on 250 GeV p or 100 GeV/n ion

- **Luminosity**
  - $10^{33}$ up to $10^{35}$ cm$^{-2}$ s$^{-1}$ per collision point, over multiple interaction points

- **Ion Species**
  - Polarized H, D, $^3$He, possibly Li
  - Up to heavy ion A = 208, all stripped

- **Polarization**
  - Longitudinal at the IP for both beams, transverse of ions
  - Spin-flip of both beams
  - All polarizations >70% desirable

- **Positron Beam** desirable

Advantages (and a great opportunity) at JLab

- 12 GeV CEBAF as a full energy injector into the electron collider ring
  - High polarization high repetition CW electron beam

- New Ion Complex
  - High repetition high average current ion beams with short bunch length
  - New Figure-8 shape collider rings for high polarization
Three compact rings:
- 3 to 11 GeV electron
- Up to 12 GeV/c proton (warm)
- Up to 60 GeV/c proton (cold)

High energy full size collider ring
- 11 GeV electron
- Up to 250 GeV/c proton (cold)

Electrons take crab crossing to collider ions in low or medium energy ion rings

Electrons preserve polarization by avoiding spin resonances during acceleration
- Energy independence of spin tune
- Only practical way for including polarized deuterons (g-2 very small)

Figure-8 ring optimum for polarized ion beams
- Preserving polarization by avoiding spin resonances during acceleration
- Energy independence of spin tune
- Only practical way for including polarized deuterons (g-2 very small)
## ELIC Main Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>High energy</th>
<th>Medium energy</th>
<th>Low energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>GeV</td>
<td>250/10</td>
<td>150/7</td>
<td>60/5</td>
</tr>
<tr>
<td>Collision freq.</td>
<td>MHz</td>
<td>499</td>
<td>499</td>
<td>499</td>
</tr>
<tr>
<td>Particles/bunch</td>
<td>$10^{10}$</td>
<td>1.1/3.1</td>
<td>0.5/3.25</td>
<td>0.74/2.9</td>
</tr>
<tr>
<td>Beam current</td>
<td>A</td>
<td>0.9/2.5</td>
<td>0.4/2.6</td>
<td>0.59/2.3</td>
</tr>
<tr>
<td>Energy spread</td>
<td>$10^{-4}$</td>
<td>7.3</td>
<td>5.1</td>
<td>8</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>mm</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Horiz.. emit., norm.</td>
<td>µm</td>
<td>0.7/51</td>
<td>0.5/43</td>
<td>0.56/85</td>
</tr>
<tr>
<td>Vert. emit. Norm.</td>
<td>µm</td>
<td>0.03/2</td>
<td>0.03/2.87</td>
<td>0.11/17</td>
</tr>
<tr>
<td>Horizontal beta-star</td>
<td>mm</td>
<td>125</td>
<td>75</td>
<td>25</td>
</tr>
<tr>
<td>Vertical beta-star</td>
<td>mm</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Vert. b-b tune shift/IP</td>
<td></td>
<td>0.01/0.1</td>
<td>0.015/.05</td>
<td>0.01/0.03</td>
</tr>
<tr>
<td>Laslett tune shift</td>
<td>p-beam</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Peak Lumi/IP, $10^{34}$</td>
<td>cm$^{-2}$s$^{-1}$</td>
<td>11</td>
<td>4.1</td>
<td>1.9</td>
</tr>
</tbody>
</table>

**High energy**

**Medium energy**

**Low energy**
**Luminosity concepts**  \((L \sim 4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \text{ for } 60 \times 3 \text{ GeV})\)
- High bunch collision frequency  \((0.5 \text{ GHz}, \text{ can be up to } 1.5 \text{ GHz})\)
- Very small bunch charge  \((10^{10} \text{ or less protons per bunch})\)
- Very small beam spot size at collision points  \((\beta^*_y \sim 5 \text{ mm})\)
- Short ion bunches  \((\sigma_z \sim 5 \text{ mm})\)

**Keys to implementing these concepts**
- Making very short ion bunches with small emittance
- SRF ion linac and (staged) electron cooling
- Need crab crossing for colliding beams

**Other design features**
- Ultra high luminosity, based on prove concepts/technologies
- Polarized electron and light ion beams
- Up to three IPs (detectors) for high science productivity
- “Figure-8” ion and lepton storage rings
  - Ensures spin preservation and ease of spin manipulation
  - Avoids energy-dependent spin sensitivity for all species
- Present CEBAF injector meets MEIC requirements
- Simultaneous operation of collider & CEBAF fixed target program if required
- Experiments with polarized positron beam would be possible
Some Design Details

ERL Circulator e-Cooler
(for delivering a 3A CW electron beam)

Q1  G[kG/cm] = -3.4
Q2  G[kG/cm] = 2.1
Q3  G[kG/cm] = -4.1

Natural Chromaticity
ζₓ = -278  ζᵧ = -473
ELIC R&D and Path Forward

Short Term Design Goals
- Focusing on completion of a conceptual design with sufficient technical details for delivering to the next EIC AC meeting.
- Scaling back several key parameters (particularly, increasing vertical beta-star to 2 cm) for reducing immediate R&D requirements, however still preserving high luminosity.
- Concentrating available resources and manpower strategically to a minimum set of required R&D issues.
- Optimizing ELIC design iteratively.

Intermediate ELIC R&D Goals

Focal Point 1:
- Complete Electron & Ion Ring designs
  - sub tasks: Insert interaction region design
  - Chromaticity correction w/ tracking
  - Led by Ya. Derbenev & A. Bogacz (JLab)

Focal Point 2:
- IR design, feasibilities of advanced schemes
  - sub tasks: Develop a complete IR design
  - Beam dynamics with crab crossing
  - Traveling final focusing
  - Led by M. Sullivan (SLAC)

Focal Point 3:
- Conceptual design of ion injector/prebooster
  - sub tasks: bunch dynamics & space charge effect
  - Led by P. Ostroumov (ANL)

Focal Point 4:
- Beam-beam interaction
  - sub tasks: Single and multiple IPs
  - With crab crossing and/or space charge
  - Led by Y. Zhang & B. Terzic (JLab)

ELIC Long Term R&D Issues
- IR design with chromatic compensation
- High energy electron cooling
- Crab crossing and crab cavity
- Forming high intensity low energy ion beam
- Beam-beam effect
- Beam polarization and tracking
- Traveling focusing for very low energy ion

Established Collaborations
- Interaction region design M. Sullivan (SLAC)
- ELIC ion complex front end P. Ostroumov (ANL)
- Ion source V. Dudnikov, R. Johnson (Muons, Inc)
- V. Danilov (ORNL)
- SRF Linac P. Ostroumov (ANL), B. Erdelyi (NIU)
- Beam-beam simulation J. Qiang (LBNL)
eRHIC: QCD Facility at BNL

V.N. Litvinenko, IPAC'11, Kyoto, May 26, 2010
eRHIC: QCD Facility at BNL

Add electron accelerator to the existing $2B$ RHIC

Unpolarized and 80% polarized leptons, 2-30 GeV

70% polarized protons
50-250 (325) GeV

Light ions (d,Si,Cu)
Heavy ions (Au,U)
50-100 (130) GeV/u

Polarized light ions
(He$^3$) 215 GeV/u

Center of mass energy range: 20-200 GeV
Any polarization direction in lepton-hadrons collisions

V.N. Litvinenko, IPAC'11, Kyoto, May 26, 2010
Brief history of eRHIC

ERHIC QCD FACTORY -
I WANT YOU
**Brief history of eRHIC**

- First eRHIC paper, 2000, I. Ben. Zvi et al., ~300 papers after that, 138 @JACoW, 26 Phys. Revs, 54 NIMs....

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**ACCELERATOR PHYSICS ISSUES FOR FUTURE ELECTRON-ION COLLIDERS**

S. Pegge, I. Ben-Zvi, J. Keivich, J. Murphy, BNL.

1 INTRODUCTION

Interest continues to grow in the physics of collisions between electrons and heavy ions, and between polarized electrons and polarized protons [1, 2, 3]. Table 1 compares the parameters of some machines under discussion. DESY has began to explore the possibility of upgrading the existing HERA p-ring to store heavy ions, in order to collide them with electrons (or protons) in the HERA e-ring, or from TESLA [4]. An upgrade to store polarized protons in the HERA e-ring is also under discussion [1]. BNL is considering adding polarized electrons to the RHIC superproton, which already includes heavy and light ions, and polarized protons. The authors of this paper have made a first pass analysis of this “HERIC” possibility [5]. MIT-NANTEX is also considering electron-ion collider designs [6].

Ring-Ring and Linear-Ring scenarios. Figure 1 compares the ring-ring and linear-ring scenarios, using eRHIC as a conventional example. In the “ring-ring” scenario (TOP), pre-polarized electrons are injected into an electron storage ring from a full energy linac (or from a booster). Collisions are possible with the clockwise rotating ions at up to 5 interaction points. The average electron beam power passing a single point—a few GW—is conserved as a stored beam energy which is conserved except for synchrotron radiation losses of about 1 MW. In the linear-ring scenario (BOTTOM) the beam circulates only once, hence the average electron beam power—about 1 GW—is recovered by passing the beam back through the linac. The recirculation ring may, or may not, share a turn with the ion ring. The Energy Recovery Linac (ERL) must be superconducting in a linear-ring design, constructed of superconducting cavities (for example using 1.3 GHz TESLA cavities). In the ring-ring scenario the linac could simultaneously be constructed with copper cavities (for example at the SLAC linac frequency of 2.566 GHz, where cavities and RF controls are readily available). Such a copper linac has no particular new issues or difficulties, except in the need for an electron gun which can provide polarized electrons at up to 80% polarization [7, 8].

Figure 1: In the ring-ring scenario (TOP) electrons are stored for hours in their own ring. In the linear-ring scenario (BOTTOM) electrons circulate the ring once, before re-arriving at the superconducting Energy Recovery Linac.

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**V.N. Litvinenko, IPAC’11, Kyoto, May 26, 2010**
Brief history of eRHIC

- First eRHIC paper, 2000, I. Ben. Zvi et al., ~300 papers after that, 138 @JACoW, 26 Phys. Revs, 54 NIMs....

- First White Paper on eRHIC/EIC, 2002

The Electron Ion Collider

A high luminosity probe of the partonic substructure of nucleons and nuclei
A white paper summarizing the scientific opportunities and the preliminary detector and accelerator design options
February 2002
Brief history of eRHIC

• First eRHIC paper, 2000, I. Ben. Zvi et al., ~300 papers after that, 138 @JACoW, 26 Phys. Revs, 54 NIMs....

• First White Paper on eRHIC/EIC, 2002

• 2003, eRHIC appears in DoE’s “Facilities for the Future Sciences. A Twenty-Year Outlook”
Brief history of eRHIC

- First eRHIC paper, 2000, I. Ben. Zvi et al., ~300 papers after that, 138 @JACoW, 26 Phys. Revs, 54 NIMs….

- First White Paper on eRHIC/EIC, 2002


- “eRHIC Zeroth-Order Design Report” with cost estimate for Ring-Ring, 2004
Brief history of eRHIC

- First eRHIC paper, 2000, I. Ben. Zvi et al., ~300 papers after that, 138 @JACoW, 26 Phys. Revs, 54 NIMs....
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Brief history of eRHIC

- First eRHIC paper, 2000, I. Ben. Zvi et al., ~300 papers after that, 138 @JACoW, 26 Phys. Revs, 54 NIMs....
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• 2003, eRHIC appears in DoE’s “Facilities for the Future Sciences. A Twenty-Year Outlook”

• “eRHIC Zeroth-Order Design Report” with cost estimate for Ring-Ring, 2004

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• Present – returned to the cost-effective (green) all in tunnel high-luminosity eRHIC design with staging electron energy from 5 GeV to 30 GeV

V.N. Litvinenko, IPAC'11, Kyoto, May 26, 2010
MeRHIC – 2007/2008

- Completed 2 technical designs of 3-pass 4 GeV ERL – selected a racetrack over a dog-bone
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V.N. Litvinenko, IPAC’11, Kyoto, May 26, 2010
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- Completed development of IR with detector
- Studied in details all aspects of beam dynamics - no showstoppers

- Longitudinal dynamics
- Transverse dynamics
- Energy loss & compensation
- Emittances growth
- Wake-fields: CSR, cavity, resistive wall...
- Beam losses
  Touschek, residual gas
- Ion accumulation
- Transverse Beam Break-Up
- Magnet errors
- Beam-Beam effect on protons
- Noise in electron beam
- Electron beam disruption
- Effect of clearing gap
- Kink instability........

Beam losses: Collisions with residual gas

Scattering

Bremsstrahlung

V.N. Litvinenko, IPAC'11, Kyoto, May 26, 2010
MeRHIC - 2007/2008

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- Completed development of IR with detector
- Studied in details all aspects of beam dynamics – no showstoppers
- Finally went through a lengthy bottoms-up cost estimate and internal review

• Learned a lot and shelved it
Staging of all-in-tunnel e-RHIC

Electron energy increases from 5 to 30 GeV by building-up SRF linacs

RHIC: 325 GeV p or 130 GeV/u Au

The most cost effective design

V.N. Litvinenko, IPAC'11, Kyoto, May 26, 2010
ARC’s

RHIC: 325 GeV \( p \) or 130 GeV/u \( Au \)

Staging of all-in-tunnel e-RHIC

The most cost effective design

30 GeV e\(^+\) ring

1.27 m beam high

30 GeV ERL

6 passes

30 GeV e\(^+\) ring

“clear zone”

25 GeV

20 GeV

15 GeV

10 GeV

5 GeV

Common vacuum chamber

27.5 GeV

2.5 GeV

Beam-dump

Polarized e-gun

eRHIC detector

ARC’s

V.N. Litvinenko, IPAC’11, Kyoto, May 26, 2010
eRHIC IRs, $\beta^*=5\text{cm}$, $l^*=4.5$ m

Plan to use newly commissioned LARP Ni$_3$Sn SC quads with 200 T/m gradient

$L=1.4\times10^{34}\text{cm}^{-2}\text{s}^{-1}$, 200 T/m gradient
Plan to use newly commissioned LARP Ni$_3$Sn SC quads with 200 T/m gradient

MOOCRA02 Design and Test of the First Long Nb$_3$Sn Quadrupole by LARP, G. Ambrosio, G. Chlachidze, M.J. Lamm, A. Nobrega, E. Prebys (Fermilab) S. Caspi, H. Felice, P. Ferracin, G.L. Sabbi (LBNL) T.W. Markiewicz (SLAC) J. Schmalzle, P. Wanderer (BNL) The first Nb$_3$Sn Long Quadrupole (LQS01) designed and fabricated by the US LHC Accelerator Research Program (LARP) reached its target gradient of 200 T/m during the first test. LQS01 is a 90 mm aperture, 4 meter long quadrupole with Nb$_3$Sn coils made of RRP 54/61 strand (by Oxford Superconducting Technology)..............\
A detector integrated into IR
Dipoles needed to have good forward momentum resolution
- Solenoid no magnetic field @ r ~ 0
- DIRC, RICH hadron identification → π, K, p
- high-threshold Cerenkov → fast trigger for scattered lepton
- radiation length very critical → low lepton energies
### eRHIC Luminosity at Top Energy

<table>
<thead>
<tr>
<th></th>
<th>e</th>
<th>p</th>
<th>$^2$He$^3$</th>
<th>$^{79}$Au$^{197}$</th>
<th>$^{92}$U$^{238}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy, GeV</strong></td>
<td>20</td>
<td>325</td>
<td>215</td>
<td>130</td>
<td>130</td>
</tr>
<tr>
<td><strong>CM energy, GeV</strong></td>
<td>161</td>
<td>131</td>
<td>102</td>
<td>102</td>
<td></td>
</tr>
<tr>
<td><strong>Number of bunches/distance between bunches</strong></td>
<td>74 nsec</td>
<td>166</td>
<td>166</td>
<td>166</td>
<td>166</td>
</tr>
<tr>
<td><strong>Bunch intensity (nucleons) , $10^{11}$</strong></td>
<td>0.24 (.05)</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>Bunch charge, nC</strong></td>
<td>3.8 (0.4)</td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td><strong>Beam current, mA</strong></td>
<td>50 (10)</td>
<td>420</td>
<td>420</td>
<td>420</td>
<td>420</td>
</tr>
<tr>
<td><strong>Normalized emittance of hadrons, 95%, mm mrad</strong></td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Normalized emittance of electrons, rms, mm mrad</strong></td>
<td>23 (34)</td>
<td>35 (52)</td>
<td>57 (85)</td>
<td>57 (85)</td>
<td></td>
</tr>
<tr>
<td><strong>Polarization, %</strong></td>
<td>80</td>
<td>70</td>
<td>70</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td><strong>rms bunch length, cm</strong></td>
<td>0.2</td>
<td>4.9</td>
<td>4.9</td>
<td>4.9</td>
<td>4.9</td>
</tr>
<tr>
<td><strong>$\beta^*$, cm</strong></td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>Luminosity per nucleon, cm$^{-2}$s$^{-1}$</strong></td>
<td>$1.46 \times 10^{34}$</td>
<td>$(0.29 \times 10^{34})$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Hourglass effect is included:** $h(\sigma_s / \beta^*) = 0.851$

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eRHIC R&D highlights

- Polarized gun for e-p program - LDRD at BNL + MIT
- Development of compact magnets - LDRD at BNL, ongoing
- SRF R&D ERL - ongoing
- Beam-beam effects, beam disruption, kink instability suppression, etc.
- Polarized He\textsuperscript{3} source
- Coherent Electron Cooling including PoP - plan to pursue
Layout for Coherent Electron Cooling proof-of-principle experiment in RHIC IR 2
Collaboration between BNL & JLab

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species in RHIC</td>
<td>Au ions, 40 GeV/u</td>
</tr>
<tr>
<td>Electron energy</td>
<td>21.8 MeV</td>
</tr>
<tr>
<td>Charge per bunch</td>
<td>1 nC</td>
</tr>
<tr>
<td>Rep-rate</td>
<td>78.3 kHz</td>
</tr>
<tr>
<td>e-beam current</td>
<td>0.078 mA</td>
</tr>
<tr>
<td>e-beam power</td>
<td>1.7 kW</td>
</tr>
</tbody>
</table>
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0.078 mA
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V.N. Litvinenko, IPAC'11, Kyoto, May 26, 2010
LHeC Scope

LHeC Machine Study Group

CERN: Simona Bettone, Frederick Bondy, Chiara Bracco, Oliver Bruning, Helmut Burkhardt, Rama Galoga, Edmond Ciapala, Miriam Fitterer, Massimo Giovannozzi, Brennan Goddard, Werner Herr, Bernhard Holzer, John M. Jowett, Trevor Linsecker, Karl Hubert Meas, Steve Myers, Yvan Mutzani, John Andrew Osborne, Louis Binelli, Stephan Russenschuck, Daniel Schulte, Rogello Tomas, Davide Tommasini, Joachim Tuckmantel, Alessandro Vivaldi, Uli Wienands, Frank Zimmermann

BNL: Tian Ben Zvi, Vladimir Litvinenko, Ferdinand Willeke

BINF: Eugene B, Levichev, Ivan Marozov, Yuriev Pupkov, Pavel Vobly, Alexander Skrinsky

Bologna University: Alessandro Palini

University of Antwerp: Pierre Van Mechelen

Cockcroft Institute: Rob Appleby, Ian Bailey, Graeme Burt, Maxim Karstensley, Neil Marks, Luke Thompson

Cornell University: Georg Hofstetter

DESY: Desmond P. Barber, Sergey Levantian, Alexander Kling, Peter Koets, Uwe Schneekloth

Liverpool University: John B. Dainton, Tim Greenaway, Max Klein

KEK: Tsunehiro Omori, Junji Urakawa

SLAC: Chris Adolphsen, Tor Rubenheimer, Michael Sullivan, Yipeng Sun

TAC: A. Kenan Gifitci, Saleh Sultansoy

ITEP, Moscow: Vladimir Andreev

UCLA: Rainer Wallny

EPFL: Leonid Rifkin

Forgotten someone? ... apologies!
LHeC Scope

Electron accelerator

Unpolarized and polarized leptons 60-140 GeV

LHC

Protons up to 7 TeV

Heavy ions 3 TeV/u

Other ions?

Center mass energy range: 0.5–2 TeV
Both ring-ring and linac-ring options are in development for LHeC

Option 1: “ring-ring” (RR)  
e-/e+ ring in LHC tunnel  

Option 2: “ring-linac” (RL) 

≤ 70 GeV: cw operation and energy recovery  
> 70 GeV: pulsed operation; γ-hadron option

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LHeC Ring-Ring layout

One of the next steps:
Detailed design of CMS and ATLAS bypasses

Bypass design:
+ shutdown time
+ cost for tunnel
+ match LHC and LHeC circumference

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LHeC Ring-Ring layout

Interference with LHC

6.6 m long DFBMs every 106.9 m (= \( L_{\text{FODO LHC}} \)) \( \rightarrow \) \( L_{\text{FODO LHC}} \) must be equal or a multiple/fraction of \( L_{\text{FODO LHC}} \) \( \rightarrow \) Natural choice: \( L_{\text{FODO LHC}} = L_{\text{FODO LHC}} \) \( \Rightarrow \) too large emittance
LHeC Ring-Ring layout

New beam in Survey Gallery (UPS54)

© H.Burkhard

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IR layout & crab crossing (for RR)

- LHeC RR has IR designs for high and low acceptance interaction regions
- p/e achieved with IR dipole, offset electron quads and crossing angle.
- SR production minimized by smooth, weak bends, and concentrated on dedicated SR masks on the proton triplet
  - 10° acceptance
    - Luminosity possible with crab cavities ~1.1x10^{33}
    - Separation/SR trade-off looks OK
    - SR power ~60kW
  - 1° acceptance
    - Luminosity achieved - ~1.5x10^{32}
    - Separation achieved with a crossing angle
    - SR generation sufficiently low
    - SR power ~10kW

1-2 mrad crossing angle for early separation
Proton crab cavities: 15-30 MV at 800 MHz

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LHeC Linac-Ring layouts

- Design is in flux with the main layouts

- **p-60**
  - 30-GeV linac
  - 0.34 km
  - 1.67 km

- **p-140**
  - 70-GeV linac
  - 3.9 km
  - 2.0 km

- **elr**
  - 10-GeV linac
  - 2.0 km
  - 1.0 km

- LHC $p$
LHeC Linac-Ring layouts

- Design is in flux with the main layouts
- There are various advantages of these three options, with ERL having maximum luminosity

<table>
<thead>
<tr>
<th></th>
<th>p-60</th>
<th>erl</th>
<th>p-140</th>
</tr>
</thead>
<tbody>
<tr>
<td>e⁻ energy at IP [GeV]</td>
<td>60</td>
<td>60</td>
<td>140</td>
</tr>
<tr>
<td>luminosity (10^{32}) cm(^{-2}) s(^{-1})</td>
<td>1.1</td>
<td>10.1</td>
<td>0.4</td>
</tr>
<tr>
<td>polarization [%]</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>bunch population (10^9)</td>
<td>4.5</td>
<td>2.0</td>
<td>1.6</td>
</tr>
<tr>
<td>e⁻ bunch length [(\mu m)]</td>
<td>300</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>bunch interval [ns]</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>transv. emit. (\gamma_{x,y}) [(\mu m)]</td>
<td>50</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>rms IP beam size [(\mu m)]</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>hourglass reduction (H_{hg})</td>
<td>0.91</td>
<td>0.91</td>
<td>0.94</td>
</tr>
<tr>
<td>crossing angle (\theta_c)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>repetition rate [Hz]</td>
<td>10</td>
<td>CW</td>
<td>10</td>
</tr>
<tr>
<td>bunches/pulse (10^5)]</td>
<td>1</td>
<td>N/A</td>
<td>1</td>
</tr>
<tr>
<td>pulse current [mA]</td>
<td>16</td>
<td>10</td>
<td>6.6</td>
</tr>
<tr>
<td>beam pulse length [ms]</td>
<td>5</td>
<td>N/A</td>
<td>5</td>
</tr>
<tr>
<td>ER efficiency (\eta)</td>
<td>0</td>
<td>94%</td>
<td>0</td>
</tr>
<tr>
<td>total wall plug power [MW]</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>
LHeC Linac-Ring layouts

- Design is in flux with the three main layouts.
- There are various advantages of these three options, with ERL having maximum luminosity.
- Linac and IR lattice has been designed.
LHeC Linac-Ring layouts

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<table>
<thead>
<tr>
<th></th>
<th>protons</th>
<th>electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>energy [GeV]</td>
<td>7000</td>
<td>60</td>
</tr>
<tr>
<td>Lorentz factor $\gamma$</td>
<td>7460</td>
<td>117400</td>
</tr>
<tr>
<td>tr. norm. emittance $\gamma\epsilon_{x,y}$ [(\mu m)]</td>
<td>3.75</td>
<td>50</td>
</tr>
<tr>
<td>tr. geom. emittance $\epsilon_{x,y}$ [nm]</td>
<td>0.50</td>
<td>0.43</td>
</tr>
<tr>
<td>IP beta function $\beta^{*}_{x,y}$ [m]</td>
<td>0.10</td>
<td>0.12</td>
</tr>
<tr>
<td>rms IP beam size $\sigma_{x,y}^{*}$ [(\mu m)]</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>rms IP divergence $\sigma^{*}_{x,y}$ [(\mu rad)]</td>
<td>70</td>
<td>58</td>
</tr>
<tr>
<td>disruption parameter $D$</td>
<td>$2 \times 10^{-6}$</td>
<td>6.0</td>
</tr>
<tr>
<td>disruption angle $\theta_0$ [(\mu rad)]</td>
<td>0.06</td>
<td>572</td>
</tr>
<tr>
<td>beam current [mA]</td>
<td>430–580</td>
<td>6.6</td>
</tr>
</tbody>
</table>
Luminosity in all cases is limited by allowed AC-plug power consumption set at 100 MW.

Energy flux is carried out by 10 GeV beams.

V.N. Litvinenko, IPAC’11, Kyoto, May 26, 2010
### Main Accelerator Challenges

In red – increase/reduction beyond the state of the art

<table>
<thead>
<tr>
<th>ENC at FAIR</th>
<th>ELIC at JLab</th>
<th>eRHIC at BNL</th>
<th>LHeC at CERN</th>
</tr>
</thead>
<tbody>
<tr>
<td><em><em>β</em> = 0.5 cm</em>*&lt;br&gt;50x reduction</td>
<td>Polarized electron gun - 50x increase</td>
<td>Depolarization at the top energy</td>
<td>Polarized e⁻ source</td>
</tr>
<tr>
<td><strong>8 MV, 3 A magnetized electrostatic (Voltage<em>2, Current</em>6)</strong></td>
<td>HE Electron Cooling - 100x increase in the rate of cooling</td>
<td>Coherent Electron Cooling - New concept</td>
<td>Energy reach beyond 70 GeV for leptons</td>
</tr>
<tr>
<td><strong>Investigation of large beam-beam tune shift in space charge dominated regimes</strong></td>
<td>High current recirculating ring with ERL-injector&lt;br&gt;New concept</td>
<td>Multi-pass SRF ERL&lt;br&gt;5x increase in current&lt;br&gt;30x increase in energy</td>
<td>Synchrotron radiation losses in the arcs</td>
</tr>
<tr>
<td><strong>Crab crossing</strong>&lt;br&gt;(compliance with acceptance of PANDA)</td>
<td>Crab crossing&lt;br&gt;5x the angle&lt;br&gt;New for hadrons</td>
<td>Crab crossing&lt;br&gt;New for hadrons</td>
<td>Crab crossing&lt;br&gt;New for hadrons</td>
</tr>
<tr>
<td><strong>Limited space for electron ring</strong>&lt;br&gt;Never explored beam-beam parameter range&lt;br&gt;3-4x in $\xi$</td>
<td>Understanding of beam-beam affects&lt;br&gt;New type of collider</td>
<td>Complexity of the sharing tunnel with LHC</td>
<td>Very challenging to have e⁺ source</td>
</tr>
<tr>
<td><strong>Polarization life time in electron ring</strong>&lt;br&gt;(lattice considerations)</td>
<td>Dispersive crab crossing&lt;br&gt;Traveling focus&lt;br&gt;New concepts</td>
<td>$\beta* = 5$ cm&lt;br&gt;5x reduction</td>
<td>Using crossing angle to avoid SR in IR</td>
</tr>
<tr>
<td><strong>Space charge limits beam dynamics, Bunching (1→200)</strong></td>
<td>Sub-nsec kicker with MHz rep-rate&lt;br&gt;50x shorter pulses</td>
<td>Multi-pass SRF ERL&lt;br&gt;3-4x in # of passes</td>
<td>Need new injector</td>
</tr>
<tr>
<td><strong>Figure-8 ring spin dynamics</strong>&lt;br&gt;New concept</td>
<td>Feedback for kink instability suppression&lt;br&gt;Novel concept</td>
<td>Synchrotron radiation in the IR</td>
<td></td>
</tr>
</tbody>
</table>

V.N. Litvinenko, IPAC'11, Kyoto, May 26, 2010
Conclusions

• There is very strong scientific case for electron hadron colliders
• Four colliders, covering CM energy range from 10 GeV to 2 TeV, are in various stages of development/design
• All of these colliders are aiming at very high luminosity and have a challenging problem to reach two-to-four orders of magnitude beyond the luminosity demonstrated by the very successful, but the only, electron-hadron collider HERA
• These electron-hadron colliders promise to deliver very rich physics not only in the quantity but also in the precision
• eRHIC and ELIC are competing for becoming the US-based Electron Ion Collider (EIC). Their physics program have significant (but not complete) overlap
• Administrations of BNL and Jlab, in concert with US DoE office of Nuclear Physics, work on the strategy for down-selecting between eRHIC and ELIC
• The ENC, EIC and LHeC QCD physics programs (to a large degree) complimentary to each other. The LHeC would also complements the LHC physics beyond the standard model
• Intense R&D program (both in accelerators and in detectors) is pursued by US DoE to address the challenges posed by the EIC
Back-up slides
## Major IEC Accelerator R&D in the US

### Common R&D activities for eRHIC and ELIC

- **Polarized 3He production and acceleration (BNL)**
  
  - 5 FTE-yrs; M&S: $1.0 M Total: $2M

- **Coherent Electron Cooling (BNL)**
  
  - 15 FTE-yrs; M&S: $5.0 M Total: $8M

- **Energy recovery technology for 100 MeV level electron beam. (JLab)**
  
  - 20 FTE-yrs; M&S: $4.5 M Total: $8.5M

- **Crab cavities**
  
  - 8 FTE-yrs; M&S: $1.2M Total: $2.8M

### R&D activities specific to eRHIC

- **High current polarized electron source (MIT)**
  
  - 7.5 FTE-yrs; M&S: $2.0 M Total: $3.5M

- **Energy recovery technology for high energy and high current beams (BNL)**
  
  - 10 FTE-yrs; M&S: $3.0 M Total: $5M

- **Development of eRHIC-type SRF cavity (BNL)**
  
  - 10 FTE-yrs; M&S: $2.0 M Total: $4M

### R&D activities specific to ELIC

- **Ion space charge sim. (JLab in collab. with SNS)**
  
  - 2 FTE-yrs; M&S: $0.5M Total: $0.9M

- **Spin track studies for ELIC (JLab)**
  
  - 8 FTE-yrs; Total: $1.6M

- **Studies traveling focus scheme (JLab)**
  
  - 3 FTE-yrs; Total: $0.6M

- **Simulation studies supporting ELIC project (JLab)**
  
  - 5 FTE-yrs; Total: $1.0M
**Polarization**

**Ring**

**LEP polarization vs. energy**

Sokolov-Ternov polarization time decreases from 5 hr at 46 GeV to $\frac{1}{2}$ hr at 70 GeV but depolarizing rate increases faster

![Graph showing LEP polarization vs. energy](image)

**Linac**

e- : from polarized dc gun with ~90% polarization, 10-100 mm normalized emittance
e+: up to ~60% from undulator or Compton-based source

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V.N. Litvinenko, IPAC'11, Kyoto, May 26, 2010
**eRHIC luminosity at low energy**

<table>
<thead>
<tr>
<th></th>
<th>e</th>
<th>p</th>
<th>$^2\text{He}^3$</th>
<th>$^{79}\text{Au}^{197}$</th>
<th>$^{92}\text{U}^{238}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy, GeV</strong></td>
<td>2</td>
<td>50</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td><strong>CM energy, GeV</strong></td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td><strong>Number of bunches/distance between bunches</strong></td>
<td>74 nsec</td>
<td>166</td>
<td>166</td>
<td>166</td>
<td>166</td>
</tr>
<tr>
<td><strong>Bunch intensity (u), 10^{11}</strong></td>
<td>0.24</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>Bunch charge, nC</strong></td>
<td>3.8</td>
<td>32</td>
<td>32</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td><strong>Beam current, mA</strong></td>
<td>50</td>
<td>420</td>
<td>420</td>
<td>420</td>
<td>420</td>
</tr>
<tr>
<td><strong>Normalized emittance, mm mrad, 95% for hadrons, rms for electrons</strong></td>
<td>15</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td><strong>Polarization, %</strong></td>
<td>80</td>
<td>70</td>
<td>70</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td><strong>rms bunch length, cm</strong></td>
<td>0.2</td>
<td>4.9</td>
<td>4.9</td>
<td>4.9</td>
<td>4.9</td>
</tr>
<tr>
<td><strong>$\beta^*$, cm</strong></td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>Luminosity per nucleon, cm^{-2}s^{-1}</strong></td>
<td>$0.22 \times 10^{34}$</td>
<td>$0.34 \times 10^{34}$</td>
<td>$0.56 \times 10^{34}$</td>
<td>$0.56 \times 10^{34}$</td>
<td></td>
</tr>
</tbody>
</table>

Hourglass effect is included: $h(\sigma_s/\beta^*) = 0.851$

V.N. Litvinenko, IPAC'11, Kyoto, May 26, 2010
Kink instability – a possible instability of the proton beam caused by its interaction with the electrons. Specific for linac-ring scheme.

Simple feed-back on electron beam suppress kink instability completely for all eRHIC parameter ranges.
Electron beam disruption for eRHIC. Optimization of beam parameters

\[ \beta^* = 1 \text{m} \]
Emittance: 1nm-rad

\[ \beta^* = 0.2 \text{m} \]
Emittance: 5nm-rad

V.N. Litvinenko, IPAC'11, Kyoto, May 26, 2010
Energy of electron beam is increased in stages by increasing the length of the linacs.

V.N. Litvinenko, IPAC'11, Kyoto, May 26, 2010
Main technical challenge for eRHIC is 50 mA CW polarized gun: we are building two versions.

Single large size cathode @ MIT

* The Gatling gun is the first successful machine gun, invented by Dr. Richard Jordan Gatling.

V.N. Litvinenko, IPAC'11, Kyoto, May 26, 2010
Transverse Beam BreakUp (TBBU) instability (©E. Pozdeyev)

- HOMs based on R. Calaga’s simulations/measurements
- 70 dipole HOM’s to 2.7 GHz in each cavity
- Polarization either 0 or 90°
- 6 different random seeds
- HOM Frequency spread 0-0.001

<table>
<thead>
<tr>
<th>F (GHz)</th>
<th>R/Q (Ω)</th>
<th>Q</th>
<th>(R/Q)Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8892</td>
<td>57.2</td>
<td>600</td>
<td>3.4e4</td>
</tr>
<tr>
<td>0.8916</td>
<td>57.2</td>
<td>750</td>
<td>4.3e4</td>
</tr>
<tr>
<td>1.7773</td>
<td>3.4</td>
<td>7084</td>
<td>2.4e4</td>
</tr>
<tr>
<td>1.7774</td>
<td>3.4</td>
<td>7167</td>
<td>2.4e4</td>
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<tr>
<td>1.7827</td>
<td>1.7</td>
<td>9899</td>
<td>1.7e4</td>
</tr>
<tr>
<td>1.7828</td>
<td>1.7</td>
<td>8967</td>
<td>1.5e4</td>
</tr>
<tr>
<td>1.7847</td>
<td>5.1</td>
<td>4200</td>
<td>2.1e4</td>
</tr>
<tr>
<td>1.7848</td>
<td>5.1</td>
<td>4200</td>
<td>2.1e4</td>
</tr>
</tbody>
</table>

Threshold significantly exceeds the beam current, especially for the scaled gradient solution.

V.N. Litvinenko, IPAC’11, Kyoto, May 26, 2010
eRHIC: polarized protons

RHIC only polarized proton collider in the world
polarization: up to 65% achieved at 100 GeV
and presently up to 40% at 250 GeV
Coherent Electron Cooling (CeC)

At a half of plasma oscillation

\[ q_{beam} = \frac{\lambda_{FEL}}{\rho} \int \rho(z) \cos(k_{FEL}z)dz \]

\[ \rho = kq(\phi); \quad n_k = \frac{\rho_k}{2\pi\beta\epsilon} \]

\[ \lambda_{FEL} \]

Debye radii

\[ R_{D\perp} >> R_{D//} \]

\[ R_{D//,lab} = \frac{c\sigma_T}{\gamma^2\omega_p} \ll \lambda_{FEL} \]

Dispersion section (for hadrons)

\[ E \cdot E_h \]

\[ E > E_h \]

Amplifier of the e-beam modulation in an FEL with gain \( G_{FEL} \approx 10^2 - 10^3 \)

\[ A_L = \frac{2\pi\beta\epsilon_n}{\gamma_o} \]

\[ k_{FEL} = 2\pi/\lambda_{FEL}; \quad k_{cm} = k_{FEL}/2\gamma_o \]

\[ n_{amp} = G_o \cdot n_k \cos(k_{cm}z) \]

\[ \Delta\varphi = 4\pi n \Rightarrow \varphi = -\varphi_0 \cdot \cos(k_{cm}z) \]

\[ E = -\nabla \varphi = -\frac{Ze}{\beta\epsilon_{cm}} \cdot X \sin(k_{cm}z) \]

\[ E_o = 2G_o\gamma_o \frac{e}{\beta\epsilon_{cm}} \]

\[ X = q/e \approx Z(1 - \cos\phi_1) \sim Z \]
Electron polarization in eRHIC

The polarization benefits greatly from the linac acceleration geometry

- No coherent buildup of small depolarizing errors → No problem with depolarizing resonances
- No depolarization due to synchrotron radiation
- Simple control of spin orientation at the collision point

The polarization orientation at the eRHIC detector:

\[ \phi_d = \phi_0 + G \int_0^{\theta_d} \gamma(\theta) d\theta \]

Adjusted by Wien filter rotator after the source

Adjusted by modifications of energy gains in the linacs

\( e \)-gun, \( P_e \) stays in horizontal plane and rotates in arcs around vertical direction
Additional advantage of linac-ring – removing systematic errors

It is built-in feature of the linac-ring eRHIC: we can arbitrary select polarization of individual bunches

a) In RHIC this is already implemented by injection scheme (ion source) for protons
b) In eRHIC ERL electron polarization is reversible by switching helicity of the laser photons

It is impossible in ring-ring EIC
Positrons

Ring
A rebuilt conventional e\(^+\) source would suffice

Linac
True challenge: 10x more e\(^+\) than ILC!
Large # bunches → damping ring difficult
Candidate e\(^+\) sources under study:
- ERL Compton source for CW operation
e.g. 100 mA ERL w. 10 optical cavities
- undulator source using spent e- beam
- Linac-Compton source for pulsed operation

Complementary options: collimate to shrink emittance, extremely fast damping in laser cooling ring?, recycle e\(^+\) together with recovering their energy?

T. Omori, J. Urakawa, et al

V.N. Litvinenko, Europhysics HEP Conference, Krakow, July 17, 2009