Electron-Ion Collider Proposals Worldwide

Yuhong Zhang

Thomas Jefferson National Accelerator Facility

North American Particle Accelerator Conference (NA-PAC’13)
29 September – 4 October 2013, Pasadena, California
Outline

• Introduction
• Accelerator Designs
• Technology Innovation
• Outlook and Summary

Electron-ion collider ➔ electron-proton collisions
+ electron-(light to heavy) ion collisions
1. Introduction
Electron-Ion Collider: The Next Generation

• HERA, the only electron-proton collider ever built and operated, ended its highly successful physics program in 2007.

• **Five** next generation electron-ion colliders have been envisioned worldwide for reaching new frontiers of high energy and nuclear physics.

• Four proposals are built upon existing or under construction facilities which provide one of two colliding beams. Only one proposal calls for a complete new facility in a green field design.

• Driven by the science programs, each of the new proposals focuses on a distinct CM energy range from a few GeV to above TeV, accommodates one to three interaction points, and aims for much higher collider performances than HERA.

• Presently, both the science cases and accelerator designs of these proposals are under active development. Collaborations among the physicists and accelerator designers are picking up momentum and have already yielded some interesting results.
Science Goals

The High-Energy/Nuclear Science of LHeC

**Overarching Goal: lepton-proton at the TeV Scale**
- Hunt for quark substructure & high-density matter (saturation)
- High precision QCD and EW studies and *precision Higgs measurements*

The Nuclear Science of eRHIC/MEIC

**Overarching Goal: Explore and Understand QCD:**
- Map the spin and spatial structures of quarks and gluons in nucleons
- Discover the collective effects of gluons in atomic nuclei
  
  *(role of gluons in nuclei & onset of saturation)*

**Emerging Themes:**
- Understand the emergence of hadronic matter from quarks and gluons & EW

The Nuclear Science of ENC and HIAF(?)

**Overarching Goal: Explore Hadron Structure**
- Map the spin and spatial structure of valence & sea quarks in nucleons
Science Goals

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**e-p @ LHeC is a very serious & affordable Higgs facility**

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R. Ent

JLab
A Snapshot of Machine Design

Sources

HERA
• F. Willeke, talk at DIS 2004, April 17, 2004, Strbske Pleso

LHeC
• M. Klein, talk at IPAC11, San Sebastian, Sept. 4-9, 2011
• O. Bruning, talk at IPAC13, Shanghai, May 12-17, 2013
• LHeC Design Report

ENC
• K. Aulenbacher, talk at Spin 2010, Sept. 27, 2010, and private communication

HIAF
• J. Yang, private communication

eRHIC
• V. Litvinenko, talk at POETIC Workshop, Chile, March 4-8, 2013
• V. Ptitsyn, talk at PSTP 2013, UVA, Sept. 9-13, 2013

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Acknowledgement
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Alessandra Valloni
“Beam Physics in Future Electron Hadron Colliders”
2. Accelerator Designs
(from high to low CM energy)
HERA: The 1st EIC Ever Built

A Ring-Ring (polarized) Lepton-Proton collider with 320 GeV CM energy

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>1981</td>
<td>Proposal</td>
</tr>
<tr>
<td>1984</td>
<td>Start construction</td>
</tr>
<tr>
<td>1991</td>
<td>Commissioning, first Collisions</td>
</tr>
<tr>
<td>1992</td>
<td>Start Operations for H1 and ZEUS,</td>
</tr>
<tr>
<td></td>
<td>➔ 1st exciting results with low luminosity</td>
</tr>
<tr>
<td>1994</td>
<td>Install East Spin Rotators</td>
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<td></td>
<td>➔ Longitudinal polarized leptons for HERMES</td>
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<tr>
<td>1996</td>
<td>Install 4th Interaction region for HERA-B</td>
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<td>High Luminosity Run with electrons</td>
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<tr>
<td>2000</td>
<td>High efficient luminosity production: 100 /pb/y</td>
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<tr>
<td>2001</td>
<td>Install luminosity upgrade, Spin Rotators for H1 and ZEUS</td>
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<tr>
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<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Energy (GeV)</td>
<td>27.5</td>
</tr>
<tr>
<td>Intensities (mA)</td>
<td>60</td>
</tr>
<tr>
<td>Magnetic field (T)</td>
<td>0.15</td>
</tr>
<tr>
<td>Acc. voltage (MV)</td>
<td>130</td>
</tr>
<tr>
<td>e-polarization (%)</td>
<td>30 to 50</td>
</tr>
<tr>
<td>Final luminosity (cm$^{-2}$s$^{-1}$)</td>
<td>(1.5 to 5)x10$^{31}$</td>
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**Successful end of HERA with 500 pb⁻¹ delivered**

**Parameters**

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<tr>
<td>Energy (GeV)</td>
<td>27.5</td>
<td>920</td>
</tr>
<tr>
<td>Intensities (mA)</td>
<td>60</td>
<td>180x10¹¹</td>
</tr>
<tr>
<td>Magnetic field (T)</td>
<td>0.15</td>
<td>1.5</td>
</tr>
<tr>
<td>Acc. voltage (MV)</td>
<td>130</td>
<td>2</td>
</tr>
<tr>
<td>e-polarization (%)</td>
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<td>--</td>
</tr>
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LHeC: Ring-Ring

- Electron/positron is up to 60 GeV
- \(e^+ / e^-\) stored in the main ring
- Needs a 10 GeV \(e^+ / e^-\) injector, the current design is a recirculating linac
- Total filling time is less than 10 min
LHeC: Ring-Ring

- Electron/positron is up to 60 GeV
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New ring in LHC tunnel

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<tr>
<td>Energy</td>
<td>60 GeV</td>
<td>7 TeV</td>
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<tr>
<td>Current</td>
<td>100 mA</td>
<td>860 mA</td>
</tr>
<tr>
<td>Part. per bunch</td>
<td>$2 \times 10^{10}$</td>
<td>$1.7 \times 10^{11}$</td>
</tr>
<tr>
<td>Numb. of bunches</td>
<td>2808</td>
<td>2808</td>
</tr>
<tr>
<td>$e_x / e_y$</td>
<td>5.0 / 2.5 nm</td>
<td>0.5 / 0.5 nm</td>
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<tr>
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<td>&lt; 50 MW</td>
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Thera (2001)
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LHeC: Ring-Ring

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10 GeV recirculating SRF linac with 3 passes

Power Limit: 100 MW wall plug!

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### High Acceptance (1 deg.)

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<tbody>
<tr>
<td>$\beta_x$</td>
<td>0.4 m</td>
<td>4.05 m</td>
</tr>
<tr>
<td>$\beta_y$</td>
<td>0.2 m</td>
<td>0.97 m</td>
</tr>
<tr>
<td>$I^*$</td>
<td>6 m</td>
<td>22.96 m</td>
</tr>
<tr>
<td>$\sigma_x$</td>
<td>45 $\mu$m</td>
<td></td>
</tr>
<tr>
<td>$\sigma_y$</td>
<td>22 $\mu$m</td>
<td></td>
</tr>
<tr>
<td>Crossing angle</td>
<td>1 mrad</td>
<td></td>
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<tr>
<td>Luminosity</td>
<td>8.54 $10^{32}$ cm$^{-2}$ s$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Luminosity loss factor</td>
<td>86%</td>
<td></td>
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<tr>
<td>Luminosity</td>
<td>7.33 $10^{32}$ cm$^{-2}$ s$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$P_{\gamma}$</td>
<td>51 kW</td>
<td></td>
</tr>
<tr>
<td>$E_c$</td>
<td>163 keV</td>
<td></td>
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</tbody>
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### High Luminosity (10 deg.)

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<tbody>
<tr>
<td>$\beta_x$</td>
<td>0.18 m</td>
<td>1.8 m</td>
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<td>$\beta_y$</td>
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<td>1.8 $10^{33}$ cm$^{-2}$ s$^{-1}$</td>
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<td>Luminosity loss factor</td>
<td>75%</td>
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<td>1.34 $10^{33}$ cm$^{-2}$ s$^{-1}$</td>
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<td>$E_c$</td>
<td>126 keV</td>
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### e-A Collisions

- Assuming present normal Pb beam in LHC
  - Same beam size as protons
  - Few bunches (592)
  - 7x10$^7$ fully stripped $^{208}$Pb$^{82}$
- Assuming e-injector chain can provide the design bunch pattern (596 bunches of 6x10$^{10}$)
- Electron SR loss 45 MW
- Lepton-nucleon Luminosity at 60 GeV lepton energy
  $$L_{eA}=1x10^{32} \text{ cm}^{-2}\text{s}^{-1}$$

**Lepton polarization**

- Polarization of 25% to 40% can be reasonably aimed for at 60 GeV with harmonic closed orbit spin matching
- Precision alignment of the magnets to better than 150 $\mu$m RMS needed to achieve a high polarization level
- Option of having Siberian snake
LHeC: Ring-Ring

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LHeC Polarization vs. Energy

$L_{eA} = 1 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
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- Polarization of 25% to 40% can be reasonably aimed for at 60 GeV with harmonic closed orbit spin matching
- Precision alignment of the magnets to better than 150 $\mu$m RMS needed to achieve a high polarization level
- Option of having Siberian snake

**Installation is very challenging!**

---

**No principal problem found yet!**
LHeC: Linac(ERL)-Ring

Lots of linac options

Why ERL?

- High energy, high current beams require GW-class RF systems in conventional linacs
- ERL alleviates extreme RF power demand ➔ nearly independent of beam current
- ERL maintains superior beam quality: emittance, energy spread, short bunches
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recirculating linac

Least expensive Luminosity limited by power

Why ERL?

• High energy, high current beams require GW-class RF systems in conventional linacs
• ERL alleviates extreme RF power demand ➔ nearly independent of beam current
• ERL maintains superior beam quality: emittance, energy spread, short bunches
LHeC: Linac(ERL)-Ring

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Straight linac

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Higher Energy limited by power and cost
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#### Electron beam

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- Cryo for two 10 GeV SRF Linacs: 28.9 MW
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- Injector RF: 6.4 MW
- Magnets: 3.0 MW

Total: 88.3 MW

**Power Limit: 100 MW wall plug!**

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### LHeC: Linac(ERL)-Ring

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**LHeC: Linac(ERL)-Ring**

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  - 60 140
- Luminosity [10^{32} cm^{-2}s^{-1}]: 10 0.44
- Polarization [%]: 90 90
- Bunch population [10^9]: 2.0 2.0
- e- bunch length [mm]: 0.3 0.3
- Bunch interval [ns]: 50 50
- Trans. emit. γε_{xy} [mm]: 0.05 0.1
- rms IP beam size σ_{xy} [µm]: 7 7
- e- IP beta funct. β*_{xy} [m]: 0.12 0.14
- Full crossing angle [mrad]: 0 0
- Geometric reduction H_{hg}: 0.91 0.94
- Repetition rate [Hz]: N/A 10
- Beam pulse length [ms]: N/A 5
- ER efficiency: 94% N/A
- Average current [mA]: 6.6 5.4
- Tot. wall plug power [MW]: 100 100

**Proton beam**
- Bunch population [10^{11}]: RR LR
  - 1.7 1.7
- Trans. emit. γε_{xy} [µm]: 3.75 3.75
- Spot size σ_{xy} [µm]: 30, 16 7
- β*_{xy} [m]: 1.8, 0.5 0.5
- Bunch spacing [ns]: 25 25

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**Post CDR:** choice of frequency (802 MHz) and consideration of increased luminosity for ep→HX
The latest LHeC ERL-ring design assumes the HL-LHC proton beam parameters for further boosting its performance reach (pushing luminosity up to $10^{34}$ cm$^{-2}$s$^{-1}$) → A serious candidate of Higgs facility

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LHeC Design Report

Total of ca. 500 pages

Detailed coverage of many topics:

- Sources
- Damping rings & injector complex
- Injection and injector complex
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Next LHeC Workshop
20 – 21 January 2013
Near CERN

http://iopscience.iop.org/0954-3899/39/7/075001
**eRHIC: ERL-Ring**

**Electron accelerator to be built**

- Existing = $2B
- Polarized protons 50-250 GeV
- Light ions (d, Si, Cu) Heavy ions (Au, U) 50-100 GeV/u
- Polarized light ions He³ 166 GeV/u

**Brief History**

- 2000 – 1st eRHIC paper (I. Ben Zvi et al.)
- 2002 – 1st White Paper on eRHIC
- 2003 – eRHIC appears in DoE’s “Facilities for the Future Sciences. A Twenty-Year Outlook”
- 2004 – “eRHIC Zeroth-Order Design Report” with cost estimate for Ring-Ring
- 2007 – Linac-ring became baseline (~10-fold higher luminosity)
- 2008 – first staging option of eRHIC
- 2009 – completed technical design, dynamics studies and cost estimate for MeRHIC with 4 GeV ERL
- Present - returned to the cost-effective (green) all in tunnel high-luminosity eRHIC design with staging electron energy from 10 GeV to 30 GeV

**Unpolarized and polarized leptons**

- 5-20 (30) GeV
- 70% e⁻ beam polarization goal

**Polarized electrons with $E_e \leq 30$ GeV will collide with either polarized protons with $E_p \leq 325$ GeV or heavy ions $E_A \leq 130$ GeV/u**

**Center mass energy range:** $\sqrt{s} = 30-200$ GeV; Luminosity $\sim 10^{34}-10^{35}$ cm⁻² sec⁻¹

**Unpolarized and polarized leptons**

- e⁻, e⁺, p, n

**Unpolarized and polarized leptons**

- 5-20 (30) GeV

**Polarized electron beam polarization goal**

- 70% e⁻ beam polarization goal
eRHIC: ERL-Ring

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### eRHIC: ERL-Ring

<table>
<thead>
<tr>
<th></th>
<th>e</th>
<th>p</th>
<th>$^2\text{He}$</th>
<th>$^{79}\text{Au}$</th>
<th>$^{92}\text{U}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy, GeV</td>
<td>20</td>
<td>250</td>
<td>167</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>CM energy, GeV</td>
<td>100</td>
<td>82</td>
<td>63</td>
<td>63</td>
<td>63</td>
</tr>
<tr>
<td>Number of bunches/distance between bunches, ns</td>
<td>107</td>
<td>111</td>
<td>111</td>
<td>111</td>
<td>111</td>
</tr>
<tr>
<td>Bunch intensity (nucleons), $10^{11}$</td>
<td>0.36</td>
<td>4</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Bunch charge, nC</td>
<td>5.8</td>
<td>64</td>
<td>60</td>
<td>39</td>
<td>40</td>
</tr>
<tr>
<td>Beam current, mA</td>
<td>50</td>
<td>556</td>
<td>556</td>
<td>335</td>
<td>338</td>
</tr>
<tr>
<td>Normalized emittance of hadrons, 95%, mm mrad</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Normalized emittance of electrons, rms, mm mrad</td>
<td>16</td>
<td>24</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Polarization, %</td>
<td>80</td>
<td>70</td>
<td>70</td>
<td>none</td>
<td>None</td>
</tr>
<tr>
<td>rms bunch length, cm</td>
<td>0.2</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$\beta^*$, cm</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Luminosity per nucleon, $x10^{34}$ cm$^{-2}$ s$^{-1}$ (with hourglass effect)</td>
<td>2.7</td>
<td>2.7</td>
<td>1.6</td>
<td>1.7</td>
<td>1.7</td>
</tr>
</tbody>
</table>

**Reaching high luminosity:**

- high average electron current ($50\ mA = 3.5\ nC \times 14\ MHz$)
- energy recovery linacs; SRF technology
- high current polarized electron source
- cooling of high energy hadrons (Coherent Electron Cooling)
- $\beta^*$=5 cm IR with crab-crossing

**Limiting factors:**

- hadron $\Delta Q_{sp} \leq 0.035$
- hadron $\xi \leq 0.015$
- polarized e current $\leq 50\ mA$
- SR power loss $\leq 7\ MW$

**Space charge compensation boosts luminosity with low ion energies**
eRHIC: Electron ERL Development

**ERL R&D**

- **Polarized e-injector**
- **704 MHz SRF cavity**
- **Compact arc magnets**
- **Electron beams**
- **Heavy ions and polarized protons already there at BNL**

**Splitter & combiner**

- **2nd 2.45 GeV LINAC**

**3.05 GeV**
- **7.95 GeV**
- **12.85 GeV**
- **17.75 GeV**
- **22.65 GeV**
- **27.55 GeV**
- **5.5 GeV**
- **10.4 GeV**
- **15.3 GeV**
- **20.2 GeV**
- **25.1 GeV**

Thomas Jefferson National Accelerator Facility
MEIC: Ring-Ring

Brief History
2001 1st paper on JLab EIC proposal: An ERL-Ring design based on CEBAF
2002 Circulator ring added to ERL-ring design
2003 ERL based circulator e-cooler
2006 Baseline changed to ring-ring
2007 ELIC 0th Order Design Report
2009 Medium energy (MEIC) became the baseline with a future energy upgrade
2012 MEIC Design Report released

Present baseline: Ring-Ring
- Energy: 3-12 GeV e on 20-100 GeV p or up 40 GeV/u ion
- Polarized light ions (p, d, ³He), unpolarized ions up to A=200 (Au, Pb)
- New ion complex & two collider rings
- Up to 3 interaction points
- High polarization for both beams
- Conventional electron cooling
- Upgradable to 20 GeV electron, 250 GeV proton or 100 GeV/u ion
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### MEIC: Ring-Ring

<table>
<thead>
<tr>
<th></th>
<th>Proton</th>
<th>Electron</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Beam energy</strong></td>
<td>GeV</td>
<td>60</td>
</tr>
<tr>
<td><strong>Collision frequency</strong></td>
<td>MHz</td>
<td>750</td>
</tr>
<tr>
<td><strong>Beam current / Particles/bunch</strong></td>
<td>A /10^{10}</td>
<td>0.5 / 0.416</td>
</tr>
<tr>
<td><strong>Polarization</strong></td>
<td>%</td>
<td>&gt; 70</td>
</tr>
<tr>
<td><strong>RMS bunch length</strong></td>
<td>cm</td>
<td>10</td>
</tr>
<tr>
<td><strong>Emittance, norm. (x/y)</strong></td>
<td>μm</td>
<td>0.35 / 0.07</td>
</tr>
<tr>
<td><strong>Horizontal and vertical β</strong></td>
<td>cm</td>
<td>10 / 2 (4 / 0.2)</td>
</tr>
<tr>
<td><strong>Vert. beam-beam tune shift</strong></td>
<td></td>
<td>0.014</td>
</tr>
<tr>
<td><strong>Laslett tune shift</strong></td>
<td></td>
<td>0.06</td>
</tr>
<tr>
<td><strong>Dist. from IP to 1st FF quad</strong></td>
<td>m</td>
<td>7 (4.5)</td>
</tr>
<tr>
<td><strong>Luminosity per IP, 10^{33} cm^{-2}s^{-1}</strong></td>
<td></td>
<td>5.6 (14.2)</td>
</tr>
</tbody>
</table>

**Interaction region for a full acceptance Detector**
MEIC: A New Ion Complex

• Generate/accumulate and accelerate ion beams
• Covering all required varieties of ion species
• Matching time, spatial and phase space structure of the ion beam with electron beam

<table>
<thead>
<tr>
<th></th>
<th>Length (m)</th>
<th>Max. energy (GeV/c)</th>
<th>Electron Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRF linac</td>
<td>~300</td>
<td>0.2 (0.08)</td>
<td></td>
</tr>
<tr>
<td>Pre-booster</td>
<td>~1300</td>
<td>3 (1.2)</td>
<td>DC</td>
</tr>
<tr>
<td>booster</td>
<td>~1300</td>
<td>20 (8 to 15)</td>
<td></td>
</tr>
<tr>
<td>collider ring</td>
<td>~1300</td>
<td>96 (40)</td>
<td>Staged/ERL</td>
</tr>
</tbody>
</table>

* Numbers in parentheses represent energies per nucleon for heavy ions

![Scheme diagram](image)

Pre-booster

Electron Cooling

Extraction

Collimation

Beam from LINAC

Ion linac

RF Cavities

Solenoids

[Image of ion linac with labels: HWR (Half-Wave Resonator), QWR (Quarter Wave Resonator)]
MEIC Design Report Released!

Table of Contents

Executive Summary
1. Introduction
2. Nuclear Physics with MEIC
3. Baseline Design and Luminosity Concept
4. Electron Complex
5. Ion Complex
6. Electron Cooling
7. Interaction Regions
8. Outlook

arXiv:1209.0757
Facility for Antiproton & Ion Research (FAIR@GSI)

- Nuclear structure physics
- Physics with antiprotons
- Nuclear matter physics
- Plasma physics
- Atomic physics

ENC@FAIR

- Use High Energy Storage Ring (HESR) for storing 15 GeV proton beam
- Add an electron storage ring for 3 GeV 2 A beam
- Share PANDA detector

- Head-on collision
- Baseline: $\beta^*=30 \text{ cm} \rightarrow 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- Aggressive: $\beta^*=10 \text{ cm} \rightarrow 6 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- With “traveling focusing” $\rightarrow 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

Vision: Electron Nucleon Collider @ FAIR
• Due to availability of HESR storage ring & PANDA detector (from about year 2018 on), an upgrade to collider operation requires only a fraction of the cost of other projects.

• Considerable R&D is required to achieve the parameter set; however there seem to be no issues which are beyond the accepted potential of accelerator physics.

• Physics potential of ENC approaches stage 1 of the EIC concepts at BNL and JLab
polarized protons out of SIS-18 Synchrotron

Energy
Current
Solenoid field
Straightness (rad rms)
Interaction length
Bending radius

[Table]

Conventional electron cooling

Cooling times at low or ‘high’ energy with un-bunched beams ~1000s
Tricky interplay between space charge/bunching/cooling!
High Intensity Heavy Ion Accelerator Facility (HIAF) at Institute of Modern Physics, CAS

Science goals of HIAF
- Nuclear physics
- High energy density physics
- Science based on the EIC
- Atomic physics
- Application

Main Components
- High intensity ion source
- High intensity pulsed SC-Linac
- Multi-function booster and collector ring
- Long straight ion collider
- Figure-8 electron collider
- Large acceptance RIBs line

- A multi-purpose science complex w/ a green field design
- Already approved (2013) by Chinese central government (total $2.3B RMB (~$380M) plus labors)
- Electron-ion Collider is likely in the 2nd stage
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(eLinac)
Electron injector

Collision & Compression Ring (CRing-43Tm)

Multi-function Booster Ring (BRing-34Tm)

Spectrometer Ring (SRing)

ion Linac (iLinac)

Low Energy RIBs beam station

HIAF first stage

HIAF upgrade

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**Diagram**
- HIAF first stage
- HIAF upgrade

**Electron injector**

**Collision & Compression Ring**
(CRing-43Tm)

**Multi-function Booster Ring**
(BRing-34Tm)

**Spectrometer Ring**
(SRing)

**Field-8 electron collider**

**High precision spectrometer**

**Electron Linac (eLinac)**

**SC ECR (SECR)**

---

Jefferson Lab  NA-PAC’13

Thomas Jefferson National Accelerator Facility
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**Diagram**
- Electron injector
- Multi-function Booster Ring (BRing-34Tm)
- Spectrometer Ring (SRing)
- Collision & Compression Ring (CRing-43Tm)
- 4 High purity & quality RIB station
**High Intensity Heavy Ion Accelerator Facility (HIAF)** at Institute of Modern Physics, CAS

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- ion Linac (iLinac)
- Electron injector
- HIAF first stage
- HIAF upgrade

**High energy density matter terminal**

---

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SC ECR (SECR)

External target

(eLinac)
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- Electron ring
- EIC
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- Spectrometer Ring (SRing)
- SC ECR (SECR)
- Electron injector
- Collision & Compression Ring (CRing-43Tm)
- Spectrometer Ring (SRing)
- ion Linac (iLinac)
- eLinac
HIAF @ IMP, A Green Field Project

1. Low energy nuclear structure spectrometer
2. Low energy RIBs beam station
3. High precision spectrometer
4. High purity & quality RIBs station
5. Electron-ion recombination resonance spectrometer
6. High energy irradiation terminal
7. High-Energy-Density Matter terminal
8. External target station
HIAF @ IMP, A Green Field Project
<table>
<thead>
<tr>
<th></th>
<th>Proton</th>
<th>Electron</th>
<th>$^{238}\text{U}^{92+}$</th>
<th>Electron</th>
</tr>
</thead>
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<tr>
<td>Beam energy</td>
<td>GeV</td>
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<td>3</td>
<td>0.769</td>
</tr>
<tr>
<td>Collision frequency</td>
<td>MHz</td>
<td>500</td>
<td>54.6</td>
<td>-</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$10^{10}$</td>
<td>0.54</td>
<td>3.7</td>
<td>0.00032</td>
</tr>
<tr>
<td>Beam Current</td>
<td>A</td>
<td>0.43</td>
<td>3</td>
<td>0.0026</td>
</tr>
<tr>
<td>Polarization</td>
<td>%</td>
<td>&gt; 70</td>
<td>~ 80</td>
<td>-</td>
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<tr>
<td>Energy spread</td>
<td>$10^{-4}$</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>cm</td>
<td>2</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Horiz. Emitt., geom.</td>
<td>nm•rad</td>
<td>150</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>Vert. emitt., geom.</td>
<td>nm•rad</td>
<td>50</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Horiz. &amp; vert. $\beta^*$</td>
<td>cm</td>
<td>2</td>
<td>10</td>
<td>100 / 15</td>
</tr>
<tr>
<td>Vert. b-b tune shift</td>
<td>0.0048</td>
<td>0.015</td>
<td>0.018</td>
<td>0.008</td>
</tr>
<tr>
<td>Laslett tune shift</td>
<td>0.045</td>
<td>small</td>
<td>0.1</td>
<td>Small</td>
</tr>
<tr>
<td>Luminosity/IP, $10^{32}$</td>
<td>cm$^{-2}$s$^{-1}$</td>
<td>4.0</td>
<td>-</td>
<td>2.9$\times10^{-5}$</td>
</tr>
</tbody>
</table>

**HIAF Low energy DC electron cooling**

Expected to use the similar cooler for the existing HIREL
General Design Trends

- EIC machine design aims for high performance to meet science needs
  
  NSAC Long Range Plan (2007): eRHIC/MEIC 100x higher luminosity than HERA

- New concepts and technologies have been incorporated into the designs, and shared by multiple proposals

<table>
<thead>
<tr>
<th></th>
<th>LHeC R-R</th>
<th>LHeC L-R</th>
<th>eRHIC</th>
<th>MEIC</th>
<th>ENC</th>
<th>HIAF</th>
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<tbody>
<tr>
<td>New beam facility</td>
<td>Electron</td>
<td>Electron</td>
<td>Electron</td>
<td>Ion</td>
<td>Electron</td>
<td>Both</td>
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<tr>
<td>CM energy range, up to (GeV)</td>
<td>1296</td>
<td>1296</td>
<td>81@stage 1</td>
<td>66@stage 1</td>
<td>13.4</td>
<td>12</td>
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<tr>
<td>Max. luminosity ($10^{33} \text{ cm}^{-2}\text{s}^{-1}$)</td>
<td>1.3</td>
<td>1 → 10</td>
<td>14.6</td>
<td>14.2</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>Ion species</td>
<td>p &amp; lead</td>
<td>p &amp; lead</td>
<td>p to uranium</td>
<td>p to lead</td>
<td>p</td>
<td>p to uranium</td>
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<tr>
<td>Polarized lepton</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Polarized hadron</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Linac(ERL)-Ring</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduction of ion emittance</td>
<td>High energy</td>
<td>High energy</td>
<td>Cooling</td>
<td>Cooling</td>
<td>Cooling</td>
<td>Cooling</td>
</tr>
<tr>
<td>Small beta-star of $e/p$ (cm)</td>
<td>18 / 50</td>
<td>12 / 10</td>
<td>5</td>
<td>10 (x), 2 (y)</td>
<td>30</td>
<td>10 (x), 2 (y)</td>
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<tr>
<td>Proton beam-beam tune-shift</td>
<td>Very small</td>
<td>Very small</td>
<td>0.015 x 3 IP</td>
<td>0.015 x 2 IP</td>
<td>0.015</td>
<td>0.0048</td>
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<tr>
<td>Electron beam-beam disruption</td>
<td>6</td>
<td>0.2 to 140</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Crab crossing</td>
<td>Small angle, no crab cavity</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Advanced IR Scheme</td>
<td>Detector-integrated dipole</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Traveling focus</td>
</tr>
</tbody>
</table>
General Design Trends

- EIC machine design aims for high performance to meet science needs.

NSAC Long Range Plan (2007):
- eRHIC/MEIC: 100x higher luminosity than HERA.

New concepts and technologies have been incorporated into the designs, and shared by multiple proposals.

- LHeC: R-R, LHeC, L-R, eRHIC, MEIC, ENC, HIAF, HIAF.
- CM energy range, up to (GeV): 12, 96, 81@stage 1, 161@stage 2, 66@stage 1, 141@stage 2.
- Max. luminosity (10^33 cm^-2 s^-1): 1.3, 14.6, 14.2, 0.2, 0.4.
- Ion species: P & lead, P & lead, P to uranium, P to lead, P to uranium.
- Polarization: Yes, Yes, Yes, Yes, Yes.
- Linac(RRL)-Ring: Yes, Yes.
- Reduction of ion emittance: High energy, High energy.
- Cooling: Cooling, Cooling, Cooling, Cooling.
- Small beta-star of e/p (cm): 18/50, 12/10, 5, 10 (x), 2 (y).
- Proton beam-beam tune-shift: Very small, Very small, 0.015 x 3 IP, 0.015 x 2 IP, 0.015, 0.0048.
- Electron beam-beam disruption: 6, 0.2 to 140.
- Crab crossing: Small angle, No crab cavity.

Advanced IR Scheme:
- Detector-integrated dipole, Travelling focus.

Max Klein
Univ. of Liverpool
• Ring-ring:

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

Electron storage ring

\( \xi_e \sim 0.1 \)

• Linac-ring:

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

Electron linear accelerator

\( \xi_e > 1 \)

Natural staging strategy

\( L \times 50 \)

• In a linac-ring collider, a lepton beam can tolerate much higher non-linear beam-beam perturbations since it is not stored in a ring, thus leading to a higher luminosity than a ring-ring collider of same collision frequency and other beam parameters

• ERL provides a practical way to accelerate high current lepton beam with a low RF power
MEIC Approach to High Luminosity

- MEIC design concept for high luminosity is based on *high bunch repetition rate CW colliding beams*, specifically

**Beam Design**
- High repetition rate
- Low bunch charge
- Short bunch length
- Small emittance

**IR Design**
- Small $\beta^*$
- Crab crossing

**Cooling**
- Multi-phase
- During collision

**KEK-B already reached above $2 \times 10^{34}$/cm$^2$/s**

**MEIC is designed to replicate same success in EIC:**
- A high repetition rate electron beam from CEBAF
- A new ion complex (so can match e-beam)

<table>
<thead>
<tr>
<th></th>
<th>KEK-B</th>
<th>MEIC</th>
<th>eRHIC ring-ring</th>
</tr>
</thead>
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<tr>
<td>Repetition rate</td>
<td>MHz</td>
<td>509</td>
<td>748.5</td>
</tr>
<tr>
<td>Energy ($e^-/e^+$ or $p/e^-$)</td>
<td>GeV</td>
<td>8/3.5</td>
<td>60/5</td>
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<tr>
<td>Particles/bunch (e$^-$/e$^+$ or $p/e^-$)</td>
<td>$10^{10}$</td>
<td>3.3/1.4</td>
<td>0.42</td>
</tr>
<tr>
<td>Beam current</td>
<td>A</td>
<td>1.2/1.8</td>
<td>0.5/3</td>
</tr>
<tr>
<td>Bunch length</td>
<td>cm</td>
<td>0.6</td>
<td>1/0.75</td>
</tr>
<tr>
<td>Horiz. &amp; vert. $\beta^*$</td>
<td>cm</td>
<td>56/0.56</td>
<td>10/2 ~ 4/0.8</td>
</tr>
<tr>
<td>Luminosity/IP, $10^{34}$/cm$^2$/s</td>
<td>2</td>
<td>0.56 ~ 1.4</td>
<td>0.044</td>
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</table>
3. Technology Innovations
Coherent Electron Cooling for eRHIC

- Recent development, V. Litvinenko & Y. Derbenev, PRL 2009
- A promising scheme for efficient cooling of high energy hadron beam, orders of magnitude reduction of cooling time
- Important application in hadron-hadron & lepton-hadron colliders
- **Potential luminosity increase:** RHIC polarized $pp \sim 6$ fold, eRHIC $\sim 5–10$ fold, LHC $\sim 2$ fold

<table>
<thead>
<tr>
<th>Machine</th>
<th>Species</th>
<th>Energy GeV/n</th>
<th>Synchrotron radiation, hrs</th>
<th>Electron cooling, hrs</th>
<th>CEC, hrs</th>
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<tbody>
<tr>
<td>RHIC</td>
<td>Au</td>
<td>100</td>
<td>20,961 $\infty$</td>
<td>$\sim 1$</td>
<td>0.03</td>
</tr>
<tr>
<td>RHIC</td>
<td>protons</td>
<td>250</td>
<td>40,246 $\infty$</td>
<td>$&gt; 30$</td>
<td>0.8</td>
</tr>
<tr>
<td>LHC</td>
<td>protons</td>
<td>450</td>
<td>48,489 $\infty$</td>
<td>$&gt; 1,600$</td>
<td>0.95</td>
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<tr>
<td>LHC</td>
<td>protons</td>
<td>7,000</td>
<td>13/26 $\infty$</td>
<td>$\infty \infty$</td>
<td>$&lt; 2$</td>
</tr>
</tbody>
</table>

©G. Mahler

*Proof-of-Principle experiment in RHIC IR 2*

*Collaboration between BNL, JLab & Tech-X*
Coherent Electron Cooling for eRHIC

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<tr>
<td>LHC</td>
<td>protons</td>
<td>7,000</td>
<td>13/26</td>
<td>$\infty \infty$</td>
<td>$&lt; 2$</td>
</tr>
</tbody>
</table>

Proof-of-Principle experiment in RHIC IR 2
Collaboration between BNL, JLab & Tech-X

©G.Mahler
ERL Circulator Electron Cooler for MEIC

Electronic bunches circulate 100+ times, leading to a factor of 100+ reduction of current from a photo-injector/ERL.

Design choice
- to meet design challenges
  - RF power (up to 50 MW)
  - Cathode lifetime (130 kC/day)

Required technology
- High bunch charge gun (ok)
- ERL (50 MeV, 15 mA) (ok)
- Ultra fast kicker

Cooling section at the center of Figure-8

Earlier proposals:
- RHIC: ERL
- HERA: circulator ring

Jefferson Lab NA-PAC’13 Thomas Jefferson National Accelerator Facility
**eRHIC Gatling Electron Gun Concept**

- Bunches from *multiple photo-cathodes* of a *single gun* merge together to form one high average current beam.
- BNL Gatling gun requires 20 cathodes (each delivering 2.5 mA polarized electron current) to meet 50 mA current requirement of present ERL-ring baseline design.
- A recent JLab breakthrough pushed single gun polarized current to 4 mA. This could reduce number of cathodes down to 12 in the BNL Gatling gun design concept.

**First gun prototype testing is scheduled at the end of 2014**

**JLab 200kV inverted polarized gun recently reached 4 mA**
Figure-8 optimum for polarized ion beams

- Simple solution to preserve ion polarization by avoiding spin resonances during acceleration
- Energy independence of spin tune
- A figure-8 ring is the *only practical way* for accelerating, storing and colliding polarized deuterons (g-2 is small for deuterons)

**Case 1: Achieving longitudinal polarization of deuterons at one IP**

- Magnetic inserts provide small spin rotation, thus shift the spin tune sufficiently away from 0
- Polarization is stable as long as additional spin rotation exceeds perturbations of spin motion

**Case 2: Achieving transverse polarization of deuterons at all IP's**

- Magnetic insert(s) in straight(s) rotating spin by relatively small angle around vertical axis (A. Kondratenko)

Ya. Derbenev 1993
MEIC Figure-8 Ring for Achieving High Ion Polarization

**Figure-8 optimum for polarized ion beams**

- Simple solution to preserve ion polarization by avoiding spin resonances during acceleration
- Energy independence of spin tune
- A figure-8 ring is the **only practical way** for accelerating, storing and colliding polarized deuterons (g-2 is small for deuterons)

**Case 1: Achieving longitudinal polarization of deuterons at one IP**

<table>
<thead>
<tr>
<th>Solenoid</th>
<th>$\vec{P}_I$</th>
<th>$\vec{P}_L$</th>
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</thead>
</table>

- Magnetic inserts provide small spin rotation, thus shift the spin tune sufficiently away from 0
- Magnetic insert(s) in straight(s) rotating spin by relatively small angle around vertical axis (A. Kondratenko)

**Case 2: Achieving transverse polarization of deuterons at all IP’s**

<table>
<thead>
<tr>
<th>Insertion</th>
<th>$\vec{P}_I$</th>
<th>$\vec{P}_L$</th>
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</thead>
</table>

- Magnetic insert(s) in straight(s) rotating spin by small angle around vertical axis

**HIAF ion ring now also adopts a figure-8 shape**

Ya. Derbenev 1993
High-gradient SC IR quadrupoles based on Nb3Sn for colliding proton beam with common low-field exit hole for electron beam and non-colliding proton beam.

**LHeC is designed to run synchronous to LHC**
4. Outlook and Summary
# Accelerate R&D Needs for EIC

V. Ptitsyn, O. Bruning, R. Ent and R. Roser for Snowmass 2013

<table>
<thead>
<tr>
<th>Requirement</th>
<th>LHeC RR</th>
<th>LHeC LR</th>
<th>eRHIC</th>
<th>MEIC</th>
<th>ENC</th>
<th>HIAF</th>
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</thead>
<tbody>
<tr>
<td>Cooling of hadron beams</td>
<td></td>
<td></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Low $\beta^*$ interaction regions</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Crab crossing</td>
<td></td>
<td></td>
<td>Yes</td>
<td>Yes</td>
<td></td>
<td>Yes</td>
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<td>High beam power ERL and High current SRF cavities</td>
<td></td>
<td></td>
<td>Yes</td>
<td>Yes</td>
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<td>Preserving electron beam polarization in ring-ring colliders</td>
<td>Yes</td>
<td></td>
<td></td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Proton and light ion polarization</td>
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<td></td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>High current polarized electron source</td>
<td></td>
<td></td>
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<td>Yes</td>
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<td>Beam-beam effects in the linac-ring scheme</td>
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<td></td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Intense positron beam in the linac-ring</td>
<td></td>
<td></td>
<td>Yes</td>
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<tr>
<td>Matching electron and hadron bunch frequencies at different hadron energies</td>
<td></td>
<td></td>
<td></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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</tbody>
</table>
Coherent Electron Cooling Proof-of-Principle Experiment at RHIC

Beam dump

CeC

20 MeV linac

2 MeV Gun

Start of commissioning - 2015

Courtesy of C. Brutus

V. Litvinenko, POETIC 2013
Purpose

- Demonstrate the cooler design concept
- Develop/test key accelerator technologies (faster beam kickers, etc.)
- Study dynamics of the cooling electron bunches in a circulator ring

Phase 1 scope

- Using the existing ERL without new upgrade except two $180^\circ$ beam lines (available at JLab)
- Supporting MEIC to deliver the high luminosity ($5.6 \sim 14 \times 10^{33}$ $1/cm^2/s$),
- To be completed before 2016
Why ERL TF @ CERN?

- Physics motivation
  - ERL demo, FEL, γ-source, e-cooling demo!
  - Ultra-short electron bunches
- The 1st low-freq. multi-pass SC-ERL
  - synergy with SPL/ESS & BNL activities
- High energies (200 to 400 MeV) & CW
- Multi-cavity cryomodule layout – validation and gymnastics
- Two-Linac layout (similar to LHeC)
- MW class power coupler tests in non-ER mode
- Complete HOM characterization and instability studies
- Cryogenics & instrumentation test bed

A multi-purpose test facility
- SC magnet development
  - A test stand for quenching magnets with beam in cryogenic environment
  - Provide a irradiation test facility for detector component development
ERL Test Facility for LHeC

E. Jensen, LHeC Meeting 22-23/01/2013

ERL TF @ CERN?

Physics motivation
- ERL demo, FEL, γ-source, e-cooling demo!
- Ultra-short electron bunches
- Test low-freq. multi-pass SC-ERL
- Highest energy with SPL/ESS & BNL activities
- High energies (200 to 400 MeV) & CW
- Multi-cavity cryomodule layout – validation and gymnastics
- Two-Linac layout (similar to LHeC)
- MW class power coupler tests in non-ERL mode
- Complete HOM characterization and instability studies
- Cryogenics & instrumentation test bed

CERN is looking into an ultimate test facility which allows a complete beam dynamics and RF analysis for a three recirculation ERL with a maximum beam energy up to 0.5 - 1 GeV

(Alessandra Valoni’s talk)

A multi-purpose test stand for:
- SC magnet development
- A test stand for quenching magnets with beam in cryogenic environment
- Cryogenics & instrumentation test bed
- Provide a irradiation test facility for detector component development

900 600 300 MeV ERL Layout

DUMP
LINAC 2
150 450 750
LINAC 1
INJECTOR

Table:

<table>
<thead>
<tr>
<th></th>
<th>units</th>
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<tr>
<td>Energy</td>
<td>[MeV]</td>
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<tr>
<td>Frequency</td>
<td>[MHz]</td>
</tr>
<tr>
<td>Charge</td>
<td>[pC]</td>
</tr>
<tr>
<td>Rep. rate</td>
<td></td>
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# NuPECC Roadmap: New Large-Scale Facilities (12/2010)

<table>
<thead>
<tr>
<th>Facility</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
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<tr>
<td>FAIR</td>
<td>R&amp;D</td>
<td>Construction</td>
<td>Commissioning</td>
<td>Exploitation</td>
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<td>CBM</td>
<td>R&amp;D</td>
<td>Construction</td>
<td>Commissioning</td>
<td>Exploitation</td>
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<td>EHD</td>
<td>R&amp;D</td>
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<td>PW/PNC</td>
<td>Design Study</td>
<td>R&amp;D</td>
<td>Tests</td>
<td>Construction/Commissioning</td>
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<tr>
<td>SPIRAL2</td>
<td>R&amp;D</td>
<td>Constr./Commission.</td>
<td>Exploitation</td>
<td>150 MeV/u Post-accelerator</td>
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<td>MESA</td>
<td>Constr./Commission.</td>
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<td>SPAL5</td>
<td>Constr./Commission.</td>
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<td>EUBISOL</td>
<td>Design Study</td>
<td>R&amp;D</td>
<td>Preparatory Phase / Site Decision</td>
<td>Engineering Study</td>
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<td>LHC</td>
<td>Design Study</td>
<td>R&amp;D</td>
<td>Engineering Study</td>
<td>Construction/Commissioning</td>
</tr>
</tbody>
</table>
US EIC Realization Imagined

Note: 12 GeV LRP recommendation in 2002 – CD3 in 2008

(H. Montgomery @ INT)
# HIAF Project Schedule

## Critical Points

<table>
<thead>
<tr>
<th>20~</th>
<th>09</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
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<tbody>
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<td><strong>Design</strong></td>
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## Construction and Installation

**Civil construction**

**Equipment construction, Fabrication**

**Installation**

**Linac, ABR, CBR commissioning**

**Combined commissioning**

**Start of operation**

## Commissioning

## Budget periods

- BP1
- BP2
- BP3
- BP4
### HIAF Project Schedule

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**EIC added to the baseline**
Summary

• A class of new electron-ion colliders have been proposed worldwide for future high energy and nuclear physics research. Both the science programs and the accelerator designs are under active development.

• All new electron-ion collider accelerator designs aim for high performance, orders of magnitude better than HERA, to meet science needs.

• In order to deliver the high performance, a class of new technologies have been integrated into the conceptual designs; some are adopted from other facilities; others are very forward looking, resulting in high demands on technology R&D.

• All machine designs are still at relatively early stages of their evolutions, either some baseline design decisions have not been made yet, or key design parameters are still in dynamic evolution, driven by both science and accelerator technology development.
EIC 14
An International Workshop on Accelerator Science and Technology for Electron-Ion Colliders

Jefferson Lab
Newport News, Virginia, USA
March 17-21, 2014

Topics:
- Beam physics including beam dynamics and collective effects, beam polarization, and cooling
- Interaction region, detector integration and background
- Superconducting RF technology and energy recovery linacs
- Electron/positron sources, proton/ion sources

Contact:
eic14@jlab.org
Acknowledgement

I would like to thank all the following colleagues for helping me to prepare this talk

LHeC:  Oliver Bruning, Max Klein

eRHIC:  Vadim Ptitsyn, Thomas Roser

ENC:    Kurt Aulenbacher

HIAF:   Jiangchen Yang

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