ERL Based Lepton-Hadron Colliders: eRHIC and LHeC

Frank Zimmermann
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Many thanks to:
Jose Abelleira, Mei Bai, Sergey Belomestnkyh, Ilan Ben-Zvi, Alex Bogacz, Oliver Brüning, Rama Calaga, Ed Ciapala, Friedrich Haug, Erk Jensen, John Jowett, Max Klein, Vladimir Litvinenkov, Vadim Ptitsyn, Louis Rinolfi, Stephan Russenschuck, Daniel Schulte, Mike Sullivan, Rogelio Tomas, Davide Tomassini, Joachim Tückmantel, ...
colliding lepton & hadron beams

ring-ring
\[ \varepsilon_e \gg \varepsilon_h \]

minimum beta function
and beam size
limited by hourglass effect
(large \( \varepsilon_e \) & large \( \sigma_{z,h} \)!) ;
small crossing angle acceptable;
little disruption

linac-ring
\[ \varepsilon_e \approx \varepsilon_h \]

smaller beta function
and beam size possible;
head-on collision required;
significant disruption

geometric overlap factor
\[ H_{hg} = \frac{\sqrt{\pi} ze^2 \text{erfc}(z)}{S} ; \quad z \equiv 2 \frac{(\beta_e^*/\sigma_{z,h})(\varepsilon_e/\varepsilon_h)}{\sqrt{1+(\varepsilon_e/\varepsilon_h)^2}} S ; \quad S \equiv \sqrt{1 + \frac{\sigma_{z,h}^2 \theta_c^2}{8 \sigma^*^2}} \]
luminosity of linac-ring collider

with round matched beams

\[
L = \frac{1}{4\pi e} \frac{N_{h,p}}{\varepsilon_h} \frac{1}{\beta_h^*} \cdot I_e H_{hg} H_D
\]

hadron beam brightness

hadron IP $\beta$ function
- small $I^*$
- only one hadron beam
- new magnet technology $Nb_3Sn$

average $e^-$ current
boosted by energy recovery!

pinch enhancement (1.3 for $e^-$, 0.3 $e^+$)

geometric overlap factor
- head-on collision
- small $e^-$ emittance

→ ERL-ring collider
two proposals for ERL-ring lepton-hadron colliders:

- **LHeC based on the LHC at CERN**
  - 7 TeV $p$ or few TeV/nucleon heavy-ion beams
  - adding a 60-GeV ERL with 6.4 mA current

- **eRHIC based on RHIC at BNL**
  - 250 (325) GeV polarized $p$’s (& light ions) and 100 (130)-GeV unpolarized heavy ions
  - adding a 5-30 GeV ERL with 50-220 mA current
ERL-Ring LHeC

60-GeV recirculating linac with energy recovery in separate 9-km RACETRACK tunnel intersecting LHC in Point 2.
LHeC  ERL layout

two 10-GeV SC linacs, 3-pass up, 3-pass down; 6.4 mA, 60 GeV e’s collide w. LHC protons/ions

(C=1/3 LHC allows for ion clearing gaps)

A. Bogacz, O. Brüning, M. Klein, D. Schulte, F. Zimmermann, et al
R&D for LHeC SC linac in synergy with many future projects: ILC, $\nu$ factory, $p$-driven plasma acceleration, and Higgs factory $\gamma\gamma$ collider

**LHeC-ERL**

- 10-GeV linac
- 0.12 km
- 0.17 km
- 1.0 km
- LHC $p$

**SAPPHiRE**

- 11-GeV linac
- 1.1 km
- 0.26 km
- 2.0 km
- $\gamma\gamma$ Higgs factory

*Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons*
ERL-Ring eRHIC

eRHIC staging: All energies scale proportionally

3rd detector

Coherent e-cooler

eRHIC staging: All energies scale proportionally

Beam dump

Polarized e-gun

30 GeV

27.55 GeV

25.1 GeV

22.65 GeV

20.2 GeV

17.75 GeV

15.3 GeV

12.85 GeV

10.4 GeV

7.95 GeV

5.5 GeV

3.05 GeV

ARC’s

30 GeV e’ collider

“clear zone”

2.45 GeV SC linacs, 6-pass up, 6-pass down; 50(220)-mA 5-30 GeV (un)polarized e’s collide with RHIC polarized protons (250-325 GeV) or heavy ions (100-130 GeV / nucleon)
<table>
<thead>
<tr>
<th>LHeC</th>
<th>eRHIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>precision QCD</td>
<td>origin of the proton spin</td>
</tr>
<tr>
<td>electroweak physics</td>
<td>quantum phase space</td>
</tr>
<tr>
<td>high parton densities</td>
<td>tomography of the nucleon</td>
</tr>
<tr>
<td>new physics at high energies</td>
<td>strong color fields</td>
</tr>
<tr>
<td></td>
<td>...</td>
</tr>
</tbody>
</table>
collider parameters
<table>
<thead>
<tr>
<th>Collider Parameters</th>
<th>eRHIC (ult.)</th>
<th>LHeC (ult.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Species</td>
<td>$e^-$</td>
<td>$e^+$</td>
</tr>
<tr>
<td>$b.$ energy (/nucleon) [GeV]</td>
<td>15 (30)</td>
<td>60</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>18</td>
<td>25, 100</td>
</tr>
<tr>
<td>Bunch intensity (nucl.) [10^9]</td>
<td>24</td>
<td>1, 4</td>
</tr>
<tr>
<td>Beam current [A]</td>
<td>0.22 (.01)</td>
<td>0.006</td>
</tr>
<tr>
<td>RMS bunch length [mm]</td>
<td>2</td>
<td>49</td>
</tr>
<tr>
<td>Polarization [%]</td>
<td>80</td>
<td>70, 0</td>
</tr>
<tr>
<td>Norm. RMS emittance [μm]</td>
<td>5.8-57</td>
<td>0.2, 0.2 CEC</td>
</tr>
<tr>
<td>$\beta_{x,y} ,[m]$</td>
<td>0.05</td>
<td>0.12</td>
</tr>
<tr>
<td>$\sigma_{x,y} ,[μm]$</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Beam-beam parameter $\xi_h$</td>
<td>0.015</td>
<td>0.0001</td>
</tr>
<tr>
<td>Lepton disruption $D$</td>
<td>52, 22</td>
<td>6</td>
</tr>
<tr>
<td>CM energy [TeV]</td>
<td>140 (197)</td>
<td>88 (125)</td>
</tr>
<tr>
<td>luminosity / nucleon $[10^{34} cm^{-2} s^{-1}]$</td>
<td>14 (4), 8.2 (2.1)</td>
<td>0.1, 0.02</td>
</tr>
</tbody>
</table>
eRHIC - special features

$p$ polarization
  55% now $\rightarrow$ 70%

high $e^-$ current
  50 mA polarized, 220 mA unpolarized

small hadron beam emittances $\sim 1/10$ LHC
  achieved with novel Coherent Electron Cooling, space-charge compensation with other $e^-$ beam

staged installation
  steps in beam energy every few years
possible layout of CEC system for both RHIC hadron beams
<table>
<thead>
<tr>
<th>Parameter</th>
<th>eRHIC</th>
<th>LHeC</th>
</tr>
</thead>
<tbody>
<tr>
<td>#linacs</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>length/linac [km]</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>energy gain / linac [GeV]</td>
<td>2.45</td>
<td>10.0</td>
</tr>
<tr>
<td>#acceleration passes</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>maximum final energy [GeV]</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>real estate gradient [MV/m]</td>
<td>12.45</td>
<td>10.0</td>
</tr>
<tr>
<td>energy gain / cavity [MeV]</td>
<td>20.4</td>
<td>20.8</td>
</tr>
<tr>
<td>cells / cavity ; cavities / linac</td>
<td>5 ; 120</td>
<td>5 ; 480</td>
</tr>
<tr>
<td>RF frequency [MHz]</td>
<td>703.8</td>
<td>721</td>
</tr>
<tr>
<td>cavity length [m]</td>
<td>1.065</td>
<td>1.04</td>
</tr>
<tr>
<td>R/Q [linac Ω]</td>
<td>506</td>
<td>570</td>
</tr>
<tr>
<td>$Q_0 [10^{10}]$</td>
<td>4.0</td>
<td>2.5</td>
</tr>
<tr>
<td>power loss / cavity [W]</td>
<td>23.7</td>
<td>32</td>
</tr>
<tr>
<td>electrical cryopower per linac [MW]</td>
<td>2</td>
<td>10</td>
</tr>
</tbody>
</table>
linac features

LHeC linac 5x longer with 4x the energy gain
  (cavity filling factor 0.50 vs 0.64)
eRHIC linac: no focusing
LHeC linac: ~100 quadrupoles
  increase multi-pass BBU threshold
LHeC linac quadrupole options:
  - electromagnets with indiv. powering
  - clustered electromagnets
  - permanent magnets

$Q_0$: a key parameter!
721.4 MHz RF, 5-cell cavity:

\[ \lambda = 41.557 \text{ cm} \]
\[ L_c = \frac{5\lambda}{2} = 103.89 \text{ cm} \]
\[ \text{Grad} = 20 \text{ MeV/m (20.8 MeV per cavity)} \]
\[ \Delta E = 80 \text{ MV per Half Cryo Module} \]
eRHIC: no cryo module; cavity “cryounit” - easy addition or removal

preliminary layout of eRHIC cryounit

BNL3 Nb cavity

Sergey Belomestnykh
# electrical power budgets

<table>
<thead>
<tr>
<th>parameter</th>
<th>electrical power [MW]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>eRHIC</td>
</tr>
<tr>
<td>total main linac cryopower</td>
<td>4</td>
</tr>
<tr>
<td>RF microphonics control</td>
<td>5</td>
</tr>
<tr>
<td>extra RF for SR losses</td>
<td>20</td>
</tr>
<tr>
<td>extra-RF cryopower</td>
<td>0.3</td>
</tr>
<tr>
<td>e⁻ injector</td>
<td>2.6</td>
</tr>
<tr>
<td>arc magnets</td>
<td>11</td>
</tr>
<tr>
<td>total</td>
<td>43</td>
</tr>
</tbody>
</table>

**design constraints:** SR loss < 10 MW (eRHIC); total el. power <100 MW (LHeC)
arcs
energy loss from synchrotron radiation

LHeC: $\rho=764$ m ($E_{\text{max}}=60$ GeV), $\Delta E_{\text{tot}}=2$ GeV

eRHIC: $\rho=234$ m ($E_{\text{max}}=30$ GeV), $\Delta E_{\text{tot}}=0.77$ GeV

compensation with additional RF systems

LHeC: 750 MV at 60 GeV (721 MHz)

675 MV at lower energy (1.44 GHz)

eRHIC: 389 MV at 1.4 GHz at 27.55 GeV
eRHIC: 6 passes, low-emittance near isochronous arc lattice building block: 35 m long with 7 dipoles & 9 quadrupoles

LHeC: 3 passes, flexible momentum compaction arc lattice building block: 52 m long with 2 (10) dipoles & 4 quadrupoles

LHeC flexible momentum compaction cell; tuned for small beam size (low energy) or low $\Delta\varepsilon$ (high energy)

$\langle H \rangle = 8.8 \times 10^{-3} \text{ m}$

limit chamber size
($>12 \sigma$ at 25 mm diameter)

$\langle H \rangle = 2.2 \times 10^{-3} \text{ m}$

factor of 18 smaller than FODO

$\langle H \rangle = 1.2 \times 10^{-3} \text{ m}$

limit emittance growth

Alex Bogacz
arc magnets

**eRHIC dipole model**

- 5 mm gap
- Max. field 0.43 T (30 GeV)

**LHeC dipole model**

- 25 mm gap
- Max. field 0.264 T (60 GeV)
ERL beam dynamics

• multi-pass beam break up
  – suppressed by cavity HOM damping & detuning
  – further suppression possible using correlated energy spread & arc chromaticity if needed (V. Litvinenko, PRST-AB 15, 074401 (2012))

• ion accumulation & ion instabilities
  – clearing gaps (circumference choice), excellent vacuum in warm ($10^{-9}$ hPa) and cold regions ($10^{-11}$ hPa)

• others: resistive wall, surface roughness, CSR, Touschek effect
beam stability requires both damping ($Q \sim 10^5$) & detuning ($\Delta f/f_{\text{rms}} \sim 0.1\%$), 720 MHz

Daniel Schulte
injectors
source $e^-$ beam parameters

<table>
<thead>
<tr>
<th>parameter</th>
<th>eRHIC</th>
<th>LHeC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^-$/bunch [$10^9$]</td>
<td>5.6, 24</td>
<td>1.1</td>
</tr>
<tr>
<td>charge / bunch [nC]</td>
<td>0.9, 3.8</td>
<td>0.18</td>
</tr>
<tr>
<td>rms bunch length [mm]</td>
<td>2</td>
<td>3-30</td>
</tr>
<tr>
<td>bunch spacing [ns]</td>
<td>18</td>
<td>25</td>
</tr>
<tr>
<td>average current [mA]</td>
<td>50, 220</td>
<td>7</td>
</tr>
<tr>
<td>bunch peak current [A]</td>
<td>50, 200</td>
<td>7-70</td>
</tr>
<tr>
<td>polarization</td>
<td>85-90%, none</td>
<td>&gt;90%</td>
</tr>
</tbody>
</table>
eRHIC polarized electron gun - candidates

large-sized GaAs cathode gun

Gatling gun, combing beams from an array of 24 GaAs cathodes

Evgeni Tsentalovich

Vladimir Litvinenko
beam quality from DC gun

impact of non-Gaussian $e^-$ beam shape on the hadron beam?

beam structure at ALICE with 230-kV DC gun voltage:

Jlab’s “humming bird” beam image:

Yuri Saveliev
**injector & dump**

**eRHIC:** 60-m 600 MeV injector linac operated in energy recovery mode

50-mA beam is dumped at 10 MeV $\rightarrow$ 500 kW power

**LHeC:** 500-MeV injector dumping 6.4-mA beam at 500 MeV $\rightarrow$ 3 MW;

3 m$^3$ water dump (0.5 m diameter and 8 m length) with 3 m x 3 m x 10 m shielding or energy recovery, decelerating 6.4-mA beam to 10 MeV $\rightarrow$ 64 kW
# LHeC Linac-Ring $e^+$ source

<table>
<thead>
<tr>
<th></th>
<th>SLC</th>
<th>CLIC (3 TeV)</th>
<th>ILC (RDR)</th>
<th>LHeC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>1.19 GeV</td>
<td>2.86 GeV</td>
<td>5 GeV</td>
<td>60 GeV</td>
</tr>
<tr>
<td>$e^+$/bunch at IP</td>
<td>$40 \times 10^9$</td>
<td>$3.72 \times 10^9$</td>
<td>$20 \times 10^9$</td>
<td>$2 \times 10^9$</td>
</tr>
<tr>
<td>$e^+$/bunch before DR inj.</td>
<td>$50 \times 10^9$</td>
<td>$7.6 \times 10^9$</td>
<td>$30 \times 10^9$</td>
<td>N/A</td>
</tr>
<tr>
<td>Bunches/macropulse</td>
<td>1</td>
<td>312</td>
<td>2625</td>
<td>N/A</td>
</tr>
<tr>
<td>Macropulse repet. rate</td>
<td>120</td>
<td>50</td>
<td>5</td>
<td>CW</td>
</tr>
<tr>
<td>Bunches/second</td>
<td>120</td>
<td>15600</td>
<td>13125</td>
<td>$20 \times 10^6$</td>
</tr>
<tr>
<td>$e^+$/second</td>
<td>$0.06 \times 10^{14}$</td>
<td>$1.1 \times 10^{14}$</td>
<td>$3.9 \times 10^{14}$</td>
<td>$400 \times 10^{14}$</td>
</tr>
</tbody>
</table>
LHeC $e^+$ source

- recycle, re-collide, re-cool $e^+$
- compact tri-ring scheme proposed for $e^+$ cooling

remaining $e^+$ intensity produced by Compton ERL, Compton ring, or coherent pair production
interaction region
zero field on $e^-$ trajectory, Q1 combined function magnet; only 1.9 W of soft radiation through IR (from 2.4 mT field); large crossing angle of 10 mrad:

$\sim$23-MV $\sim$200-MHz (+harm) crab-cavities for hadron beam
1-MV 700-MHz crab-cavity for lepton beam
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

crab-cavity solution excluded; head-on collision realized by detector integrated dipole: 0.3 T over +/- 9 m

48 kW of X-rays ($1.8 \times 10^{18} \gamma/s$)
critical energy 718 keV
beam-beam effects
$e^-$ beam strongly focused by hadron beam $\rightarrow$ **emittance growth** by a factor of 2-3 in collision; effect minimized by re-matching exit line optics; aperture for deceleration must include these effects;

**beam-beam kink instability** - in eRHIC: cured by broad-band hadron-beam feedback, in LHeC: not expected to occur
$e^-$ polarization
**eRHIC**: no $e^-$ spin rotators; spin freely rotating in horizontal plane while beam passes through ERL; → condition on final beam energy $E = n \times 0.07216$ GeV; polarization loss due to finite energy spread = 5% for $2 \times 10^{-4}$ rms at 30 GeV

**LHeC**: spin is rotated into vertical direction prior to acceleration; **no depolarization**; full control of IP spin vector orientation by **RHIC type spin-rotator system at high energy**; e.g. 4 x 15 m long helical dipoles with fields 0.46 T and 0.37 T (→ **0.3 MW SR**)

Mei Bai
50-mA CW polarized $e^-$ source

Coherent Electron Cooling POP experiment (with JLAB, Daresbury, BINP, and Tech-X)

SRF ERL technology on BNL’s existing R&D ERL

RF cryostat, small-gap magnets, arc vacuum chambers

Start operation with 5-10 GeV $e^-$
ERL-Test Facility (TF) at CERN

200-400 MeV ERL Layout
4 x 5 cell, 721 MHz

<table>
<thead>
<tr>
<th></th>
<th>units</th>
<th>1-CM</th>
<th>2-CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>[MeV]</td>
<td>100</td>
<td>200-400</td>
</tr>
<tr>
<td>Frequency</td>
<td>[MHz]</td>
<td>721</td>
<td>721</td>
</tr>
<tr>
<td>Charge</td>
<td>[pC]</td>
<td>~500</td>
<td>~500</td>
</tr>
<tr>
<td>Rep. rate</td>
<td></td>
<td>CW</td>
<td>CW</td>
</tr>
</tbody>
</table>

Rama Calaga
ERL-TF (300 MeV) – Layout

Two passes ‘up’ + Two passes ‘down’
could the LHeC TF later become the LHeC ERL injector ERL?
thank you for your attention!

for more details:

• LHeC web site [http://cern.ch/lhec](http://cern.ch/lhec)


• eRHIC web site [http://www.bnl.gov/cad/eRhic](http://www.bnl.gov/cad/eRhic)

• ICFA Beam Dynamics Newsletter No. 58, special issue on future electron-hadron colliders, August 2012