ERL-based electron-hadron colliders: From eRHIC to LHeC?

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Design consideration of two scenarios for electron-hadron collider eRHIC at Brookhaven (ring-ring and ring-ERL) clearly demonstrated use of energy-recovery linac as the electron drive allows attainment of significantly higher luminosities. This talk will be focus of ERL based design of eRHIC, its advantages and challenges.

Relevance of this approach for LHeC will be also discussed.
Content

• What eRHIC is about
• Choosing the focus: ERL or ring for electrons?
  – Advantages and challenges of ERL driver
  – R&D items for ERL-based eRHIC
  – New developments
    • 5-cell SRF cavity
    • Small magnets for eRHIC loops
    • Kink instability
    • Electron beam disruption during the collision
    • Simulations of the beam-beam effects
    • Coherent electron cooling
    • Staging
• Relevance to LHeC - some results & numbers
• Conclusions
Conclusions first

- ERL seems to be the most promising approach for high energy, high luminosity electron-ion and polarized electron-proton collider
- It can take advantage of any ring-ring concept and go further
- There is a clear possibility for eRHIC (LHeC?) staging
- Presently there is no show-stoppers but a significant amount of R&D
- At BNL the R&D ERL tests start in 2009, MIT’s progress with developing high current polarized gun, prototyping of small gap magnets are in progress ….
- LHeC based on this principle reach $10^{34}$-$10^{35}$ level of luminosity -natural topic for collaborating with BNL
**eRHIC Scope - QCD Factory**

**Electron accelerator**

- Unpolarized and polarized leptons
  - 2-20 (30) GeV
- 70% beam polarization goal
- Positrons at low intensities

**RHIC**

- Polarized protons
  - 25 ↓ 50-250 (325) GeV
- Heavy ions (Au)
  - 50-100 (130) GeV/u
- Polarized light ions
  - (He³) 215 GeV/u

**Center mass energy range:** 15-200 GeV

New requirements: eA program for eRHIC needs as high as possible energies of electron beams even with a trade-off for the luminosity. 20 GeV is absolutely essential and 30 GeV is strongly desirable.
eRHIC is based on the main BNL’s investment: hadron complex of RHIC

eRHIC will take full advantage of e-cooling

RHIC: ions (D, Cu, Au...) 10-100 GeV/u
polarized protons 25-250 GeV

2 superconducting rings
3.8 km circumference

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View from 2004: How eRHIC can be realized?

- Ring-ring: 

- Linac (ERL)-ring: 

Electron storage ring 

\[ L = \left( \frac{4 \pi \gamma h \gamma_e}{r_h^2 \xi_e} \right) \left( \frac{\xi h \xi_e}{\sigma h \sigma_e} \right) f \]

Electron linear accelerator 

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

Advantages & Challenges of ERL based eRHIC

- Allows use of RHIC tunnel
- 2-3 fold higher energy of electrons
- Higher luminosity up to \(10^{34} \text{ cm}^{-2} \text{ sec}^{-1}\)
- Multiple IPs
- Higher range of CM-energies + high luminosities
- Full spin transparency at all energies
- No machine elements inside detector(s)
- No significant limitation on the lengths of detectors
- ERL is simply upgradeable
- eRHIC can be staged

- Novel technology
- Need R&D on polarized gun
- May need a dedicated ring positrons

In Ring-ring luminosity reduces 10-fold for 30 GeV CME. Required norm.emittance (for 50 GeV protons) \(\sim 3 \text{ mm}^*\text{mrad}\)

http://www.agsrhichome.bnl.gov/eRHIC/

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Calculations for 166 bunch mode and 250 GeV(p) x 10 GeV(e) setup

Markers show electron current and (for linac-ring) normalized proton emittance.
In dedicated mode (only e-p collision): maximum $\xi_p \approx 0.016-0.018$;

Transverse cooling can be used to improve luminosity or to ease requirements on electron source current in linac-ring option.
For proton beam only e-cooling at the injection energy is possible at reasonable time (~1h)

Courtesy of V. Ptitsyn
CM vs. Luminosity

- Variable beam energy
- Polarizes electrons and protons
- $^3\text{He}$-$\text{U}$ ion beams
- Light ion polarization
- Large luminosity
ERL spin transparency at all energies

\[ \frac{ds}{dt} = \frac{e}{mc} s \times \left[ \left( \frac{g}{2} - 1 + \frac{1}{\gamma} \right) \bar{B} - \frac{\gamma}{\gamma + 1} \left( \frac{g}{2} - 1 \right) \bar{B} \hat{B} - \left( \frac{g}{2} - \frac{\gamma}{\gamma + 1} \right) \left[ \hat{B} \times \hat{E} \right] \right] \]

\[ a = g/2 - 1 = 1.1596521884 \times 10^{-3} \]

\[ \hat{\mu} = \frac{g}{2 m_o} \hat{s} = (1 + a) \frac{e}{m_o} \hat{s} \]

\[ v_{spin} = a \cdot \gamma = \frac{E_e}{0.44065[GeV]} \]

Total angle

\[ \Delta \varphi = a \cdot \gamma \theta \]

Has solution for all energies!

\[ \Delta \gamma = \frac{\left( \gamma_f - \gamma_i \right)}{2n} \]

\[ 2 \pi a \cdot \left( (n - 1/2) \gamma_i + \left\{ 2n(n-2) - 1/6 \right\} \Delta \gamma \right) + \varphi_i = \theta + N \pi \]

\[ E_i = \frac{0.44065[GeV]}{n + 1 + 1/3n} \mod \left( \varphi_f - \varphi_i - \left( n - 2 - \frac{1}{3n} \right) \frac{E_f}{0.44065[GeV]} \pi \right) \]

\[ \delta E_{i, max} = \pm \frac{37}{n} \text{ MeV} \quad \forall \ n = 5 \]
Baseline: ERL-based eRHIC

- 10 GeV electron beam energy, upgradeable to 20 GeV by doubling the main linac
- 5 recirculation passes (4 of them in the RHIC tunnel)
- Multiple electron-hadron interaction points (IPs) and detectors
- Full polarization transparency at all energies for the electron beam
- Ability to take full advantage of transverse cooling of the hadron beams
- Possible options to include polarized positrons (compact storage ring; Compton backscattered) - Though at lower luminosity
### Baseline: ERL-based eRHIC Parameters

<table>
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<th>Low energy setup</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>p</td>
<td>e</td>
</tr>
<tr>
<td>Energy, GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of bunches</td>
<td></td>
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<tr>
<td>Bunch spacing, ns</td>
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<tr>
<td>Bunch intensity, 10^{11}</td>
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<td>Beam current, mA</td>
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<td>Normalized 95% emittance, p mm.mrad</td>
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<td>460</td>
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<tr>
<td>Rms emittance, nm</td>
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<td>4</td>
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<td>β⁺, x/y, cm</td>
<td>26</td>
<td>25</td>
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<tr>
<td>Beam-beam parameters, x/y</td>
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<tr>
<td>Rms bunch length, cm</td>
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<tr>
<td>Polarization, %</td>
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<td>80</td>
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<tr>
<td>Peak Luminosity, 1.e33 cm^{-2}s^{-1}</td>
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<tr>
<td>Aver.Luminosity, 1.e33 cm^{-2}s^{-1}</td>
<td></td>
<td>0.87</td>
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<tr>
<td>Luminosity integral /week, pb^{-1}</td>
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<td>530</td>
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</table>

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Current vision of eRHIC:
Increased the Energy Reach and Luminosity
Effective use of cooling
Staging

• **MEIC**: Medium Energy Electron-Ion Collider
  - Located at IP2 (with a modest detector)
  - $2 \text{ GeV} \times 250 \text{ GeV p (45 GeV c.m.)}, L \sim 10^{32} \text{ cm}^2 \text{ sec}^{-1}$

• **eRHIC** - Full energy, nominal luminosity, inside RHIC tunnel
  - 30% increase of RHIC energy is possible with replacing DX magnets
  - Polarized $20 \text{ GeV} \times 325 \text{ GeV p (160 GeV c.m.)}, L \sim 4 \times 10^{33} \text{ cm}^2 \text{ sec}^{-1}$
  - $30 \text{ GeV} \times 130 \text{ GeV/n Au (120 GeV c.m.)}, L \sim 10^{31} \text{ cm}^2 \text{ sec}^{-1}$
  - Based on present RHIC beam intensities
  - With coherent electron cooling the electron beam current is 25 mA
  - 1.92 MW total for synchrotron radiation.
  - Power density is 1 kW/meter and is well within B-factor limits (8 kW/m)

• **eRHIC** - High luminosity at reduced energy, inside RHIC tunnel
  - Polarized $10 \text{ GeV} \times 325 \text{ GeV p, L} \sim 10^{35} \text{ cm}^2 \text{ sec}^{-1}$
  - Polarized positrons (with lower luminosity)

• Potential for replacing RHIC lattice with 8T, 0.8 TeV ring
  - i.e. potential for HERA with tow-three orders higher luminosity
MEIC with 2 GeV ERL @ IP2

- Asymmetric detector
- 0.95 GeV SRF linac
- 2 GeV e-beam pass through the detector
- 100 MeV ERL
- 3 vertically separated passes at 0.1 GeV, 1.05 and 2 GeV
20 GeV e x 325 GeV p eRHIC with ERL inside RHIC tunnel

- 2 x 200 m SRF linac
- 10-12.5 MeV/m
- 4-5 GeV per pass

5 (6) vertically separated passes

ePHENIX

eSTAR
Main advantages of ERL + cooling

\[ L = \gamma_p \frac{f_{col} N_p}{\beta_p^* r_p} \xi_p \]
\[ \xi_p = \frac{r_p}{4 \pi} \frac{N_e}{\epsilon_p^{\text{norm}}}; \]
\[ \frac{N_e}{\epsilon_p^{\text{norm}}} = \text{const} \Rightarrow \xi_p = \text{const}; \quad L = \text{const} \]

\[ N_e \propto \epsilon_p^{\text{norm}} \Rightarrow I_e \propto \epsilon_p^{\text{norm}} \Rightarrow P_{SR} \propto \epsilon_p^{\text{norm}}! \]

- Main point is very simple: if one cools the emittance of a hadron beam in electron-hadron collider, the intensity of the electron beam can be reduced proportionally without any loss in luminosity or increase in the beam-beam parameter for hadrons.
- Hadron beam size is reduced in the IR triplets - hence it opens possibility of further \( \beta^* \) squeeze and increase in luminosity.
- Electron beam current goes down, losses for synchrotron radiation going down, X-ray background in the detectors goes down....

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Coherent electron cooling

\[ Q = -G_{\text{FEL}} \cdot 4Ze \]

\[ A_{\perp} = \frac{2\pi\beta_n E_n}{\gamma_0} \]

\[ k_{cm} = \frac{\pi}{\gamma_0 \lambda_{\text{FEL}}} \]

\[ \rho_{\text{amp}} = \frac{G \cdot Ze}{2\pi\beta_n} \cdot \frac{4k_{cm}}{\pi} \cos(k_{cm}z) \]

\[ \Delta \varphi = 4\pi \rho \Rightarrow \varphi = -\frac{8G \cdot Ze}{\pi\beta_n k_{cm}} \cdot \cos(k_{cm}z) \]

\[ \vec{E} = -\hat{\nabla} \varphi = -2 \frac{8G \cdot Ze}{\pi\beta_n} \cdot \sin(k_{cm}z) \]

**Longitudinal dispersion for hadrons**

\[ \Delta t = -D \cdot \frac{\gamma_0}{\gamma} \cdot \frac{L}{D_{\text{free}} + D_{\text{chicane}}} \]

Electrons

\[ Q_{\text{ele}} \approx \int_0^{\lambda_{\text{ele}}} \rho(z) \cos(k_{\text{FEL}}z)dz \]

\[ Q_{\text{ele}}(\text{max}) = -2Ze, \rho_k = -Ze \cdot \frac{4k}{\pi A_{\perp}} \]

**Modulator: region 1**

a quarter to a half of plasma oscillation

**Amplifier of the e-beam modulation via FEL with gain \( G_{\text{FEL}} \sim 10^2 - 10^3 \)**

Hadrons

\[ q = -Ze \cdot (1 - \cos \omega_p t) \]

\[ \varphi = \omega_p L_1 / c \gamma \]

Kicker: region 2, less than a quarter of plasma oscillation

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Transition to a stationary state: Coherent Electron Cooling vs. IBS

\[ X = \frac{\xi}{\xi_0}; \quad S = \left( \frac{\sigma_s}{\sigma_{s0}} \right)^2 = \left( \frac{\sigma_{sE}}{\sigma_{sE0}} \right)^2; \]

\[ \frac{dX}{dt} = \frac{1}{\tau_{IBS//} X^{3/2} S^{1/2}} - \frac{1}{\tau_{CeC} S}; \]

\[ \frac{dS}{dt} = \frac{1}{\tau_{IBS//} X^{3/2} Y} - \frac{1}{\tau_{CeC} X^2}; \]

\[ \xi_{x0} = 2 \mu m; \quad \sigma_{s0} = 13 cm; \quad \sigma_{\delta 0} = 4 \cdot 10^{-3} \]

\[ \tau_{IBS//} = 4.6 \text{ hrs}; \quad \tau_{IBS//} = 1.6 \text{ hrs}; \]

\[ \epsilon_{x_n} = 0.2 \mu m; \quad \sigma_s = 4.9 \text{ cm} \]

Dynamics: Takes 12 mins to reach stationary point

This allows
a) keep the luminosity as it is
b) reduce polarized beam current down to 25 mA (5 mA for e-I)
c) increase electron beam energy to 20 GeV (30 GeV for e-I)
d) increase luminosity by reducing $\beta^*$ from 25 cm down to 5 cm

IBS in RHIC for eRHIC, 250 GeV, $N_p=2 \times 10^{11}$

Taken from Beta-cool, © A. Fedotov

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Decrement for hadron beams with coherent electron cooling

<table>
<thead>
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<tbody>
<tr>
<td>RHIC PoP</td>
<td>Au</td>
<td>40</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.02/0.06</td>
</tr>
<tr>
<td>eRHIC</td>
<td>Au</td>
<td>130</td>
<td>~1</td>
<td>20,961 ∞</td>
<td>~ 1</td>
<td>0.015/0.05</td>
</tr>
<tr>
<td>eRHIC</td>
<td>p</td>
<td>325</td>
<td>~100</td>
<td>40,246 ∞</td>
<td>&gt; 30</td>
<td>0.1/0.3</td>
</tr>
<tr>
<td>LHC</td>
<td>p</td>
<td>7,000</td>
<td>~ 1,000</td>
<td>13/26</td>
<td>∞ ∞</td>
<td>0.3/&lt;1</td>
</tr>
</tbody>
</table>

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Main R&D Items

• **Electron beam R&D**
  - Energy recovery technology for high power beams (BNL)
    - **R&D ERL** - high current, low emittance beams, stability, low losses
    - Multi-cavity cryo-module development
  - High intensity polarized electron source (MIT & BNL)
    - Development of large cathode DC guns
      - existing current densities ~ 50 mA/cm², good cathode lifetime.
    - Development of SRF polarized gun
  - Development of compact recirculating loop magnets (LDRD @ BNL)
    - Design, build and test a prototype of dipole and quadrupole
    - Design, build and test a prototype vacuum chamber

• **Main R&D items for hadron beams (BNL)**
  - Polarized $^3$He production (EBIS) and acceleration
  - 166 bunches (50% more bunches in RHIC)
  - Proof-of-Principle of the Coherent Electron Cooling
IR-2 layout for Coherent Electron Cooling proof-of-principle experiment

19.6 m

Kicker 3 m Wiggler 7m Modulator 4 m

DX

DX

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eRHIC loop magnets and vacuum chamber: LDRD project

- Small gap provides for low current, low power consumption magnets
- Magnetic design - W. Meng, mechanical engineering - G. Mahler
- Starting studies of the acceptable field errors and of the alignment tolerances
- First dipole prototype is in hands

All vacuum chamber
Thickness - 0.75 mm
Sag - 3.6 microns

Field, Gs

C-Quad

G=26 T/m

B=0.33 T
Why Linac-Ring for LHeC looks not as strong?

Comparison Linac-Ring and Ring-Ring

<table>
<thead>
<tr>
<th></th>
<th>Linac-Ring</th>
<th>Ring-Ring</th>
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</thead>
<tbody>
<tr>
<td>Energy / GeV</td>
<td>40-140</td>
<td>40-80</td>
</tr>
<tr>
<td>Luminosity / 10^{32} cm^{-2} s^{-1}</td>
<td>0.5</td>
<td>10</td>
</tr>
<tr>
<td>Mean Luminosity, relative</td>
<td>2</td>
<td>1 [dump at L_{peak}/e]</td>
</tr>
<tr>
<td>Lepton Polarisation</td>
<td>60-80%</td>
<td>30% [?]</td>
</tr>
<tr>
<td>Tunnel / km</td>
<td>6</td>
<td>2.5-0.5 * 5 bypasses</td>
</tr>
<tr>
<td>Biggest challenge</td>
<td>CW cavities</td>
<td>Civil Engineering</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ring+RF installation</td>
</tr>
<tr>
<td>Biggest limitation</td>
<td>luminosity (ERL,CW)</td>
<td>maximum energy</td>
</tr>
<tr>
<td>IR</td>
<td>not considered yet</td>
<td>allows ep+pp</td>
</tr>
<tr>
<td></td>
<td>one design? (eRHIC)</td>
<td>2 configurations [lo, hiq]</td>
</tr>
</tbody>
</table>
Nobody can afford a regular full-energy linac for a full-luminosity electron-hadron collider!

In eRHIC ERL 20GeV, 500mA beam will have reactive power of 10 GW! Regular linac - RF transmitter alone will cost $5/W -> $50,000M
Hence - ENERGY RECOVERY IS THE MUST
Scaling for ERL based LHeC

In the ERL-based eRHIC we collide two round beams with equal size. The main distinct feature of the ERL-based eRHIC is that the attainable luminosity is completely defined by the energy and intensity of protons or ion beam in RHIC:

\[
L = f_c \cdot \xi \cdot \frac{\gamma_i}{\beta_i^*} \cdot \frac{Z \cdot N_i}{r_i} \cdot \frac{N_e \cdot r_h/Z}{4 \pi \varepsilon_h}
\]

i.e. by the intensity \(N_i\), rep-rate \(f_c\), the energy of the ion/proton \(\gamma_i = E_i/Mc^2\), its charge \(q = Ze\) and classical radius \(r_i = Z^2e^2/Mc^2\) and allowable beam-beam tune shift \(\xi\). The ERL based eRHIC luminosity is in dependent of the electron beam energy and linearly proportional to the energy of the proton or ion beam. It means that that the same center of mass energy, (given no preference of the energy ratio), can be reached using higher energy protons (ions) and lower energy electrons, hence the high luminosity.

\[
L_{\text{LHeC}} = \frac{f_{c_{\text{LHeC}}}}{f_{c_{\text{eRHIC}}}} \cdot \frac{\xi_{\text{p_{LHeC}}}}{\xi_{\text{p_{eRHIC}}}} \cdot \frac{\gamma_{p_{\text{LHeC}}}}{\gamma_{p_{\text{eRHIC}}}} \cdot \frac{\beta_{p^*_{eRHIC}}}{\beta_{p^*_{\text{LHeC}}}} \cdot \frac{N_{p_{\text{LHeC}}}}{N_{p_{\text{eRHIC}}}} = 2.6 \cdot 10^{33} \cdot \frac{40}{14} \cdot \frac{0.024}{0.015} \cdot \frac{7000}{250} \cdot \frac{0.25}{0.5} \cdot \frac{1.7 \cdot 10^{11}}{2 \cdot 10^{11}} = 1.4 \cdot 10^{35}
\]

Thus, in LHeC practical limit is the power of RF system to compensate synchrotron radiation of electrons.
ERL based LHeC with cooling:

20 x luminosity

<table>
<thead>
<tr>
<th></th>
<th>Electron</th>
<th>Protons</th>
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<tbody>
<tr>
<td>Energy</td>
<td>70 GeV</td>
<td>7 TeV</td>
</tr>
<tr>
<td>N per bunch</td>
<td>$0.14 \times 10^{11}$</td>
<td>$1.7 \times 10^{11}$</td>
</tr>
<tr>
<td>Rep rate, MHz</td>
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<tr>
<td>Beam current, mA</td>
<td>27</td>
<td>1090</td>
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<tr>
<td>Norm emittance, μm</td>
<td>5.5</td>
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<tr>
<td>β*, m</td>
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<td>0.25</td>
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<tr>
<td>ξ*</td>
<td>12.7</td>
<td>0.0057</td>
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<tr>
<td>D</td>
<td>6.52</td>
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<tr>
<td>Luminosity, x $10^{33}$ cm$^{-2}$ sec$^{-1}$</td>
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<td>Loss for SR, MW</td>
<td>20</td>
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# ERL based LHeC with cooling: additional considerations

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<td>7 TeV</td>
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<tr>
<td><strong>Angular spread, µrad</strong></td>
<td>4.83</td>
<td>9.26</td>
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<td><strong>Distance to parasitic collision point, m</strong></td>
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<tr>
<td><strong>Crossing angle, µrad</strong></td>
<td>±100</td>
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</tr>
<tr>
<td><strong>Separation (in sigma)</strong></td>
<td>15.1</td>
<td>28.2</td>
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**ERL based LHeC with cooling 100 GeV electrons**

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<td>7 TeV</td>
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<tr>
<td><strong>N per bunch</strong></td>
<td>0.033 $10^{11}$</td>
<td>1.7 $10^{11}$</td>
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<tr>
<td><strong>Rep rate, MHz</strong></td>
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</tr>
<tr>
<td><strong>Beam current, mA</strong></td>
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<td>1090</td>
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<tr>
<td><strong>Norm emittance, μm</strong></td>
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<tr>
<td><em><em>β</em>, m</em>*</td>
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<td>0.25</td>
</tr>
<tr>
<td><strong>ξ</strong>*</td>
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<td>0.00137</td>
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<tr>
<td><strong>D</strong></td>
<td>4.56</td>
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<td><strong>Luminosity, x 10^{33} cm^{-2} sec^{-1}</strong></td>
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<td><strong>Loss for SR, MW</strong></td>
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### ERL based LHeC with cooling: higher energy

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</tr>
<tr>
<td><strong>N per bunch</strong></td>
<td>0.088 $10^{11}$</td>
<td>1.7 $10^{11}$</td>
</tr>
<tr>
<td><strong>Rep rate, MHz</strong></td>
<td></td>
<td>40</td>
</tr>
<tr>
<td><strong>Beam current, mA</strong></td>
<td>1.7</td>
<td>1090</td>
</tr>
<tr>
<td><strong>Norm emittance, μm</strong></td>
<td>16</td>
<td>0.3</td>
</tr>
<tr>
<td><strong>$\beta^*$, m</strong></td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td><strong>$\xi^*$</strong></td>
<td>6.3</td>
<td>0.0006</td>
</tr>
<tr>
<td><strong>Luminosity, x $10^{33}$ cm$^{-2}$ sec$^{-1}$</strong></td>
<td>1.5 / 0.12</td>
<td></td>
</tr>
<tr>
<td><strong>Loss for SR, MW</strong></td>
<td>20</td>
<td>Kink $\Lambda=0.03$</td>
</tr>
</tbody>
</table>

Hard radiation may be a problem
Without cooling - luminosity is 13 times lower
ERL based LHeC: lower current e-beam

\[ \xi_p = \frac{N_e \cdot r_p}{\gamma_p \cdot 4 \pi \epsilon_p} = \frac{N_e \cdot r_p}{4 \pi \epsilon_p \text{norm}}; \]

- Luminosity \(3 \cdot 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}\) at all energies of e-beam (probably will be limited by burn-off of the proton beam)
  - Or "ring-ring" luminosity of \(10^{33} \text{ cm}^{-2} \text{ sec}^{-1}\) with 3 mA electron beam current and 2.2 MW loss for SR
- e-beam current is low (because of the cooling!)
- If further reduction of \(\beta^*\) is possible, L\(10^{35}\) is feasible
- Higher energies of electrons are possible
- e-Beams with very low emittance are possible \(\rightarrow\) larger \(\beta^*\) for electron \(-\) easier optics, longer detectors, less modulation effects by synchrotron oscillations….
- 100 GeV e-beam with luminosity up to \(9 \cdot 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}\)

- Normalized emittance of electrons \(\sim 3 \mu m\) is possible \(-\) no problems to match the proton beam
  - @ 100 GeV, \(\gamma_e=2 \cdot 10^5 \sim 300 \gamma_p\), i.e. proton normalized emittance can be as low a 0.01 \(\mu m\)
- \(N_e \sim \epsilon_{\text{norm}}\): \(\epsilon_{\text{norm}} : 3.8 \mu m \rightarrow 0.1 \mu m \rightarrow N_e = 4 \cdot 10^9\)
- \(E_e=100 \text{ GeV}, I_e= 20 \text{ mA}, SR_{\text{loss}}=57 \text{ MW}\) (the same as Ring-Ring with 100 x luminosity)
- This case requires additional studies of beam disruption and kink instability
Other considerations

• Is there room for linac in the straights?
• Would ERL (for the most part) fit inside the LHC tunnel.

V. N. Litvinenko, 1st ECFA-CERN LHCC Workshop, Divonne-les-Bains, France, September 2, 2008
Conclusions

- ERL seems to be the most promising approach for high energy, high luminosity electron-ion and polarized electron-proton collider
- It can take advantage of any ring-ring concept and go further
- There is a clear possibility for eRHIC (LHeC?) staging
- Presently there is no show-stoppers but a significant amount of R&D
- At BNL the R&D ERL tests start in 2009, MIT’s progress with developing high current polarized gun, prototyping of small gap magnets are in progress ..... 
- LHeC based on this principle reach $10^{34}-10^{35}$ level of luminosity - natural topic for collaborating with BNL
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Inputs

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C. Montag - following talk