ERL-BASED ELECTRON-ION COLLIDERS

Vadim Ptitsyn
Collider-Accelerator Department
BNL
Lepton-nucleon scattering

- Deep Inelastic Scattering (DIS) of electron, muon and neutrino beams on nucleons (fixed targets) has been a vital scientific exploration tool for several decades.
- Experiments at SLAC (late 60s) led to the quark-parton model of nucleons, and ultimately to establishing QCD theory.
- Numerous DIS experiments in 70-80s uncovered the momentum and spin distribution of quark constituents of proton and neutron.

Higher CME -> reach to the momentum distribution of quark and gluons at very low momentum fraction (x)

Selection of physics results:
- precise data on details of the proton structure
- the discovery of very high density of sea quarks and gluons present in the proton at low-x
- detailed data on electro-weak electron-quark interactions
- precision tests of QCD ($\alpha_s$ measurements)
From HERA to future colliders

HERA

Polarized $e^-,e^+$ (27.5 GeV)
Unpolarized protons (920 GeV)
Peak luminosity: $5 \times 10^{31}$ cm$^{-2}$ s$^{-1}$

Future colliders

Much higher luminosity:
$10^{33}-10^{34}$ cm$^{-2}$ s$^{-1}$

Polarized protons and light ions
(in addition to polarized electrons)

Heavy ion beams

Different (and variable)
Center-of-Mass Energy range
Major physics objectives of future electron-ion colliders
Major physics objectives of future electron-ion colliders

3-dimensional imaging of the nucleons

Electron-ion colliders
Major physics objectives of future electron-ion colliders

- Electron-ion colliders
- Probing the nucleon’s spin structure
- 3-dimensional imaging of the nucleons
Major physics objectives of future electron-ion colliders

- Mapping the gluon content of ions and protons; High-density gluon state
- 3-dimensional imaging of the nucleons
- Probing the nucleon’s spin structure

Electron-ion colliders
Major physics objectives of future electron-ion colliders

- Mapping the gluon content of ions and protons; High-density gluon state
- 3-dimensional imaging of the nucleons
- Probing the nucleon’s spin structure
- Spatial and Momentum Structure of the Nucleus
- Electron-ion colliders
Major physics objectives of future electron-ion colliders

Spatial and Momentum Structure of the Nucleus

Mapping the gluon content of ions and protons; High-density gluon state

3-dimensional imaging of the nucleons

Electron-ion colliders

Probing the nucleon’s spin structure

Searches and the understanding of new physics (GUT, LQs, Higgs, ….)
Electron-Hadron Collider Designs

**Ring-ring**

- Ion ring
- Electron storage ring

**Linac-ring**

- Ion ring
- Electron linear accelerator

<table>
<thead>
<tr>
<th></th>
<th>Center of Mass Energy</th>
<th>On the base of</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHeC ring-ring</td>
<td>1.3 TeV</td>
<td>LHC (CERN)</td>
</tr>
<tr>
<td>MEIC</td>
<td>15-65 (140) GeV</td>
<td>CEBAF (JLab)</td>
</tr>
<tr>
<td>e-HIAF</td>
<td>12 GeV</td>
<td>HIAF (IMP)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Center of Mass Energy</th>
<th>On the base of</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHeC linac-ring</td>
<td>1.3 (2) TeV</td>
<td>LHC (CERN)</td>
</tr>
<tr>
<td>eRHIC</td>
<td>20-145 GeV</td>
<td>RHIC (BNL)</td>
</tr>
</tbody>
</table>

- Overcoming the electron beam-beam limit
- Spin transparency

Energy Recovery Linacs have to be used for high luminosity in CW mode.
Large Hadron electron Collider at CERN

60 GeV (e) x 7 TeV (p)

- Protons/ions from LHC
- 0.5 GeV injector
- A pair of SCRF linacs with energy gain 10 GeV per pass
- Six 180° arcs, each arc 1 km radius
- Re-accelerating stations to compensate energy lost by SR
- Switching stations at the beginning and end of each linac
- Matching optics
- Extraction dump at 0.5 GeV
Large Hadron electron Collider at CERN

- Protons/ions from LHC
- 0.5 GeV injector
- CRF linacs with energy gain 10 GeV per pass
- Six 180° arcs, each arc 1 km radius
- Re-accelerating stations to compensate energy lost by SR
- Switching stations at the beginning and end of each linac
- Matching optics
- Extraction dump at 0.5 GeV
eRHIC at BNL

Add an electron accelerator to the existing $2.5B RHIC including existing RHIC tunnel, detector buildings and cryo facility

- Center-of-mass energy range: 20 – 145 GeV
- Full electron polarization at all energies
  Full proton and He-3 polarization with six Siberian snakes
- Any polarization direction in electron-hadron collisions:
  - 80% polarized electrons: 1.3 – 21.2 GeV
  - 70% polarized protons 25 - 250 (275*) GeV
  - Light ions (d, Si, Cu)
    Heavy ions (Au, U)
    Pol. light ions (He-3)
    10 - 100 (110*) GeV/u
    17 - 167 (184*) GeV/u

Luminosity:

\[ 10^{33} – 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \]

* It is possible to increase RHIC ring energy by 10%
Novel FFAG lattice allows 16 beam recirculations using only two beam transport loops.
## Parameter Table

<table>
<thead>
<tr>
<th>Parameters</th>
<th>eRHIC</th>
<th>LHeC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>e</td>
<td>p</td>
</tr>
<tr>
<td>Energy (GeV)</td>
<td>15.9</td>
<td>250</td>
</tr>
<tr>
<td>Bunch spacing (ns)</td>
<td>106</td>
<td></td>
</tr>
<tr>
<td>Intensity, $10^{11}$</td>
<td>0.07</td>
<td>3.0</td>
</tr>
<tr>
<td>Current (mA)</td>
<td>10</td>
<td>415</td>
</tr>
<tr>
<td>rms norm. emit. (mm-mrad)</td>
<td>23</td>
<td>0.2</td>
</tr>
<tr>
<td>$\beta_{x/y}$ (cm)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>rms bunch length (cm)</td>
<td>0.4</td>
<td>5</td>
</tr>
<tr>
<td>IP rms spot size ($\mu$m)</td>
<td></td>
<td>6.1</td>
</tr>
<tr>
<td>Beam-beam parameter</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>Disruption parameter</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Polarization, %</td>
<td>80</td>
<td>70</td>
</tr>
<tr>
<td>Luminosity, $10^{33}$cm$^{-2}$s$^{-1}$</td>
<td>3.3</td>
<td></td>
</tr>
</tbody>
</table>
Technological challenges

- High intensity (6 – 50 mA) polarized electron source
- High power ERL with multiple recirculations (high current SRF cavities, machine protection, MBBU, …)
- Strong cooling of hadron beams (eRHIC)
- Low hadron $\beta^*$ interaction region
- Crab-crossing (eRHIC)
- Beam-beam effects
- Techniques for intense $e^+$ beam (LHeC)

![Diagram of a modulator, dispersion section, and kicker for electron and hadron beams.](Image)
Polarized e-source: BNL Gatling Gun

Prototype has been built. Initial tests with 2 cathodes are ongoing.

Ultimate goal: 2.5 mA/cathode, 50 mA total

First beam detected by the YAG screen.
High current SRF cavities

LHeC: 802 MHz cavity and cryomodule development. CERN-JLab-Mainz Collaboration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c$</td>
<td>5</td>
</tr>
<tr>
<td>$W_{\text{core}}$</td>
<td>18 MV</td>
</tr>
<tr>
<td>$f_b$</td>
<td>801.58 MHz</td>
</tr>
<tr>
<td>$W_W$</td>
<td>131 J</td>
</tr>
<tr>
<td>aperture $\phi$</td>
<td>75 mm</td>
</tr>
<tr>
<td>equator $\phi$</td>
<td>347 mm</td>
</tr>
<tr>
<td>$R_W | Q$</td>
<td>462 $\Omega$</td>
</tr>
<tr>
<td>$G$</td>
<td>276 $\Omega$</td>
</tr>
<tr>
<td>$\varepsilon B_{\text{rms}}$</td>
<td>41 MV/m</td>
</tr>
<tr>
<td>$H_{\text{rms}}$</td>
<td>86 mT</td>
</tr>
<tr>
<td>$P_{\text{loss}} @ 2K$</td>
<td>&lt; 28 W</td>
</tr>
</tbody>
</table>

HOM power must be effectively damped:
LHeC: $\sim 200$ W
eRHIC: $\sim 8$ kW (in worst case)

eRHIC: 422 MHz cavity
Designed prototype:

Largest total beam current: 700 mA (for 9.3 GeV top electron energy)

@W.Xu
Multipass Beam Break-Up

Multipass beam-breakup thresholds for 16 pass operation (simulation results)

<table>
<thead>
<tr>
<th>$\Delta f/f$ (rms)</th>
<th>Current Threshold (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>53</td>
</tr>
<tr>
<td>5e-4</td>
<td>95</td>
</tr>
<tr>
<td>1e-3</td>
<td>137</td>
</tr>
<tr>
<td>3e-2</td>
<td>225</td>
</tr>
<tr>
<td>1e-2</td>
<td>329</td>
</tr>
</tbody>
</table>
**FFAG recirculation passes**

- eRHIC uses two FFAG beamlines to do multiple recirculations. (FFAG-I: 1.3-5.4 GeV, FFAG-II: 6.6-21.2 GeV)
- All sections of a FFAG beamline is formed using a same FODO cell. Required bending in different sections is arranged by proper selection of the offsets between cell magnets (or, alternatively, with dipole field correctors).
- Permanent magnets can used for the FFAG beamline magnets (no need for power supplies/cables and cooling).

@S.Brooks, D.Trbojevic

Each of two eRHIC FFAGs contain 1066 FFAG cells
Advanced Cooling for eRHIC ion beam

High energy, high density ion beam need cooling with high band-width. **Coherent electron cooling:** $10^{13}-10^{17}$ Hz

PoP CeC experiment in 2016-2017 RHIC runs.

**Classic - FEL amplifier** *(V.Litvinenko, Ya.Derbenev)*

**Micro-bunching instability amplifier** *(D.Ratner)*
Since using ERL:
Beam quality must be acceptable for deceleration.
Halo formation by due to electron beam disruption by the beam-beam interaction should be moderate.

Other specific beam-beam effects of linac-ring scheme:
-Kink instability of hadron beam
-Heating of protons by electron parameter (orbit offset, intensity, emittance) fluctuations.

The effects are being studied by simulations and experimentally.
Since using ERL:
Beam quality must be acceptable for deceleration.
Halo formation by due to electron beam disruption by the beam-beam interaction should be moderate.

Other specific beam-beam effects of linac-ring scheme:
- Kink instability of hadron beam
- Heating of protons by electron parameter (orbit offset, intensity, emittance) fluctuations.

The effects are being studied by simulations and experimentally.
Using HERA and B-factories experience to resolve IR design issues:
- Strong beam focusing
- Fast separation (*avoiding parasitic beam-beam*)
- Managing synchrotron radiation fan (*absorbers, masks; precise orbit control; protection of SC magnets*)
- Detector integration (*Large acceptance; Large magnet apertures for propagation of the collision products*)
- Correction of chromatic effects
ERL SCRF facility at CERN

- Test facility for SCRF cavities and modules
- Test facility for multi-pass multiple cavity ERL
- Injector studies: DC gun or SRF gun
- Study reliability issues, operational issues
- Vacuum studies related to FCC
- Possible use for detector development, experiments and injector suggests ~1 GeV as final stage energy
- Test facility for controlled SC magnet quench tests
- Could it be foreseen as the injector to LHeC ERL and to FCC?

**D. Pellegrini’s Plenary talk**

<table>
<thead>
<tr>
<th>TARGET PARAMETER*</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injection Energy [MeV]</td>
<td>5</td>
</tr>
<tr>
<td>Final Beam Energy [MeV]</td>
<td>900</td>
</tr>
<tr>
<td>Normalized emittance $y\varepsilon_{x,y}$ [μm]</td>
<td>50</td>
</tr>
<tr>
<td>Beam Current [mA]</td>
<td>10</td>
</tr>
<tr>
<td>Bunch Spacing [ns]</td>
<td>25 (50)</td>
</tr>
<tr>
<td>Passes</td>
<td>3</td>
</tr>
</tbody>
</table>

*in few stages

Conceptual Design
Study is underway
Cornell-BNL FFAG-ERL Test Facility (Cβ)

- NS-FFAG arcs, four passes (similar to first eRHIC loop)
- Momentum aperture of x4, as for eRHIC
- Uses Cornell DC gun, injector (ICM), dump, 70MeV SRF CW Linac
- Prototyping of essential components of eRHIC design

Also, possible ERL-related experiments for eRHIC are under consideration in JLab. (Satellite meeting, Thursday morning, Lecture Hall 1)
DOE NP Facilities and possible eRHIC schedule

Tentative Schedule for eRHIC

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>12/GeV Upgrade</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FRIB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RHIC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Energy RHIC Electron Cooling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sPHENIX</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>eRHIC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R&D/PED/Design (CD0-CD3) | Projects/Construction (CD3-CD4) | Operations/physics
Summary

- ERL technology provides a pathway for a high-luminosity electron-ion collider
- ERL-based EIC designs have been developed in CERN (LHeC) and BNL (eRHIC)
- Several R&D projects are underway to address the technological challenges for an ERL-based collider
- ERL test facilities are planned in order to verify related technologies
eRHIC. Luminosity

Detector e/h energy ratio

Minimum electron energy

Electron beam current

SR power

EIC White Paper: Peak luminosity and CoM energy range

EIC White Paper: Upgrade

Luminosity [cm⁻² sr⁻¹ GeV⁻¹]

Center-of-Mass Energy [GeV]

- $E_p = 250$ GeV
- $E_e = 5.1$ GeV
- $I_e = 50$ mA

- $E_p = 250$ GeV
- $E_e = 9.4$ GeV
- $I_e = 50$ mA

- $E_p = 100$ GeV
- $E_e = 2.6$ GeV
- $I_e = 50$ mA

- $E_p = 50$ GeV
- $E_e = 2.6$ GeV
- $I_e = 50$ mA

- $E_p = 250$ GeV
- $E_e = 15.9$ GeV
- $I_e = 10$ mA

- $E_p = 250$ GeV
- $E_e = 21.2$ GeV
- $I_e = 3$ mA