An Electron-Ion Collider for JLab

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Center for Advanced Studies of Accelerators

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Jefferson Lab
June 12-14, 2006
Outline

- Nuclear Physics Motivation / Requirements
- ELIC: An Electron-Light Ion Collider at CEBAF
- Achieving the Luminosity of ELIC
- Achieving Polarization in ELIC
- ELIC Parameters
- Advantages/Features of the ELIC Design
- R&D Required
- Summary
Nuclear Physics Motivation

- A high luminosity polarized electron – light ion collider has been proposed as a powerful new microscope to probe the partonic structure of matter.

- Over the past two decades we have learned a great amount about the hadronic structure.

- Some crucial questions remain open …
CEBAF II/ELIC Upgrade - Science

Science addressed by the second Upgrade:

- How do quarks and gluons provide the binding and spin of the nucleons?
- How do quarks and gluons evolve into hadrons?
- How does nuclear binding originate from quarks and gluons?

From A. W. Thomas at NSAC LRP implementation review (2005)
The features of the facility necessary to address these questions:

- **Center-of-mass energy between 20 GeV and 65 GeV**
  with energy asymmetry of ~10, which yields
  \[ E_e \sim 3 \text{ GeV on } E_i \sim 30 \text{ GeV up to } E_e \sim 7 \text{ GeV on } E_i \sim 150 \text{ GeV} \]

- **CW Luminosity from \(10^{33}\) to \(10^{35}\) \(\text{cm}^{-2} \text{ sec}^{-1}\)**

- **Longitudinal polarization of both beams in the interaction region \(\geq 50\% – 80\%\)** required for the study of generalized parton distributions and transversity

- **Transverse polarization of ions** extremely desirable

- **Spin-flip of both beams** extremely desirable
ERL-based ELIC Design

Ion Linac and pre-booster

Electron Cooling

Solenoid
Snake

3 -7 GeV electrons
30 -150 GeV light ions

Electron Injector

CEBAF with Energy Recovery

Beam Dump
Challenges of ERL-based ELIC

- Polarized electron current of 10’s of mA is required for ERL-based ELIC with circulator ring. Present state of art ~0.3 mA.

- A fast kicker with sub-nanosecond rise/fall time is required to fill the circulator ring. Present state of art is ~10 nsecs.

- Substantial upgrades of CEBAF and the CHL (beyond the 12 GeV Upgrade) are required. Integration with the 12 GeV CEBAF accelerator is challenging.

- Exclusion of physics experiments with positron beam.

- Electron cooling of the high energy ion beam is required.
A New Concept for ELIC

30-150 GeV light ions

Electron Cooling

Snake

IR

3-7 GeV electrons
Polarized Electron Injection & Stacking

**Injector**

- 1 mA
- 4 ms
- 3000 pulses
- 5 μs

*4 ms is the radiation damping time at 7 GeV*

**Storage ring**
Low emittance e⁻ storage ring at 7 GeV

135° FODO lattice - Thanks, Andrew Hutton!

Emittance = 8.5 mm-mrad (norm. rms)

Dipoles
L = 50 cm
B = 6.4 kG

Quads
L = 30 cm
G = 16 kG/cm

Dipoles
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Quads
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G = 16 kG/cm
“Optimum” emittance e⁻ ring at 7 GeV

135° FODO lattice

Emittance = 85 mm-mrad (norm. rms)

Dipoles
L = 100 cm
B = 6.8 kG

Quads
L = 60 cm
G = 4 kG/cm
“Figure-8” boosters and storage rings

- Zero spin tune avoids intrinsic spin resonances.
- No spin rotators required around the IR.
- Ensure longitudinal polarization for deuterons at 2 IP’s simultaneously, at all energies.
Figure-8 Ion Ring at 150 GeV – Lattice

15 cells

17 cells

17 cells

15 cells

footprint

175 m

100 m

30°
Positrons!

Generation of positrons:
(based on CESR experience)
- Electron beam at 200 MeV yields unpolarized positron accumulation of ~100mA/min
- ½ hr to accumulate 3 A of positron current

Possible applications:
- $e^+i$ colliding beams (longitudinally polarized)
- $e^+e^-$ colliding beams (longitudinally polarized up to 7x7 GeV)
- .....

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ELIC for Positrons

30-150 GeV light ions

Electron Cooling

3-7 GeV electrons

3-7 GeV positrons
Achieving the Luminosity of ELIC

\[ L = \frac{N_i N_e}{4 \pi \sigma^*} f_b \]

For 150 GeV protons on 7 GeV electrons, \( L \approx 7.7 \times 10^{34} \text{ cm}^{-2} \text{ sec}^{-1} \) compatible with realistic Interaction Region design.

Beam Physics Issues

- Beam – beam interaction between electron and ion beams
  \( (\xi_i \approx 0.01 \text{ per IP}; 0.025 \text{ is presently utilized in Tevatron}) \)
- High energy electron cooling
- Interaction Region
  - High bunch collision frequency \( (f = 1.5 \text{ GHz}) \)
  - Short ion bunches \( (\sigma_z \approx 5 \text{ mm}) \)
  - Very strong focus \( (\beta^* \approx 5 \text{ mm}) \)
  - Crab crossing
Electron Cooling

- Beam cooling required to suppress IBS and reduce emittances
- Bunch length shortening particularly important

- EC for RHIC
  - 55 MeV ERL at 100 mA electron beam
  - Use of an SRF gun
  - R&D in progress

- EC for ELIC
  - 75 MeV at 2A electron beam
  - Use circulator ring with 100 revolutions
  - Staged cooling
ELIC Interaction Region Concept

Focal Points

- Spin detector
- Crab cavity
- Focusing triplet
- Detector
- Cross bend
- Spin tune solenoid
- 80 MV
- 4 m
- 2 m
- 0.1 rad

Office of Nuclear Physics
Thomas Jefferson National Accelerator Facility
L. Merminga Users Group Meeting, June 12-14 2006
Crab Crossing

Short bunches make Crab Crossing feasible.

SRF deflectors at 1.5 GHz can be used to create a proper bunch tilt.

Parasitic collisions are avoided without loss of luminosity.
ELIC Interaction Region Design

IR for ions at E = 150 GeV

max quad gradient ~ 250 Tesla/m
IR for electrons at $E = 7$ GeV

BETA X and Y [m]

DISP X and Y [m]
Achieving Polarization in ELIC

- Polarization of Ions (protons, deuterons, $^3\text{He}$)
- Polarization of Electrons
- Polarization of Positrons
Polarization of Ions

Protons and $^3$He:
Two IP’s (along straight section) with simultaneous longitudinal polarization with no snakes. Two snakes are required to ensure longitudinal polarization at 4 IP’s simultaneously.

Deuterons:
Two IP’s with simultaneous longitudinal polarization with no snakes (can be switched between two cross-straight). Solenoid (or snake for protons) to stabilize spin near longitudinal direction for all species.
Spin injected vertical in arcs (using Wien filter). Self-polarization in arcs to maintain injected polarization. Spin rotators matched with the cross bends of IPs.
Electron Spin Matching at the IR

Rotation of spin from vertical in arcs to longitudinal at IP:
- Beam crossing bend causing energy-dependent spin rotation, together with
- **Energy-independent orbit** spin rotators [two SC solenoids with bend in the middle] in the arc and after the arc.
Sokolov-Ternov polarization for positrons

Vertical spin in arcs
4 IP’s with longitudinal spin
Polarization time is 2 hrs at 7 GeV – varies as $E^{-5}$ (can be accelerated by introduction of wigglers or polarizing at maximum energy).
Quantum depolarization in spin rotators $\rightarrow$ *Equilibrium polarization* $\leq 90\%$
## e⁻ / e⁺ Polarization Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>3</th>
<th>5</th>
<th>7</th>
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<tbody>
<tr>
<td>Energy</td>
<td>GeV</td>
<td>3</td>
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<tr>
<td>Beam cross bend at IP</td>
<td>mrad</td>
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<tr>
<td>Radiation damping time</td>
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<td>Accumulation time</td>
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<td>Self-polarization time*</td>
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<tr>
<td>Equilibrium polarization, max**</td>
<td>%</td>
<td>92</td>
<td>91.5</td>
<td>90</td>
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<tr>
<td>Beam run time</td>
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*One e-folding. Time can be shortened using high field wigglers.
**Ideal max equilibrium polarization is 92.4%. Degradation is due to radiation in spin rotators.
## ELIC Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>ERL</th>
<th>Ring-Ring</th>
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<tbody>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>150/7</td>
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<td>Bunch collision rate</td>
<td>GHz</td>
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<tr>
<td>Number of particles/bunch</td>
<td>10^{10}</td>
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<td>.4/1.1</td>
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<td>Beam current</td>
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<td>Cooling beam energy</td>
<td>MeV</td>
<td>75</td>
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<tr>
<td>Cooling beam current</td>
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<td>Energy spread, rms</td>
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<td>Bunch length, rms</td>
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<td>Beta-star</td>
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<td>Horizontal emittance, norm</td>
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<td>Vertical emittance, norm</td>
<td>μm</td>
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<td>Beam-beam tune shift (vertical) per IP</td>
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<td>Laslett tune shift (p-beam)</td>
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<td>Luminosity per IP, 10^{34}</td>
<td>cm^{-2} s^{-1}</td>
<td>7.7</td>
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<td>Number of interaction points</td>
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<tr>
<td>Core &amp; luminosity IBS lifetime</td>
<td>h</td>
<td>24</td>
<td>24</td>
</tr>
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</table>
Advantages/Features of ELIC

- JLab DC polarized electron gun already meets beam current requirements for filling the storage ring.
- A conventional kicker already in use in many storage rings would be sufficient.
- The 12 GeV CEBAF accelerator can serve as an injector to the ring. RF power upgrade might be required later depending on the performance of ring.
- Physics experiments with polarized positron beam are possible.
- Possibilities for $e^+e^-, e^-e^-, e^+e^+$ colliding beams.
- No spin sensitivity to energy and optics.
- No orbit change with energy despite spin rotation.
- Collider operation appears compatible with simultaneous 12 GeV CEBAF operation for fixed target program.
R&D Required for Ring-Ring ELIC

- High energy electron cooling of protons/ions.
- Beam dynamics issues with crab crossing.
- Ion space charge at stacking in pre-booster.
- Beam-beam interactions.
Workshop on Future Prospects in QCD at High Energy
Joint EIC2006 & Hot QCD Meeting Hosted by Brookhaven National Laboratory

Date:       July 17-22, 2006
Location:  Brookhaven National Laboratory
Summary

- A compelling scientific case is developing for a high luminosity, polarized electron-light ion collider, to address fundamental questions in hadron Physics.

- JLab design studies have led to an approach that promises luminosities up to nearly $10^{35}$ cm$^{-2}$ sec$^{-1}$, for electron-light ion collisions at a center-of-mass energy between 20 and 65 GeV.

- A fundamentally new approach has led to a design that can be realized on the JLab site using CEBAF as a full energy injector into an electron storage ring and can be integrated with the 12 GeV fixed target program for physics.

- This ring-ring design requires significantly less technological development compared to the ERL-based design, for the same luminosity level.

- Planned R&D will address open readiness issues.
Lifetime due to Background Processes

Proton beam lifetime from small-angle elastic ep-scattering

Contributions from inelastic processes have smaller effect by factor of ~10

Courtesy: A. Afanasev, et al.