The Electron Ion Collider: Physics Opportunities & Realization Challenges

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Stony Brook University

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INT@UW
The layout of this talk:

**QCD:**
- What we know
- What we know we don’t know, and
- What we don’t know.....

**Electron Ion Collider Proposals**
- A brief overview
  - The anticipated science output of this meeting: plots to be updated... golden measurements to be identified

**Towards the NSAC Long Range Planning**... & a brief summary
QCD

“Folks, we need to stop “testing” QCD and start understanding it”

Yuri Dokshitzer

1998, ICHEP Vancouver, CA in his Summary Talk

2004 For the discovery of asymptotic freedom in QCD
Do we understand QCD?

While there is no reason to doubt QCD, our level of understanding of QCD remains extremely unsatisfactory: both at low & high energy

- We don’t understand the basic properties of hadrons such as mass and spin from the QCD degrees of freedom
- We don’t understand what are the effective degrees of freedom at high energy
- We don’t understand how these degrees of freedom interact with each other and with other hard probes
- What can we learn from them about confinement & universal features of the theory of QCD?

We are only beginning to explore the high energy many body dynamics of QCD
Origin of Mass – Gluons in QCD

• Protons and neutrons form most of the mass of the visible universe

• 99% of the nucleon mass is due to self generated gluon fields
  – Similarity between p, n mass indicates that gluon dynamics is identical & overwhelmingly important

• Lattice QCD supports this

  Higgs Mechanism, often credited with mass generation, is of no consequence
Measurement of Glue at HERA

- Scaling violations of $F_2(x,Q^2)$
  \[
  \frac{\partial F_2(x, Q^2)}{\partial \ln Q^2} \propto G(x, Q^2)
  \]

- NLO pQCD analyses: fits with linear DGLAP* equations

*Gluon dominates

*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi
Gluon distribution at low-x understood?

- Indefinite rise: Infinite hadron-hadron cross section?
  - Could this be an artifact of using of linear DGLAP in gluon extraction?

How would we find out?
- Need theory development
- Need experimental measurements at lower x!
What is the effect of including non-linear effects in DGLAP equation?

→ Small coupling, high gluon densities → Color Glass Condensate

\[ (Q_s^A)^2 \approx c Q_0^2 \left( \frac{A}{x} \right)^{1/3} \]

No unambiguous experimental evidence yet, but many smoking guns (HERA, RHIC, LHC)

No higher energy e-p collider than HERA!

→ Nuclei, naturally enhance the densities of partonic matter

Why not use Nuclear DIS at high energy?
Time evolution: Our Understanding of Nucleon Spin

We have come a long way, but do we understand nucleon spin?
Time evolution of our understanding of the “nucleon spin”:

1980s

1990/2000s

Recent: \( J_G = \Delta G + L_G \)

\[
\frac{1}{2} \Delta \Sigma = \frac{1}{2} \\
\frac{1}{2} \Delta \Sigma + \Delta G = \frac{1}{2} \\
\frac{1}{2} \Delta \Sigma + \Delta G + L_Q + L_G = \frac{1}{2}
\]

\[
J_Q + J_G = \frac{1}{2} \Delta \Sigma + L_Q + \Delta G + L_G = \frac{1}{2}
\]
Status of “Nucleon Spin Crisis Puzzle”

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_Q + \Delta G + L_G
\]

• We know how to measure \( \Delta \Sigma \) and \( \Delta G \) precisely using pQCD
  – \( \frac{1}{2} (\Delta \Sigma) \sim 0.15 \): From fixed target pol. DIS experiments
  – RHIC-Spin: \( \Delta G \) not large as anticipated in the 1990s, but measurements & precision needed at low & high \( x \)

• Orbital angular momenta: \( L_Q \) (\( L_G \)?)
  – Quark GPDs: the 12 GeV Jlab & COMPASS
  – Gluon GPDs: low \( x \) \( \rightarrow \) \( J_G \) \( \rightarrow \) will need the future EIC!

• It would be great to have a (2+1)D tomographic image of the proton…. TMDs, GPDs: Quarks & Gluons… full understanding of hadron structure
Fundamental Questions in QCD

• How do gluons contribute to the structure of the nucleon?
• What role do the gluons play in determining the spin structure of the nucleon?
• What is the spatial distribution of the gluons and sea quarks in the nucleon?
• How do the gluons contribute to the structure of the nuclei?
• What are the properties of high density gluon matter?
• How do fast quarks and gluons interact when they traverse through nuclear matter?

How do we get to the answers?

Precise imaging of the sea-quarks and gluons in the nucleon

Need to explore a new QCD frontier: of strong color fields in nuclei
The Proposal:
Future DIS experiment at an Electron Ion Collider: A high energy, high luminosity (polarized) $ep$ and $eA$ collider and a suitably designed detector

Measurements:
[1] $\rightarrow$ Inclusive
[1] and [2] and [3] $\rightarrow$ Exclusive

Inclusive $\rightarrow$ Exclusive
Low $\rightarrow$ High Luminosity
Demanding Detector capabilities
EIC : Basic Parameters

- \( E_e = 10 \) GeV (5-30 GeV variable)
- \( E_p = 250 \) GeV (50-325 GeV Variable)
- \( \sqrt{S_{ep}} = 100 \) (30-200) GeV
- \( X_{\text{min}} = 10^{-4}; \ Q^2_{\text{max}} = 10^4 \) GeV
- Beam polarization \( \sim 70\% \) for e,p
- Luminosity \( L_{ep} = 10^{33-34} \) cm\(^{-2}\)s\(^{-1}\)
- Minimum Integrated luminosity:
  - 50 fb\(^{-1}\) in 10 yrs (100 x HERA)
  - Possible with \( 10^{33} \) cm\(^{-2}\)s\(^{-1}\)
  - Recent projections much higher

Nuclei:
- \( p \rightarrow U; \ E_A = 20-100 \) (140) GeV/N
- \( \sqrt{S_{eA}} = 12-63 \) (75) GeV
- \( L_{eA}/N = 10^{33} \) cm\(^{-2}\)s\(^{-1}\)
Science of EIC:

• Nucleon (spin) structure
  – Precision measurements of ΔQ and ΔG via inclusive and semi-inclusive DIS → Spin puzzle
  – Measurement of (gluon) GPDs & TMDs: via semi-inclusive and exclusive DIS
    • 3D momentum and position (correlations) of the nucleon → Explore and understand the detailed nucleon structure
    • possibly leading to orbital angular momentum → Spin puzzle

• Study of extreme high gluon densities via inclusive and semi-inclusive DIS off a wide range of nuclei

• High energy, beam polarization, and a full acceptance detector: why not explore precision electroweak physics and EW (spin) structure functions
REALIZATION CHALLENGES
Machine Designs

eRHIC at Brookhaven National Laboratory using the existing RHIC complex

ELIC at Jefferson Laboratory using the Upgraded 12GeV CEBAF

Both planned to be STAGED
Three compact rings:
• 3 to 11 GeV electron
• Up to 12 GeV/c proton (warm)
• Up to 60 GeV/c proton (cold)
Abhay Deshpande at INT/UoW, Gluons and Sea Quarks at High Energy
**ELIC: High Energy & Staging**

Serves as a large booster to the full energy collider ring

<table>
<thead>
<tr>
<th>Stage</th>
<th>Max. Energy (GeV/c)</th>
<th>Ring Size (m)</th>
<th>Ring Type</th>
<th>IP #</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>e</td>
<td>p</td>
<td>e</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>96</td>
<td>11</td>
<td>1000</td>
<td>Cold</td>
</tr>
<tr>
<td>High</td>
<td>250</td>
<td>20</td>
<td>2500</td>
<td>Cold</td>
</tr>
<tr>
<td>Parameter</td>
<td>Proton</td>
<td>Electron</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>--------</td>
<td>----------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>60</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Collision frequency</td>
<td>GHz</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>(10^{10})</td>
<td>0.416</td>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td>Beam current</td>
<td>A</td>
<td>1</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Polarization</td>
<td>%</td>
<td>&gt; 70</td>
<td>~ 80</td>
<td></td>
</tr>
<tr>
<td>Energy spread</td>
<td>(10^{-4})</td>
<td>~ 3</td>
<td>7.1</td>
<td></td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>mm</td>
<td>10</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>Horizontal emittance, normalized</td>
<td>µm rad</td>
<td>0.35</td>
<td>53.5</td>
<td></td>
</tr>
<tr>
<td>Vertical emittance, normalized</td>
<td>µm rad</td>
<td>0.07</td>
<td>10.7</td>
<td></td>
</tr>
<tr>
<td>Horizontal (\beta^*)</td>
<td>cm</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Vertical (\beta^*)</td>
<td>cm</td>
<td>0.8</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Vertical beam-beam tune shift</td>
<td></td>
<td>0.007</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Laslett tune shift</td>
<td></td>
<td>0.07</td>
<td>Very small</td>
<td></td>
</tr>
<tr>
<td>Distance from IP to 1\textsuperscript st FF quad</td>
<td>m</td>
<td>4.5</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>Luminosity per IP, (10^{33})</td>
<td>cm(^{-2})s(^{-1})</td>
<td></td>
<td>14.2</td>
<td></td>
</tr>
</tbody>
</table>
### ELIC Luminosity: 2.5 km Ring, 8 Tesla

<table>
<thead>
<tr>
<th>Proton Energy (GeV)</th>
<th>Electron Energy (GeV)</th>
<th>CM Energy (GeV)</th>
<th>Full acceptance Luminosity ((L=7\text{m}, \beta*=2\text{cm})) (10^{33} \text{ cm}^{-2}\text{s}^{-1})</th>
<th>High luminosity Luminosity ((L=4.5\text{m}, \beta*=8\text{mm})) (10^{33} \text{ cm}^{-2}\text{s}^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>3</td>
<td>54.8</td>
<td>8.3</td>
<td>20.7</td>
</tr>
<tr>
<td>250</td>
<td>5</td>
<td>70.7</td>
<td>18.5</td>
<td>46.4</td>
</tr>
<tr>
<td>250</td>
<td>6</td>
<td>77.5</td>
<td>20.2</td>
<td>50.5</td>
</tr>
<tr>
<td>250</td>
<td>7</td>
<td>83.7</td>
<td>20.7</td>
<td>64.5</td>
</tr>
<tr>
<td>250</td>
<td>8</td>
<td>89.5</td>
<td>18.9</td>
<td>57.6</td>
</tr>
<tr>
<td>250</td>
<td>9</td>
<td>94.9</td>
<td>15.8</td>
<td>39.6</td>
</tr>
<tr>
<td>250</td>
<td>11</td>
<td>104.9</td>
<td>7.5</td>
<td>18.8</td>
</tr>
<tr>
<td>250</td>
<td>20</td>
<td>141.4</td>
<td>3.1</td>
<td>6.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Proton Energy (GeV)</th>
<th>Electron Energy (GeV)</th>
<th>Ring Circumference (m)</th>
<th>Luminosity Full acceptance ((L=7\text{m}, \beta*=2\text{cm})) (10^{33} \text{ cm}^{-2}\text{s}^{-1})</th>
<th>Luminosity High luminosity ((L=4.5\text{m}, \beta*=8\text{mm})) (10^{33} \text{ cm}^{-2}\text{s}^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>3</td>
<td>2500/2500</td>
<td>1.1</td>
<td>2.6</td>
</tr>
<tr>
<td>30</td>
<td>3</td>
<td>1000/2500</td>
<td>2.1</td>
<td>4.9</td>
</tr>
</tbody>
</table>

- The second option is using 1 km medium-energy ion ring for higher proton beam current at 30 GeV protons for lowering the space charge tune-shift.
e-RHIC is a triple IP collider
5 to 30 GeV $e^- \times 325$ GeV p - 130/u Au

- Up to 6 passes in the tunnel already from the first stage
- Staging by electron energy increase by lengthening the linacs
- The possibility of using upgraded STAR and PHENIX detectors on first stage for $e$-$p$ ($e$-$Au$) collisions. (eSTAR and ePHENIX)
- Dedicated eRHIC detector will be added at IR12.
- Reduced civil construction cost

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ARC’s

Recent developments: lattice of recirculating passes for 20-30 GeV electron energy; spreader/combiners (D. Trbojevic, N. Tsoupas)

30 GeV e+ ring

1.27 m beam high

30 GeV ERL
HE ERL passes
LE ERL passes
6 passes

30 GeV
25 GeV
20 GeV

15 GeV
10 GeV
5 GeV

OUTER AISLE
INNER AISLE

CENTER OF RING
MeRHIC $\rightarrow$ eRHIC at BNL

**Planning:**

- **Stage 1 eRHIC:**
  - ePHENIX & eSTAR
  - 5 GeV e-beam

- **eRHIC:**
  - eRHIC detector at IP12
  - 20-30 GeV e-beam
EIC Luminosity vs. Time (Detector)

- Inclusive
- Semi-Inclusive
- Exclusive

Stage 1 Physics
ePHENIX/eSTAR
MEIC Detector

eRHIC/ELIC detector with good PID & full acceptance

Time & Detector
PHENIX in 2012

South Muon Magnet

Central Magnet

MPC

BBC

(F)VTX

MuTr

MuID

South

Side View

North

10.9 m = 36 ft

18.5 m = 60 ft

RPC3

ZDC South

ZDC North

MuID

MuID

Abhay Deshpande at INT/UoW, Gluons and Sea Quarks at High Energy

11/16/2010
sPHENIX: Compact detector!

Details in E. Aschenauer’s talk today

18.5 m = 60 ft
First ideas for a “eRHIC” detector

- Dipoles needed to have good forward momentum resolution
  - Solenoid no magnetic field @ r ~ 0
- DIRC, RICH hadron identification → π, K, p
- high-threshold Cerenkov → fast trigger for scattered lepton
- radiation length very critical → low lepton energies

EIC Task Force at BNL
Aschenauer, Ullrich et al

Dipol 3Tm

FED

Solenoid (4T)

ZDC

FPD

 hadron-beam

lepton-beam

Detector Location IP12

Solenoid / Dipol
Hadronic Calorimeter
EM–Calorimeter
RICH
High Threshold Cerenkov
DIRC
Tracking
Detect particles with angles down to $0.5^\circ$ before ion FFQs. Need 1-2 Tm dipole.

Detect particles with angles below $0.5^\circ$ beyond ion FFQs and in arcs.

Very-forward detector

Large dipole bend @ 20 meter from IP (to correct the 50 mr ion horizontal crossing angle) allows for very-small angle detection ($<0.3^\circ$)

Central detector

Detector & IR Design: ELIC

Solenoid yoke + Hadronic Calorimeter

Solenoid yoke + Muon Detector

RICH or DIRC/LTCC

Tracking

Solenoid yoke + Muon Detector

TOF

EM Calorimeter

Hadron Calorimeter

Muon Detector

Nadel-Turonski, Horn, Ent
In spite of very different starting points for the collider concepts:

• Both eRHIC and ELIC designs are now converging to similar luminosities:
  – Few x $10^{34}$ cm$^{-2}$ sec$^{-1}$ for high energy
  – Few x $10^{33-34}$ cm$^{-2}$ sec$^{-1}$ for low energy
  – Many ideas and cautions from one to the other side

• Both plan a staged realization

• Both designs have settled on more than one IR point

• Both machine designs incorporate the detector design into the machine lattice

• Detectors concepts include a central solenoid and forward dipole, extensive low mass tracking for low x and good particle ID
Scientific Frontiers Open to EIC

- **Nucleon Spin structure**
  - Polarized quark and gluon distributions
    - Longitudinal spin structure (Low x critical)
    - Transverse spin structure (wide $Q^2$ arm critical)
  - Correlations between partons
    - Exclusive processes --> Generalized Parton Distributions
  - Precision measurements of QCD and of EW parameters in SM

- **Un-polarized Nucleon Structure**
  - Understanding confinement with low x/low$Q^2$ measurements
  - Un-polarized quark and gluon distributions

- **Nuclear Structure, role of partons in nuclei**
  - Confinement in nuclei through comparison e-p/e-A scattering

- **Hadronization in nucleons and nuclei & effect of nuclear media**
  - How do knocked off partons evolve in to colorless hadrons

- **Partonic matter under extreme conditions**
  - For various A, inclusive & diffraction

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Abhay Deshpande at INT/UoW, Gluons and Sea Quarks at High Energy

11/16/2010
Towards Golden Measurements..... ?

Updates on many of these plots anticipated: This Workshop

\[ \frac{d g_1}{d \log(Q^2)} \propto -\Delta g(x, Q^2) \]

"Diffusion"

x \sim 0.001 \quad x < 0.1 \quad x \sim 0.3 \quad x \sim 0.8
Towards golden measurements....?
Updates on many plots: This Workshop

25-40% diffractive Events in e-A
Vs. 10% at HERA

Can nuclear Diffraction be Successfully tagged?
... and then some... with precision polarimetry and/or very high luminosity

Bjorken Sum rule:

\[ \sin^2 \theta_W \]

Comprehensive detectors

EW structure functions...

Sub-3% p, d, He polarimetry

Sub 0.5-1% electron beam polarimetry
Electron Ion Colliders in Europe...

LHeC & ENC
Physics:
Proton structure & QCD
Small x physics eP & eA
Electron-Quark systems
BSM: at 1 TeV scale
Search for new EW physics: RH-W’s, Contact Interactions

More in LHeC talks this week
ENC at FAIR

Principle focus: GPDs and TMDs

L > 4 \times 10^{32} /\text{cm}^2s
s^{1/2} > 10 \text{ GeV} \quad (3.3 \text{ GeV} e^- \leftrightarrow 15 \text{ GeV} p)
polarised e^- (80%)
\leftrightarrow
polarised p / d (80%)
(transversal + longitudinal)

More in a dedicated talk this week

Abhay Deshpande at INT/UoW, Gluons and Sea Quarks at High Energy

11/16/2010
Focus on complementarity!

- **Nucleon spin**: Polarized hadron beams essential
  - US EIC proposals: $x << 0.1$ Gluon, low $x$, high $Q^2$
  - ENC at FAIR: $x \sim 0.1$ Quark GPDs & TMDs

- **High partonic density studies**: High an energy essential
  - LHeC with eP & eA
  - US EIC with eA

- **EW & BSM Physics**: High energy or/and luminosity & polarization essential
  - LHeC with e-beam polarization
  - US EIC with e & p/n beam polarization (BSM?)

Each with its own advantages and disadvantages….
Path forward.....

For US EIC proposal.....

A significant decision making process: the DOE’s Nuclear Physics Office’s 5 year planning review

Anticipated in 2012-2013
Towards the Next Long Range Plan

• **INT2010**: This workshop! Establish the EIC Case including golden measurements

• **After INT2010**: Initiate writing of a community wide White Paper laying out the full EIC science in broad compelling strokes followed by sufficient details of “golden experiments” –establish credibility. Complete White Paper Draft in 2011. Describe science program for full-energy and full-luminosity EIC, but with clear science deliverables for the Stage 1

• **In 2011**: JLAB, BNL, EIC Collaboration, EICAC & DOE define a facility design down-select criteria and review mechanism.

• **Some time in 2012**: Down-select review, informed by latest R&D results on critical technologies and a fair bottoms-up cost estimate comparison for the designs

• **Winter 2012**: Update White Paper with realizable EIC design, cost range, performance goals, science deliverables, upgrade paths, and prepare for the **LRP 2013**
Summary

• The science of EIC is exciting:
  — *A precision study of gluon in protons & nuclei*
  — *Many other equally interesting and compelling investigations…*
  — Needs to be articulated as best as we can to the broader nuclear science community within the next two years
  — NSAC Long Range Plan: some time in 2013…

• Realization of the EIC is technically and otherwise challenging: but chances realization are good *as long as* the science case is made by the entire nuclear science community
  — Always remember: *at best one collider will be built….*

• We won’t do these things because they are easy; we know they are difficult, *but the fruit is worth striving for!*
Thanks!

The conveners of this workshop:

Boer, Diehl, Milner, Venugopalan & Vogelsang

And to all conveners: (your work is not done yet!)

Hasch, Stratmann, Yuan, Burkardt, Guzey, Sabatie, Accardi, Lamont, Marquet, Kumar, Li, Marciano

And of course:

The INT & its staff for supporting this workshop!