The Study of the Fundamental Structure of Matter with a future Electron-Ion Collider

On behalf of the EIC Collaboration

http://web.mit.edu/eicc
• Introduction

• Scientific motivation

• Accelerator
  - Concepts, R&D

• Detector
  - Concepts, R&D

• Realization
  - Plans for the near future
  - Perspective on the longer term
The Fundamental Structure of Matter

• Essentially all of the observable matter in the universe is made of protons and neutrons.

• QCD describes these building blocks in terms of pointlike quarks and gluons.

• It has been a major goal of physicists to understand the structure and properties of the nucleon.

• Recent work has brought our understanding to a new level of precision.
Baryonic mass is dominated by QCD

B. Müller, Nucl. Phys. A 750 (2005) 84

Richard Milner
MAMI and Beyond
April 1 2009
QCD is unique

- It is the only fully consistent theory that we are certain that describes the real world: in the limit $m_q \to 0$, there are no free parameters.
- All the interactions are a consequence of deep symmetry principles like gauge invariance and chiral symmetry.
- Most of the visible phenomena are emergent; quarks and gluons are not seen.
- This makes QCD the only laboratory for exploring the dynamics of a non-trivial, consistent relativistic theory.
- The `silent partners’ (gluons and sea quarks) of QCD are largely unexplored and poorly understood.
High Energy Lepton Scattering

- Interpretable within a rigorous QCD framework
- Directly probes quarks and gluons
- Virtual photon imparts energy and momentum to quark in a completely controllable way

\[ Q^2 = -q^2 = s x y \]
\[ x = \frac{Q^2}{2p \cdot q} \]
\[ y = \frac{p \cdot q}{p \cdot l} \]
\[ s = 4E_e E_P \]
\[ W = (q + p)^2 \]
QCD remarkably successful

Bjorken scaling
DGLAP evolution

HERA $F_2$

PDF's

$Q^2=10 \text{ GeV}^2$

Running coupling $\alpha_s$

Richard Milner

MAMI and Beyond

April 1 2009
Scientific frontiers

• Spin structure of nucleon
  - $g_{1}^{p}(x)$ at low $x$ dramatic QCD prediction
  - gluon and sea quark polarization
  - Bjorken sum rule QCD test
  - new (GPD, transversity) parton distributions

• Partonic understanding of nuclei
  - gluon momentum distribution in nuclei: essential to understand hot QCD in RHI collisions
  - fundamental explanation of nuclear binding
  - saturation
Why a high luminosity lepton-ion collider?

- The lepton probe provides the precision of the electroweak interaction but requires high luminosity to be effective.
- Lepton scattering on hadron targets in new regimes has consistently yielded new insights, e.g. DIS, EMC effect, Glue.
- High $E_{cm}$ ⇒ large range of $x$, $Q^2$ \[ Q_{\text{max}}^2 = E_{\text{CM}}^2 \times x \]
  - $x$ range: valence, sea quarks, glue
  - $Q^2$ range: utilize evolution equations of QCD.
- High polarization of lepton, nucleon achievable.
- Complete range of nuclear targets.
- Collider geometry allows complete reconstruction of the final state.

EIC is needed to complete the study of the fundamental structure of matter.
EIC evolution

• Substantial international interest in high luminosity (~$10^{33}$ cm$^{-2}$s$^{-1}$) polarized lepton-ion collider over more than a decade
• Workshops
  Seeheim, Germany  1997  MIT, USA  2000
  IUCF, USA  1999  BNL, USA  2002
  BNL, USA  1999  JLab, USA  2004
  Yale, USA  2000  BNL, USA  2006
• In early 2007 an EIC Collaboration was formed
  [http://web.mit.edu/eicc](http://web.mit.edu/eicc)
• Recent EICC meetings approx. every six months
  2007: MIT, Stony Brook  2008: Hampton, Berkeley
  2009: GSI, Germany joint with ENC on May 28, 29, 30
• Over the last decade, EIC has become established as the leading candidate for the next QCD machine
• EIC viewed as part of the future at both BNL and JLab.
EIC science has evolved from new insights and technical accomplishments over the last decade

- ~1996 development of Generalized Parton Distributions
- ~1999 high-power energy recovery linac technology
- ~2000 universal properties of strongly interacting glue
- ~2000 emergence of transverse-spin phenomenon
- ~2001 world’s first high energy polarized proton collider
- ~2003 tantalizing hints of saturation
- ~2006 electron cooling for high-energy beams

Still many ongoing developments: constraints on gluon polarization, 1st tests of crab cavities, development of semi-inclusive DIS framework at NLO, 2nd round of deep exclusive measurements, Lattice QCD progress, etc., etc.
“An Electron-Ion Collider (EIC) with polarized beams has been embraced by the U.S. nuclear science community as embodying the vision for reaching the next QCD frontier. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia. In support of this new direction:

We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron Ion Collider. The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton.”
Overview

The EIC will explore the most compelling issues in nuclear science and technology.

– The structure of visible matter
– The role of gluons in hadronic matter
– Fundamental symmetries of nature

This will require a new generation of accelerator and detectors.
Goal of the Electron-Ion Collider: To explore the structure of visible matter

- **What is the internal landscape of the hadron?**
  - Benchmark: Spatial, spin, flavor and gluonic structure
- **What is the nature of the nuclear force that binds protons and neutrons into nuclei?**
  - Frontier: QCD properties of nuclear force
  - Mysteries: QCD effects in nuclei
Understanding the proton spin

Where is the Spin of the proton?

- Modern data yields:
  \[ \Sigma = 0.33 \pm 0.03 \pm 0.05 \]
  (c.f. 0.14 ± 0.03 ± 0.10 originally)

- In addition, there is little or no polarized glue
  - COMPASS: \( g_1^D = 0 \) to \( x = 10^{-4} \)
  - \( A_{LL} (\pi^0 \text{ and jets}) \) at PHENIX & STAR \( \rightarrow \Delta G \sim 0 \)
  - Hermes, COMPASS and JLab: \( \Delta G / G \) small

- ALL effects, relativity and OGE and the pion cloud have the effect of swapping quark spin for valence orbital angular momentum and anti-quark orbital angular momentum (>60% of the spin of the proton)

A. Thomas: gluon contribution small

J. Negele: Quark orbital A.M. small

Richard Milner
MAMI and Beyond
April 1 2009
The Spin of the Proton

Nobel Prize, 1943: "for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton"

\[ \mu_p = 2.5 \text{ nuclear magnetons, } \pm 10\% \quad (1933) \]

Proton spins are used to image the structure and function of the human body using the technique of magnetic resonance imaging.

Nobel Prize, 2003: "for their discoveries concerning magnetic resonance imaging"

Paul C. Lauterbur

Sir Peter Mansfield

Otto Stern
Explore the structure of the nucleon

- Parton distribution functions
- Longitudinal and transverse spin distribution functions
- Generalized parton distributions
- Transverse momentum distributions

Richard Milner
MAMI and Beyond
April 1 2009
EIC will extend reach of spin-dependent inclusive measurements by several orders of magnitude.

Scaling violations directly observed!

7 GeV e on 150 GeV p
5 fb⁻¹ integrated luminosity

Richard Milner
MAMI and Beyond
April 1, 2009
Low x inclusive polarized DIS measurements constrain $\Delta g(x)$

7 GeV e on 150 GeV $p$
5 fb$^{-1}$ integrated luminosity

A. Bruell
R. Ent
Light quark structure – chiral properties

Tagged structure functions to reach $x > 0.9$

Spectator forward tagging to minimize deuteron structure – similar requirements as exclusive, DVCS, diffraction
Strange quark distributions

HERMES data

- Asymmetric strange-antistrange sea can explain NuTeV anomaly
- Data on same time scale as disconnected diagrams in lattice calculations.
- What about charm quark contributions?
Test of Charge Symmetry Violation

- Charge symmetry < 1%
- \( u \equiv u^p = d^n, \ d \equiv d^p = u^n \)

- e+ and e- beams can probe different flavor aspects of the nucleon
- Neutral and charged current cross section measurements have been carried out at HERA
- Polarized e+/e- beams can add additional capability

For the sea alone, Ma (Phys Lett B274 (1992) 111) defined a charge symmetry sum-rule:

\[
S_{cs} = \int_0^1 \frac{dx}{x} \left[ F_2^{W^+} (p(x) + F_2^{W^+} (x) - F_2^{W^+} (d(x) - F_2^{W^+} (d(x)) \right]
= \int_0^1 \frac{dx}{x} \left[ \delta \bar{u}(x) + \delta \bar{d}(x) \right]
\]
Generalized Parton Distributions

\[ Q^2 \sim \xi + x \rho \]

\( \xi \sim x_{Bj} \)

Form factors

\[ H(x, \xi, t) \quad x \neq x_{Bj} \]

PDFs

\[ H^{q,g}(x,0,0) = q(x) \]

GPD’s provide a 2D spatial image as a function of \( x \)

Richard Milner
MAMI and Beyond
April 1 2009
99% of the proton’s mass/energy is due to the self-generating gluon field
- Higgs mechanism has almost no role.

The similarity of mass between the proton and neutron arises from the fact that the gluon dynamics are the same
- Quarks contribute almost nothing.
Explore gluon-dominated matter

- What is the role of gluons and gluon self-interactions in nucleons and nuclei? NSAC-2007
  - Gluon dominance in the proton

Gluon distribution $G(x,Q^2)$
- Scaling violation in $F_2$: $dF_2/d\ln Q^2$
- $F_L \sim a_s G(x,Q^2)$
- Inelastic vector meson production (e.g. $J/\psi$)
- Diffractive vector meson production \( \sim [G(x,Q^2)]^2 \)
- ...

EIC: most precise measure of gluon densities

Richard Milner  
MAMI and Beyond  
April 1 2009
Recent progress – direct $F_L$ measurements from HERA

\[
\frac{d^2\sigma^{ep\to eX}}{dx dq^2} = \frac{4\pi\alpha^2}{x q^4} \left[ \left( 1 - y + \frac{y^2}{2} \right) F_2(x, q^2) - \frac{y^2}{2} F_L(x, q^2) \right]
\]

EIC – an $F_L$ factory

Richard Milner

MAMI and Beyond

April 1 2009
Gluon Contribution to the Proton Spin

Projected data on $D_{g/g}$ with an EIC, via $g + p \rightarrow D^0 + X$.

Advantage: measurements directly at fixed $Q^2 \sim 10$ GeV$^2$ scale!
Using Nuclei to Increase the Gluon Density

- Parton density at low $x$ rises as
- Unitarity $\Rightarrow$ saturation at some
- In a nucleus, there is a large enhancement of the parton densities / unit area compared to a nucleon

$$\frac{G_A}{G_N} \approx A^{1/3}$$

$$x_{ep} \left( Q_s^2 \right) = \frac{X_{eA} \left( Q_s^2 \right)}{\left( \frac{4}{3} A^{1/3} \right)^{1/\delta}}$$

Example:

- $Q^2 = 4 \text{ (GeV/c)}^2$
- $\delta < 0.3$
- $A = 200$
- $X_{ep} = 10^{-6}$ for $X_{eA} = 10^{-3}$

$eA$ at eRHIC $\approx$ same parton density as ep at LHC energies!
Explore gluon-dominated matter

- What is the role of gluons and gluon self-interactions in nucleons and nuclei? NSAC-2007
  - The nucleus as a “gluon amplifier”

At high gluon density, gluon recombination should compete with gluon splitting ⇒ density saturation.

Color glass condensate

- Oomph factor stands up under scrutiny.
- Nuclei greatly extend x reach:
  \[ x_{\text{EIC}} = x_{\text{HERA}}/18 \] for 10+100 GeV, Au
Explore the low energy precision frontier

“The task of the physicist is to see through the appearances down to the underlying, very simple, symmetric reality.”

- S. Weinberg

What are the unseen forces present at the dawn of the Universe but have disappeared from view as the universe evolved? **precision electroweak experiments:** \(\sin^2(q_W)\), ...

Questions for the Universe, Quantum Universe, HEPAP, 2004; NSAC Long Range Plan, 2007

R. Holt
- 5 GeV polarized e on 50 GeV unpolarized deuteron
- \(\sim 500 \text{ fb}^{-1}\) integrated luminosity
- full simulation required

Richard Milner  
MAMI and Beyond  
April 1 2009
Lattice QCD

J. Negele

Outlook

- Dramatic increase in computer resources for Lattice QCD
  - Teraflops → Petaflops → Exaflops
- Innovation in algorithms
- Chiral fermions down to physical pion mass
- Disconnected diagrams
  - Calculate proton and neutron separately, not just difference
  - Strangeness content of nucleon
- Gluon observables
  - Contribution to mass, momentum, spin

Synergy between Lattice and Experiment

- Use solution of QCD as a quantitative tool in concert with experiment
- Example: GPD’s
  - Experiment: Integrals over GPD’s
  - Lattice: Moments of GPD’s
- Together, obtain much stronger constraints on GPD’s than from either alone
EIC accelerator concepts

eRHIC

Peak lumi ~ $2.6 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$

ELIC

Peak lumi ~ $6 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$

“We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron-Ion Collider.”

NSAC LRP 2007

Richard Milner

MAMI and Beyond

April 1 2009
EIC accelerator R&D is underway

• Electron beam R&D for ERL-based design:
  – High intensity polarized electron source
    • Development of large cathode guns with existing current densities \( \sim 50 \text{ mA/cm}^2 \) with good cathode lifetime.
  – Energy recovery technology for high power beams
    • Multicavity cryomodule development; BNL test ERL; loss protection; instabilities.
  – Development of compact recirculation loop magnets
    • Design, build and test a prototype of a small gap magnet and its vacuum chamber.
  – Evaluation of electron-ion beam-beam effects, including the kink instability and e-beam disruption

• Ion beam R&D:
  – Polarized \(^3\text{He} \) production (EBIS) and acceleration
  – Increasing number of bunches, number of ions/bunch in RHIC

• Cooling:
  – Cooling of ion beam
High intensity polarized electron source R&D

Electrons follow electrical field lines, but ions have different trajectory. Usually, they tend to damage central area of the cathode.

E. Tsentalovich
MIT-Bates

JLAB data

Ring-like cathodes?

Cathode
Damage groove

Laser spot

Richard Milner
MAMI and Beyond
April 1 2009
### Lifetime

- Axicon, anode grounded, $t \approx 120h$
- Axicon, anode at 1 kV, $t \approx 230h$
- Large spot X1.4, $t \approx 60h$
- Small spot (center) X17, $t \approx 50h$

![Graph showing QE vs Time for different conditions](chart.png)

QE, %

Time, hours

---

Richard Milner

MAMI and Beyond

April 1 2009
Cathode Cooling

- HV
- Water in
- Water out
- Manipulator
- Crystal
- Cathode
- Laser
ERL Test Facility

- test of high current (~ 0.5 A)
  high brightness ERL operation
- 5-cell cavity SRF ERL
- test of high current beam stability issues
- highly flexible lattice
- 704 MHz SRF gun test

Start of commissioning in 2009.

5 cell SRF cavity arrived in BNL in March 2008.
Recirculation passes

- Separate recirculation loops
- Small aperture magnets
- Low current, low power consumption
- Minimized cost

Approved LDRD for the compact magnet development

Richard Milner
MAMI and Beyond
April 1 2009
EIC central detector: emerging concept

• 2 “main” components
  • electron detection in forward direction (theta<40°)
  • final state detection and hadron identification in proton direction (theta > 140° ?)
• some low resolution energy measurement for central angles
• vertex detection (resolution better than 100 μm)
• plus:
  • electron detection at very low angles (how?)
  • detection of “recoiling” neutron and proton (maximum acceptance)
• plus:
  • luminosity measurement with accuracy of ~ 1%
  • polarization measurements with accuracy of ~ 1% (both electron and ion !)
Open issues/questions

• What is the optimal magnetic field configurations for such a detector?
  - simple solenoid most likely NOT sufficient
  - solenoid plus toroid or solenoid plus dipole?
• What angular/momentum resolution do we need for the electron?
• What angular resolution do we need in the hadron detection?
• Study of jet physics
• e-A Monte-Carlo development
• Calculation of backgrounds from beam gas events
Emerging detector concept

8 meters (for scale)

TOF

Offset IP

140 degrees

PbWO₄
ECAL

π/K/ρ?

Tracking

HCAL

RICH

dipole

Solenoid

Needed?

Issues:
1) would need to change (E)TOF with HTCC if 500 MHz operation
2) need add’l Particle Id. (RICH/DIRC) for large angle π/K/ρ?
3) conflict with charm measurements that require low central field?

Richard Milner
MAMI and Beyond

April 1, 2009
A Detector for Forward Physics at eRHIC

Feasibility Study

I. Abt, A. Caldwell, X. Liu, J. Sutiak

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

July 20, 2004

Figure 5: Conceptual layout of the detector with a 7m long dipole field and an interaction region without machine elements extending from -3.8 m to +5.2 m
Interaction Region Design

Present IR design features:
- No crossing angle at the IP
- Detector integrated dipole: dipole field superimposed on detector solenoid.
- No parasitic collisions.
- Round beam collision geometry with matched sizes of electron and ion beams.
- Synchrotron radiation emitted by electrons does not hit surfaces in the detector region.
- Blue ion ring and electron ring magnets are warm.
- First quadrupoles (electron beam) are at 3m from the IP
- Yellow ion ring makes 3m vertical excursion.

HERA type half quadrupole used for proton beam focusing

Richard Milner
MAMI and Beyond
April 1 2009
Staging of EIC

- Can one consider an initial stage of EIC where
  - cost is a fraction of that of full EIC
  - it can be realized on a significantly faster timescale than the full EIC?
- It must have a strong science case, i.e. it must open up a dramatic new capability.
- It should naturally evolve to the full EIC.
- Considerations include
  - luminosity $\sim 3 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
  - center of mass energy $\sim 4 \text{ GeV} \ e^{\pm}$ on 250 GeV RHIC
  - polarized nucleon and nuclear beams
- Fortuitously, the ISABELLE tunnel has a region of large diameter near IP2
  - 2 to 4 GeV ERL in tunnel
  - eRHIC detector in IP2
- Staging scenario for ELIC as defined above hard for me to see but if there is one, it should be pursued.
MEeIC @ IP2: up to 2 GeV with RT magnets
up to 4 GeV with SC magnets

2 x (0.5-0.7) GeV SRF linacs

100 MeV injector

2-4 passes, depending on top energy

Richard Milner
MAMI and Beyond
April 1 2009
## MEeIC parameters for e-p collisions (2 GeV option)

<table>
<thead>
<tr>
<th></th>
<th>not cooled</th>
<th>pre-cooled</th>
<th>high energy cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>p</td>
<td>e</td>
<td>p</td>
</tr>
<tr>
<td>Energy, GeV</td>
<td>250</td>
<td>2</td>
<td>250</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>111</td>
<td></td>
<td>111</td>
</tr>
<tr>
<td>Bunch intensity, 10^{11}</td>
<td>2.0</td>
<td>0.31</td>
<td>2.0</td>
</tr>
<tr>
<td>Bunch charge, nC</td>
<td>32</td>
<td>5</td>
<td>32</td>
</tr>
<tr>
<td>Normalized emittance, 1e-6 m, 95% for p / rms for e</td>
<td>15</td>
<td>37</td>
<td>6</td>
</tr>
<tr>
<td>rms emittance, nm</td>
<td>9.4</td>
<td></td>
<td>3.8</td>
</tr>
<tr>
<td>beta*, cm</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>rms bunch length, cm</td>
<td>40</td>
<td>1</td>
<td>40</td>
</tr>
<tr>
<td>beam-beam for p /disruption for e</td>
<td>1.5e-3</td>
<td>12</td>
<td>3.8e-3</td>
</tr>
<tr>
<td>Peak Luminosity, 1e32, cm^{-2}s^{-1}</td>
<td>0.93</td>
<td>2.3</td>
<td>9.3</td>
</tr>
</tbody>
</table>
Institute for Nuclear Theory Programs

Physics at a High Energy Electron Ion Collider

October 19-23, 2009

Daniel Boer
Markus Diehl
Raju Venugopalan
Werner Vogelsang

Gluons and the quark sea at high energies: distributions, polarizations, tomography

Three months in fall 2010

Daniel Boer
Markus Diehl
Richard Milner
Raju Venugopalan
Werner Vogelsang
Electron Ion Collider Collaboration

Steering Committee
• Abhay Deshpande, Stony Brook, RBRC (Co-Chair/Contact person)
• Rolf Ent, Jlab
• Charles Hyde, ODU/UBP, France
• Peter Jacobs, LBL
• Richard Milner, MIT (Co-Chair/Contact person)
• Thomas Ulrich, BNL
• Raju Venugopalan, BNL
• Antje Bruell, Jlab
• Werner Vogelsang, BNL

International Advisory Committee
• Jochen Bartels (DESY)
• Allen Caldwell (MPI, Munich)
• Albert De Roeck (CERN)
• Walter Henning (ANL)
• Dave Hertzog (UIUC)
• Xiangdong Ji (U. Maryland)
• Robert Klanner (U. Hamburg)
• Katsunobu Oide (KEK)
• Naohito Saito (KEK)
• Uli Wienands (SLAC)

Working Groups and Convenors
• ep Physics
  • Antje Bruell, JLAB
  • Ernst Sichterman, LBL
  • Werner Vogelsang, BNL
  • Christian Weiss, JLAB
• eA Physics
  • Vadim Guzey, JLAB
  • Dave Morrison, BNL
  • Thomas Ulrich, BNL
  • Raju Venugopalan, BNL
• Detector
  • Elke Aschenauer, JLAB
  • Edward Kinney, Colorado
  • Bernd Surrow, MIT
• Electron Beam Polarimetry
  • Wolfgang Lorenzon, Michigan
• As proposed by EICC, work out a clear and well-defined matrix of science goals vs. accelerator performance parameters (and cost).
• Distill and appropriately formulate from the range of research opportunities that the EIC provides a short list of the most compelling science objectives (and possibly “golden experiments”) that can convince, and generate support from, the broader science community as represented by NSAC
• Further develop the schedule including approximate resource-loading, to provide a timeline for major decisions (including, if at all possible, site decision), technical developments, and (staged) realization
• In particular, strive for a timeline (under reasonable assumptions) that provides for data taking before 2020
• An obvious important near-term activity is to work out a detailed and comprehensive R&D plan. The proposed common effort between BNL and JLab should focus, to a substantial extent, on R&D for technologies needed for both facility concepts
• It would be desirable for the EICAC to see a detailed common plan at the next meeting with deliverables & resources needed to reach a buildable design for the LRP.
Summary

• The Electron-Ion Collider is the next generation accelerator concept for the study of QCD in the U.S.
• In Europe, LHeC as a future evolution for CERN and ENC@FAIR are under discussion.
• It is essential to lay the foundations for the next Long Range Plan Exercise in ~ 2013.
  - It will be necessary to broaden and deepen the science case.
  - Strong, international support is required.
  - It is highly desirable to have a single EIC accelerator design by ~ 2012.
• Study of the staged eRHIC scenario is getting underway.
• R&D on the accelerator and detector must have a high priority.
• While the path to the full EIC is uncertain, considerable progress has been made by a determined group of highly motivated people.
• We look forward to the joint ENC/EIC meeting at GSI, Germany on May 28, 29, 30.