What is possible at the (M)EIC?

Pawel Nadel-Turonski

Jefferson Lab
Outline

The Electron-Ion Collider

Some physics highlights

Accelerator and detectors
Requirements for a generic EIC

The EIC project is pursued by BNL and JLab

- Polarized electron, nucleon, and light ion beams
  - Electron and nucleon polarization > 70%
  - Transverse polarization at least for nucleons

- Ions from hydrogen to $A > 200$

- Luminosity reaching $10^{34} \text{ cm}^{-2}\text{s}^{-1}$

- Stage I energy: $\sqrt{s} = 20 – 70 \text{ GeV}$ (variable)

- Stage II energy: $\sqrt{s}$ up to about 150 GeV
EIC staging

Already the first stage of an EIC gives access to sea quarks and gluons.

Need polarization and good acceptance to detect spectators & fragments.

An EIC aims to study the sea quark and gluon-dominated matter.
EIC staging at BNL and JLab

**Stage I**

- $\sqrt{s} = 34 – 71$ GeV
- $E_e = 3 – 5$ GeV (?)
- $E_p = 100 – 255$ GeV
- $E_{Pb} = $ up to 100 GeV/A

**Stage II**

- $\sqrt{s} = $ up to ~180 GeV
- $E_e = up to ~30$ GeV (?)
- $E_p = $ up to 275 GeV
- $E_{Pb} = $ up to 110 GeV/A

**MEIC / EIC @ JLab**

- $\sqrt{s} = 13 – 70$ GeV
- $E_e = 3 – 12$ GeV
- $E_p = 15 – 100$ GeV
- $E_{Pb} = $ up to 40 GeV/A

- $\sqrt{s} = $ up to ~140 GeV
- $E_e = $ up to 20 GeV
- $E_p = $ up to at least 250 GeV
- $E_{Pb} = $ up to at least 100 GeV/A
Physics highlights from the EIC program

- 3D structure of nucleons and nuclei is not trivial
  
  How do gluons and quarks bind into 3D hadrons?

- Gluon dynamics plays a large role in proton spin
  
  Why do quarks contribute so little (~30%) to proton spin?

- Gluons in nuclei (light and heavy)
  
  *EIC stage I measurement*
  
  Does the gluon density saturate at small $x$?
  
  *EIC stage II measurement?*
  
  Saturation-scale dependence on centrality of collision (from fragment detection)?
Imaging in coordinate and momentum space

GPDs

2+1 D picture in **impact-parameter space**

- Accessed through *exclusive* processes
- Ji sum rule for nucleon spin

TMDs

2+1 D picture in **momentum space**

- Accessed through *Semi-Inclusive* DIS
- OAM through spin-orbit correlations?

QCDSF/UKQCD Coll., 2006

Anselmino et al., 2009
Imaging in coordinate and momentum space

**GPDs**

2+1 D picture in **impact-parameter space**

![Distribution of gluons](image1.png)

Transverse gluon distribution from J/ψ production

**TMDs**

2+1 D picture in **momentum space**

![Up quark Sivers function](image2.png)

Projections from EIC white paper
The spin of the proton

The number $\frac{1}{2}$ reflects both intrinsic parton properties and their interactions

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma (\mu) + L_q(\mu) + \Delta G(\mu) + L_g(\mu)$$

polarization orbit polarization orbit

quarks gluons

Two complementary approaches to resolve proton spin puzzle

Measure $\Delta G$ - gluon polarization
Measure TMD and GPDs - orbital motion
GPDs and angular momentum

• DVCS on a *transversely* polarized target is sensitive to the *GPD E*
  – *GPD H* can be measured through the beam spin asymmetry
  – Opportunity to study spin-orbit correlations (Ji sum rule)

\[
J^q = \frac{1}{2} \int_{-1}^{+1} dx \left[ H^q(x, \xi, t) + E^q(x, \xi, t) \right]
\]
Longitudinal spin – $\Delta G$ (gluon polarization)

- EIC stage I will greatly improve our understanding of $\Delta G$
  - Stage II will further reduce the uncertainty

Green: RHIC spin, COMPASS, etc
Red: EIC Stage I (MEIC or eRHIC)
Yellow: EIC Stage II

M. Stratmann
Quark propagation in matter (hadronization)

**Accardi, Dupre**

- Broadening of $p_T$ distribution
- Heavy flavors: B, D mesons, J/$\Psi$
- Hadron jets at $s > 1000$ GeV$^2$
- **Impact parameter dependence?**
  - Fragments and “wounded nucleons” can help understanding the path length
Detection requirements for forward processes

Recoils in deep-exclusive (diffractive) processes

- Large $t (p_T)$ range desirable for recoil baryons
- Coherent nuclear processes
  - Recoiling heavy ions are difficult to detect
  - Good acceptance at small $p_T$ extends the mass range

Partonic fragmentation in SIDIS

- Also decays of strange and charmed baryons

Nuclear spectators and fragments

- Measure complete final state (all fragments) in heavy-ion reactions
  - Centrality of collision (shadowing, saturation, hadronization, etc)
- Spectator tagging with polarized light ions
  - $p_T$ resolution < Fermi momentum
  - LDRD proposal approved at JLab in FY13
Opportunities with polarized light ions

**Experiment**: requires excellent forward detection and spectator tagging

**Theory**: combines high-momentum-transfer processes and low-energy nuclear structure

**Partonic structure of the neutron (including spin)**

- Spin/flavor decomposition of parton densities

**The bound nucleon in QCD**

- Modifications of nucleon's quark/gluon structure due to nuclear binding
  - Off-shellness controlled by kinematics

**Collective quark/gluon fields**

- Coherent scattering probes the quark/gluon field of the entire nucleus
- Tensor-polarized structure function of deuterium identifies the QCD double-scattering contribution - insight into onset of gluon saturation

➔ *Talk by C. Hyde tomorrow!*
The EIC at Jefferson Lab

- 12 GeV CEBAF is a full-energy e-injector
  - Continuous injection as at SLAC (~50 nA)
  - Parallel running with fixed target possible

- Both the MEIC and CEBAF have a 1.4 km circumference

- MEIC can store 20-100 GeV protons, or heavy ions up to 40 GeV/A.

- The stage II EIC will increase the energy to 250 GeV for protons and 20 GeV for electrons.

- Two detectors
  - IP2 could host sPHENIX
MEIC – specific design goals

Spin control for all light ions
- Figure-8 layout
- Vector- and tensor polarized deuterium

Full-acceptance detector
- Ring designed around detector requirements
- Detection of all fragments – nuclear and partonic

Minimized technical risk

Stable concept – detailed design report released August 2012
# MEIC accelerator parameters

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<th>50 x 5 GeV²</th>
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<td>Horizontal emittance, normalized</td>
<td>µm rad</td>
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<td>3.5 (upstream)</td>
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<td>Luminosity per IP*</td>
<td>cm⁻²s⁻¹</td>
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<td>2.4 x 10³³</td>
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<td>8.3 x 10³³</td>
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* Includes space-charge effects and assumes conventional electron cooling

Red indicates parameters specific to the full-acceptance detector
Conventional electron cooling using a 55 MeV ERL

- Conventional electron cooling using an accelerating high-voltage is a well-established technique (e.g. at Fermilab)
- A single-pass Energy-Recovery Linac (ERL) allows reaching higher electron energies and currents
- A recirculator ring is not needed for the ready-to-build MEIC cooling scheme, but would reduce source current requirements
- Recirculator tests are planned at the JLab Free-Electron Laser (FEL) ERL
MEIC – ion polarization in figure-8 ring

- Science program demands highly polarized (>70%) light ions (p, D, \(^3\)He, Li, ...)
- Figure-8 shape used for all ion booster and collider rings
  - Spin precession in one arc is canceled by the other arc
  - No preferred periodic spin direction
  - Energy-independent spin tune
  - Simplified polarization control and preservation for all ion species
  - Needs only small magnetic fields (instead of Siberian Snakes) to control polarization at Ips
  - The electron ring has a figure-8 shape because it shares a tunnel with the ion ring

- Figure-8 ring is the only practical way to accelerate polarized deuterons
The MEIC detector locations (in CAD)

- Detector locations minimize synchrotron- and hadronic backgrounds
  - *Close* to arc where ions exit
  - *Far* from arc where electrons exit

The background is an artist's impression

- The MEIC magnetic lattice design is complete
The MEIC full-acceptance detector concept

Forward hadron detection in three stages:

1. Endcap with 50 mrad crossing angle
2. Small dipole covering angles up to a few degrees
3. Far-forward, up to one degree, for particles passing the accelerator quads

(from GEANT4)
Central detector options

- **Goal:** two sufficiently different, complementary central detectors
  - No need to for beam sharing at a ring-ring collider!

- **IP1 (shown above):** new 3T dual solenoid and large tracker
  - Si-pixel disks and micropattern gas detector (GEM/micromega) forward trackers
  - Low-mass cluster-counting He-filled DC, and/or micropattern central tracker

- **IP2** can be instrumented using an old magnet (CLEO or BaBar)
  - Focus on hadronic calorimetry + small TPC central tracker
The MEIC IP2 could host an upgraded PHENIX

- The planned PHENIX detector upgrade is based on the BaBar solenoid
  - Staged implementation denoted by various prefixes (s/fs/e)
  - Relatively small and can easily be moved

- Main physics focus of sPHENIX is jet physics using hadronic calorimeter

- MEIC IP2 is designed to be compatible with the new PHENIX
  - Good starting point for bringing the communities together
The MEIC full-acceptance detector concept

Forward hadron detection in three stages:
1. Endcap with 50 mrad crossing angle
2. Small dipole covering angles up to a few degrees
3. Far-forward, up to one degree, for particles passing the accelerator quads

(from GEANT4)
The low-$Q^2$ tagger – small angle electron detection

Tagger detectors and polarimetry

Electron beam aligned with solenoid axis

Ion scattering and polarimetry

low-$Q^2$ tagger

(final focusing elements)
Hadron detection between endcap and ion quads

7 m from IP to first ion quad

**Ion quadrupoles:** gradient, peak field, length

- 36 T/m, 7.0 T, 1.2 m
- 89 T/m, 9.0 T, 1.2 m
- 51 T/m, 9.0 T, 2.4 m

**Permanent magnets**

- 2 x 15 T/m
- 34 T/m
- 46 T/m
- 38 T/m

**Electron quadrupoles**

- 2 T dipole
- 5 T, 4 m dipole

**Endcap detectors**

- 1 m
- 1 m

**Crossing angle**

- Large crossing angle (50 mrad)
  - Moves spot of poor resolution along solenoid axis into the periphery
  - Minimizes shadow from electron FFQs

- Dipole before quadrupoles further improves resolution in the few-degree range

- Low-gradient quadrupoles allow large apertures for detection of all ion fragments
  - Peak field = quad gradient x aperture radius
Detection after the ion quads

- S-shaped transport optimizes acceptance for both neutrals and charged particles.
- Lots of space for Zero-Degree Calorimeter (ZDC) on the outside of the ring
  - EMcal and Hcal (~30%/√E)
- Quad acceptance depends on peak field, but in 1-2° range.

Red: Detection before ion quadrupoles
Blue: Detection after ion quadrupoles
Far-forward charged hadron detection – requirements

1. **Good acceptance for ion fragments** (rigidity different from beam)
   - Large downstream magnet apertures
   - Small downstream magnet gradients (realistic peak fields)
   - Roman pots not needed

2. **Good acceptance for low-\(p_T\) recoil baryons** (rigidity similar to beam)
   - Small beam size at second focus (to get close to the beam)
   - Large dispersion (to separate scattered particles from the beam)
   - Roman pots important

3. **Good momentum- and angular resolution**
   - Large dispersion (but with \(D = D' = 0\) at IP)
   - Long, instrumented, magnet-free drift space

4. **Sufficient separation between beam lines** (~1 m)
Asymmetric ion optics

- $\beta^* x/y$ asymmetry allows a high luminosity with relatively small $\beta_{\text{max}}$

- $7 \text{ m}$ from IP to first downstream ion quad

- Only dispersion component (D) generated after the IP aids detection. Any dispersion slope ($D'$) at IP adds to the beam angular spread ($D' \cdot \Delta p/p$)

- Beam angular spread is also proportional to $\sqrt{\varepsilon/\beta^*} \rightarrow$ good ion beam cooling essential
Far-forward detection of charged fragments

(protons rich fragments) \[ \Delta p/p = -0.5 \]
(spectator protons from deuterium)

(exclusive / diffractive recoil protons)

(neutron rich fragments) \[ \Delta p/p = 0.5 \]
(tritons from N=Z nuclei)

- For light ions focus the mass/charge ratio of fragments is usually very different from the beam
- For heavy ions one needs both good acceptance and momentum resolution
Fragment acceptance vs quadrupole peak field

Red: Detection before ion quadrupoles
Blue: Detection after ion quadrupoles

- Q3P can be weaker
  - “9 T” is actually 9, 9, and 7 Tesla
- The angle is the original scattering angle at the IP
Far-forward hadron detection summary

- **Neutrals** detected in a 25 mrad (total) cone *down to zero degrees*
  - Space for large (> 1 m diameter) Hcal + EMcal

- Excellent acceptance for *all ion fragments*

- **Recoil baryon** acceptance:
  - up to 99.5% of beam energy for *all angles*
  - down to at least 2-3 mrad for *all momenta*
  - full acceptance for $x > 0.005$

- Resolution limited only by beam
  - Longitudinal ($dp/p$): $3 \times 10^{-4}$
  - Angular ($\theta$, for all $\phi$): $0.2 \text{ mrad}$

- 15 MeV/c resolution for a 50 GeV/A tagged deuteron beam
Summary

The EIC is the next-generation US QCD facility

- JLab or BNL implementations possible
  - Agreement on global parameters
  - Collaboration on detector R&D

The EIC at JLab offers some unique capabilities

- Vector- and tensor polarized deuterium
- Excellent detection of recoil baryons, spectators, and target fragments
  - Full acceptance, high resolution

Complementarity with the LHC/LHeC

- The MEIC will cover all kinematics between JLab 12 GeV and the LHeC
Backup
# EIC timeline

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Assumes endorsement for an EIC at the next NSAC Long Range Plan
Assumes relevant accelerator R&D for down-select process done around 2016
Generic detector R&D for an EIC – example

• R&D program not site specific
  – Coordinated by Tom Ludlam (BNL)

• As part of the program, a new, permanent EIC facility for sensor tests in high magnetic fields is being set up at Jefferson Lab
  – Two 5T magnets provided by JLab

• Tests will include MCP-PMTs with small pore size (2-6 µm), SiPMs and LAPPDs

Non-magnetic dark box with pulsed LED for the DVCS solenoid – note the GlueX SiPM (Hamamatsu S11064-050P(X))

CLAS FROST solenoid with 5 inch bore

CLAS DVCS solenoid with 9 inch bore

Floor space in the new test lab at JLab – DVCS solenoid shown.
Electron polarization – continuous injection

- Polarization at $t + \Delta t$
  \[ P_{t+\Delta t} = (1 - \frac{\Delta N}{N})(P_t + \frac{\Delta P_t}{\Delta t} \Delta t) + \frac{\Delta N}{N} P_0 \]

- Equilibrium Polarization
  \[ P_{equ} = P_0 \left(1 + \frac{T_{rev} I_{ring}}{\tau_d k I_{inj}}\right)^{-1} \]

- Note that:
  - Polarization lifetime at 5 GeV is 1 or 3 hours depending on helicity (Sokolov-Ternov)
  - 50-100 nA beam injected from CEBAF can maintain polarization close to its initial value of 80% indefinitely for any electron beam energy.
Deuteron polarization in figure-8 ring

- Beam injected longitudinally polarized, accelerated and then desired spin orientation adjusted

\[ (B\|L)_{1,2} \]

\[ \left(\frac{B\|L}{L}\right)_{1,2} \]

\[ \text{longitudinal polarization} \]

\[ \text{radial polarization} \]

\[ \varphi_{z1} = \pi \nu \frac{\sin(\varphi_y - \Psi)}{\sin \varphi_y} \]

\[ \varphi_{z2} = \pi \nu \frac{\sin \Psi}{\sin \varphi_y} \]

\[ \varphi_{zi} = (1 + G) \frac{(B\|L)_i}{B\rho} \]

\( \varphi_{z1}, \varphi_{z2} \) are the spin rotation angles in the solenoids

\( \varphi_y = \gamma \gamma \alpha \) is the spin rotation angle between the solenoids

\( \alpha \) is the orbit rotation angle between the solenoids

\( \Psi \) is the angle between the polarization and velocity directions

\[ (B\|L)_{1,2} \text{ (T\cdot m) vs. } p \text{ (GeV/c)} \]

longitudinal polarization

\[ \nu_0 = 0.001, \varphi_{orb} = 13.2^\circ, \Psi = 0^\circ \]

radial polarization

\[ \nu_0 = 0.001, \varphi_{orb} = 13.2^\circ, \Psi = 90^\circ \]
Proton polarization in figure-8 ring

Last two arc dipoles

$$(B_{\perp}L)_i \ (T \cdot m) \ vs. \ p \ (GeV/c)$$

longitudinal polarization

$\nu_p=0.01, \ \varphi_{orb}=0.82^\circ, \ \Psi=90^\circ$

radial polarization

$\nu_p=0.01, \ \varphi_{orb}=0.82^\circ, \ \Psi=0^\circ$