Design Status of Medium-energy Electron-Ion Collider at JLab

Vasiliy Morozov
for
Jefferson Lab EIC Study Group
Outline

• Introduction
• MEIC conceptual design
  • High luminosity concept
  • Polarized beam design
• Detector integration and performance
• Electron cooler
• Outlook
EIC as JLab’s Future

- JLab’s fixed target program after 12 GeV CEBAF upgrade will be world-leading for at least a decade.
- A Medium-energy Electron-Ion Collider (MEIC) at JLab will open new frontiers in nuclear science.
- The timing of MEIC construction can be tailored to match available DOE-NP funding while the 12 GeV physics program continues.
- MEIC parameters are chosen to optimize science, technology development, and project cost. We maintain a well defined path for future upgrade to higher energies and luminosity.
- A conceptual machine design has been completed, providing a base for performance evaluation, cost estimation, and technical risk assessment.
MEIC Design Parameters

- **Energy** *(bridging the gap of 12 GeV CEBAF & HERA/LHeC)*
  - Full coverage of $s$ from a few 100 to a few 1000 GeV$^2$
  - Electrons 3-11 GeV, protons 20-100 GeV, ions 12-40 GeV/u

- **Ion species**
  - Polarized light ions: p, d, $^3$He, and possibly Li
  - Un-polarized light to heavy ions up to A above 200 (Au, Pb)

- **Up to 3 detectors**
  - One optimized for full acceptance, another for high luminosity

- **Luminosity**
  - Greater than $10^{34}$ cm$^{-2}$s$^{-1}$ per interaction point
  - Maximum luminosity should optimally be around $\sqrt{s}=45$ GeV

- **Polarization**
  - At IP: longitudinal for both beams, transverse for ions only
  - All polarizations >70% desirable

- **Upgradeable to higher energies and luminosity**
  - 20 GeV electron, 250 GeV proton, and 100 GeV/u ion
MEIC Layout

- Warm large booster (up to 20 GeV)
- Cold ion collider ring (up to 100 GeV)
- Transfer beam line
- Medium energy IPs
- 12 GeV CEBAF
- Electron collider ring (3 to 11 GeV)

Three compact figure-8 rings stacked vertically
Stacked Figure-8 Rings

Interaction point locations:
• Downstream ends of the electron straight sections to reduce synchrotron radiation background
• Upstream ends of the ion straight sections to reduce residual gas scattering background

• Vertical stacking for identical ring circumferences
• Horizontal crab crossing at IPs due to flat colliding beams
• Ion beams execute vertical excursion to the plane of the electron orbit for enabling a horizontal crossing

• Ring circumference: 1340 m
• Maximum ring separation: 4 m
• Figure-8 crossing angle: 60 deg.
Design Features: High Luminosity

- Based on the following concepts
  - Very short bunch length
  - Small transverse emittance
  - Very high bunch repetition rate
  - Very small bunch charge
  - Very small $\beta^*$
  - Crab crossing

- A proved concept: KEK-B @ $2 \times 10^{34}$ /cm$^2$/s

- JLab will replicate the same success in colliders w/ hadron beams
  - The electron beam from CEBAF possesses a high bunch repetition rate
  - Ion beams from a new ion complex can match the electron beam

<table>
<thead>
<tr>
<th></th>
<th>KEK-B</th>
<th>MEIC</th>
<th>eRHIC</th>
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<tr>
<td>Repetition rate</td>
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<td>1.2 / 1.8</td>
<td>0.5 / 3</td>
<td>0.42 / 0.05</td>
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<tr>
<td>Bunch length</td>
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<td>Horizontal &amp; vertical $\beta^*$</td>
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Parameters for **Full Acceptance** Interaction Point

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<th>Proton</th>
<th>Electron</th>
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<tr>
<td><strong>Beam energy</strong></td>
<td>GeV</td>
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<td><strong>Collision frequency</strong></td>
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<td><strong>Particles per bunch</strong></td>
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<td><strong>Beam Current</strong></td>
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<tr>
<td><strong>Polarization</strong></td>
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<tr>
<td><strong>Energy spread</strong></td>
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<td><strong>RMS bunch length</strong></td>
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<tr>
<td><strong>Horizontal emittance, normalized</strong></td>
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<tr>
<td><strong>Vertical emittance, normalized</strong></td>
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<td><strong>Horizontal β</strong></td>
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<td><strong>Vertical β</strong></td>
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<td><strong>Vertical beam-beam tune shift</strong></td>
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<td><strong>Laslett tune shift</strong></td>
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<td><strong>Distance from IP to 1st FF quad</strong></td>
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<td><strong>Luminosity per IP, $10^{33}$</strong></td>
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### Parameters for High Luminosity Interaction Point

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<th>Electron</th>
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<td>Particles per bunch</td>
<td>$10^{10}$</td>
<td>0.416</td>
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<tr>
<td>Beam Current</td>
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<tr>
<td>RMS bunch length</td>
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<td>7.5</td>
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<tr>
<td>Horizontal emittance, normalized</td>
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<tr>
<td>Vertical emittance, normalized</td>
<td>µm rad</td>
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<td>11</td>
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<tr>
<td>Horizontal $\beta^*$</td>
<td>cm</td>
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<tr>
<td>Vertical $\beta^*$</td>
<td>cm</td>
<td>0.8</td>
<td>0.8</td>
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<tr>
<td>Vertical beam-beam tune shift</td>
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<td>0.014</td>
<td>0.03</td>
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<tr>
<td>Laslett tune shift</td>
<td></td>
<td>0.06</td>
<td>Very small</td>
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<tr>
<td>Distance from IP to 1$^{\text{st}}$ FF quad</td>
<td>m</td>
<td>4.5</td>
<td>3.5</td>
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<td>Luminosity per IP, $10^{33}$</td>
<td>cm$^{-2}$s$^{-1}$</td>
<td>14.2</td>
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Design Features: High Polarization

- All ion rings (two booster, collider) have a figure-8 shape
  - Spin precessions in the left & right parts of the ring are exactly cancelled
  - Net spin precession (spin tune) is zero, thus energy independent

- Ensures spin preservation and ease of spin manipulation
- Avoids energy-dependent spin sensitivity for ion all species
- The only practical way to accommodate polarized deuterons

This design feature promises a high polarization for all light ion beams

(The electron ring has a similar shape since it shares a tunnel with the ion collider ring)

- Use Siberian Snakes/solenoids to arrange polarization at IPs

Proton or Helium-3: longitudinal polarization at both IPs
Proton or Helium-3: transverse polarization at both IPs
Deuteron: Longitudinal polarization at one IP
Deuteron: transverse polarization at both IPs
MEIC Primary Full-Acceptance Detector

- Large 50 mrad crossing angle: no parasitic collisions, improved detection, fast beam separation
- Forward small-angle hadrons pass through large-aperture FFB quads before detection
- FFB / spectrometer dipole combo optimized for acceptance and detector resolution

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Central detector, more detection space in ion direction as particles have higher momenta

Detect particles with angles down to 0.5° before ion FFQs. Need up to 2 Tm dipole in addition to central solenoid.

Detect particles with angles below 0.5° beyond ion FFQs and in arcs.

Make use of the (50 mr) crossing angle for ions!
Interaction region: Ions

- **Final Focusing Block (FFB)**
- **Chromaticity Compensation Block (CCB)**
- **Beam Extension Section**

**β_x^* = 10 cm**
**β_y^* = 2 cm**

- Distance from the IP to the first FF quad = 7 m
- Maximum quad pole tip field at 100 GeV/c = 6 T
  - Allows ±0.5° forward detection
  - Evaluating detailed detector integration and positions of collimators
- Symmetric CCB design for efficient chromatic correction

Whole Interaction Region: 158 m
Chromaticity and Dynamic Aperture

• Compensation of chromaticity with 2 sextupole families only using symmetry

![Graph showing chromaticity compensation](image1)

- **Ions**: $\Delta p/p = 0.3 \times 10^{-3}$ at 60 GeV/c

- **Electrons**: $\Delta p/p = 0.7 \times 10^{-3}$ at 5 GeV/c

• Non-linear dynamic aperture optimization under way

![Graph showing normalized dynamic aperture](image2)
3D Detector Model
Acceptance of Downstream Ion FFB

- 60 GeV/c protons, uniform spreads: $\pm 0.7$ in $\Delta p/p$ and $\pm 1^\circ$ in horizontal/vertical angle
- Apertures: Quads = 9, 9, 7 T / ($\partial B_y / \partial x$ @ 100 GeV/c)
Momentum & Angle Resolution

- Protons with $\Delta p/p$ spread launched at different angles to nominal 60 GeV/c trajectory
- Red hashed band indicates $\pm 10\sigma$ beam stay-clear

$|\Delta p/p| > 0.005 @ \theta_{x,y} = 0$

16 m downstream of the big dipole
Electron Cooling

- Essential to achieve high luminosity for MEIC
- Traditional electron cooling, not Coherent Electron Cooling
- MEIC cooling scheme
  - Pre-booster: *Cooling* for assisting accumulation of positive ion beams
    (Using a low energy DC electron beam, existing technology)
  - Collider ring: *Initial cooling* after injection
    *Final cooling* after boost & re-bunching, for reaching design values
    *Continuous cooling* during collision for suppressing IBS
    (Using new technologies)
- Challenges in cooling at MEIC collider ring
  - High ion energy
    *(State-of-the-art: Fermilab recycler, 8 GeV anti-proton, DC e-beam)*
  - High current, high bunch repetition rate CW cooling electron beam
ERL Circulator Electron Cooler

Design challenges
- Large RF power (up to 81 MW)
- Long gun lifetime (average current 1.5 A)

Proposed solution
- Energy Recovery Linac (ERL)
- Compact circulator ring

Required technologies
- High bunch charge magnetized gun
- High current ERL (55 MeV, 15 to 150 mA)
- Ultra fast kicker

Optimization
- reduce return path to improve cooling rate and beam dynamics

Proposal: A technology demonstration using JLab FEL facility
Immediate Outlook and R&D

• **Electron cooling**
  - Electron cooling of medium energy ion beam (by simulations)
  - ERL circulator cooler design optimization, technology development
  - ERL-circulator cooler demo (using JLab FEL facility)

• **Interaction region**
  - Detector integration
  - Sufficient dynamic aperture with low beta insertions

• **Polarization**
  - Demonstrate superior ion polarization with figure-8 ring
  - Electron spin matching

• **Collective beam effects**
  - Beam-beam with crab crossing
  - Space charge effects in pre-booster
  - Electron cloud in the ion rings and mitigation

• **Ion Injector complex optimization and beam studies**
JLab EIC Study Group


J. Delayen, S. DeSilva, H. Sayed -- Old Dominion University

M. Sullivan -- Stanford Linear Accelerator Laboratory

S. Manikonda, P. Ostroumov -- Argonne National Laboratory

S. Abeyratne, B. Erdelyi -- Northern Illinois University

V. Dudnikov, R. Johnson -- Muons, Inc

A. Kondratenko -- STL “Zaryad”, Novosibirsk, Russian Federation

Y. Kim -- Idaho State University
Crab Crossing

- Restore effective head-on bunch collisions with 50 mrad crossing angle ⇒ Preserve luminosity
- Dispersive crabbing (regular accelerating / bunching cavities in dispersive region) vs. Deflection crabbing (novel TEM-type SRF cavity at ODU/JLab, very promising!)

Incoming

At IP

Outgoing