ELIC Accelerator Design

Balša Terzić
CASA
For the JLab EIC Study Group

Workshop on Perturbative and Non-perturbative Aspects of QCD at Collider Energies
University of Washington, September 13, 2010
Outline

• Introduction and the big picture
• Machine design status
• Critical R&D and path forward
• Summary
**ELIC: JLab’s Future Nuclear Science Program**

Over the last decade:

- JLab has been developing a preliminary design of an electron-ion collider (ELIC) based on the CEBAF recirculating SRF linac.

- Requirements of the future nuclear science program drives ELIC design efforts to focus on achieving:
  - ultra-high luminosity per detector (up to $10^{35}$ cm$^{-2}$s$^{-1}$) in multiple detectors
  - high polarization (>80%) for both electrons & light ions

Over the last 12 months:

- We have made significant progress on design optimization.
  - The primary focus is on a Medium-energy Electron Ion Collider (MEIC) as the best compromise between science, technology and project cost
    - Energy range is up to 100 GeV ions and 11 GeV electrons
  - A well-defined upgrade capability to higher energies is maintained (ELIC)
  - High luminosity & high polarization continue to be the design drivers
Highlights of Last Six Months of MEIC Design Activities

• Continuing design optimization
  – Tuning main machine parameters to serve better the science program
  – Now aim for high luminosity **AND** full detector acceptance
  – Simplified design and reduced R&D requirements

• Focused on detailed design of major components
  – Completed baseline design of two collider rings
  – Completed 1\textsuperscript{st} design of Figure-8 pre-booster
  – Completed beam polarization scheme with universal electron spin rotators
  – Updated IR optics design

• Continued work on critical R&D
  – Beam-beam simulations
  – Nonlinear beam dynamics and instabilities
  – Chromatic corrections
Short-Term Strategy: 6-Month Design “Contract”

• MEIC accelerator team is committed to completing a MEIC design according to recommendations by the International Advisory Comm.

• Focus of MEIC accelerator team during the “contract” period is to work out a complete machine design with sufficient technical detail

• Design “contract” will be reviewed every 6 months and the design specifications updated to reflect developments in:
  • Nuclear science program
  • Accelerator R&D

• We are taking a **conservative** technical position by limiting many MEIC design parameters *within or close to* the present state of the art in order to minimize technical uncertainty
  • Maximum peak field of ion superconducting dipole is 6 T
  • Maximum synchrotron radiation power density is 20 kW/m
  • Maximum betatron value at final focusing quad is 2.5 km (field gradient <200 T/m)
Short-Term Strategy: 6-Month Design “Contract”

• This conservative technical design will form a baseline for future design optimization guided by:
  - Evolution of the science program
  - Technology innovation and R&D advances

• Our present design (assuming 6T magnets) has the following features:
  - CM energy up to 51 GeV: up to 11 GeV electron, 60 (30) GeV proton (ion)
  - Upgrade option to high energy
  - 3 IPs, at least 2 of which are available for medium energy collisions
  - Luminosity up to of order $10^{34}$ cm$^{-2}$s$^{-1}$ per collision point
  - Full acceptance for at least one medium-energy detector (large acceptance for other detectors)
  - High polarization for both electron and light ion beams
Outline

• Introduction and the big picture
• Machine design status
• Critical R&D and path forward
• Summary
MEIC: Medium Energy EIC

Three compact rings:
- 3 to 11 GeV electron
- Up to 12 GeV/c proton (warm)
- Up to 60 GeV/c proton (cold)
MEIC: Detailed Layout

- Big booster (up to 12 GeV/c)
- Warm ring
- Cold ring
- 3 Figure-8 rings stacked vertically
- Medium energy IP with horizontal crab crossing
- 12 GeV CEBAF

Additional features:
- Prebooster
- Ion source
- SRF Linac
- 60 GeV/c proton collider ring
- Injector
- Lepton ring
- Ion booster
- Medium energy ion ring

Dimensions:
- 1.5 m
- 0.5 m
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>Cold</td>
<td>3</td>
</tr>
<tr>
<td>1000</td>
<td></td>
<td></td>
<td>Warm</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>250</td>
<td>20</td>
<td>Cold</td>
<td>4</td>
</tr>
<tr>
<td>2500</td>
<td></td>
<td></td>
<td>Warm</td>
<td></td>
</tr>
</tbody>
</table>
MEIC Ring-Ring Design Features

- Ultra-high luminosity
- Polarized electrons and polarized light ions (longitudinal and transverse at IP)
- Up to 3 IPs (detectors) for high science productivity
- “Figure-8” ion and lepton storage rings
  - Ensures spin preservation and ease of spin manipulation
  - Avoids energy-dependent spin sensitivity for all species
  - Only practical way to accommodate polarized deuterons
- 12 GeV CEBAF meets MEIC requirements
  - Simultaneous operation of collider & CEBAF fixed target program possible
- Experiments with polarized positron beam would be possible
### MEIC Design Parameters For a Full-Acceptance Detector

<table>
<thead>
<tr>
<th></th>
<th>Proton</th>
<th>Electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>60</td>
</tr>
<tr>
<td>Collision frequency</td>
<td>GHz</td>
<td>1.5</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$10^{10}$</td>
<td>0.416</td>
</tr>
<tr>
<td>Beam current</td>
<td>A</td>
<td>1</td>
</tr>
<tr>
<td>Polarization</td>
<td>%</td>
<td>&gt; 70</td>
</tr>
<tr>
<td>Energy spread</td>
<td>$10^{-4}$</td>
<td>~ 3</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>mm</td>
<td>10</td>
</tr>
<tr>
<td>Horizontal emittance, normalized</td>
<td>µm rad</td>
<td>0.35</td>
</tr>
<tr>
<td>Vertical emittance, normalized</td>
<td>µm rad</td>
<td>0.07</td>
</tr>
<tr>
<td>Horizontal $\beta^{*}$</td>
<td>cm</td>
<td>10</td>
</tr>
<tr>
<td>Vertical $\beta^{*}$</td>
<td>cm</td>
<td>2</td>
</tr>
<tr>
<td>Vertical beam-beam tune shift</td>
<td></td>
<td>0.007</td>
</tr>
<tr>
<td>Laslett tune shift</td>
<td></td>
<td>0.07</td>
</tr>
<tr>
<td>Distance from IP to 1st FF quad</td>
<td>m</td>
<td>7</td>
</tr>
<tr>
<td>Luminosity per IP, $10^{33}$</td>
<td>cm$^2$s$^{-1}$</td>
<td>5.6</td>
</tr>
</tbody>
</table>
### MEIC Design Parameters For a High-Luminosity Detector

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Proton</th>
<th>Electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>60</td>
</tr>
<tr>
<td>Collision frequency</td>
<td>GHz</td>
<td>1.5</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$10^{10}$</td>
<td>0.416</td>
</tr>
<tr>
<td>Beam current</td>
<td>A</td>
<td>1</td>
</tr>
<tr>
<td>Polarization</td>
<td>%</td>
<td>&gt; 70</td>
</tr>
<tr>
<td>Energy spread</td>
<td>$10^{-4}$</td>
<td>~ 3</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>mm</td>
<td>10</td>
</tr>
<tr>
<td>Horizontal emittance, normalized</td>
<td>µm rad</td>
<td>0.35</td>
</tr>
<tr>
<td>Vertical emittance, normalized</td>
<td>µm rad</td>
<td>0.07</td>
</tr>
<tr>
<td>Horizontal $\beta^*$</td>
<td>cm</td>
<td>4</td>
</tr>
<tr>
<td>Vertical $\beta^*$</td>
<td>cm</td>
<td>0.8</td>
</tr>
<tr>
<td>Vertical beam-beam tune shift</td>
<td></td>
<td>0.007</td>
</tr>
<tr>
<td>Laslett tune shift</td>
<td></td>
<td>0.07</td>
</tr>
<tr>
<td>Distance from IP to 1st FF quad</td>
<td>m</td>
<td>4.5</td>
</tr>
<tr>
<td>Luminosity per IP, $10^{33}$</td>
<td>cm$^{-2}$s$^{-1}$</td>
<td>14.2</td>
</tr>
</tbody>
</table>
**MEIC Luminosity: 1 km Ring, 8 Tesla**

Assuming maximum peak field for ion magnets of 8 Tesla, highest proton energy can be 96 GeV

<table>
<thead>
<tr>
<th>Proton Energy</th>
<th>Electron Energy</th>
<th>$s$</th>
<th>CM Energy</th>
<th>Luminosity ($L=7m, \beta^*=2cm$)</th>
<th>Luminosity ($L=4.5m, \beta^*=8mm$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GeV</td>
<td>GeV</td>
<td>GeV</td>
<td>GeV</td>
<td>$10^{33} \text{ cm}^{-2}\text{s}^{-1}$</td>
<td>$10^{33} \text{ cm}^{-2}\text{s}^{-1}$</td>
</tr>
<tr>
<td>96</td>
<td>3</td>
<td>1152</td>
<td>34.0</td>
<td>12.5</td>
<td>30.4</td>
</tr>
<tr>
<td>96</td>
<td>4</td>
<td>1536</td>
<td>39.2</td>
<td>10.0</td>
<td>25.0</td>
</tr>
<tr>
<td>96</td>
<td>5</td>
<td>1920</td>
<td>43.8</td>
<td>6.6</td>
<td>16.4</td>
</tr>
<tr>
<td>96</td>
<td>6</td>
<td>2340</td>
<td>48.0</td>
<td>2.6</td>
<td>6.6</td>
</tr>
<tr>
<td>96</td>
<td>7</td>
<td>2688</td>
<td>51.9</td>
<td>1.2</td>
<td>2.9</td>
</tr>
<tr>
<td>96</td>
<td>9</td>
<td>3456</td>
<td>55.8</td>
<td>0.3</td>
<td>0.74</td>
</tr>
<tr>
<td>96</td>
<td>11</td>
<td>4224</td>
<td>65.0</td>
<td>0.1</td>
<td>0.2</td>
</tr>
</tbody>
</table>
## ELIC Luminosity: 2.5 km Ring, 8 Tesla

<table>
<thead>
<tr>
<th>Proton Energy</th>
<th>Electron Energy</th>
<th>s</th>
<th>CM Energy</th>
<th>Luminosity (L=7m, β*=2cm)</th>
<th>Luminosity (L=4.5m, β*=8mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GeV</td>
<td>GeV</td>
<td>GeV$^2$</td>
<td>GeV</td>
<td>$10^{33}$ cm$^{-2}$s$^{-1}$</td>
<td>$10^{33}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>250</td>
<td>3</td>
<td>3000</td>
<td>54.8</td>
<td>8.3</td>
<td>20.7</td>
</tr>
<tr>
<td>250</td>
<td>5</td>
<td>5000</td>
<td>70.7</td>
<td>18.5</td>
<td>46.4</td>
</tr>
<tr>
<td>250</td>
<td>6</td>
<td>6000</td>
<td>77.5</td>
<td>20.2</td>
<td>50.5</td>
</tr>
<tr>
<td>250</td>
<td>7</td>
<td>7000</td>
<td>83.7</td>
<td>20.7</td>
<td>64.5</td>
</tr>
<tr>
<td>250</td>
<td>8</td>
<td>8000</td>
<td>89.5</td>
<td>18.9</td>
<td>57.6</td>
</tr>
<tr>
<td>250</td>
<td>9</td>
<td>9000</td>
<td>94.9</td>
<td>15.8</td>
<td>39.6</td>
</tr>
<tr>
<td>250</td>
<td>11</td>
<td>11000</td>
<td>104.9</td>
<td>7.5</td>
<td>18.8</td>
</tr>
<tr>
<td>250</td>
<td>20</td>
<td>20000</td>
<td>141.4</td>
<td>3.1</td>
<td>6.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Proton Energy</th>
<th>Electron Energy</th>
<th>Ring Circumference</th>
<th>Luminosity (L=7m, β*=2cm)</th>
<th>Luminosity (L=4.5m, β*=8mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GeV</td>
<td>GeV</td>
<td>m</td>
<td>$10^{33}$ cm$^{-2}$s$^{-1}$</td>
<td>$10^{33}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<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
MEIC & ELIC: Luminosity Vs. CM Energy

e + p facilities

e + A facilities

https://eic.jlab.org/wiki/index.php/Machine_designs
MEIC Adopts Proven Luminosity Approaches

High luminosity at B factories comes from:

- Very small $\beta^*$ (~6 mm) to reach very small spot sizes at collision points
- Very short bunch length ($\sigma_z \sim \beta^*$) to avoid hour-glass effect
- Very small bunch charge which makes very short bunch possible
- High bunch repetition rate restores high average current and luminosity
- Synchrotron radiation damping

→ KEK-B and PEPII already over $2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

<table>
<thead>
<tr>
<th></th>
<th>KEK B</th>
<th>MEIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetition rate</td>
<td>MHz</td>
<td></td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$10^{10}$</td>
<td>3.3/1.4</td>
</tr>
<tr>
<td>Beam current</td>
<td>A</td>
<td>1.2/1.8</td>
</tr>
<tr>
<td>Bunch length</td>
<td>cm</td>
<td>0.6</td>
</tr>
<tr>
<td>Horizontal &amp; vertical $\beta^*$</td>
<td>cm</td>
<td>56/0.56</td>
</tr>
<tr>
<td>Luminosity per IP, $10^{33}$</td>
<td>cm$^{-2}$s$^{-1}$</td>
<td>20</td>
</tr>
</tbody>
</table>

JLab believes these ideas should be replicated in the next electron-ion collider

( ): high-luminosity detector
Figure-8 Ion Rings

• Figure-8 is optimum for polarized ion beams
  – Simple solution to preserve full ion polarization by avoiding spin resonances during acceleration
  – Energy independence of spin tune
  – $g$-2 is small for deuterons; a figure-8 ring is the only practical way to accelerate deuterons and to arrange for longitudinal spin polarization at interaction point
  – Transverse polarization for deuterons looks feasible
Figure-8 Collider Rings

Ion Ring

Siberian snake

IP

Potential IP

Electron Ring

RF

Spin rotators

IP

Spin rotators

Potential IP

RF

Siberian snake
Our present design is mature, having addressed -- in various degrees of detail -- the following important aspects of MEIC:

- Beam synchronization
- Ion polarization (RHIC-type Siberian snakes)
- Electron polarization
- Universal spin rotator
- Electron beam time structure & RF system
- Forming the high-intensity ion beam: SRF linac, pre-booster
- Synchrotron rad. background
- Beam-beam simulations
- Beam stability
- Detector design
- IR design and optics
- Electron and ion ring optics
Outline

• Introduction and the big picture
• Machine design status
• Critical R&D and path forward
• Summary
**MEIC Critical Accelerator R&D**

We have identified the following critical R&D issues for MEIC:

- Interaction region design and limits with chromatic compensation
- Electron cooling
- Crab crossing and crab cavity
- Forming high-intensity low-energy ion beam
- Beam-beam effect
- Depolarization (including beam-beam) and spin tracking
- Traveling focusing for very low energy ion beam

<table>
<thead>
<tr>
<th>Level of R&amp;D</th>
<th>Low-to-Medium Energy (12x3 GeV/c) &amp; (60x5 GeV/c)</th>
<th>High Energy (up to 250x10 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Challenging</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi Challenging</td>
<td>Electron cooling</td>
<td>Electron cooling</td>
</tr>
<tr>
<td></td>
<td>Traveling focusing (for ion energies ~12 GeV)</td>
<td>IR design/chromaticity</td>
</tr>
<tr>
<td>Likely</td>
<td>IR design/chromaticity</td>
<td>Crab crossing/crab cavity</td>
</tr>
<tr>
<td></td>
<td>Crab crossing/crab cavity</td>
<td>High intensity low energy ion beam</td>
</tr>
<tr>
<td></td>
<td>High intensity low energy ion beam</td>
<td></td>
</tr>
<tr>
<td>Know-how</td>
<td>Spin tracking</td>
<td>Spin tracking</td>
</tr>
<tr>
<td></td>
<td>Beam-Beam</td>
<td>Beam-beam</td>
</tr>
</tbody>
</table>
Electron Cooling: ERL Circulator Cooler

**Design goal**
- Up to 33 MeV electron energy
- Up to 3 A CW unpolarized beam (~nC bunch charge @ 499 MHz)
- Up to 100 MW beam power!

**Solution: ERL Circulator Cooler**
- ERL provides high average current CW beam with minimum RF power
- Circulator ring for reducing average current from source and in ERL
  (# of circulating turns reduces ERL current by same factor)

**Technologies**
- High intensity electron source/injector
- Energy Recovery Linac (ERL)
- Fast kicker

Derbenev & Zhang, COOL 2009
IR Design

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.

Central detector

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 ($<0.3^\circ$)

Pawel Nadel-Turonski & Rolf Ent
Ongoing Accelerator R&D

We are concentrating R&D efforts on the most critical tasks:

**Focal Point 1:** Forming high-intensity short-bunch ion beams & cooling
  Sub tasks: Complete design of the RF linac and pre-booster
  Ion bunch dynamics and space charge effects (simulations)
  **Led by Peter Ostroumov (ANL)**

**Focal Point 2:** Electron cooling of medium-energy ion beam
  Sub tasks: Electron cooling dynamics (simulations)
  Complete design of the ERL-based circulator cooler
  Dynamics of cooling electron bunch in ERL circulator ring

**Focal Point 3:** Beam-beam interaction
  Sub tasks: Include crab crossing and/or space charge
  Include multiple bunches and interaction points
Collaborations Established

- IR/detector design  M. Sullivan (SLAC)
- MEIC ion complex front end  P. Ostroumov (ANL) (From source up to injection into collider ring)
  - Ion source  V. Dudnikov, R. Johnson (Muons, Inc)
    V. Danilov (ORNL)
  - SRF Linac  P. Ostroumov (ANL), B. Erdelyi (NIU)
- Chromatic compensation  A. Netepenko (Fermilab)
- Beam-beam simulation  J. Qiang (LBNL)
- Electron cooling simulation  D. Bruhwiler (Tech X)
- Polarization  A. Kondratenko (Novosibirsk)
- Electron spin tracking  D. Barber (DESY)
EIC Study Group

W. Fischer, C. Montag - Brookhaven National Laboratory
D. Barber - DESY
V. Danilov - Oak Ridge National Laboratory
V. Dudnikov - Brookhaven Technology Group
P. Ostroumov - Argonne National Laboratory
B. Erdelyi - Northern Illinois University and Argonne National Laboratory
V. Derenchuk - Indiana University Cyclotron Facility
A. Belov - Institute of Nuclear Research, Moscow, Russia
R. Johnson - Muons Inc.
A. Kondratenko - Novosibirsk
Summary

• MEIC is optimized to collide a wide variety of polarized light ions and unpolarized heavy ions with polarized electrons (or positrons)
• MEIC covers an energy range matched to the science program proposed by the JLab nuclear physics community (~4200 GeV²) with luminosity up to $3 \times 10^{34}$ cm⁻²s⁻¹
• An upgrade path to higher energies (250x10 GeV²), has been developed which should provide luminosity of close to $10^{35}$ cm⁻²s⁻¹
• The design is based on a Figure-8 ring for optimum polarization, and an ion beam with high repetition rate, small emittance and short bunch length
• Electron cooling is absolutely essential for cooling & bunching the ion beam
• We have identified the critical accelerator R&D topics for MEIC, and are presently working on them
• Our present MEIC design is *mature and flexible*, able to accommodate revisions in design specifications and advances in accelerator R&D

*MEIC is the future of Nuclear Physics at Jefferson Lab*