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 $10^{35} \text{cm}^{-2}\text{s}^{-1}$) 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 1st 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
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
- Ion source
- Prebooster
- SRF Linac
- 60 GeV/c proton collider ring
- 3 Figure-8 rings stacked vertically
- Medium energy IP with horizontal crab crossing
- Injector
- 12 GeV CEBAF
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 e</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>96</td>
<td>11 1000</td>
<td>Cold Warm</td>
<td>3</td>
</tr>
<tr>
<td>High</td>
<td>250</td>
<td>20 2500</td>
<td>Cold Warm</td>
<td>4</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-Accceptance Detector

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Proton</th>
<th>Electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>60</td>
<td>5</td>
</tr>
<tr>
<td>Collision frequency</td>
<td>GHz</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$10^{10}$</td>
<td>0.416</td>
<td>1.25</td>
</tr>
<tr>
<td>Beam current</td>
<td>A</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Polarization</td>
<td>%</td>
<td>&gt; 70</td>
<td>~ 80</td>
</tr>
<tr>
<td>Energy spread</td>
<td>$10^{-4}$</td>
<td>~ 3</td>
<td>7.1</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>mm</td>
<td>10</td>
<td>7.5</td>
</tr>
<tr>
<td>Horizontal emittance, normalized</td>
<td>µm rad</td>
<td>0.35</td>
<td>53.5</td>
</tr>
<tr>
<td>Vertical emittance, normalized</td>
<td>µm rad</td>
<td>0.07</td>
<td>10.7</td>
</tr>
<tr>
<td>Horizontal $\beta^*$</td>
<td>cm</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Vertical $\beta^*$</td>
<td>cm</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Vertical beam-beam tune shift</td>
<td></td>
<td>0.007</td>
<td>0.03</td>
</tr>
<tr>
<td>Laslett tune shift</td>
<td></td>
<td>0.07</td>
<td>Very small</td>
</tr>
<tr>
<td>Distance from IP to 1st FF quad</td>
<td>m</td>
<td>7</td>
<td>3.5</td>
</tr>
<tr>
<td>Luminosity per IP, $10^{33}$</td>
<td>cm$^2$s$^{-1}$</td>
<td></td>
<td>5.6</td>
</tr>
</tbody>
</table>
# MEIC Design Parameters For a High-Luminosity Detector

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Proton</th>
<th>Electron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td>60</td>
<td>5</td>
</tr>
<tr>
<td>Collision frequency</td>
<td>GHz</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$10^{10}$</td>
<td>0.416</td>
<td>1.25</td>
</tr>
<tr>
<td>Beam current</td>
<td>A</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Polarization</td>
<td>%</td>
<td>&gt; 70</td>
<td>~ 80</td>
</tr>
<tr>
<td>Energy spread</td>
<td>$10^{-4}$</td>
<td>~ 3</td>
<td>7.1</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>mm</td>
<td>10</td>
<td>7.5</td>
</tr>
<tr>
<td>Horizontal emittance, normalized</td>
<td>µm rad</td>
<td>0.35</td>
<td>53.5</td>
</tr>
<tr>
<td>Vertical emittance, normalized</td>
<td>µm rad</td>
<td>0.07</td>
<td>10.7</td>
</tr>
<tr>
<td>Horizontal $\beta^*$</td>
<td>cm</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Vertical $\beta^*$</td>
<td>cm</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Vertical beam-beam tune shift</td>
<td></td>
<td>0.007</td>
<td>0.03</td>
</tr>
<tr>
<td>Laslett tune shift</td>
<td></td>
<td>0.07</td>
<td>Very small</td>
</tr>
<tr>
<td>Distance from IP to 1st FF quad</td>
<td>m</td>
<td>4.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Luminosity per IP, $10^{33}$</td>
<td>cm$^{-2}$s$^{-1}$</td>
<td></td>
<td>14.2</td>
</tr>
</tbody>
</table>
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>Full acceptance Luminosity (L=7m, $\beta^*=2\text{cm}$)</th>
<th>High luminosity Luminosity (L=4.5m, $\beta^*=8\text{mm}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GeV</td>
<td>GeV</td>
<td>GeV$^2$</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>
<tr>
<td>Proton Energy</td>
<td>Electron Energy</td>
<td>s</td>
<td>CM Energy</td>
<td>Full acceptance Luminosity (L=7m, β*=2cm)</td>
<td>High luminosity Luminosity (L=4.5m, β*=8mm)</td>
</tr>
<tr>
<td>---------------</td>
<td>-----------------</td>
<td>------</td>
<td>-----------</td>
<td>------------------------------------------</td>
<td>------------------------------------------</td>
</tr>
<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>Full acceptance Luminosity (L=7m, β*=2cm)</th>
<th>High luminosity 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 $2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$

<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**
  - IP
  - Potential IP

- **Electron Ring**
  - IP
  - Spin rotators
  - Potential IP

- **RF**
  - Siberian snake
  - Spin rotators

- **Supporting Elements**
  - Jefferson Lab
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><strong>Electron cooling</strong></td>
<td>Electron cooling IR design/chromaticity</td>
</tr>
<tr>
<td></td>
<td>Traveling focusing (for ion energies ~12 GeV)</td>
<td></td>
</tr>
<tr>
<td>Likely</td>
<td><strong>IR design/chromaticity</strong></td>
<td>Crab crossing/crab cavity High intensity low energy ion beam</td>
</tr>
<tr>
<td></td>
<td>Crab crossing/crab cavity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High intensity</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
Detect particles with angles **down to 0.5°** before ion FFQs. Need 1-2 Tm dipole.

Detect particles with angles **below 0.5°** 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°)**

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 GeV^2) with luminosity up to $3 \times 10^{34}$ cm^{-2}s^{-1}

• An upgrade path to higher energies (250x10 GeV^2), has been developed which should provide luminosity of close to $10^{35}$ cm^{-2}s^{-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*