Machine Design Status

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CASA
For the JLab EIC Study Group

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Outline

• Introduction & Highlights
• Machine Design Status
• Design Details
• Path forward
• Summary
**ELIC: JLAB’s Future Nuclear Science Program**

- JLab has been developing a preliminary design of an EIC based on the CEBAF recirculating SRF linac for nearly a decade.

- Requirements of the future nuclear science program drives ELIC design efforts to focus on achieving
  - ultra high luminosity per detector (up to $10^{35}$) in multiple detectors
  - very 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 60 GeV ions and 11 GeV electrons
  - A well-defined upgrade capability to higher energies is maintained
  - 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 better serve the science program
  – Now aim for high luminosity AND large 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 (B Erdelyi, July 30)
  – Completed beam polarization scheme with universal electron spin rotators (P. Chevtsov, July 30, Morozov)
  – Updated IR optics design (A. Bogacz, July 31)

• Continued work on critical R&D
  – Beam-beam simulations (B. Terzic, July 29)
  – Nonlinear beam dynamics and instabilities (B. Yunn, July 31, Zhang)
  – Chromatic corrections (V. Morozov, July 31)
Short Term (6 Months) Design “Contract”

MEIC accelerator team is committed to completing a MEIC design within by International Advisory Committee Meeting with the following features

- CM energy up to 51 GeV, up to 11 GeV electron, 60 (30) GeV proton (ion)
- Upgrade option to high energy
- Three IPs, at least two of them are available for medium energy collisions
- Luminosity up to of order $10^{34}$ cm$^{-2}$ s$^{-1}$ per collision point
- **Large acceptance for at least one medium-energy detector**
- High polarization for both electron and light ion beams

This “contract” will be renewable every 6 months with major revision of design specifications due to development of

- Nuclear science program
- Accelerator R&D
Short Term Technical Strategy

• Focus of MEIC accelerator team during this period is to work out a complete machine design with sufficient technical detail.

• We are taking a **conservative** technical position by limiting many MEIC design parameters *within or close to* the present state-of-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 FF quad is 2.5 km

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

- Big booster (up to 12 GeV/c)
- 3 Figure-8 rings stacked vertically
- Ion ring jump
- Medium energy IP with horizontal crab crossing
- Injector
- 12 GeV CEBAF
- Prebooster
- Ion source
- SRF Linac
- 60 GeV/c proton collider ring (cold ring)

Jefferson Lab
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>Cold</td>
<td>3</td>
</tr>
<tr>
<td>Medium</td>
<td>60</td>
<td>5 (11)</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>250</td>
<td>10</td>
<td>1800</td>
<td></td>
</tr>
</tbody>
</table>
Collider Luminosity

- Probability an event is generated by a Beam 1 bunch with Gaussian density crossing a Beam 2 bunch with Gaussian density

\[
P = \frac{N_1 N_2}{2\pi \sqrt{\sigma_{1x}^2 + \sigma_{2x}^2} \sqrt{\sigma_{1y}^2 + \sigma_{2y}^2}} \sigma
\]

- Event rate with equal transverse beam sizes

\[
\frac{dN}{dt} = \frac{fN_1 N_2}{4\pi \sigma_x \sigma_y} \sigma = \mathcal{L} \sigma
\]

- Linear beam-beam tune shift

\[
\xi_x = \frac{N_1 r_i}{2\pi \gamma_i} \frac{1}{\xi_x \left(1 + \frac{\sigma_y}{\sigma_x}\right)}
\]

\[
\xi_y = \frac{N_1 r_i}{2\pi \gamma_i} \frac{1}{\xi_y \left(1 + \frac{\sigma_y}{\sigma_x}\right) \left(\frac{\sigma_x}{\sigma_y}\right)}
\]
Luminosity beam-beam tune-shift relationship

• Express Luminosity in terms of the (larger!) vertical tune shift ($i$ either 1 or 2)

$$\mathcal{L} = \frac{fN_i \xi_i \gamma_i}{2r_i \beta^*} \left(1 + \sigma_y / \sigma_x \right) = \frac{I_i \xi_i \gamma_i}{e} \frac{1}{2r_i \beta^*} \left(1 + \sigma_y / \sigma_x \right)$$

• Necessary, but not sufficient, for self-consistent design

• Expressed in this way, and given a “known” limit to the beam-beam tune shift, the only variables to manipulate to increase luminosity are the stored current, the aspect ratio, and the $\beta^*$ (beta function value at the interaction point)

• Applies to ERL-ring colliders, stored beam (ions) only
# Design Parameters for a Large Acceptance 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>cm</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>
<tr>
<td></td>
<td>Proton</td>
<td>Electron</td>
</tr>
<tr>
<td>-------------------------</td>
<td>--------</td>
<td>----------</td>
</tr>
<tr>
<td>Beam energy</td>
<td>60 GeV</td>
<td>5 GeV</td>
</tr>
<tr>
<td>Collision frequency</td>
<td>1.5 GHz</td>
<td>1.5 GHz</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$10^{10}$</td>
<td>0.416 (0.3)</td>
</tr>
<tr>
<td>Beam Current</td>
<td>1 A (0.7)</td>
<td>3 A</td>
</tr>
<tr>
<td>Polarization</td>
<td>&gt;70 %</td>
<td>~ 80 %</td>
</tr>
<tr>
<td>Energy spread</td>
<td>$10^{-4}$</td>
<td>~ 3</td>
</tr>
<tr>
<td>RMS bunch length</td>
<td>10 (5) cm</td>
<td>7.5 cm</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>5 (2) cm</td>
<td>5 (2) cm</td>
</tr>
<tr>
<td>Vertical $\beta^*$</td>
<td>1 (0.4) cm</td>
<td>1 (0.4) cm</td>
</tr>
<tr>
<td>Vertical beam-beam tune shift</td>
<td>0.007</td>
<td>0.03</td>
</tr>
<tr>
<td>Laslett tune shift</td>
<td>0.07 (0.1)</td>
<td>Very small</td>
</tr>
<tr>
<td>Distance from IP to 1st FF quad</td>
<td>5 (3) m</td>
<td>3.5 m</td>
</tr>
<tr>
<td>Luminosity per IP, $10^{33}$</td>
<td>cm$^{-2}$s$^{-1}$</td>
<td>11.2 (20) cm$^{-2}$s$^{-1}$</td>
</tr>
</tbody>
</table>
### MEIC: CM Energy Range

<table>
<thead>
<tr>
<th>Figure-8 Ring Circumference</th>
<th>Maximum Peak Dipole Field</th>
<th>Luminosity Design Point</th>
<th>Maximum Energy</th>
<th>CM Energy Range (S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>T</td>
<td>GeV x GeV</td>
<td>GeV</td>
<td>GeV²</td>
</tr>
<tr>
<td>1000</td>
<td>6</td>
<td>~ 60 x 5 (s=1200)</td>
<td>60/11</td>
<td>2640</td>
</tr>
<tr>
<td>1000</td>
<td>8</td>
<td>~ 80 x 5 (s=1600)</td>
<td>80/11</td>
<td>3520</td>
</tr>
</tbody>
</table>

After LHC demonstrates its SC magnets can provide 8 T peak field

<table>
<thead>
<tr>
<th>Figure-8 Ring Circumference</th>
<th>Maximum Peak Dipole Field</th>
<th>Luminosity Design Point</th>
<th>Maximum Energy</th>
<th>CM Energy Range (S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>T</td>
<td>GeV x GeV</td>
<td>GeV</td>
<td>GeV²</td>
</tr>
<tr>
<td>1250</td>
<td>6</td>
<td>~ 100 x 7 (s=2800)</td>
<td>108/11</td>
<td>4752</td>
</tr>
<tr>
<td>1250</td>
<td>8</td>
<td>~ 125 x 7 (s=3500)</td>
<td>154/11</td>
<td>6776</td>
</tr>
</tbody>
</table>

- Increase of arc part only by 50%, cost increase is about 10%.
- More space for arc dipoles for bending higher energy ions.
- Increase electron current by reducing synchrotron radiation by 50%.
- There is no need to increase length of the straight sections.
- Where is the richest physics program?
MEIC

Ring-Ring Design Features

- Ultra high luminosity
- Polarized electrons and polarized light ions
- Up to three 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
- Present CEBAF injector meets MEIC requirements
  - 12 GeV CEBAF can serve as a full energy injector
    - Simultaneous operation of collider & CEBAF fixed target program possible
- Experiments with polarized positron beam would be possible
Figure-8 Ion Rings

- Figure-8 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 arrange for longitudinal spin polarization at interaction point
  - Long straights can be useful
    - Allows multiple interactions in the same straight – can help with chromatic correction
  - Main disadvantage is small cost increase
  - There are no technical disadvantages
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 PEPIII already over $2 \times 10^{34}$/cm$^2$/s

<table>
<thead>
<tr>
<th></th>
<th>KEK B</th>
<th>MEIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetition Rate</td>
<td>MHz</td>
<td>509</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
Electron Figure-8 Collider Ring

- Figure-8 crossing angle: 2x30°
- Experimental Hall (radius 15 m)
- Spin Rotator (8.8°/4.4°, 50 m)
- IR (60 m)
- Spin Rotator (8.8°/4.4°, 50 m)
- 1/4 Electron Arc (106.8°, 117.5 m)
- RF Straight (20 m)
- Spin Rotator (8.8°/4.4°, 50 m)
- Injection from CEBAF
- Potential 3rd IR (60 m)
- polarimetry
Electron Collider Ring

Electron ring is designed in a modular way
- two long (140 m) straights (for two IPs)
- two short (20 m) straights (for RF module), dispersion free
- four identical (106.8°) quarter arcs, made of 135° phase advance FODO cell with dispersion suppressing
- four 50 m long electron spin rotator blocks

135° FODO Cell for arc

<table>
<thead>
<tr>
<th></th>
<th>Length</th>
<th>Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole</td>
<td>1.1 m</td>
<td>1.25 T (2.14 deg)</td>
</tr>
<tr>
<td>Quad</td>
<td>0.4 m</td>
<td>9 kG/cm</td>
</tr>
<tr>
<td>Cell</td>
<td>4 m</td>
<td></td>
</tr>
</tbody>
</table>

One quarter arc

26 FODO cells

Figure-8 Collider Ring - Footprint

circumference ~1000 m
Electron Polarization in Figure-8 Ring

Self polarization time in MEIC

<table>
<thead>
<tr>
<th>GeV</th>
<th>Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>14.6</td>
</tr>
<tr>
<td>4</td>
<td>3.5</td>
</tr>
<tr>
<td>5</td>
<td>1.1</td>
</tr>
<tr>
<td>6</td>
<td>0.46</td>
</tr>
<tr>
<td>9</td>
<td>0.06</td>
</tr>
<tr>
<td>11</td>
<td>0.02</td>
</tr>
</tbody>
</table>

- Polarized electron beam is injected at full energy from 12 GeV CEBAF
- Electron spin is in vertical direction in the figure-8 ring, taking advantage of self-polarization effect
- Spin rotators will rotate spin to longitudinal direction for collision at IP, than back to vertical direction in the other half of the ring
Universal Spin Rotator

\[ \alpha_2 = a \gamma \alpha_2 \]
\[ \phi_2 = 4.4^\circ \]
\[ \alpha_1 = a \gamma \alpha_1 \]
\[ \phi_1 = 8.8^\circ \]

<table>
<thead>
<tr>
<th>E</th>
<th>Solenoid 1</th>
<th>Solenoid 2</th>
<th>Spin rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td>GeV</td>
<td>rad T m</td>
<td>rad T m</td>
<td>rad</td>
</tr>
<tr>
<td>3</td>
<td>(\pi/2)</td>
<td>15.7</td>
<td>0</td>
</tr>
<tr>
<td>4.5</td>
<td>(\pi/4)</td>
<td>11.8</td>
<td>(\pi/2)</td>
</tr>
<tr>
<td>6</td>
<td>0.63</td>
<td>12.3</td>
<td>(\pi-1.23)</td>
</tr>
<tr>
<td>9</td>
<td>(\pi/6)</td>
<td>15.7</td>
<td>2(\pi/3)</td>
</tr>
<tr>
<td>12</td>
<td>0.62</td>
<td>24.6</td>
<td>(\pi-1.23)</td>
</tr>
</tbody>
</table>

\[ BL = 28.712 \text{ Tesla m} \]

\[ M = \begin{pmatrix} C & 0 \\ 0 & -C \end{pmatrix} \]
Electron Beam Time Structure & RF System

From CEBAF SRF Linac

- 0.67 ns (20 cm)
- 1.5 GHz
- <3.3 ps (<1 mm)
- 0.2 pC

Microscopic bunch duty factor $5 \times 10^{-3}$

10-turn injection
- 33.3 μs (2 pC)

40 ms (~5 damping times)
- 25 Hz

3000 “pulses” = 120 s

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF operation frequency</td>
<td>MHz</td>
</tr>
<tr>
<td>Total Power</td>
<td>MW</td>
</tr>
<tr>
<td>Harmonic number</td>
<td></td>
</tr>
<tr>
<td>RF Voltage</td>
<td>MV</td>
</tr>
<tr>
<td>Beam current</td>
<td>A</td>
</tr>
<tr>
<td>Energy loss per turn</td>
<td>MeV</td>
</tr>
<tr>
<td>R/Q</td>
<td></td>
</tr>
<tr>
<td>HOM Power</td>
<td>kW</td>
</tr>
<tr>
<td>Accelerating voltage gradient</td>
<td>MV/m</td>
</tr>
<tr>
<td>Unloaded Q</td>
<td></td>
</tr>
<tr>
<td>Number of cavities</td>
<td></td>
</tr>
</tbody>
</table>
Possible Electron Ring RF Systems

RF may prefer 748.5 MHz (coupler limits)
Beam Synchronization

- Electron speed is already speed of light at 3 to 11 GeV, ion speed is not, there is 0.3% variation of ion speed from 20 to 60 GeV
- Needs over 67 cm path length change for a 1000 m ring
- Solution for case of two IPs on two separate straights
  - At the higher energies (close to 60 GeV), change ion path length
  - At the higher energies (close to 60 GeV), change ion path length
    - ion arc on movers
  - At the lower energies (close to 20 GeV), change bunch harmonic number
  - Varying number of ion bunches in the ring
- With two IPs in a same straights ➔ Cross-phasing
- More studies/implementation scheme needed

### Harmonic Number vs. Proton Energy

<table>
<thead>
<tr>
<th>n</th>
<th>$\beta=(h-n)/h$</th>
<th>$\gamma$</th>
<th>Energy (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>inf</td>
<td>Inf</td>
</tr>
<tr>
<td>1</td>
<td>0.9998</td>
<td>47.44</td>
<td>43.57</td>
</tr>
<tr>
<td>2</td>
<td>0.9996</td>
<td>33.54</td>
<td>30.54</td>
</tr>
<tr>
<td>3</td>
<td>0.9993</td>
<td>27.39</td>
<td>24.76</td>
</tr>
<tr>
<td>4</td>
<td>0.9991</td>
<td>23.72</td>
<td>21.32</td>
</tr>
<tr>
<td>5</td>
<td>0.9989</td>
<td>21.22</td>
<td>18.97</td>
</tr>
<tr>
<td>6</td>
<td>0.9987</td>
<td>19.37</td>
<td>17.24</td>
</tr>
</tbody>
</table>
Forming the High-Intensity Ion Beam

Stacking/proton beam in ACR

<table>
<thead>
<tr>
<th></th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>m</td>
</tr>
<tr>
<td>Energy/u</td>
<td>GeV</td>
</tr>
<tr>
<td>Cooling electron current</td>
<td>A</td>
</tr>
<tr>
<td>Cooling time for protons</td>
<td>ms</td>
</tr>
<tr>
<td>Stacked ion current</td>
<td>A</td>
</tr>
<tr>
<td>Norm. emit. After stacking</td>
<td>μm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source/SRF linac</th>
<th>Energy (GeV/c)</th>
<th>Cooling</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prebooster/Accumulator-Ring</td>
<td>3</td>
<td>DC electron</td>
<td>Stacking/accumulating</td>
</tr>
<tr>
<td>Low energy ring (booster)</td>
<td>12</td>
<td>Electron</td>
<td>RF bunching (for collision)</td>
</tr>
<tr>
<td>Medium energy ring</td>
<td>60</td>
<td>Electron</td>
<td>RF bunching (for collision)</td>
</tr>
</tbody>
</table>

Stacking/accumulation process

- Multi-turn (~20) pulse injection from SRF linac into the prebooster
- Damping/cooling of injected beam
- Accumulation of 1 A coated beam at space charge limited emittance
- Fill prebooster/large booster, then accelerate
- Switch to collider ring for booster, RF bunching & staged cooling
### Ion SRF Linac (First Cut)

<table>
<thead>
<tr>
<th>Component</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>IS MEBT</td>
<td></td>
</tr>
<tr>
<td>RFQ</td>
<td>(3 m)</td>
</tr>
<tr>
<td>IH</td>
<td>(9 m)</td>
</tr>
<tr>
<td>QWR</td>
<td>(24 m)</td>
</tr>
<tr>
<td>QWR</td>
<td>(12 m)</td>
</tr>
<tr>
<td>HWR</td>
<td>(24 m)</td>
</tr>
<tr>
<td>DSR</td>
<td>(50 m)</td>
</tr>
</tbody>
</table>

- **Ion species**
  - Up to Lead
- **Ion species for reference design**
  - $^{208}$Pb
- **Kinetic energy of lead ions**
  - MeV/u: 100
- **Maximum beam current averaged over the pulse**
  - mA: 2
- **Pulse repetition rate**
  - Hz: 10
- **Pulse length**
  - ms: 0.25
- **Maximum beam pulsed power**
  - kW: 680
- **Fundamental frequency**
  - MHz: 115
- **Total length**
  - m: 150

- Accelerating a wide variety of polarized light ions and unpolarized heavy ion
- Up to 285 MeV for H\(^-\) or 100 MeV/u for $^{208}$Pb\(^{+67}\)
- Requires stripper for heavy ions (Lead) for efficiency optimization
### MEIC Ion Pre-booster

<table>
<thead>
<tr>
<th>Parameter</th>
<th>m</th>
<th>0.35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drift (arc)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drift (SS)</td>
<td>m</td>
<td>3</td>
</tr>
<tr>
<td>Quad</td>
<td>m</td>
<td>0.4</td>
</tr>
<tr>
<td>Max Quad Field (arc)</td>
<td>T</td>
<td>0.81</td>
</tr>
<tr>
<td>Dipole</td>
<td>m</td>
<td>2</td>
</tr>
<tr>
<td>Bending angle</td>
<td>deg</td>
<td>11.47</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
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<th>300</th>
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<tbody>
<tr>
<td>Total length</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Straight (long)</td>
<td>m</td>
<td>2x57</td>
</tr>
<tr>
<td>Straight (short, in arc)</td>
<td>m</td>
<td>2x23</td>
</tr>
<tr>
<td>Figure-8 angle</td>
<td>deg</td>
<td>95.35</td>
</tr>
<tr>
<td>Max particle γ</td>
<td></td>
<td>4.22</td>
</tr>
<tr>
<td>Transition γ</td>
<td></td>
<td>5.4</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td></td>
<td>0.0341</td>
</tr>
</tbody>
</table>

---

![Diagram of the MEIC Ion Pre-booster](image)
IR Optics (electrons)

\[ \beta(\ell) = \beta^* + \frac{\ell^2}{\beta^*} \]

\[ \beta^{\|} \approx \frac{\ell^2}{\beta^*} = \frac{3.5^2}{2 \times 10^{-2}} \approx 6 \times 10^2 \text{m} \]

\[ \zeta_{IR} \sim \frac{f^2}{\beta^*} \frac{1}{f} = \frac{f}{\beta^*} \]

**Natural Chromaticity:**

\[ \zeta_x = -47 \quad \zeta_y = -66 \]

- \( \beta_x^* = 10 \text{ cm} \)
- \( \beta_y^* = 2 \text{ cm} \)

- \( \ell^* = 3.5 \text{ m} \)

- FF doublets
Beam current = 2.32 A
2.9x10^{10} particles/bunch

Rate per bunch incident on the surface
> 10 keV

Rate per bunch incident on the detector
beam pipe assuming 1% reflection
coefficient and solid angle acceptance of
4.4 %

Michael Sullivan, SLAC
Simulating the beam-beam effects becomes critically important as part of the feasibility study of this conceptual design.

Staged approach to simulations (Terzić talk on 7/29):
- Current: isolate beam-beam effects at IP (idealized linear beam transport)
- Next: incorporate non-linearity in the beam transport around the ring

Main points of this stage of beam-beam simulations:
- Developed a new, automated search for working point based on an evolutionary algorithm (near half-integer resonance: exceeds design luminosity by ~33%)
- Short-term stability verified to within capabilities of strong-strong code
- As beam current is increased, beam-beam effects do not limit stability
- Beam-beam effects are not expected limit the capabilities of the MEIC
Electron Beam Stability

The following issues have been studied:

- Impedances
  - Inductive impedance budget
  - Resistive wall impedance
  - CEBAF cavity
  - HOM loss
- Single bunch instabilities
- Multibunch instabilities
- Intrabeam scattering
- Touschek scattering
- Beam-gas scattering
- Ion trapping & fast beam-ion instability
- Electron clouds

- As long as design of vacuum chamber follows the examples of ring colliders, especially B-factories, we will be safe from the single bunch instabilities.
- No bunch lengthening and widening due to the longitudinal microwave instability is expected.
- No current limitation from transverse mode coupling instability.
- The performance of MEIC e-ring is likely to be limited by multi-bunch instabilities. Feedback system able to deal with the growth has to be designed.
- All ion species will be trapped. Total beam current limitation and beam lifetime will depend upon the ability of the vacuum system to maintain an acceptable pressure, about 5 $nTorr$ in the presence of 3 A of circulating beam.
### MEIC Critical Accelerator R&D

We have identified the following critical R&D 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
- Beam polarization and 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>IR design/chromaticity</td>
<td>IR design/chromaticity</td>
</tr>
<tr>
<td></td>
<td>Electron cooling</td>
<td>Electron cooling</td>
</tr>
<tr>
<td></td>
<td>Traveling focusing (for very low ion energy)</td>
<td></td>
</tr>
<tr>
<td>Likely</td>
<td>Crab crossing/crab cavity</td>
<td>Crab crossing/crab cavity</td>
</tr>
<tr>
<td></td>
<td>High intensity low energy ion beam</td>
<td>High intensity low energy ion beam</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>
Future Accelerator R&D

We will concentrate R&D efforts on the most critical tasks

**Focal Point 1:** Complete Electron and Ion Ring designs

- sub tasks: Finalize chromaticity correction of electron ring and complete particle tracking
- Insert interaction region optics in ion ring
- Start chromaticity correction of ion ring, followed by particle tracking

**Focal Point 2:** IR design and feasibility studies of advanced IR schemes

- sub tasks: Develop a complete IR design
- Beam dynamics with crab crossing
- Traveling final focusing and/or crab waist?
Future Accelerator R&D

**Focal Point 3:** Forming high-intensity short-bunch ion beams & cooling
  sub tasks: Ion bunch dynamics and space charge effects (simulations)
  Electron cooling dynamics (simulations)
  Dynamics of cooling electron bunch in ERL circulator ring
  Led by Peter Ostroumov (ANL)

**Focal Point 4:** Beam-beam interaction
  sub tasks: Include crab crossing and/or space charge
  Include multiple bunches and interaction points

Additional design and R&D studies
  Electron spin tracking, ion source development
  Transfer line design
Electron Cooling of Colliding Ion Beams

- Electron cooler is located at center for figure-8 ring
- Compact cooler design
- Doubled length of cooling section, therefore the cooling rate
- Reduces number of circulation

<table>
<thead>
<tr>
<th></th>
<th>Cooling (Derbenev)</th>
<th>IBS (Piwinski)</th>
<th>IBS (Derbenev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>s</td>
<td>s</td>
<td>S</td>
</tr>
<tr>
<td>Longitudinal</td>
<td>7.8</td>
<td>86</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>66</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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
Collaborations Established

- Interaction region design  M. Sullivan (SLAC)
- ELIC 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)
- Electron spin tracking  D. Barber (DESY)
ELIC 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
V. Derenchuk - Indiana University Cyclotron Facility
A. Belov - Institute of Nuclear Research, Moscow, Russia
V. Shemelin - Cornell University
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 (~2500 GeV²) with luminosity up to $6 \times 10^{33}$ cm⁻²s⁻¹.
• An upgrade path to higher energies (250x10 GeV²), has been developed which should provide luminosity of $1 \times 10^{35}$ 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 and bunching the ion beams.
• We have identified the critical accelerator R&D topics for MEIC, and hope to start working on them soon.

MEIC is the future of Nuclear Physics at Jefferson Lab.
MEIC: Reaching Down Low Energy

- Space charge effect is the leading factor for limiting ion beam current and luminosity
- A small ring with one IP, two snake, injection/ejection and RF
- Ion energy range from 12 GeV to 20 GeV
- Increasing ion current by a factor of 6, thus luminosity by 600%
ELIC Design Goals

- **Energy**
  
  Wide CM energy range between 10 GeV and 100 GeV
  
  - Low energy: 3 to 10 GeV e on 3 to 12 GeV/c p (and ion)
  
  - Medium energy: up to 11 GeV e on 60 GeV p or 30 GeV/n ion and *for future upgrade*
  
  - High energy: up to 10 GeV e on 250 GeV p or 100 GeV/n ion

- **Luminosity**

  - $10^{33}$ up to $10^{35}$ cm$^{-2}$ s$^{-1}$ *per* collision point
  
  - Multiple interaction points

- **Ion Species**

  - Polarized H, D, $^3$He, possibly Li
  
  - Up to heavy ion $A = 208$, all stripped

- **Polarization**

  - Longitudinal at the IP for both beams, transverse of ions
  
  - Spin-flip of both beams
  
  - All polarizations $>70\%$ desirable

- **Positron Beam** *desirable*
MEIC Science Drivers

Key issues in nucleon structure & nuclear physics

- Sea quark and gluon imaging of nucleon with GPDs ($x \sim 0.01$)
- Orbital angular momentum, transverse spin, and TMDs
- QCD vacuum in hadron structure and fragmentation
- Nuclei in QCD: Binding from EMC effect, quark/gluon radii from coherent processes, transparency

Machine/detector requirements

- High luminosity $> 10^{34}$: Low rates, differential measurements
- CM energy $s \sim 1000$ GeV: Reach in $Q^2$, $x$
- Detectability: Angular coverage, particle ID, energy resolution

$favors$ lower & more symmetric energies

R. Ent
MEIC Enabling Technologies

• Pushing the limits of present accelerator theory
  – Issues associated with short ion bunches (e.g., cooling)
  – Issues associated with small $\beta^*$ at collision points
    • Focus on chromatic compensation
    – Beam-beam effects

• Development of new advanced concepts
  – Dispersive crabbing
  – Beam-based fast kicker for circulator electron cooler
Achieving High Luminosity

MEIC design luminosity

\[ L \sim 6 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \] for medium energy (60 GeV x 3 GeV)

Luminosity Concepts

• High bunch collision frequency  (0.5 GHz, can be up to 1.5 GHz)
• Very small bunch charge  (<3x10^{10} particles per bunch)
• Very small beam spot size at collision points  (\(\beta^* y \sim 5 \text{ mm}\))
• Short ion bunches  (\(\sigma_z \sim 5 \text{ mm}\))

Keys to implementing these concepts

• Making very short ion bunches with small emittance
• SRF ion linac and (staged) electron cooling
• Need crab crossing for colliding beams

Additional ideas/concepts

• Relative long bunch (comparing to beta*) for very low ion energy
• Large synchrotron tunes to suppress synchrotron-betatron resonances
• Equal (fractional) phase advance between IPs
Minimizing crossing angle reduces crab cavity challenges.

Vertical crossing angle (~30 mrad)

Interaction Region

~ 60 m
IP

Detector space
Technology Under Consideration: Crab Waist

- Proposed for Super-B factory for luminosity enhancement (Raimondi)
- Deals with large Piwinski angle and low vertical beta-star
- Super-B design calls for 0.2 mm $\beta^*$ while bunch length is 6 mm
- Recent proof-of-principle experiment at DAΦNE very positive

Crabbed waist can be realized with a sextupole in with IP in x and at $\pi/2$ in $\gamma$
Positrons in CEBAF/MEIC

- Unpolarized positrons generated from the modified electron injector by a converter
- Self-polarization in the lepton storage ring

During positron production:
- Polarized source is off
- Dipoles are turned on

Proof of Principle Experiment: extendible to higher energy (& yield)

Position-ion collisions should reach same luminosity as electron-ion collisions

Positron source development at JLab
- “CEPBAF”, S. Golge (Ph. D thesis)
- Polarized e+ Source, J. Dumas (PhD thesis)
- Joint JLab/Idaho Univ. Positron Program

International Workshop on Positrons at Jefferson Lab
March 25-27, 2009
Technology Under Consideration: Traveling Final Focusing

- Space charge effect dominates in a very low energy ion beam
- Laslett tune-shift limits total charge that can be loaded into a bunch
- Long ion bunch can hold more charge with same charge density, therefore increasing luminosity
- Hour glass effect can kill luminosity if the bunch length is much larger than $\beta^*$
- “Traveling final focusing” has been proposed to mitigate hour glass effect (Brinkmann/Dohlus), originally using RF cavity
- New realization scheme: crab crossing with sextupoles