Electron-Ion Collider at JLab: Conceptual Design, and Accelerator R&D

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for

JLab Electron-Ion Collider Accelerator Design Team

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Outline

• Introduction
• Machine Design Baseline
• Anticipated Performance
• Accelerator R&D Highlights
• Summary
Introduction

• 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-ONP 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 luminosities.

• A conceptual machine design has been completed recently, providing a base for performance evaluation, cost estimation, and technical risk assessment.

• A design report was released on August, 2012.
MEIC Design Goals

Base EIC Requirements per INT Report & White Paper

• **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 3-12 GeV, protons 20-100 GeV, ions 12-40 GeV/u

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

• **Up to 2 detectors**

• **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
• Vertical stacking of nearly identical rings (max. deviation: 4 m; ring circumferences: 1350 m)
• Ion beams execute vertical excursion to the plane of the electron orbit for a horizontal crossing
• Horizontal crab crossing (50 mrad) at Ips; Figure-8 crossing angle: 60 deg.

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
New Ion Complex

- Goals: covering all required ion species & energies, matching phase-space structures
- Challenges: beam formation \(\Rightarrow\) space charge effect at low energy
  maintaining beam phase density \(\Rightarrow\) intra-beam scatterings
- Low energy DC electron cooling for assisting accumulation of heavy ions
- SRF linac and boosters. No transition energy crossing in all rings.
- High energy electron cooling

<table>
<thead>
<tr>
<th>Components</th>
<th>Max. energy (GeV/u)</th>
<th>Electron Cooling</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRF linac</td>
<td>0.2 (0.08)</td>
<td></td>
<td>Stripping</td>
</tr>
<tr>
<td>Pre-booster</td>
<td>3 (1.2)</td>
<td>DC</td>
<td>Accumulating</td>
</tr>
<tr>
<td>Large booster</td>
<td>20 (8)</td>
<td></td>
<td>Stacking</td>
</tr>
<tr>
<td>collider ring</td>
<td>100 (40)</td>
<td>Multi-phased/ERL</td>
<td>Coasting/rebunching</td>
</tr>
</tbody>
</table>

* Numbers in parentheses represent energies per nucleon for heavy ions.
## MEIC Design Point Parameters

<table>
<thead>
<tr>
<th>Detector type</th>
<th>Full acceptance</th>
<th>high luminosity &amp; Large Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Proton</td>
<td>Electron</td>
</tr>
<tr>
<td>Beam energy</td>
<td>GeV</td>
<td></td>
</tr>
<tr>
<td>Collision frequency</td>
<td>MHz</td>
<td></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>0.5</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>emittance, normalized</td>
<td>μm rad</td>
<td>0.35/0.07</td>
</tr>
<tr>
<td>Horizontal and vertical $\beta^{*}$</td>
<td>cm</td>
<td>10 and 2</td>
</tr>
<tr>
<td>Vertical beam-beam tune shift</td>
<td></td>
<td>0.014</td>
</tr>
<tr>
<td>Laslett tune shift</td>
<td></td>
<td>0.06</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 Report

JSA Science Council 08//29/12)
✓ “… was impressed by the outstanding quality of the present MEIC design”
✓ “The report is an excellent integrated discussion of all aspects of the MEIC concept.”

Overall MEIC design features:
• High luminosity over broad range
• Highly polarized beams (including D)
• Full acceptance & high luminosity
• Minimized technical risk and R&D

Design concept is stable

EPJA article by JLab theory on MEIC science case
Performance: High Luminosity

**High luminosity over a broad energy range**
**MEIC peak luminosity above $10^{34} \text{ cm}^{-2}\text{s}^{-1}$**
(A full/high detector acceptance can be achieved simultaneously)
MEIC High Luminosity Concept

- MEIC design concept for high luminosity is based on *high bunch repetition rate CW colliding beams*

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KeK-B has reached $>2 \times 10^{34} / \text{cm}^2/\text{s}$

JLab is poised to replicate same success in an electron-ion collider:
- A high repetition rate electron beam from CEBAF
- A new ion complex specifically designed to match e-beam
- Multi-phase electron cooling of ion beams

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<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>Energy (e$^-$/e$^+$ or p/e$^-$)</td>
<td>GeV</td>
<td>8/3.5</td>
</tr>
<tr>
<td>Particles/bunch (e$^-$/e$^+$ or p/e$^-$)</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>Horiz. &amp; vert. $\beta^*$</td>
<td>cm</td>
<td>56/0.56</td>
</tr>
<tr>
<td>Luminosity/IP, $10^{33}$</td>
<td>/cm$^2$/s</td>
<td>20</td>
</tr>
</tbody>
</table>
Performance: High Ion Polarization

We are quite confident MEIC could deliver *superior* ion polarization!

**Primary technology innovation: Figure-8 ring**

- All ion rings (two boosters, a collider) have a figure-8 shape

- **Most simple (in principle)**
  - Spin precession in the left & right parts of the ring are exactly cancelled
  - Special insertions invented to provide energy independent spin tune off 0 at constant orbit
  - Ensures an *easy means* of spin preservation and manipulation
  - Avoids energy-dependent spin sensitivity for ion all species

- **Polarized deuterons**
  - The only practical way to accommodate medium energy polarized deuterons which allows for “clean” neutron measurements

- **No-pain operation**
  - Offers *firm no-pain long term operation runs* for all polarized beams at all energies,
  - Intrinsic spin resonances stay away
  - High order intrinsic effects are diminished with *cooled emittance*
Performance: High Electron Polarization

- MEIC Physics program demands
  - High polarization (>70%) and long life-time (>10 min.)
  - Longitudinal direction at IPs and spin flip

- MEIC electron polarization design
  - CEBAF polarized electron source (superior, >85%) as a full energy injector
  - Beam in the ring can be frequently replaced
  - Inject e-beam with vertical spin in arcs
  - Using *universal spin rotators* for longitudinal spin at IP
  - Employing *spin matching* to minimizing depolarization

Universal Spin Rotator
- rotating spin from vertical to longitudinal direction
  - *energy independent*
  - *orbit (geometry) independent*
**Performance: Low Energy Electron-Ion Collisions**

**Implementation of low energy electron-ion collisions**

- Converting large ion booster to a collider ring
- Peak luminosity can reach $10^{33}$ cm$^{-2}$s$^{-1}$
- Could be a 3$^{rd}$ IP as an additional capability or the 1$^{st}$ phase of EIC@JLab

- Design flexibility, detector *interchangeable*
- No SC ring for large booster $\Rightarrow$ easier to start
- Low technology R&D challenges, reduce risk

![Diagram of electron and ion rings](image)
Performance: Polarized Positrons

MEIC/LEIC can collide polarized positrons with ions, achieving high luminosity similarly to electron-ion collisions

⇒ Only be possible with a ring-ring collider (a lepton storage ring)

• Use CEBAF beam to generate unpolarized positrons
  (Development of an optimum scheme in process)
• Accelerate in CEBAF, inject and stack in the lepton storage ring
• Arrange and wait for possibly fastest self-polarization (Sokolov-Ternov effect)
  (at 10-12 GeV, and/or by using special wigglers)
• Ramp energy down to the target value for experiment
• Use spin-resonance SC cavities for spin flip (frequent flip for the whole beam or one-time flip for half beam)
**MEIC Accelerator R&D Toward CD1**

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

- **Interaction region**
  - Optimization of detector integration
  - *Sufficient dynamic aperture with low beta insertions*

- **Beam Synchronization**
  - A scheme has been developed; SRF cavity frequency tunability study is in progress

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

- **Collective beam effects**
  - (Long time scale) 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**

*Bold font indicates priority*
Cooling: No. 1 R&D Priority

- Essential to achieve high luminosity for MEIC
- Based on traditional electron cooling
- **Multi-phase 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, reaching design values
    *Continuous cooling* during collision for suppressing IBS
    (Using new technologies)

<table>
<thead>
<tr>
<th>Energy (proton / electron)</th>
<th>GeV/MeV</th>
<th>20 / 10.9</th>
<th>100 / 54</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current &amp; Particles/bunch, p/e</td>
<td>A / 10^{10}</td>
<td>0.5/1.5 and 0.417/1.25</td>
<td></td>
</tr>
<tr>
<td>Ion bunch length</td>
<td>cm</td>
<td>coating</td>
<td>➔ 1</td>
</tr>
<tr>
<td>Electron bunch length</td>
<td>cm</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Proton emittance, horiz. /vert.</td>
<td>μm</td>
<td>0.35/0.07</td>
<td></td>
</tr>
<tr>
<td>Cooling time</td>
<td>min</td>
<td>10</td>
<td>~ 0.4</td>
</tr>
</tbody>
</table>

- Cooling of medium energy (up to 100 GeV) hadrons w/ a bunched electron beam (state-of-art: 8 GeV p-bar at Fermilab, DC)
- Generating 3 A, 55 MeV cooling electron beam
Design Concept: ERL Circulator Cooler

Design Choices
- Energy Recovery Linac (ERL)
- Compact circulator ring to meet design challenges
- Large RF power (up to 81 MW)
- Long gun lifetime (average 1.5 A)

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

Optimization:
Put it at center of the Figure-8 ring, for eliminating the long return path doubles the cooling rate

E-bunches circulates 10+ turns \( \Rightarrow \) reduction of current from an ERL by a same factor
### Design Concept Optimization

<table>
<thead>
<tr>
<th></th>
<th>Ion energy (GeV/u)</th>
<th>Ready-to-build</th>
<th>Ultimate</th>
<th>Old scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pre-booster</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DC electron cooling to assist accumulation of positive ions</td>
<td>0.1</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>DC electron cooling for emittance reduction</td>
<td>3</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td><strong>Collider ring</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ERL electron cooling at injection energy for emittance reduction</td>
<td>20</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>ERL electron cooling at top energy for emittance reduction</td>
<td>Up to 100</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>ERL electron cooling during collision to suppress IBS induced emittance growth</td>
<td>Up to 100</td>
<td></td>
<td>“Weak”</td>
<td>✓</td>
</tr>
<tr>
<td>Stochastic cooling of heavy ions during collision to suppress IBS induced emittance growth</td>
<td>Up to 100</td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td><strong>Luminosity</strong></td>
<td>10(^{33}) 1/cm(^2)/s</td>
<td>1 ~ 3</td>
<td>5.6 ~ 14</td>
<td></td>
</tr>
</tbody>
</table>

- The “ready-to-build” version utilizes only (loosely speaking) the existing and proven accelerator technologies.
- “Weak” ERL cooling means using much lower electron current
Existing Cooling Technologies

**“Weak” ERL Cooler**
- No circulating ring (no fast kicker)
- Electron current: ~100 mA (state-of-art)
- Needs ERL (e-beam power: 5.5 MW)

**Bunched Stochastic Cooling**
- Only for heavy ions
- Bandwidth: 4~9 GHz
- Lead ions: 5.1x10^7 per bunch
- Cooling time: ~ 14 min

<table>
<thead>
<tr>
<th>Medium energy</th>
<th>Bunched e-beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERL</td>
<td>Circulator ring</td>
</tr>
</tbody>
</table>
Loosely speaking, based on existing technologies:

- Low energy DC cooling only at pre-booster injection (~0.41)
- Add "weak" ERL cooling & stochastic cooling (heavy ions) during collision (~3.3)
- Add DC cooling at top energy (3 GeV) of pre-booster (~1.1)
- Full capacity electron cooling (ERL-circulator cooler) (5.6~14)
Cooling Experiments at IMP

Institute of Modern Physics, Chinese Academy of Science

Two storage rings with DC coolers for heavy ion coasting beams

Purpose: testing cooling with a bunched electron beam (Andrew Hutton)

- Modulated the DC beam into a bunched beam with a high repetition rate by applying a pulsed voltage to the bias-electrode of the electron gun (Hongwei Chao, IMP)
- Replacing the existing thermionic gun by a JLab photocathode gun (Matt Poelker, JLab)

Low cost, non-invasive experiment, as early as 08/2013

Supporting the “Ready-to-Build” design concept

Phase II: adding an RF cavity for bunching the ion beams) testing a bunched electron beam to cool a bunched ion beam
Purpose

- Demonstrate the design concept
- Develop/test key accelerator technologies (faster beam kickers, etc.)
- Study dynamics of the cooling electron bunches in a circulator ring

Phase 1 scope

- Using the existing ERL without new upgrade except two 180° beam lines (available at JLab)
- Supporting MEIC to deliver the high luminosity (5.6~14 x 10^{33} 1/cm^2/s), not needed for the “ready-to-build” version
- To be completed (hopefully) before 2016
Summary

• The MEIC design has been completed and a comprehensive design report has been released.

• Low energy electron-ion collisions can be realized either as an add-on or as a first stage, expanding the science reach.

• We anticipate superior performance of MEIC, particularly in luminosity, lepton and light ion polarization, detection acceptance, etc.

• The focus of the MEIC team has shifted to design optimization (low cost and less technical uncertainty) and critical accelerator R&D.

• Cooling is considered the most critical R&D
  – Optimizing the cooling scheme by using more existing (DC) technology
  – “Ready-to-Build” enables luminosity above $10^{33}$ cm$^{-2}$s$^{-1}$, meets the EIC white paper requirement;
  – R&D will bring an order of magnitude booster
  – Two low-cost experiments will demonstrate the design concept.
Acknowledgement


1 Jefferson Lab
2 Argonne National Laboratory
3 Brookhaven National Laboratory
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10 Lawrence Berkeley National Laboratory
11 Moscow Institute of Physics & Technology
12 Muons Inc.
13 Northern Illinois University
14 Old Dominion University
15 Paul Scherrer Institute
16 SLAC National Accelerator Lab
17 Science and Technique Lab Russia
18 Universidad de Guanajuato
19 University of Wisconsin-Madison