Project of the Electron-Ion Collider at Jefferson Laboratory

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POETIC 2013
Physics Opportunities at an Electron-Ion Collider

4-8 March 2013
Universidad Técnica Federico Santa María, Valparaíso, CHILE
MEIC project

MEIC design collaboration

1. Jefferson Lab
2. Argonne National Laboratory
3. Brookhaven National Laboratory
4. Catholic University of America
5. College of William and Mary
6. DESY
7. Hampton University
8. Idaho State University
9. Joint Institute for Nuclear Research, Dubna
10. Moscow Institute of Physics & Technology
11. Muons Inc.
12. Northern Illinois University
13. Old Dominion University
14. Paul Scherrer Institute
15. SLAC National Accelerator Lab
16. Science and Technique Lab Russia
17. Universidad de Guanajuato
18. University of Wisconsin-Madison
MEIC Project

- Electron-Ion Collider* for Nuclear Science
- Medium-Energy Electron Ion Collider (MEIC) Layout
- MEIC Basic Design Choices
- Integrated Detector and Interaction Region
- Polarized Beams in MEIC
- Electron Cooling

* EIC is the generic name for the Nuclear Science-driven Electron-Ion Collider, presently considered in the US
Into the “sea”: the EIC

(“Medium-Energy”) MEIC@JLab energy choices driven by:

- access to sea quarks and gluons
  \[ s = \text{few 100 - 1000} \] seems right ballpark
- \[ s = \text{few 1000} \] allows access to gluons, shadowing

Polarization + good acceptance to detect spectators & fragments

An EIC aims to study the sea quarks and gluon-dominated matter.
MEIC/EIC Layout

MEIC (Stage-I EIC)

Ion linac

Pre-booster

IP

IP

CEBAF

Full Energy (Stage-II EIC)
JLab is poised to design a ring-ring EIC taking the advantages of:

- **CEBAF** as a **full energy injector** for electron storage ring
- Multi-phase ERL-based *regular electron cooling* to obtain very short, low charge, small emittance ion bunches
- A high luminosity design based on **short bunches, high repetition rate, crab-crossing** colliding beams by use of **HF SC cavities**
- **Twisted Spin** dynamics in *figure 8* MEIC booster and collider rings providing for spin stability and manipulation for all polarized species *including deuterium*
- A novel **full acceptance + forward tagging detector** design suitable for **crab-crossing** beams and corresponding to the EIC aims to study the **sea quarks and gluon-dominated matter**
MEIC Design Report

- **Posted:** arXiv:1209.0757
- Stable CEBAF-based principal layout and operation concept for 7 years
- Stable IR/detector concept for 3 years

“… 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.” (JSA Science Council 08/29/12)

Overall MEIC design features:

- Highly polarized beams (including D)
- Full acceptance & high luminosity
- Minimized technical risk and R&D

- EPJA article by JLab theory on MEIC science case (arXiv:1110.1031; EPJ A48 (2012) 92)
Reduced R&D challenges
- Regular electron cooling
- Regular electron source
- No need in a new high energy e-accelerator (ERL)
- Modest ion space-charge

Running fixed-target experiments in parallel with collider

Simultaneous use of two full-acceptance detectors
- total beam-beam tune shift < 0.03

Longitudinal and transverse polarization of light ions
- protons, deuterium, \(^3\)He, ...

Longitudinally polarized leptons
- electrons and positrons
Detector/IR in pocket formulas

• Luminosity \( \sim \frac{1}{\beta^*} \)

\[
\beta_{\text{max}} \sim 2 \text{ km} = \frac{l^2}{\beta^*} \quad (l = \text{distance IP to 1}\text{st quad})
\]

*Example:*  \(l = 7 \text{ m}, \beta^* = 20 \text{ mm} \rightarrow \beta_{\text{max}} = 2.5 \text{ km}\)

• IP divergence angle \( \sim \frac{1}{\sqrt{\beta^*}} \)

*Example:*  \(l = 7 \text{ m}, \beta^* = 20 \text{ mm} \rightarrow \text{angle} \sim 0.3 \text{ mr}\)

*Example: 12 \sigma beam-stay-clear area*

\( \rightarrow 12 \times 0.3 \text{ mr} = 3.6 \text{ mr} \sim 0.2^\circ\)

• FFQ gradient \( \sim \frac{E_{p,\text{max}}}{\sqrt{\beta^*}} \) (for fixed \(\beta_{\text{max}}, \text{magnet length}\))

*Example:*  \(6.8 \text{ kG/cm for Q3 @ 12 m @ 60 GeV}\)

\( \rightarrow 7 \text{ T field for 10 cm (\sim 0.5^\circ) aperture}\)

Making \(\beta^*\) too small complicates small-angle (\(\sim 0.5^\circ\)) detection before ion Final Focusing Quads, and would require too high a peak field for these quads given the large apertures (up to \(\sim 0.5^\circ\)). But: \(\beta^* = 1-2 \text{ cm and } E_p = 20-100 \text{ GeV ballpark right!}\)
## MEIC Point Design 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>60</td>
</tr>
<tr>
<td>Collision frequency</td>
<td>MHz</td>
<td>750</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>
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<tr>
<td>Polarization</td>
<td>%</td>
<td>&gt; 70</td>
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<tr>
<td>Energy spread</td>
<td>$10^{-4}$</td>
<td>~ 3</td>
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<tr>
<td>RMS bunch length</td>
<td>mm</td>
<td>10</td>
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<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>
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<tr>
<td>Horizontal and vertical $\beta^*$</td>
<td>cm</td>
<td>10 and 2</td>
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<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>
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<tr>
<td>Distance from IP to 1$^{st}$ 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>
Crab Crossing

- Restore effective head-on bunch collisions with 50 mrad crossing angle \(\Rightarrow\) Preserve luminosity
- Dispersive crabbing (regular accelerating / bunching cavities in dispersive region) vs. Deflection crabbing (novel TEM-type SRF cavity at ODU/JLab, very promising!)
- Feasible for short bunches with HF SC cavities!
Limit as many design parameters as we can to within or close to proven technology in order to minimize technical uncertainty and R&D tasks.

- Stored electron current should not be larger than 3 A
- Stored proton/ion current should not be larger than 0.5 A
- Maximum synchrotron radiation power density is 20 kW/m
- Maximum peak field of warm electron magnet is 1.7 T
- Maximum peak field of ion superconducting dipole magnet is 6 T
- Maximum betatron value ($\beta^\text{max}$) at FF quad is 2.5 km

Choose beta-star appropriate to detector requirements:

- Full acceptance: $2.5 \text{ km } \beta^\text{max} + 7 \text{ m} \Rightarrow \beta_y^* = 2 \text{ cm}$
- Large acceptance: $2.5 \text{ km } \beta^\text{max} + 4.5 \text{ m} \Rightarrow \beta_y^* = 0.8 \text{ cm}$

(beta-star requires electron cooling of proton/ion beams $\Rightarrow$ R&D)
In general, e-p and even more e-A colliders have a large fraction of their science related to the detection of what happens to the ion beams… spectator quark or struck nucleus remnants will go in the forward (ion) direction → this drives the integrated detector/interaction region design.

Three-stage detection scheme

Full acceptance detector
• Demonstrated excellent acceptance & resolution
• Completed the detector-optimized IR optics
• Fully integrated detector and interaction region
• Working on hardware engineering design

Addressing accelerator challenges
• Demonstrated chromaticity compensation

- Neutron detection in a 25 mrad cone down to zero degrees
- Recoil baryon acceptance:
  - up to 99.5% of beam energy for all angles
  - down to 2-3 mrad for all momenta
• Momentum resolution < 3x10^{-4}
  - limited by intrinsic beam momentum spread
Ultra-forward hadron detection – requirements

1. **Good acceptance for ion fragments** (rigidity different from beam)
   - Large downstream magnet apertures
   - Small downstream magnet gradients (realistic peak fields)

2. **Good acceptance for recoil baryons** (rigidity similar to beam)
   - Small beam size at second focus (to get close to the beam)
   - Large dispersion (to separate scattered particles from the beam)

3. **Good momentum- and angular resolution**
   - Large dispersion (e.g., 60 mrad bending dipole)
   - Long, instrumented magnet-free drift space

4. **Sufficient separation between beam lines (~1 m)**
Accelerator optics – fully integrated interaction region

No other magnets or apertures between IP and FP!
Ultra-forward charged-hadron acceptance

Red: Detection before ion quadrupoles
Blue: Detection after ion quadrupoles

Forward acceptance vs. magnetic rigidity

50 mr crossing angle in ion beam

Tagged d beam: $dp/p = -0.5$
Tagged $^3$He beam: $dp/p = +0.33$
Ultra-forward hadron detection – summary

- Neutron detection in a 25 mrad cone down to zero degrees
- Excellent acceptance for all ion fragments
- Recoil baryon acceptance:
  - up to 99.5% of beam energy for all angles
  - down to 2-3 mrad for all momenta
- Momentum resolution < 3x10^-4
  - limited by intrinsic beam momentum spread
- 100 GeV maximum ion energy allows using large-aperture magnets with achievable field strengths
Chromaticity Compensation and Dynamic Aperture

- Compensation of chromaticity with 2 sextupole families only using symmetry

- Non-linear dynamic aperture optimization under way

\[ \Delta p/p = 0.3 \times 10^{-3} \text{ at 60 GeV/c} \]

\[ \Delta p/p = 0.7 \times 10^{-3} \text{ at 5 GeV/c} \]
Synchrotron radiation

• From arc where electrons exit and magnets on straight section

Random hadronic background

• Dominated by interaction of beam ions with residual gas in beam pipe between arc and IP

• Comparison of MEIC (at $s = 4,000$) and HERA (at $s = 100,000$)
  - Distance from ion exit arc to detector: $50 \text{ m} / 120 \text{ m} = 0.4$
  - Average hadron multiplicity: $(4000 / 100000)^{1/4} = 0.4$
  - $p$-$p$ cross section (fixed target): $\sigma(90 \text{ GeV}) / \sigma(920 \text{ GeV}) = 0.7$
  - At the same ion current and vacuum, MEIC background should be about 10% of HERA
    o Can run higher ion currents (0.1 A at HERA)
    o Good vacuum is easier to maintain in a shorter section of the ring

• Backgrounds do not seem to be a major problem for the MEIC
  - Placing high-luminosity detectors closer to ion exit arc helps with both background types
  - Beyond arcs proton/ion beams get manipulated (crab crossing angle), electron beam stays straight to go through detector $\rightarrow$ minimizes synchrotron radiation
  - Signal-to-background will be considerably better at the MEIC than HERA
    o MEIC luminosity is more than 100 times higher (depending on kinematics)
Ion Polarization in Twisted Rings

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

- 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 spin preservation and manipulation by *easy means*
- Avoids energy-dependent spin sensitivity for ion all species
- *The only practical way to accommodate medium energy polarized deuterons*
  *which allows for “clean” neutron measurements*

This design feature offers a *firm no-pain long term operation runs* for all polarized beams at low and high energies, since:
- Intrinsic spin resonances stay away
- High order intrinsic effects are diminished with *cooled emittance*
Ion Spin Acceleration and Manipulation

Special insertions provide **energy independent spin tune** off zero – at constant orbit

- Acceleration of all species in boosters
- **Deuterium** in Collider Ring
- Spin manipulation for all species in CR of Phase I MEIC

Longitudinal polarization in one straight

Vertical polarization over all ring

- $\alpha_1$
- $\alpha_2$
- $-\alpha_1$
- $-\alpha_2$

$G_1 \quad L_q \quad \text{Sol} \quad L_q \quad G_2 \quad G_2 \quad \text{Sol} \quad G_1$

$L_q \quad L_q \quad L_q \quad L_q \quad L_q \quad L_q \quad L_q \quad L_q$
Proton and He-3 spin in Phase II CR

“Strong solutions” based on:

two RHIC type helical snakes in arcs, switching axis

- Transverse polarization at both IPs
  - 45 degrees snake axis
  - Spin tune $\frac{1}{2}$
  - Inject vertical spin

- Longitudinal polarization at both IPs
  - Longitudinal RHIC snakes + Compact single helix snake in one of two straights
  - Spin tune $\frac{1}{2}$
  - No spin rotators at IPs
  - Inject longitudinal spin

- New /easier and more flexible/ solutions based on compact helixes and Universal Spin Rotators – in design process
Polarized e-Beam in the Storage Ring

- **MEIC Physics program demands**
  - High polarization (>70%) and long life-time (>10 min.)
  - Longitudinal direction at all collision points
  - Spin flip capability for improving data statistics

- **MEIC electron polarization design**
  - CEBAF polarized electron source (>85%)
  - Inject e-beam with vertical spin in arcs
  - Using *universal spin rotators* for longitudinal spin at IP
  - Employing *spin matching* to minimizing quantum depolarization

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From CEBAF and at IP’s

- Spin flip

In arcs

- Spin polarization
- Depolarization
Universal Spin Rotator

- Rotating spin from vertical to longitudinal
- Consists of 2 solenoids & 2 (fixed angle) arc dipoles
- **Universal**
  - **energy independent**
    - works for all energies (3 to 12 GeV)
  - **orbit independent**
    - does not affect orbital geometry

### Compensation of solenoid x-y coupling

V. Livinenko & A. Zholents, 1980

<table>
<thead>
<tr>
<th>E (GeV)</th>
<th>$\varphi_1$</th>
<th>$BL_1$ (Tm)</th>
<th>$\alpha_1$</th>
<th>$\varphi_2$</th>
<th>$BL_2$ (Tm)</th>
<th>$\alpha_2$</th>
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<tbody>
<tr>
<td>3</td>
<td>$\pi/2$</td>
<td>15.7</td>
<td>$\pi/3$</td>
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<td>0</td>
<td>$\pi/6$</td>
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<td>6</td>
<td>0.62</td>
<td>12.3</td>
<td>$2\pi/3$</td>
<td>1.91</td>
<td>38.2</td>
<td>$\pi/3$</td>
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<tr>
<td>9</td>
<td>$\pi/6$</td>
<td>15.7</td>
<td>$\pi$</td>
<td>$2\pi/3$</td>
<td>62.8</td>
<td>$\pi/2$</td>
</tr>
<tr>
<td>12</td>
<td>0.62</td>
<td>24.6</td>
<td>$4\pi/3$</td>
<td>1.91</td>
<td>76.4</td>
<td>$2\pi/3$</td>
</tr>
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</table>
Study for Polarized Positrons in MEIC

- Use CEBAF beam to generate unpolarized positrons (working out an optimum scheme in process)
- Accelerate, inject and stack in the storage ring
- Arrange and wait for possibly fastest ST polarization (at 10-12 GeV, perhaps, and (or) by use special wigglers)
- Ramp energy down to a reasonable minimum for experiment
- Use spin-resonance SC cavities for spin flip (frequent flip for the whole beam or one-time flip for half beam)

/techniques by A. Krisch – V. Morozov – A. Kondratenko and collaborators/
Electron Cooling in MEIC

• 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>Cooling length/circumference</td>
<td>m</td>
<td>60 / 1350</td>
<td></td>
</tr>
<tr>
<td>Current and Particles/bunch</td>
<td>A and 10^{10}</td>
<td>0.5 / 1.5 and 0.417 / 1.25</td>
<td></td>
</tr>
<tr>
<td>Bunch frequency</td>
<td>MHz</td>
<td>~ 1 / 748.5</td>
<td>748.5</td>
</tr>
<tr>
<td>Energy spread</td>
<td>10^{-4}</td>
<td>10 / 3</td>
<td>5 / 3</td>
</tr>
<tr>
<td>Ion bunch length</td>
<td>cm</td>
<td>coated</td>
<td>coated (\rightarrow) 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>(\mu m)</td>
<td>4</td>
<td>4 (\rightarrow) 0.35/0.07</td>
</tr>
<tr>
<td>Cooling time</td>
<td>min</td>
<td>10</td>
<td>(\sim) 0.4</td>
</tr>
</tbody>
</table>
Staged Electron Cooling In Collider Ring

**Design choices:**
- *energy recovery linac*
- *circulator ring (~100 turns)*
- *fast kicker*

- **Initial cooling:** after injection for reduction of longitudinal emittance < acceleration
- **Final cooling:** after boost & rebunching, for reaching design values of beam parameters
- **Continuous cooling:** during collision for suppressing IBS & preserving luminosity lifetime

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<table>
<thead>
<tr>
<th></th>
<th>Initial Cooling</th>
<th>after boost &amp; bunching</th>
<th>Colliding Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy</strong></td>
<td>GeV/MeV</td>
<td>20 / 8.15</td>
<td>60 / 32.67</td>
</tr>
<tr>
<td><strong>Beam current</strong></td>
<td>A</td>
<td>0.5 / 3</td>
<td>0.5 / 3</td>
</tr>
<tr>
<td><strong>Particles/Bunch</strong></td>
<td>$10^{10}$</td>
<td>0.42 / 3.75</td>
<td>0.42 / 3.75</td>
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<tr>
<td><strong>Ion and electron bunch length</strong></td>
<td>cm (coasted)</td>
<td>1 / 2~3</td>
<td>1 / 2~3</td>
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<tr>
<td><strong>Momentum spread</strong></td>
<td>$10^{-4}$</td>
<td>10 / 2</td>
<td>5 / 2</td>
</tr>
<tr>
<td><strong>Horiz. and vert. emitt, norm.</strong></td>
<td>µm</td>
<td>4 / 4</td>
<td></td>
</tr>
<tr>
<td><strong>Laslett's tune shift</strong></td>
<td>(proton)</td>
<td>0.002</td>
<td>0.006</td>
</tr>
<tr>
<td><strong>Cooling length /circumference</strong></td>
<td>m/m</td>
<td>15 / 1000</td>
<td>15 / 1000</td>
</tr>
</tbody>
</table>

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To achieve desired hadron beam properties requires ERL-based regular electron cooling
MEIC Accelerator R&D: Electron Cooling

- Electron Cooling in Collider – proof of principle of concept & techniques
  - Cooling simulations are in progress (collaboration with Tech-X established through an SBIR grant)
  - ERL circulator cooler (linear optics and ERL) design has been completed
  - Fast RF kicker concept has been developed, plan to test with two kickers from SLAC
  - Test of beam-beam kicker concept at FNAL/ASTA facility and collaboration are in planning
  - Optics design of a cooler test facility based on JLab FEL ERL has been completed

A technology demonstration possible using JLab FEL facility

- eliminating a long return path could double the cooling rate

Required R&D: demonstrate ERL-based cooler concept by 2016 (at FEL/ERL conditions)
Further ongoing MEIC Accelerator R&D

(not discussed, only for reference of committee)

• Space Charge Dominated Ion Beam in the Pre-booster
  ▪ Simulation study is in progress by Argonne-NIU collaborators

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

• Beam-Beam Interaction
  ▪ Phase 1 simulation study was completed

• Interaction Region, Chromaticity Compensation and Dynamic Aperture
  ▪ Detector integration with IR design has been completed, offering excellent acceptance
  ▪ Correction scheme has been developed, and incorporated into the IR design
  ▪ Tracking simulations show excellent momentum acceptance; dynamic aperture is increased
  ▪ Further optimization in progress (e.g., all magnet spaces/sizes defined for IR +/- 100 m)

• Beam Polarization
  ▪ Electron spin matching and tracking simulations are in progress, achieving acceptable equilibrium polarization and lifetime (collaboration with DESY)
  ▪ New ion polarization scheme and spin rotators have been developed (collaboration with Russian group) – numerical demonstration of figure-8 concept with misalignments ongoing

• Electron Cloud in Ion Ring

• Ion Sources (Polarized and Universal)
Summary

• EIC is the ultimate tool to study sea quarks and gluons
• EIC allows a unique opportunity to make a breakthrough in nucleon structure and QCD dynamics
• Collider environment provides tremendous advantages
  – Kinematic coverage (low to high center-of-mass energy)
  – Polarization measurements with excellent Figure-of-Merit
  – Detection of spectators, recoil baryons, and target fragments

• The MEIC concept has been stable for 3 years
  – Allowing for refinement of the design
  – MEIC design report completed and available on the arXiv
  – Phased options including use of 25 GeV booster under consideration
  – Some accelerator R&D funds have been allocated
  – Joint detector R&D projects have started

• The MEIC design is based predominantly on proven technology & our immediate goal is full validation of the MEIC design with R&D