JLab EIC full-acceptance detector

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EIC (2.2 km)

CEBAF (1.4 km circumference)
Polarized (light) ions at a JLab EIC

- The EIC will support a variety of light ions, including d, $^3$He, and Li
  - Polarized protons and $^3$He beams are easy figure-8
  - Polarized medium- and heavy ions possible?

- The very small deuteron g-2 requires a figure-8 ring shape for d
  - Both vector- and tensor polarization possible
Detector locations and backgrounds

- IP locations reduce synchrotron- and hadronic backgrounds
  - Far from arc where electrons exit (synchrotron)
  - Close to arc where ions exit (hadronic) – shown below

- Scaling from HERA (pp cross section, multiplicity, current) suggest comparable hadronic background at similar vacuum
  - But it should be possible to reach better vacuum! (early HERA: $10^{-7}$, PEP-II: $10^{-9}$, LHC $10^{-10}$ torr)
  - EIC luminosity is more than 100 times higher
  - Signal-to-background (random hadronic) should be $10^3$-$10^4$ times better

- Crossing angle and soft bends reduce synchrotron radiation at IP
Detector and interaction region

- The extended detector is highly integrated with the accelerator
  - Optimized Compton/low-$Q^2$ chicane and hadron spectrometer optics
  - Key design features such as a 50 mrad crossing angle simplify detector

Extended detector: 70+ m
Design goals for extended detector

- Detection/identification of complete final state
- Spectator $p_T$ resolution $<<$ Fermi momentum
- Low-$Q^2$ electron tagger for photoproduction
- Compton polarimeter with $e^-$ and $\gamma$ detection

**Electron Polarimetry**
Low-$Q^2$ tagger
Lumi monitor

**Forward hadron spectrometer**
~60 mrad bend

**ZDC for neutrons**
Beam optics for extended detector

(top view in GEANT4)

low-Q$^2$ electron detection and Compton polarimeter

Far forward hadron spectrometer

ZDC

2$^{nd}$ focus for recoil baryon detection (Roman pots)
Central detector

- Luminosity ~ 1 / total distance between ion quadrupoles (here 10.5 m)
  - No need to optimize at the 15% level. Prioritize detection needs!
  - Doubly asymmetric IP maximize space and performance
  - 50 mrad crossing angle and 2 Tm dipole boost small-angle tracking

- More details on subsystems later!
Forward hadron spectrometer

- S-shaped dipole configuration optimizes neutron acceptance and beam line separation (> 1 m)

- 50 mrad crossing angle (Belle II: 83 mrad)

- 2 Tm dipole (out)
- 20 Tm dipole (in)

- Aperture-free drift space
- ZDC \((n, \gamma)\)

- \(p \rightarrow e \leftarrow\)

- Recoil protons (e.g. DVCS)
- Spectator protons (exit windows)
- (roman pots at focal point)

- Spectator proton angle after dipole is 75 mrad wrt p beam

- Large dipole provides excellent resolution
- Large dispersion and small beam size at secondary focus (with roman pots) ensure good acceptance for recoil baryons
- Large quadrupole apertures (1 / max beam energy) give good acceptance for fragments
Fragment acceptance and resolution

- Full acceptance for all partonic and nuclear fragments has achieved!
  - Resolution limited only by beam
    - Longitudinal \( \frac{dp}{p} \): \textit{few} \( \times 10^{-4} \)
    - Angular \( \theta \), for all \( \phi \): \(< 0.3 \text{ mrad} \)

Forward charged-particle acceptance

- proton-rich fragments
  - “spectator protons from \( ^2\text{H} \)"
- neutron-rich fragments
  - “tritons from N=Z nuclei”

Neutron acceptance (x and y)

- \textbf{Red}: Detection \textit{before} ion quadrupoles
- \textbf{Blue}: Detection \textit{after} ion quadrupoles
DVCS recoil proton acceptance

- **Kinematics:** 5 GeV $e^-$ on 100 GeV $p$ at a crossing angle of 50 mrad.
  - Cuts: $Q^2 > 1$ GeV$^2$, $x < 0.1$, $E'_e > 1$ GeV, recoil proton 10σ outside of beam
- **GEANT4 simulation:** tracking through magnets done using GEMC

#### Low-$t$ acceptance
- Proton angle at IP: 10σ beam size cut: 
  - $p < 99.5\%$ of beam for all angles
  - $\theta > 2$ mrad for all momenta
- $e^-$ beam at 0 mrad

#### High-$t$ acceptance
- Proton angle at IP: $10\sigma$ beam size cut:
  - $p < 99.5\%$ of beam for all angles
  - $\theta > 2$ mrad for all momenta
- $e^-$ beam at 0 mrad

- Recoil proton angle is independent of electron beam energy: $\theta_p \approx p_T/E_p \approx \sqrt{(-t)/E_p}$
- The ion beam size (emittance, focusing, cooling) introduces a low-$p_T$ ($-t$) cutoff
- Larger cone at lower $E_p$ decreases the cutoff and make precise tracking easier
Neutron structure with tagging

**MC Simulation / GEMC**
- deuterons: - magenta -
- $e^-$: - cyan -
- protons: - orange -

- On-shell extrapolation of $F_{2n}$
  - Requires resolution better than Fermi momentum ($< 20 \text{ MeV/c}$)
  - Achievable in the JLab design, even with 50 GeV/A deuterium!
Compton polarimetry

- **Experience from HERA:** uncertainty > 1%
  - Limited to detection of Compton photon only
  - Accelerator limitations (non-colliding bunches)

- **Experience from JLab and SLAC**
  - SLD at SLAC reached 0.5% detecting the Compton electron
  - Compton polarimeters in Halls A and C at JLab reach ~1%
    detecting both the photon and the electron for cross check

  *Laser at Chicane center ensures that polarization is identical to IP*
MEIC polarimeters and low-$Q^2$ tagger

- One IP will have much larger version of the JLab Compton chicane
  - Detection of both electron and photon, the latter with low synchrotron background
- Second IP will have a similar chicane optimized for electron detection
  - Goal is to push the uncertainty of the polarimeter towards what SLAC achieved
Compton chicane for the EIC

Compton electron detector in Roman pot

Compton photon calorimeter

Very low Q2 electron detector in Roman pot

Optical table with cavity

Zero Degree calorimeter

Low Q2 tagger scintillator array

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Bunch spacing and identification

- Detectors (CLAS, BaBar, etc) at machines with high bunch crossing rates have not had problems in associating particle tracks with a specific bunch.
  - Having more bunches lowers the average number of collisions per crossing.

- Example: CLAS detector at JLab 6 GeV
  - 2 ns bunch spacing (500 MHz rep. rate)
  - 0.2 ns TOF resolution (0.5 ns FWHM)
  - The figure shows time matching of kaons in CLAS with electrons in the (low-$Q^2$) tagger, in turn matched to the accelerator RF signal.
    
    *The 2 ns bunch structure is clearly resolved*
  - CLAS12 aims at a TOF resolution of 80 ps.

- The bunch spacing in the MEIC is similar to CLAS and most $e^+e^-$ colliders
  - PEP-II/BaBar, KEKB/Belle: **8 ns**
  - Super KEKB/Belle II: **4 ns** (2 ns with all RF buckets full)
  - MEIC: **1.3 ns** [750 MHz]
  - CERN Linear Collider (CLIC): **0.5 ns** [2 GHz]
Asynchronous triggering

- The MEIC will use a “smart” asynchronous trigger and pipelined electronics
  - The MEIC L1 rate is expected to be comparable to GlueX (200 kHz)
    - Low-$Q^2$ (photoproduction) events will be pre-scaled
  - Simple tracking at L2 will suppress random background (not from vertex)
    - Already planned for CLAS12

- Data-driven, asynchronous triggers are well-established
  - If the number of collisions of interest per bunch crossing is $<< 1$, synchronizing the trigger to each RF clock cycle becomes inefficient
  - Sampling rate requirements for the pipelined electronics depend on signal properties and backgrounds, not the bunch crossing frequency
    - JLab 12 GeV uses flash ADCs with 250 MHz (4 ns) sampling
  - When a trigger condition is fulfilled (e.g., $e^-$ found), memory buffers are written to disk or passed to L3 (at PANDA signals will go directly to L3)
  - Correlations with the RF are made offline
  - $T_0$ is obtained from tracking high-$\beta$ particles (e.g., electrons in CLAS)
Central detector

- Modular design compatible CLEO/BaBar solenoids
- Whenever possible utilizes subsystems from the EIC R&D program
- Layout driven mainly by PID (see, e.g., eRD14 for subsystem details)
- Main challenge: integrate dual-radiator RICH with magnetic field

- Design of new hybrid solenoid should be ready soon!
Options for central tracker

Three options are being evaluated for the barrel
- TPC (with Hadron Blind readout for e/\pi discrimination up to 4 GeV/c)
- Low-mass cluster-counting drift chambers as ILC 4\textsuperscript{th} concept detector and mu2e proposal.
- Micromegas (could also be used in conjunction with the previous two)

- GEM-based endcap trackers
  - TRD functionality in hadron endcap is currently being evaluated

- High-resolution silicon-pixel vertex tracker needed for heavy flavor
  - Could have outer layer(s) of silicon strips to reduce channel count
The full-acceptance detector concept is now rather mature, but still requires a lot of detailed studies!
- Lots of opportunities for both design and R&D work!

I could prepare a more detailed follow-up presentation focusing on subsystems of particular interest for ANL

A quick resource for various aspects of the project can be found at the web page of the latest collaboration meeting (detector session on the last day).
- https://www.jlab.org/conferences/meic-oct15/

We are currently working on a writeup that should be available early 2016
Hadronic backgrounds

- Random hadronic background
  - Assumed to be dominated by scattering of beam ions on residual gas (mainly $^2\text{H}$) in the beam pipe between the ion exit arc and the detector.
  - Correlated background from photoproduction events is discussed separately

- The conditions at the MEIC compare favorably with HERA
  - Typical values of $s$ are 4,000 GeV$^2$ at the MEIC and 100,000 GeV$^2$ at HERA
  - Distance from arc to detector: $65 \text{ m} / 120 \text{ m} = 0.54$
  - $p$-$p$ cross section ratio $\sigma(100 \text{ GeV}) / \sigma(920 \text{ GeV}) < 0.8$
  - Average hadron multiplicity per collision $(4000 / 100000)^{1/4} = 0.45$
  - Proton beam current ratio: $0.5 \text{ A} / 0.1 \text{ A} = 5$
  - At the same vacuum the MEIC background is $0.54 \times 0.8 \times 0.45 \times 5 = 0.97$ of HERA
  - But MEIC vacuum should be closer to PEP-II ($10^{-9}$ torr) than HERA ($10^{-7}$ torr)

- The signal-to-background ratio will be even better
  - HERA luminosity reached $\sim 5 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$
  - The EIC (and the MEIC in particular) aims to be close to $10^{34} \text{ cm}^{-2}\text{s}^{-1}$
Synchrotron radiation background

Initial electron beam pipe design for evaluating SR

**Conclusion:** diameter at the vertex tracker could be reduced to 25-30 mm

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<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<td>Power (W) @ 5 GeV</td>
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<td>$\gamma &gt;10$ keV @ 5 GeV</td>
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<td>$\gamma &gt;10$ keV @ 11 GeV</td>
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<td>2.8x10^5</td>
<td>9.0x10^4</td>
<td>3.8x10^5</td>
<td>271</td>
<td>13,323</td>
</tr>
</tbody>
</table>

Photon numbers are per bunch

*Simulation by M. Sullivan (SLAC)*
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)
   - Roman pots not needed

2. Good acceptance for low-$p_T$ 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)
   - Roman pots important

3. Good momentum- and angular resolution
   - Large dispersion (but with $D = D' = 0$ at IP)
   - Long, instrumented, magnet-free drift space

4. Sufficient separation between beam lines (~1 m)
Forward detection – processes

- Recoils in exclusive (diffractive) processes
  - Recoil baryons
    \( \text{Large } t (p_T) \text{ range and good resolution desirable} \)
  - Coherent nuclear processes
    \( \text{Good small-}p_T \text{ acceptance extends detectable mass range} \)
    \( \text{Suppression of incoherent background for heaviest nuclei through detection of all fragments and photons} \)

- Partonic fragmentation in SIDIS
  - Correlations of current and target jets
  - Decays of strange and charmed baryons

- Nuclear spectators and fragments
  - Spectator tagging with polarized light ions
    \( p_T \text{ resolution } < \text{Fermi momentum} \)
  - Final state in heavy-ion reactions
    \( \text{Centrality of collision (hadronization, shadowing, saturation, etc)} \)

- Heavy flavor photoproduction (low-\(Q^2\) electron tagging)
Spectator angles at dipole exit

- True spectator fragments have very small scattering angles at the IP (black curve)
- Spectator protons from deuterium have $\Delta p/p = -0.5$
- After passing the large bending dipole, the spectator angle with respect to the ion beam is large
- The angle in the magnet-free drift section after the dipole can be calculated from the displacement at the dipole exit and a point 16 m further downstream:
  - $\theta = \text{atan} \left( \frac{(1.4 - 0.2)}{16} \right) = 75 \text{ mrad} \approx 4.3^\circ$
Acceptance and resolution at FP

- Large deflections allow precise tracking over long distances with cheaper detectors
  - Particles with deflections > 1 m at the FP will be detected closer to the dipole
- Detection past the focal point is also possible, but with acceptance restrictions