Detectors in the Far-Forward Region at the EIC

RHIC/AGS Annual User’s Meeting
June 8th - June 11th, 2021
Alex Jentsch (Brookhaven National Laboratory)
Far-forward physics at EIC

- **e+p DVCS events with proton tagging.**
- **Meson structure:**
  - with neutron tagging ($ep \rightarrow (\pi) \rightarrow e' n X$)
  - Lambda decays ($\Lambda \rightarrow p\pi^- \text{ and } \Lambda \rightarrow n\pi^0$)
- **Saturation (coherent/incoherent $J/\psi$ production):**
  - thickness
  - coherent
- **Diffraction**
- **e+d incoherent $J/\Psi$ events with proton or neutron tagging**
  - $e+p$ DVCS events with proton tagging.
  - $e+d$ incoherent $J/\Psi$ events with proton or neutron tagging.
  - $e+He3$ with spectator proton tagging.
  - Tagging of coherent light ions (d, He3, He4) from coherent scattering.
  - $e+Au$ events with neutron tagging to veto breakup and photon acceptance.

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Far-forward physics at EIC

- The various physics channels require tagging of charged hadrons (protons, pions) or neutral particles (neutrons, photons) at very-forward rapidities ($\eta > 4.5$).
- Different final states require different detector subsystem for detection.
- Different collision systems provide unique challenges due to magnetic rigidity difference between beam and final-state particles.
- Placing far-forward detectors uniquely challenging due to presence of machine components, space constraint, apertures, etc.
Far-Forward Interaction Region Design and Detectors
• Central detector spans 9 meters and is machine-component free (except for beam pipe).
• Hadron-going and electron-going directions after central detector fully instrumented.
• Hadron and electron beam cross with an angle of 25 mrad.
EIC Interaction Region Layout

- **Central detector** spans 9 meters and is machine-component free (except for beam pipe).
- **Hadron**-going and **electron**-going directions after central detector fully instrumented.
- Hadron and electron beam cross with an angle of 25 mrad.

**EIC CDR:**

**EIC Yellow Report:**
FF Hadron-Going Direction & Acceptance

<table>
<thead>
<tr>
<th>Detector</th>
<th>Acceptance</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero-Degree Calorimeter (ZDC)</td>
<td>$\theta &lt; 5.5$ mrad ($\eta &gt; 6$)</td>
<td>About 4.0 mrad at $\phi \sim \pi$</td>
</tr>
<tr>
<td>Roman Pots (2 stations)</td>
<td>$0.0^* &lt; \theta &lt; 5.0$ mrad ($\eta &gt; 6$)</td>
<td>$0.65 &lt; \frac{p_{z,nucleon}}{p_{z,beam}} &lt; 1.0$ *10$\sigma$ cut</td>
</tr>
<tr>
<td>Off-Momentum Detectors (OMD)</td>
<td>$0.0 &lt; \theta &lt; 5.0$ mrad ($\eta &gt; 6$)</td>
<td>Roughly $0.3 &lt; \frac{p_{z,nucleon}}{p_{z,beam}} &lt; 0.6$</td>
</tr>
<tr>
<td>B0 Sensors (4 layers, evenly spaced)</td>
<td>$5.5 &lt; \theta &lt; 20.0$ mrad (4.6 &lt; $\eta$ &lt; 5.9)</td>
<td>Also looking at photon tagging via EMCAL/preshower.</td>
</tr>
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</table>

\[ \text{“nucleon momentum fraction”} = \frac{p_{z,nucleon}}{p_{z,beam}} \]

Fraction of momentum for nucleon compared to beam.

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Details of Individual Detector Requirements (based on IP6 studies)
Roman Pots

\[0.0^* (10\sigma \text{ cut}) < \theta < 5.0 \text{ mrad}\]

\[\sigma(z) = \sqrt{\varepsilon \cdot \beta(z)}\]

- **Requirements:**
  - Fast timing (\(\sim 35\)ps) to remove vertex smearing effect from crab rotation.
  - 500um x 500um pixels.
  - Radiation hardness (not as stringent as LHC).
  - Large active area (25cm x 10cm).
- AC-LGADs cover these requirements in one package.

- Low-pT cutoff determined by beam optics.
  - The safe distance is \(10\sigma\) from the beam center.
- These optics choices change with energy, but can also be changed within a single energy to maximize either acceptance at the RP, or the luminosity.
Roman Pots

- Updated strawman layout with current design for LGAD sensor + ASIC.

![Diagram of ASIC layout]

- Problems to be solved:
  - Full engineering layout with insertion tooling.
  - Cooling scheme needed to go with “potless” design.

<table>
<thead>
<tr>
<th>ASIC size</th>
<th>ASIC Pixel pitch</th>
<th># Ch. per ASIC</th>
<th># ASICs per module</th>
<th>Sensor area</th>
<th># Mod. per layer</th>
<th>Total # ASICS</th>
<th>Total # Ch.</th>
<th>Total Si Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6x1.8 cm²</td>
<td>500 μm</td>
<td>32x32</td>
<td>4</td>
<td>3.2x3.2 cm²</td>
<td>32</td>
<td>512</td>
<td>524,288</td>
<td>1,311 cm²</td>
</tr>
</tbody>
</table>

AC-coupled Low Gain Avalanche Detectors (AC-LGADs)
Study of ultimate spatial resolution:
- Strips with variable pitches and geometry (e.g. zig-zag, hexagonal, crosses)
- Produced to test dependence of signal sharing (space resolution) on geometry - tested at test-beams.
- Different geometrical patterns optimized for spatial resolution could allow for larger overall pixel size, and therefore less total pixels per sensor -> leads to reduced number of channels and power consumption, and less cooling!

Test-beam at FNAL with 120 GeV protons shows that AC-LGADs meet requirements
- 30-35 ps time resolution
- < 15 µm space resolution with strip sensor: 100 µm pitch, 20 µm gap
- ~100% particle detection efficiency
- See: [https://indico.fnal.gov/event/46746/contributions/210254/attachments/141193/177718/Apresyan_4D-trackers.pdf](https://indico.fnal.gov/event/46746/contributions/210254/attachments/141193/177718/Apresyan_4D-trackers.pdf)
Roman Pots

**Assembly:** ALTIROC0 v1 prototype (4 channels) + strip AC-LGAD with pitch 100 μm, and inter-strip gap of 20 μm.
- ALTIROC0 chip: analog readout after the preamplifier, 2 TDCs (Time-Of-Arrival and Time-Over-Threshold) and threshold discriminator. Time jitter smaller than 20 ps for input charge larger than 5 fC
  - ALTIROC1 + AC-LGAD already assembled for studying the Constant Fraction Discriminator. To be studied next period.

- Signal from beta-particles from 90Sr source.
- Clear signal with negative and positive polarity.
- Fast (~5 ns) signal compatible with published results for (DC-)LGAD sensors read-out via ALTIROC0 [JINST 15 P07007 (2020)]

- **Main modifications have been identified to reduce pixel pitch from 1.3 mm to 500 μm**
- ASIC power dissipation of a 32x32 channel ASIC
  - Per pixel power dissipation of 3 mW (assuming 10% occupancy - very conservative!, as expected occupancy <<01%)
    - 3.072 W per chip, including the peripheral electronics
    - 1.067 W/cm² power density
    - total power dissipation in the whole detector of 1.573kW (Strawman layout)
      - For comparison ALTIROC for HGTD: 1.2 W/chip (300 mW/cm²) and 19.3kW total power dissipation
Roman Pots & Machine Optics

**18x275 GeV DVCS Proton Acceptance**

<table>
<thead>
<tr>
<th>e+p Beam Energy</th>
<th>Option 1 (high luminosity)</th>
<th>Option 2 (high acceptance)</th>
</tr>
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<tbody>
<tr>
<td>18x275 GeV</td>
<td>$p_T &gt; 0.35$ GeV/c</td>
<td>$p_T &gt; 0.2$ GeV/c</td>
</tr>
<tr>
<td>10x100 GeV</td>
<td>$p_T &gt; 0.2$ GeV/c</td>
<td>$p_T &gt; 0.1$ GeV/c (or better)</td>
</tr>
<tr>
<td>5x41 GeV</td>
<td>$p_T &gt; 0.1$ GeV/c</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Option 1:** higher lumi., larger beam at RP  
**Option 2:** lower lumi., smaller beam at RP

The luminosity trade-off is about a factor of 2 between the different configurations.
Off-Momentum detectors

- Off-momentum detectors used for tagging protons from nuclear breakup and decay products (e.g. $\pi^-$ and protons).
- Can use same technology as Roman Pots system.
- Placed outside the beam pipe after the B1apf dipole (last dipole before long drift section that leads to the Roman Pots).

$e^+d \rightarrow J/\psi + p + n \ (18x110\text{GeV})$

**Neutron spectator/leading proton case.**

- Acceptance mostly limited by losses of very off momentum particles in quadrupoles.

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**B0-detectors**

(5.5 < θ < 20.0 mrad)

- Charged particle reconstruction.
  - Precise tracking -> need smaller pixels (50um) than for the RP.
  - Require timing layer for the crab rotation and background rejection.
  - Shape and # of layers of B0 tracker needs to be further evaluated.

- Higher granularity detectors needed in this area (MAPS, or something similar) with layers of fast-timing detectors (e.g. LGADs), or timepix (provides high resolution space and timing information), depending on sensor layout and size.
B0-detectors

(5.5 < \theta < 20.0 \text{ mrad})

• ~1.2 meters of longitudinal space in bore.
• Could potentially have several layers of silicon for tracking, and a few layers after for some EM calorimetry (compact).

- Tagging photons is also important in differentiating between coherent and incoherent heavy-nuclear scattering.
- Potential inclusion of small EMCAL or preshower detector in the B0 bore.
- Further study needed to assess.
- Tagging photons further down-stream (ZDC) highly technically challenging.
Zero-Degree Calorimeter

- High resolution HCAL + EMCAL for detecting neutral forward-going particles (neutrons and photons) – using ALICE FoCal as starting point.
- Acceptance limited by bore of magnet where the neutron/photon cone exits.
  - $0.0 < \theta < 4.5 \text{ mrad}$
Zero-Degree Calorimeter

• High resolution HCAL + EMCAL for detecting neutral forward-going particles (neutrons and photons) – using ALICE FoCal as starting point.

• Acceptance limited by bore of magnet where the neutron/photon cone exits.
  • $0.0 < \theta < 4.5$ mrad

ZDC uses Silicon/PbW04 for EM followed Silcion/W for Hadronic Section
What about the second IR?
Some thoughts on IP8

• Most of the technology and detector concepts can be also used for IP8.
• There is (always) a desire for more acceptance!
  • Proposed secondary focus at RP location to improve low-pt acceptance.
  • Altered bending direction for separation of beam and breakup neutrons to try and improve neutron cone acceptance.
  • Different placement of between-detector gaps @ IP6/IP8 so combined measurements cover full phase-space.
• While the same basic ideas from IP6 can be used for the detector solutions, the optimization problem for the different subsystem needs careful thought.
• A first version of the IP8 design was released to the EIC proto-collaborations this week!
IP8 Layout (FF hadron-going)

- Central trajectory proton at 275 GeV shown traversing the full lattice.
  - 35 mrad crossing angle.
- Roman pots placed on central axis.
- Roman Pots @ Secondary Focus (RPSF) placed after QDS01.
- OMD placed to grab off-momentum particles
- ZDC is placed more or less in the best place, as close to a reasonable beam pipe diameter (~6cm) as was comparable to IP6.

- Detectors should be optimally placed to maximize acceptance and consideration should be given to shift “gaps” between detectors to different spots than in IP6.
- Reuse of technology from IP6 designs can help reduce overall cost.
Secondary Focus

- 270 < p < 275 GeV protons
- 0 < theta < 5 mrad

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Takeaways

• Much has been achieved during the YR in understanding the physics reach possible with IP6.
  • Many of these studies provide crucial benchmarks for deciding on options for IP8!
• Things are rapidly moving past the YR era as the proto-collaborations (ATHENA, CORE, ECCE) look at more-detailed material considerations and cost.
• Many of the lessons learned from studies in IP6 are very beneficial to the continued development of IP8.
• The far-forward region of both IPs is extremely important to the entire exclusive/diffractive physics program at the EIC!
Backup
Reminder: Timing

For exclusive reactions measured with the Roman Pots we need good timing to resolve the position of the interaction within the proton bunch. But what should the timing be?

- Because of the rotation, the Roman Pots see the bunch crossing smeared in x.
- Vertex smearing = 12.5 mrad (half the crossing angle) * 10 cm = 1.25 mm
- If the effective vertex smearing was for a 1 cm bunch, we would have 0.125 mm vertex smearing.
- The simulations were done with these two extrema and the results compared.

- From these comparisons, reducing the effective vertex smearing to that of the 1 cm bunch length reduces the momentum smearing to a negligible amount from this contribution.
- This can be achieved with timing of ~35 ps (1 cm/speed of light).
Reality of Particle Detectors: Smearing Contributions

• **Angular divergence**
  - Angular “spread” of the beam away from the central trajectory.
  - Gives some small initial transverse momentum to the beam particles.

• **Crab cavity rotation**
  - Can perform rotations of the beam bunches in 2D.
  - Used to account for the luminosity drop due to the crossing angle – allows for head-on collisions to still take place.

• **Detector Choices**
  - Pixel size, RP transfer matrix, etc.

These effects introduce smearing in our momentum reconstruction.
In the proton spectator case, essentially all spectators tagged.

Active neutrons only tagged up to 4.5 mrad.
**Spectator Tagging**

**Neutron spectator case.** Particular process in BeAGLE: incoherent diffractive J/ψ production off bounded nucleons.

- 
  \[ t = (p' - p)^2 \]
  \[ t' = (n' - d)^2 - M_p \]

- 
  \[
  \gamma^*d \rightarrow J/\psi + p' + n' \]
- 
  Leading proton reconstruction using double-tagging (both proton and neutron). Takes advantage of combined B0 + off-momentum detector coverage. Better coverage in the neutron spectator case.

- 
  Spectator information is the “dial” for the SRC region.

Ongoing Studies – Free Neutron Structure and Modifications.

- $e+d$ spectator proton tagging yields access to free-neutron $F_2$ via on-shell extrapolation.
  - Paper will be on the ArXiv in a few weeks.
- Further studies ongoing to examine nuclear modifications and effect of detector smearing.
Ongoing Studies – e+He3 scattering.

- Studies of neutron structure with a polarized neutron.
- More challenging final state tagging since both protons must be tagged in the FF region.
- MC events generated with CLASDIS in fixed-target frame, and then boosted to collider frame.
- Paper on the ArXiv soon.
e+p DVCS

• Full GEANT4 simulations with Roman Pots carried out.
• All acceptance & smearing effects included.

18x275 GeV e+p DVCS events generated with MILOU.

- Low-|t| acceptance affected by beam optics/size of beam at Roman Pots – can be mitigated with different optics configurations.
- With all smearing effects included, extraction of slope for Fourier Transform straightforward.