Fast Timing Detectors at Electron Ion Collider

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Electron Ion Collider (2031-)

Design Goals

• High Luminosity: $L = 10^{33} - 10^{34}$ cm$^{-2}$s$^{-1}$, 10–100 fb$^{-1}$/year
• Highly Polarized Beams: ~70%
• Large Center of Mass Energy Range: $E_{cm} = 20$–140 GeV
• Large Ion Species Range: protons – Uranium
• Large Detector Acceptance and Good Background Conditions
• Accommodate two Interaction Regions (IR)

Critical Decisions

Initiation

CD-0
Approve Mission Need
12/2019

Definition

CD-1
Approve Alternative Selection and Cost Range
6/2021

CD-2/3A
Approve Performance Baseline (PB)
~1/2024

CD-3
Approve Start of Construction or Execution
~4/2025

Closeout

CD-4A EF
Approve Start of Operations or Project Completion
~4/2031

Note: EIC CDR

Electron Beam: 5-18 GeV   Ion: 40, 100-275 GeV
How are the gluons and sea quarks, and their spins, distributed in space and momentum inside the nucleon? What is the role of orbital motion in building the nucleon spin?

How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions? What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

Among the highest priority of US Nuclear Physics, endorsed by National Academy of Science, Engineering and Medicine (NAS)
**EIC Detectors**

### Detector-1 (project detector)
- IP6 (25 mrad crossing angle with crabbing)
- Addresses EIC science program as outlined in the EIC white paper and NAS report
- Ready for Day-1 operations in ~2031
- Working towards pre-TDR/CD-2

### Detector-2 (strong comm. interests)
- IP8 (35 mrad crossing angle)
- Complementary to Detector-1
- Require development of 2nd IR
- Ready 2-5 years after Detector-1
- Development at WG level

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**Inclusive DIS**

$e \rightarrow e', \gamma^*$

$p \rightarrow \nu, \ldots \{ X \}$

**Semi-inclusive DIS**

$e \rightarrow e', \gamma^*$

$p \rightarrow h, \gamma \{ X \}$

**Exclusive**

$e \rightarrow e', \gamma^*$

$p \rightarrow \nu'$
AC-LGAD for EIC

- Precise timing detectors based on DC-LGAD being built by ATLAS (6.4 m$^2$) and CMS (14 m$^2$) for data taking in 2028+.

- AC-LGAD can not only provide precise timing resolution similar to DC-LGAD, but also 100% fill factor and much better spatial resolution thanks to charge sharing.

- AC-LGAD proposed for EIC experiments
  - TOF PID and tracking for central detectors
  - timing and tracking for forward detectors with common designs in sensor, ASIC etc. where possible.
EIC Detector-1 Reference Design

Tracking:
• Si MAPS
• AC-LGAD (~30 μm)
• μR WELL

PID:
• hp-DIRC
• mRICH
• dRICH
• AC-LGAD (~30 ps)

Calorimetry:
• SciGlass Barrel EMCal
• PbWO EEMCal
• Longitudinally separated EM+Hcal
• Inner HCal (instrumented frame)
• Outer HCal (sPHENIX re-use)

Different to LHC
• lower momentum
• lower occupancy
• less irradiation
Explore AC-LGAD technology and leverage established LHC DC-LGAD detector designs to minimize cost and risk

- **Time-of-flight for e/π/K/p identification** at low-to-intermediate p range
- Provide a **high spatial resolution point** for tracking

Reference Design (optimization ongoing)
- **Timing resolution**: ~25 ps per hit
- **Position resolution**: ~30 µm with 500 µm pitch
- **Material budget**: ~8% X0
- **Total area**: ~ 15 m²

TOF PID coverage
- **ETTL**: -3.7 < \(\eta\) < -1.74  \(0.15 < p < 2.5\ \text{GeV}\)
- **FTTL**: 1.5 < \(\eta\) < 3.5  \(0.15 < p < 2\ \text{GeV}\)
- **CTTL**: |\(\eta\)| < 1.4  \(0.15 < p_T < 1.5\ \text{GeV}\)
AC-LGADs in Forward Detectors: Timing + Tracking

Technologies defined
- Silicon: AC-LGAD & MAPS
- ZDC:
  - ECAL (PbWO4)
  - HCAL (PbSi + PbScint)

<table>
<thead>
<tr>
<th>Detector</th>
<th>Angular accept. [mrad]</th>
<th>p_\text{T} coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZDC @ ~30m</td>
<td>( \theta &lt; 5.5 \ (\eta &gt; 6) )</td>
<td>( \text{p}_T &lt; 1.3 \text{ GeV} )</td>
</tr>
<tr>
<td>Roman Pots</td>
<td>( 0^* &lt; \theta &lt; 5.0 \ (\eta &gt; 6) )</td>
<td>*Low ( \text{p}_T(t) ) cutoff (beam optics)</td>
</tr>
<tr>
<td>Off-Momentum Detectors</td>
<td>( 0 &lt; \theta &lt; 5.0 \ (\eta &gt; 6) )</td>
<td>Low-rigidity particles from nuclear breakups</td>
</tr>
<tr>
<td>B0 forward spectrometer</td>
<td>( 5.5 &lt; \theta &lt; 20.0 ) (( 4.6 &lt; \eta &lt; 5.9 ))</td>
<td>High ( \text{p}_T(t) )</td>
</tr>
</tbody>
</table>
eRD112: Sensor R&D

- **R&D Goals**
  - 15-20 ps timing resolution, O(~30\(\mu m\)) position resolution where needed
  - Minimal readout channel density (strip, rectangular pixel) for reduced power, material and cost

- **Plan**
  - Produce and test large area sensors with thinner active volume to achieve the desired timing resolution
  - Optimize implantation parameters and AC-pad segmentation through simulation and real device studies
  - Engage commercial vendors to improve fabrication process and yield

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![AC-LGAD Sensor Wafer by BNL IO 2021](image1)

![500 um*1cm strip AC-LGAD sensor mounted on test board](image2)

![Signal amplitude vs x position at 2022 Fermilab test beam](image3)
**EICROC by Omega/Irfu/AGH**
- Preamp, discr. taken from ATLAS ALTIROC
- I2C slow control taken from CMS HGCROC
- TOA TDC adapted by IRFU Saclay
- ADC adapted to 8bits by AGH Krakow
- Digital readout: FIFO depth8 (200 ns)

**FCFD by Fermilab**
- Adapt the Constant Fraction Discriminator (CFD) principle in a pixel paired with a TDC, one time measurement gives the final answer.
- Charge injection consistent with simulations: ~30 ps at 5 fC, and <10 ps at 30 fC
- Tests with beta sources and beam are planned

**HPSoC by Nalu Scientific LLC**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Channel no.</td>
<td>100x (pitch 300-500 μm)</td>
</tr>
<tr>
<td>Process</td>
<td>65nm CMOS</td>
</tr>
<tr>
<td>Sample rate</td>
<td>10 GSa/s</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>2 GHz</td>
</tr>
<tr>
<td>No. bits</td>
<td>10</td>
</tr>
<tr>
<td>Supply Voltage</td>
<td>1.0V (2.5V for digital I/O)</td>
</tr>
<tr>
<td>Timing accuracy</td>
<td>1 ps</td>
</tr>
<tr>
<td>Front-end stage</td>
<td>Embedded TIA</td>
</tr>
<tr>
<td>Buffer length/channel</td>
<td>256 samples</td>
</tr>
<tr>
<td>Power/channel</td>
<td>2mW</td>
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<tr>
<td>On-chip integration</td>
<td>Sampling, Digitization, Calibration, Feature Extraction, Data Fusion</td>
</tr>
</tbody>
</table>
Summary and Outlook

- **AC-LGAD** is the selected technology by EIC Detector-1 for timing and tracking in central and far-forward detectors. Other fast timing technologies could be considered for Detector-2
  - **Opportunity**: new detector technology development; multi-million and multi-year projects.
  - **Challenge**: strict detector performance requirements; tight schedule.

  TOF WG Mailing list: eic-projdet-tofpid-1@lists.bnl.gov
  Indico page: [https://indico.bnl.gov/category/414](https://indico.bnl.gov/category/414)

- **eRD112**: develop sensor, ASIC, and other key components for AC-LGAD detectors at EIC
  - **Approach**: having common design and with combined R&D efforts for different detectors when possible.

  eRD112 Mailing list: [https://mailman.rice.edu/mailman/listinfo/lgads-eic](https://mailman.rice.edu/mailman/listinfo/lgads-eic)
  Indico page: [https://indico.bnl.gov/category/323/](https://indico.bnl.gov/category/323/)

- **Everyone is VERY welcome to join eRD112 and other EIC detector/physics efforts.**

  EIC Users Group Meeting @ Stony Brook University, July 26-29, 2022, [https://indico.bnl.gov/event/15342/](https://indico.bnl.gov/event/15342/)

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**Timeline – What is Coming for EIC**

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
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<tbody>
<tr>
<td>CD-0 approval</td>
<td>December 19, 2019</td>
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<tr>
<td>Community-wide Yellow Report effort</td>
<td>Dec 2019 – Feb. 2021</td>
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<tr>
<td>CD-1 review (includes CDR)</td>
<td>January 26-29, 2021</td>
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<tr>
<td>Call for Collaboration Proposals for Detectors</td>
<td>March 6, 2021</td>
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<tr>
<td>CD-1 approval</td>
<td>June 29, 2021</td>
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<tr>
<td>DOE/OPA Status Review</td>
<td>October 19-21, 2021</td>
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<tr>
<td>Status Update to Federal Project Director</td>
<td>June 28-30, 2022</td>
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<tr>
<td>Cost and Schedule Event(s)</td>
<td>May-June 2022</td>
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<tr>
<td>Technical Subsystem Reviews</td>
<td>Jan. – Dec. 2022</td>
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<tr>
<td>OPA Status Review</td>
<td>January 2023</td>
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<tr>
<td>Preliminary Design Complete &amp; Review</td>
<td>May 2023</td>
</tr>
<tr>
<td>Final Design/Maturity Readiness for CD-3A Items</td>
<td>May 2023</td>
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<tr>
<td>CD-2/3A review (expectation), requires pre-TDR</td>
<td>~October 2023</td>
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<tr>
<td>CD-2/3A (expectation)</td>
<td>~January 2024</td>
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<tr>
<td>CD-3 review (expectation)</td>
<td>~January 2025</td>
</tr>
<tr>
<td>CD-3 (expectation), requires TDR</td>
<td>~April 2025</td>
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References