4D Trackers Based on AC-LGAD with Long Strip Readout Electrodes

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AC-coupled Low Gain Avalanche Diode (AC-LGAD) sensors:

- Large area LGAD detectors for fast timing are being built by ATLAS (6.4 m$^2$) and CMS (14 m$^2$) for data taking in 2028+
  - LGAD cells have a size of 1.3 × 1.3 mm$^2$
- Timing resolution of O(10 ps) can be achieved by LGAD
- LGAD sensor not able to achieve a 100% fill factor
- The position resolution in LGAD limited to $\sqrt{1/12}$ of cell size

**AC-LGAD:** Electrical signals in the resistive but continuous n$^+$ layer are AC-coupled to metal electrodes

- With 100% fill factor, AC-LGAD can provide much better spatial resolution due to signal sharing between metal electrodes
- Precise timing resolution similar like LGAD
- AC-LGAD, a good candidate for 4D trackers at future high energy experiments
- AC-LGAD proposed for EIC experiments
  - ToF PID and tracking for central detectors
  - Timing and tracking for far forward detectors

Large area LGAD detectors for fast timing are being built by ATLAS (6.4 m$^2$) and CMS (14 m$^2$) for data taking in 2028+...
AC-LGAD detectors for ePIC in EIC:

Central Detector: ToF PID + Tracking

- Need more than one technology to cover the entire momentum ranges at different rapidity
- Precision timing detector in EIC will provide PID capabilities below the threshold of Cherenkov PID detectors
- ToF for e/π/K/p identification at low-to-intermediate momentum range
- Provide a high spatial resolution point for tracking

<table>
<thead>
<tr>
<th>Detector</th>
<th>Angular accept.</th>
<th>p_T coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel ToF</td>
<td>$-1.4 &lt; \eta &lt; 1.4$</td>
<td>$0.15 &lt; p_T &lt; 1.5$ GeV</td>
</tr>
<tr>
<td>Forward ToF</td>
<td>$1.5 &lt; \eta &lt; 3.5$</td>
<td>$0.15 &lt; p &lt; 2.0$ GeV</td>
</tr>
</tbody>
</table>
AC-LGAD detectors for ePIC in EIC:
Far Forward Detector: Timing + Tracking

- B0 provides very forward tracking capability for charged particles
- Roman Pots to detect scattered charged particles close to beam
- The off-momentum detectors designed to capture charged particles from nuclear breakup

<table>
<thead>
<tr>
<th>Detector</th>
<th>Angular accept.</th>
<th>p_T coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>B0 Detector</td>
<td>$4.6 &lt; \eta &lt; 5.9$</td>
<td>Higher p_T</td>
</tr>
<tr>
<td>Roman Pots</td>
<td>$\eta &gt; 6$</td>
<td>Low p_T cut-off from beam optics</td>
</tr>
<tr>
<td>Off-Momentum</td>
<td>$\eta &gt; 6$</td>
<td>Low-rigidity from nucl. breakups</td>
</tr>
</tbody>
</table>
Specifications of ePIC AC-LGAD detectors:

<table>
<thead>
<tr>
<th></th>
<th>Area (m²)</th>
<th>Channel size (mm²)</th>
<th># of Channels</th>
<th>Timing Resolution</th>
<th>Spatial resolution</th>
<th>Material budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel TOF</td>
<td>10.9</td>
<td>0.5*10 (strips)</td>
<td>2.4M</td>
<td>30 ps</td>
<td>30 μm in φ</td>
<td>0.01 X0</td>
</tr>
<tr>
<td>Forward TOF</td>
<td>2.22</td>
<td>0.5*0.5 (pixels)</td>
<td>8.8M</td>
<td>25 ps</td>
<td>30 μm in x and y</td>
<td>0.08 X0</td>
</tr>
<tr>
<td>B0 tracker</td>
<td>0.07</td>
<td>0.5*0.5 (pixels)</td>
<td>0.28M</td>
<td>30 ps</td>
<td>20 μm in x and y</td>
<td>0.05 X0</td>
</tr>
<tr>
<td>RPs/OMD</td>
<td>0.14/0.08</td>
<td>0.5*0.5 (pixels)</td>
<td>0.56M/0.32M</td>
<td>30 ps</td>
<td>140 μm in x and y</td>
<td>no strict req.</td>
</tr>
</tbody>
</table>

4D Trackers

Requirements on timing and spatial resolutions and material budget are still being evaluated and are subject to change as the design matures, and we will continue to explore common designs for these detectors where possible to reduce cost and risk.
Fermilab Test Beam Facility (FTBF):

• Measurements conducted at Fermilab Test Beam Facility (FTBF)
  - Used 120 GeV primary proton beam from main injector
  - 4 second beam spill every 60 seconds

• AC-LGADs have been extensively studied using the FTBF

• First beam test in March 2022 focused on first batch of long strip BNL sensors
  - Paper detailing 2022 beam test results ([arxiv:2211.09698](https://arxiv.org/abs/2211.09698))

• Second beam test concluded in January 2023 on second batch of long strip BNL sensors
Fermilab test beam setup for AC-LGADs:

- Permanent setup in FNAL test beam facility (FTBF)
- Tracking telescope resolution ~ 5 μm
- Microchannel plate detector (MCP-PMT) time reference resolution ~ 10 ps
- AC-LGAD and MCP-PMT waveforms were recorded in the oscilloscope
- Sensor alignment based on position of sensor along beamline and rotation around beam axis
- Developed readout boards for the characterization of LGADs
Large area AC-LGAD sensors in test beam campaign 2022:

- Fabricated in a class-100 clean room at BNL on 4-inch, p-type epitaxial wafers
- A total of 15 different AC-LGAD sensors were exposed to the FNAL proton beam
- Focus on geometric optimization of the electrodes
- Operating voltage roughly 10 V to 15 V before breakdown

<table>
<thead>
<tr>
<th>Name</th>
<th>Pitch</th>
<th>Metal Width</th>
<th>Length</th>
<th>Thickness</th>
<th>Operating Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNL 5–200</td>
<td>500</td>
<td>200</td>
<td>5</td>
<td>50</td>
<td>245</td>
</tr>
<tr>
<td>BNL 10–100</td>
<td>500</td>
<td>100</td>
<td>10</td>
<td>50</td>
<td>220</td>
</tr>
<tr>
<td>BNL 10–200</td>
<td>500</td>
<td>200</td>
<td>10</td>
<td>50</td>
<td>255</td>
</tr>
<tr>
<td>BNL 10–300</td>
<td>500</td>
<td>300</td>
<td>10</td>
<td>50</td>
<td>240</td>
</tr>
<tr>
<td>BNL 25–200</td>
<td>500</td>
<td>200</td>
<td>25</td>
<td>50</td>
<td>215</td>
</tr>
</tbody>
</table>
Spatial resolution in AC-LGADs:

- Signal sharing between strips enables the $x$ position reconstruction

- Amplitude fraction $f = a_1 / (a_1 + a_2)$ where $a_1$ and $a_2$ are the leading and sub-leading strip amplitudes

- The efficiency for a proton to produce a signal in at least one strip reaches $\sim 100\%$
  \[
  \text{Efficiency} = \frac{\text{Events with Amplitude} > \text{Threshold (15 mV)}}{\text{All Events}}
  \]

- Two-strip resolution $\sim 15 - 20 \mu m$ for BNL 10-220

- One-strip resolution $\sim 80 \mu m$ for BNL 10-220
Time resolution in AC-LGADs:

- Due to larger electrodes, distant signals arrive with delays \(O(100\, \text{ps})\)
- Position-dependent time delay correction is performed in two ways,
  - using the external tracker
  - relying on position reconstruction
- Without delay correction, the time resolution to 50 ps–70 ps
- Adding the tracker-based delay corrections improves the resolution to 40 – 55 ps
- Using multi-channel timestamp with delay correction improves time resolution to 40 – 45 ps

\[
\tau_{\text{reco}} = \frac{a_1^2 t_1 + a_2^2 t_2}{a_1^2 + a_2^2}
\]
Gain uniformity of AC-LGADs:

- First batch production sensors had localized gain featured
  - High gain regions limit operating voltage, and the other regions remain underbiased
- BNL adapted their gain implantation procedure
  - Greatly improved gain uniformity with second batch sensors
  - Relatively smaller signal size observed
- Expect improved gain uniformity with high gain in large area AC-LGADs

Test Beam Campaign January 2023
(2nd batch production at BNL)
Summary:

- AC-LGADs provide excellent 4D performance, with timing resolution comparable to LGADs,
  - spatial resolution ~ 20-30x smaller than pitch
  - 100% fill factor
- Large, coarse pitch sensors show promising performance, obtaining resolutions of 20 μm & 30 ps simultaneously in best regions

- With few modifications, sensors for ePIC AC-LGAD detectors are within reach!
  - Improved gain implant uniformity with higher gain
  - Improved two-strip efficiency with reduced metal width
  - Studying time resolution with thickness variation
  - All implemented in latest prototypes to be tested soon!!

### 4D tracking performance

<table>
<thead>
<tr>
<th>Name</th>
<th>Time resolution</th>
<th>Spatial resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High gain ps</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Resolution μm</td>
<td>Eff.</td>
</tr>
<tr>
<td>BNL 5–200</td>
<td>30 ± 1</td>
<td>61 ± 1</td>
</tr>
<tr>
<td>BNL 10–100</td>
<td>35 ± 1</td>
<td>69 ± 1</td>
</tr>
<tr>
<td>BNL 10–200</td>
<td>32 ± 1</td>
<td>82 ± 1</td>
</tr>
<tr>
<td>BNL 10–300</td>
<td>36 ± 1</td>
<td>83 ± 1</td>
</tr>
<tr>
<td>BNL 25–200</td>
<td>51 ± 1</td>
<td>128 ± 1</td>
</tr>
</tbody>
</table>
AC-LGAD team:

Fermilab: Christopher Madrid, Ryan Heller, Artur Apresyan, Sergey Los, Cristián Peña, Si Xie, Irene Dutta

BNL: Wei Chen, Gabriele Giacomini, Alessandro Tricoli

Caltech: Si Xie

Universidad Técnica Federico Santa María: Claudio San Martín, William K. Brooks, René Rios

University of Illinois at Chicago: Shirsendu Nanda, Zhenyu Ye

The University of Iowa: Ohannes Kamer Köseyan

Yerevan Physics Institute: Aram Hayrapetyan

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Backup:
Pulse Shape, expected position resolution, and propagation delay:

- Expected resolution for the two-strip reconstruction,
  \[ \sigma_x^{\text{expected}} = P \left| \frac{dh}{df} \right| \frac{\sqrt{a_1^2 + a_2^2}}{(a_1 + a_2)^2} N \]  
  where, \( P \) is the pitch of sensor

- Longer strips associated with slower rising edge
  \[ \sigma_{\text{jitter}} = \frac{N}{dV/dt} \sim \frac{t_{\text{rise}}}{S/N} \]

- Noise (\( N \)) is typically \( \sim 2 \) mV and smaller amplitude (\( S \)) for longer strips

![Graphs and plots illustrating pulse shapes and resolution](image-url)