Development of AC-LGADs for large-scale high-precision timing and position measurements

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Collaborators


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Precision tracking and timing

- LHC and HL-LHC: high energies, luminosities in p-p collisions – pileup and radiation damage
- Phase-2 upgrades for ATLAS and CMS: improvement of tracking detectors (silicon pixels and strips) + installation of dedicated timing detectors to reduce effect of pileup at extreme luminosities

LHC nominal: $10^{34}$ cm$^{-2}$ s$^{-1}$

HL-LHC: $10^{35}$ cm$^{-2}$ s$^{-1}$

- 4D tracking is going to be essential in future high-energy physics experiments to mitigate effects of higher luminosity and pile-up and to improve tracking, vertexing and timing precision

CMS Collaboration, A MIP Timing Detector for the CMS Phase-2 Upgrade, CERN-LHCC-2019-003, 2019
ATLAS Collaboration, A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade, CERN-LHCC-2018-023, 2018
H. F.-W. Sadrozinski et al, 4D tracking with ultra-fast silicon detectors, Reports on Progress in Physics 2018, 81, 026101
Low gain avalanche diodes

- Silicon low-gain avalanche diodes (LGADs) are studied by the CMS and ATLAS experiments for their endcap timing detector upgrades
  - Thin sensors, typical thickness 50 µm
  - Low to moderate gain (5-50) provided by p⁺ multiplication layer
    - Timing resolution down to ca. 20 ps
    - Good radiation hardness up to $10^{15}$ $n_{eq}/cm^2$

- A more recent development: AC-coupled LGAD

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AC-coupled low gain avalanche diodes

- In AC-coupled LGADs, also referred to as Resistive Silicon Detectors (RSD), the multiplication layer and n\textsuperscript{+} contact are continuous, only the metal is patterned:
  - The signal is read out from metal pads on top of a continuous layer of dielectric
  - The underlying resistive n\textsuperscript{+} implant is contacted only by a separate grounding contact
  - No junction termination extension: fill factor \sim 100
- The continuous n\textsuperscript{+} layer is resistive, i.e. extraction of charges is not direct
  - Mirroring of charge at the n\textsuperscript{+} layer on the metal pads: AC-coupling
  - Strong sharing of charge between metal pads
  - Extrapolation of position based on signal sharing – finer position resolution for larger pitch, also allowing for more sparse readout channels

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G. Giacomini et al., Fabrication and performance of AC-coupled LGADs, *JINST* 2019, 14, P09004
A. Apresyan et al., Measurements of an AC-LGAD strip sensor with a 120 GeV proton beam, *JINST* 2020, 15, P09038
S. M. Mazza, An LGAD-Based Full Active Target for the PIONEER Experiment, *Instruments* 2021, 5(4), 40
Key developments in (AC-)LGADs

- Gain layer doping
  - Suitable gain, breakdown voltage, radiation hardness...
- Thinner sensors: from 50 to below 30 μm
  - Faster signal rise time and charge collection time
  - Reducing Landau component of the timing resolution
    ➢ *Towards 10 ps timing resolution*
- \( n^+ \) layer resistivity
- Dielectric
- Segmentation
  - Type: pad/pixel, strip
  - Geometry: rectangular, cross-shaped, ...
- **Metal size**
- **Pitch**
AC-LGAD strip sensors

Brookhaven National Laboratory

120 GeV proton beam at the Fermilab test beam facility

BNL 2021 Strip sensor
Metal width 80 µm, three different pitches:
  Narrow, 100 µm
  Medium, 150 µm
  Wide, 200 µm

IR Laser TCT

BNL 2021, new production
Variations in both pitch and metal width
  • 100/200/300 µm pitch with 50 % metal
  • Uniform strips: 500 µm pitch - 200 µm metal
Including long(er) strips of 1 cm and 2.5 cm

Strip length ca. 2.5 cm
Position resolution by signal sharing

Case of two adjacent strips

- Averaged maximum pulse height ($p_{max}$): The $p_{max}$ sum is not constant under the strip metal, but fairly constant between strip centers.

- The $p_{max}$ fraction of an individual strip is defined as:

  $$\text{fraction (channel)} = \frac{p_{max} \text{ (channel)}}{\Sigma p_{max}}$$

- The position resolution can be calculated from the fraction of $p_{max}$ at a given position (fitted with an error function):

  $$\text{position resolution } \sigma_{pos} = \sqrt{\frac{d(position)}{d(fraction)}} \frac{S}{N}$$

Signal-to-noise ratio is favourable in (AC-)LGADs due to their internal gain.
Position resolution in BNL 2021 strips

- Strip pitch is expected to - and appears to - have a large impact on charge sharing as seen in the pmax fraction profile...
- ...position resolution of ca. 15 µm at the respective strip metal centers (end of the data points in the plot): in fact very similar for all three pitches
- Between strips, a position resolution of ~6 µm or less is reached; slightly better for smaller pitch
  - At best, < 1/20 of the pitch

![Graph showing position resolution vs. strip pitch.](image)
Timing resolution

\[ \sigma_t^2 = \sigma_{\text{Landau}}^2 + \sigma_{\text{jitter}}^2 + \sigma_{\text{TimeWalk}}^2 + \sigma_{\text{TDC}}^2 + \sigma_{\text{Distortion}}^2 \]

- AC-LGADs provide comparable performance to conventional LGADs, determined by largely by the gain layer: < 40 ps established, 20 ps reachable
- Impact of signal sharing on timing resolution:
  - Weighted reconstruction of several contributions can improve timing resolution
  - But: lower signal in individual segment increases rise time and reduces signal-to-noise ratio (and thus timing resolution through the jitter component)
Charge on neighboring strips

- Closer examination of the individual strips’ pmax profiles reveals contribution from next and even second neighboring strip.
- Actual sharing extends from the central strip almost to the far edge of the next neighbor.
  - Localization indicates **induced** charge on the neighboring strips, not purely conduction through the resistive n⁺ layer.

Narrow, 100 µm pitch
Charge on neighboring strips

Medium, 150 µm pitch

Wide, 200 µm pitch
Charge sharing at long distances

- Selection: proton track on strip #6
- “in-time” data within 1 ns time window of the main signal

- Constant, position-independent pmax (above noise) at longer distance from hit – not predicted by simulations
  - Sharing or pick-up from the n+ layer?
Laser study of charge sharing

- 500µm-pitch/200µm-metal sensor differs from others in terms of charge sharing, but still provides < 20µm position resolution between metal strips
- **Strip length** also increases charge sharing

Strip length ca. 2.5 cm
Laser study of charge sharing

~0.5 cm

~2.5 cm
Electrode shape and capacitance

- Emphasis on electrode shape and geometry in FBK RSD2*
  - Various shapes: strips, regular rectangles, circles, crosses, stars...
  - Geometry: electrodes arranged on a square grid or on triangles
  - Metallization: e.g. cutting out the metal on strips, leaving a “frame” instead of a fully metallized strip

➢ *Direct impact on electrode capacitance*

*M. Mandurrino et al, 39th RD50 Workshop, November 2021 (https://indico.cern.ch/event/1074989/contributions/4602006/)*
Impact of $n^+$ implant dose on position resolution

- Charge sharing in terms of $p_{\text{max}}$ fraction, and subsequently position resolution can be determined in the same way for pad sensors.
- B2 and C2 refer here to different $n^+$ implant doses*
  - Effect of $n^+$ resistivity on $p_{\text{max}}$ is significant
  - $n^+$ resistivity is another parameter to tune charge sharing (to the requirements of specific applications)

Example of future experiments: PIONEER

- New pion decay experiment approved at PSI, data taking to be started in 2028 - first beam time assigned for May 2022
- Design baseline for the Active TARget: 2x2 cm² area with 48 planes of 120 µm thick AC-LGAD strips, pitch ca. 200 µm
  - Large energy deposition by stopping particles: need sufficient charge sharing to provide good spatial resolution, but not enough to occupy large areas of the sensor from one hit

Poster

S. M. Mazza, An LGAD-Based Full Active Target for the PIONEER Experiment, *Instruments* 2021, 5(4), 40
Electron-Ion Collider Detector 1

- Recently issued recommendation for Detector 1: largely based on the ECCE design, also influence from ATHENA
- Both designs include a time-of-flight particle ID detector layer with AC-LGADs as baseline technology

https://www.ecce-eic.org


Electron-Ion Collider Detector 1

- Recently issued recommendation for Detector 1: largely based on the ECCE design, also influence from ATHENA
- Both designs include a time-of-flight particle ID detector layer, with AC-LGADs as baseline technology
- *R&D efforts ongoing and ramping up!*

- Radiation hardness of timing detectors less challenging - more important:
  - Combination of precise temporal and spatial resolution: 25 ps and 30 µm / hit
  - Low material budget
- Decisions on sensor geometry and fabrication, and readout electronics to be made soon

https://www.ecce-eic.org
Thanks to signal sharing, AC-LGADs can achieve remarkable position resolution even with large and widely spaced electrodes
- Less than 1/20 of the pitch

Charge sharing in AC-LGADs is a complex phenomenon, and is influenced by the pattern of the metal electrode (width, pitch, geometry), as well as $n^+$ layer resistivity
- Induction of signal on neighboring electrodes is observed
- Examination of the noise distributions in terms of pulse height and time improves the separation of real signals from noise

- Extensive ongoing research on AC-LGADs towards precision timing and 4-dimensional tracking in future colliders and experiments
  - Efforts will provide valuable information for adjusting the properties of future AC-LGAD sensors to their targeted applications
  - Including development of readout electronics!

- Precise timing and position resolution and fast charge collection time is also attractive to other fields, such as synchrotron beam monitoring, photon counting, etc
Thank you!

US-Japan Collaborative Consortium
(Development of AC-LGADs for 4D trackers)

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Thank you!
J. Ott et al, AC-LGADs for high-precision timing and tracking, PM2021
Signal pulse shapes

- Signal in second neighbors is observed, but with lower amplitude, wider spread in $p_{\text{max}}$ and peak time $t_{\text{max}}$
- Pulse shape (when amplitude is normalized) is in fact not distinctly different
Pmax - tmax

- Test beam: time stamp relative to trigger
- Especially with fast sensors like (AC-)LGADs, precise timing of the signal is interesting for the understanding charge sharing and the role of noise

➢ *in-time* events: within certain tmax bin of the trigger - here: within 1 ns of the channel under investigation

➢ *out-of-time* events: events outside of the decided timeframe
  - Out-of-time bin after signal has higher noise: analysis focuses on bins before signal
Separation of real signals: In-time vs out-of-time

- Noise and signal pmax distributions can be distinct — or very close together, almost indistinguishable
  - Visible by in-time/out-of-time separation
Separation of real signals: In-time vs out-of-time

- Smaller time window reduces noise contribution to signal
- The choice of model used to describe the signal (mean, Landau, Gaussian) does not have a strong impact on signal/noise separation
- Even at large distances from the triggered channel, in-time signal pulse heights are above the noise floor

![Graph showing signal and noise separation](image)