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

Charge sharing and position resolution

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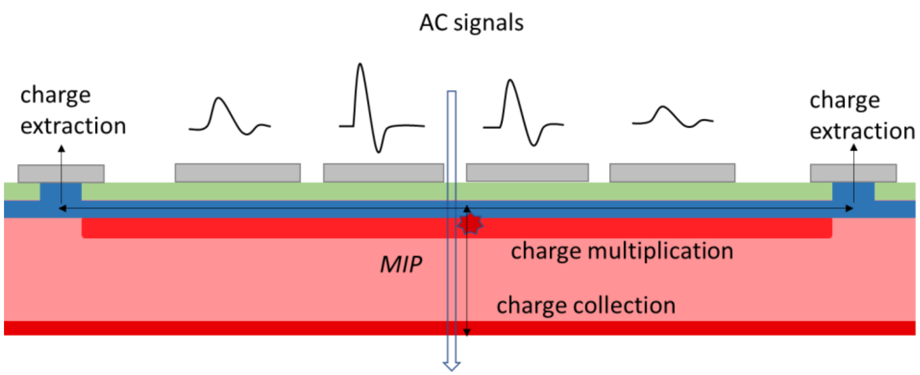
AC-coupled low gain avalanche diodes

- In AC-coupled LGADs, also referred to as Resistive Silicon Detectors (RSD), the multiplication layer and n$^+$ 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$^+$ implant is contacted only by a separate grounding contact
- The continuous n$^+$ layer is resistive, i.e. extraction of charges is not direct
  - mirroring of charge at the n$^+$ layer on the metal pads: AC-coupling
  - strong sharing of charge between metal pads



- **Impact on signal sharing by segment pitch, metal width, distance; electrode shape and geometry; n$^+$ layer resistivity?**

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

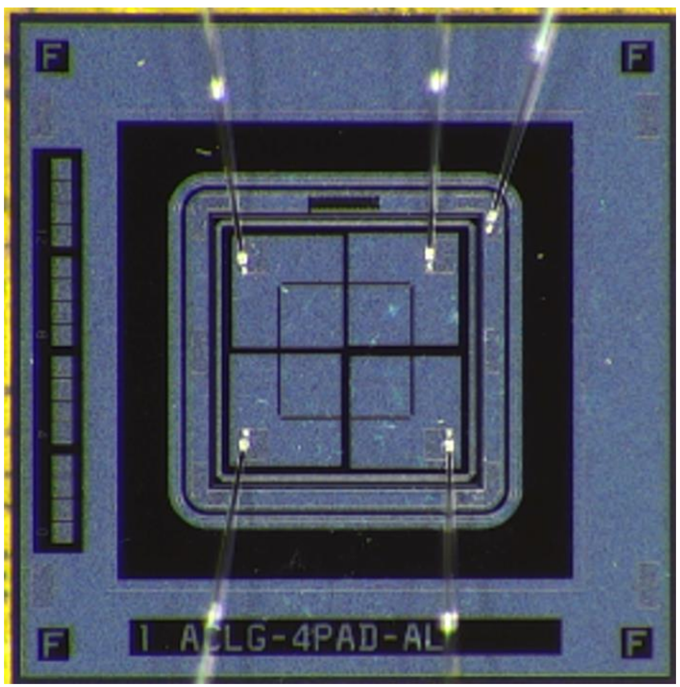
AC-LGAD sensors in beam test

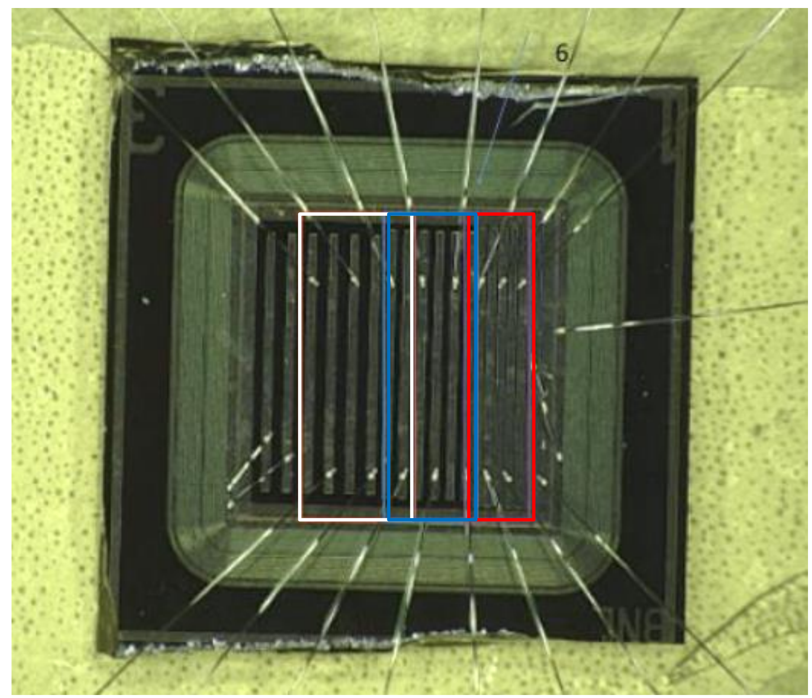
120 GeV proton beam at the Fermilab test beam facility

Hamamatsu PK
2x2 pad sensor
500 µm pitch, 490 µm metal width

Brookhaven National Laboratory
BNL 2021 Strip sensor
Metal width 80 µm, three different pitches:

- Narrow, 100 µm
- Medium, 150 µm
- Wide, 200 µm





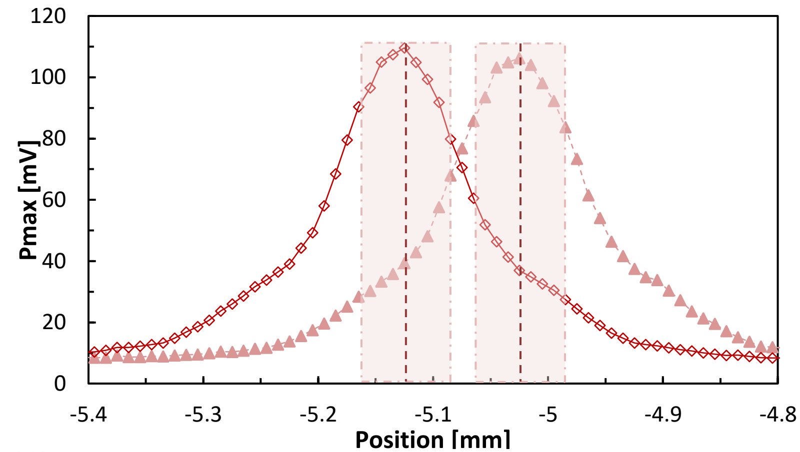
C. Madrid, 39th RD50 Workshop, November 2021 (https://indico.cern.ch/event/1074989/contributions/4602013/)

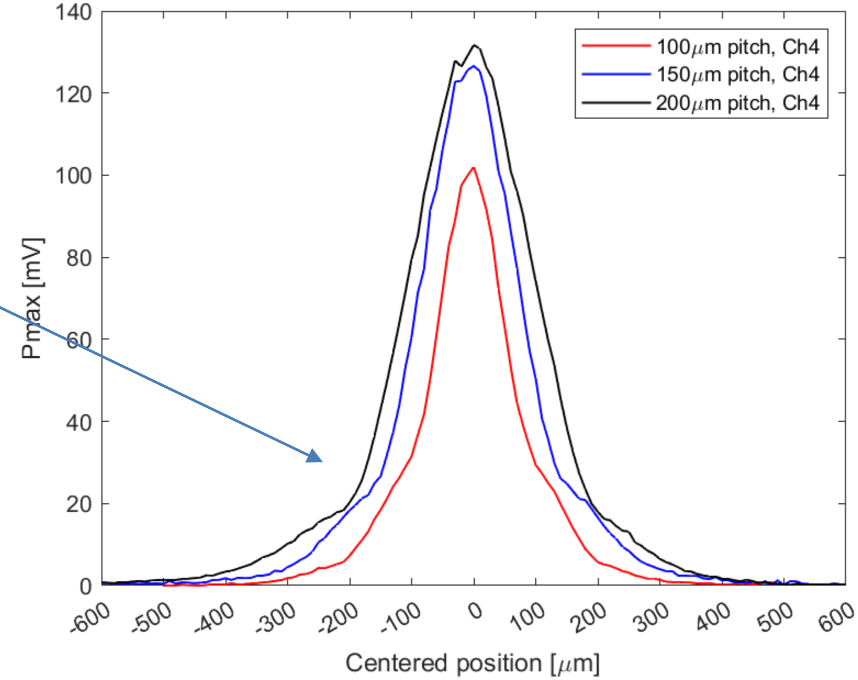
Pulse height over neighboring strips

Most examples for strips with narrow pitch (100 µm)

- Averaged maximum pulse height (*pmax*): overlapping as function of position for adjacent strips

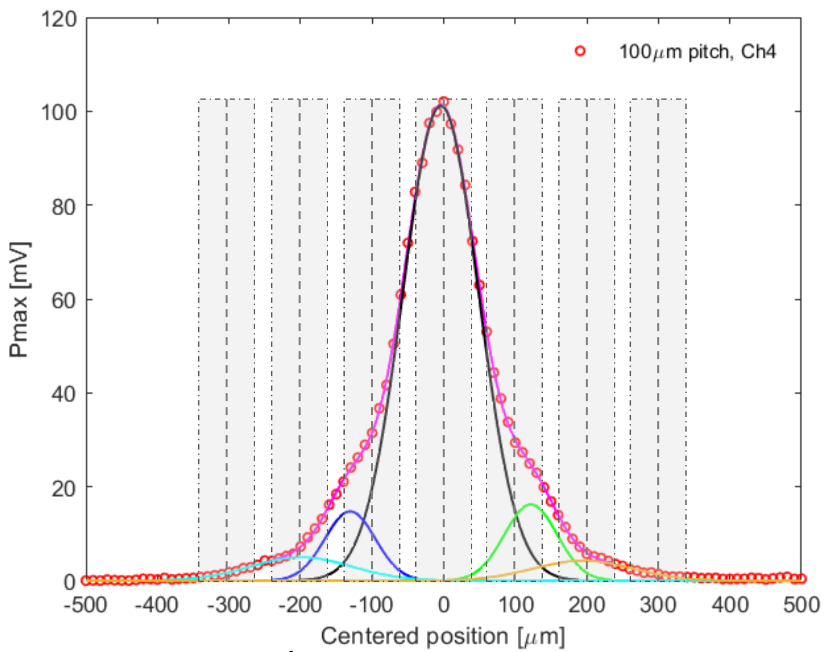
- Within the pmax curve for an individual channel, “breaks” roughly at the next strip center are seen
  - ➢ **Influence of neighboring strips?**
  - ➢ Shape of the pmax profile depends on the pitch

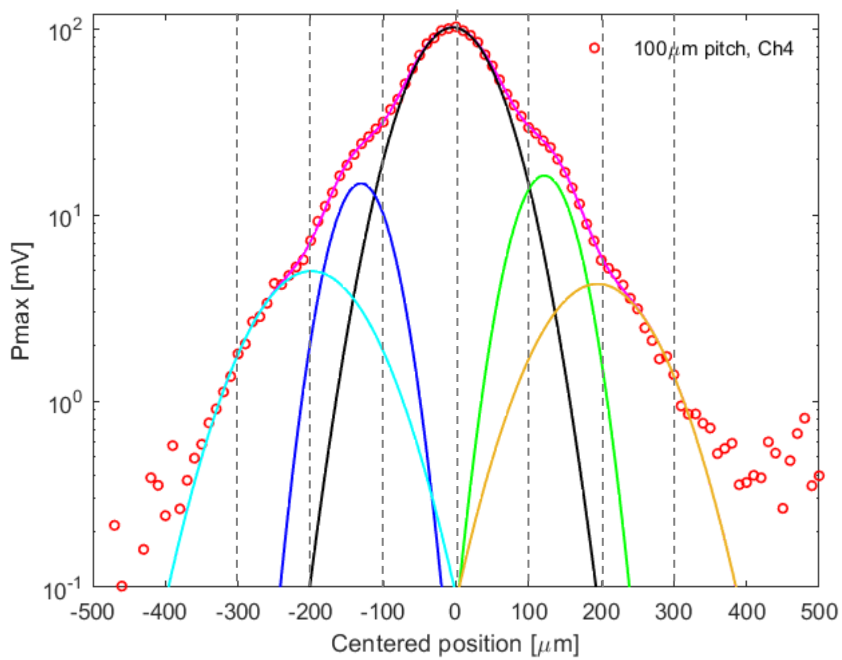




Charges on neighboring strips

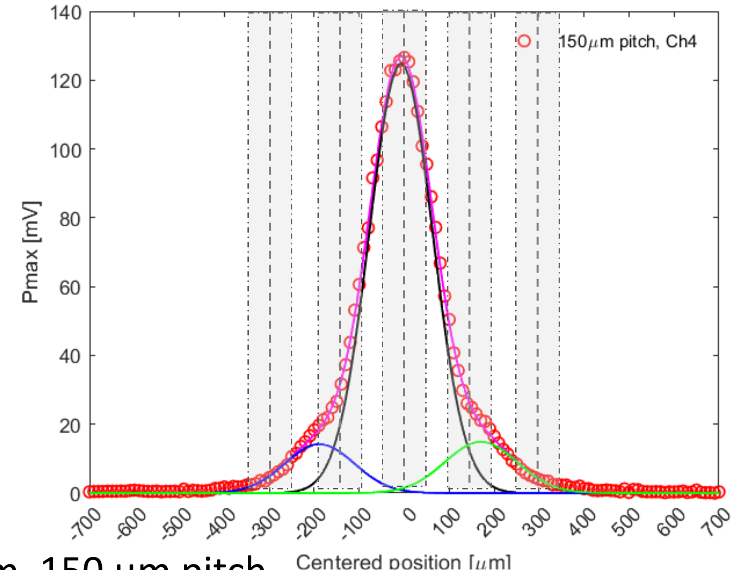
- Fitting the data (after subtraction of a constant background floor) with multiple Gaussians reveals contribution from next and even second neighboring strip
- Actual sharing extends from the central strip almost to the far edge of the next neighbor
  - Localization indicates **induced** charge on the neighboring strips, not purely conduction through the resistive n^+ layer

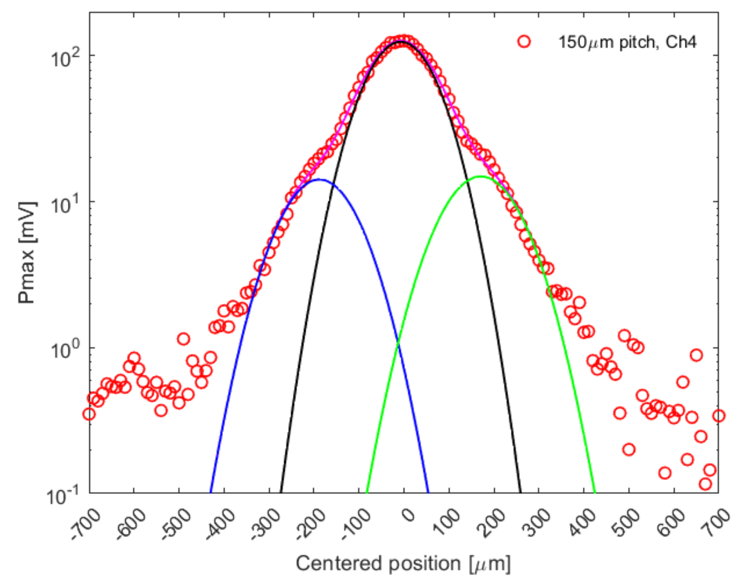




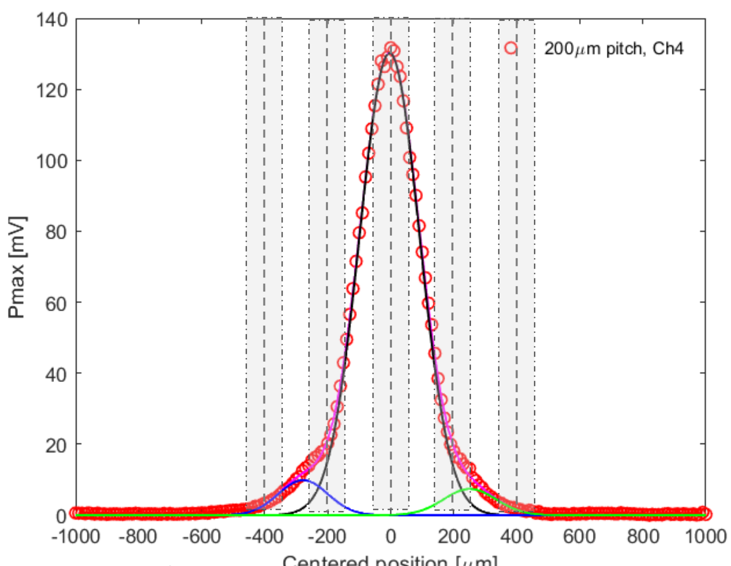
Narrow, 100 μm pitch

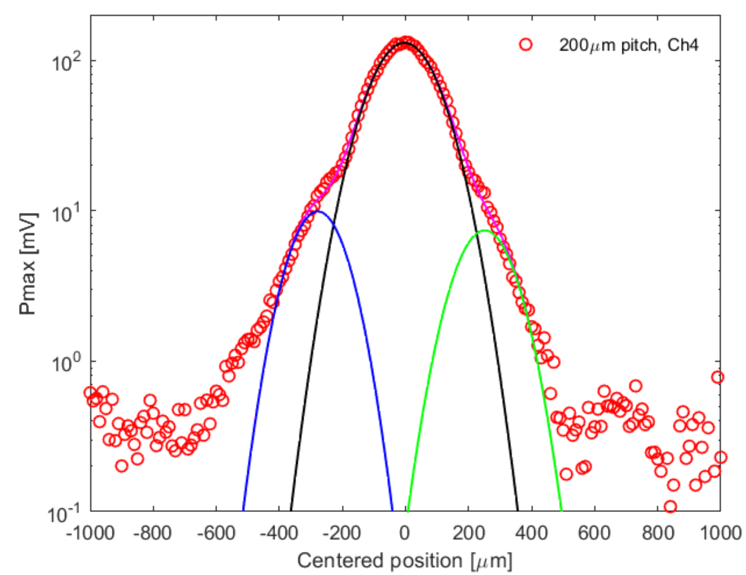
Charges on neighboring strips





Medium, 150 μm pitch

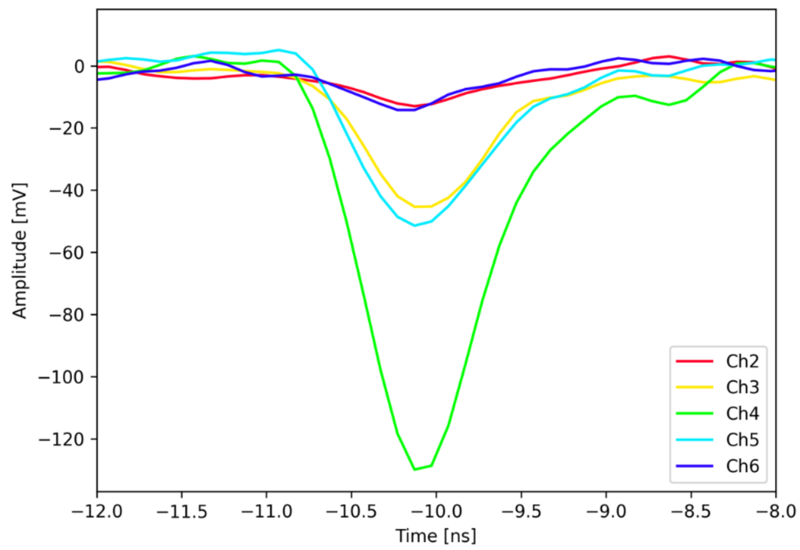


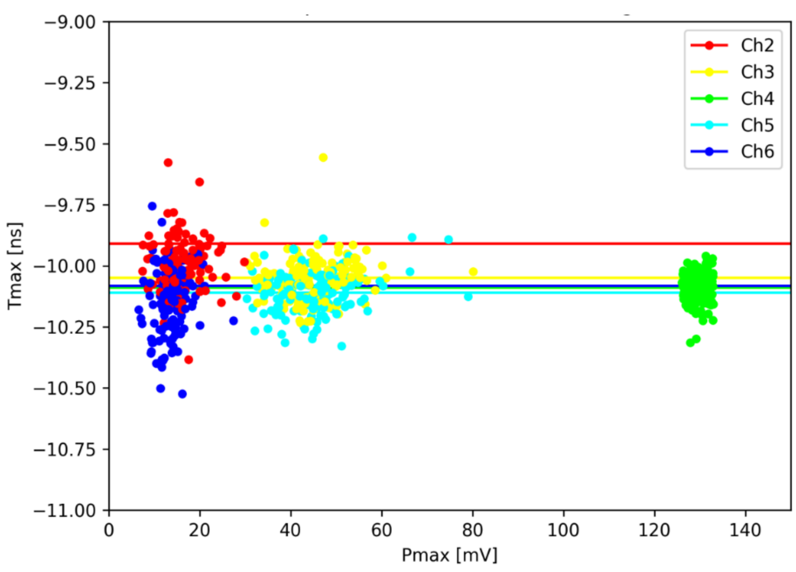


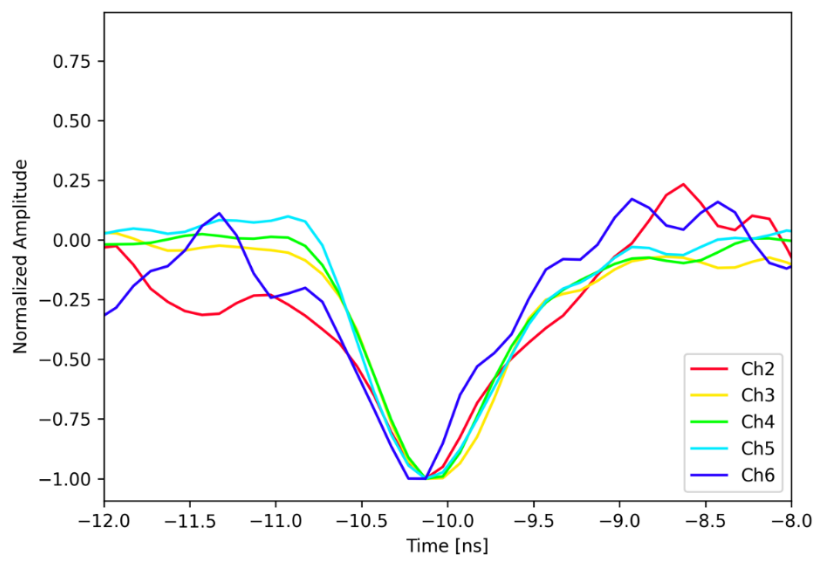
Wide, 200 μm pitch

Signal pulse shapes

- Signal in second neighbors is observed, but with lower amplitude, wider spread in pmax and peak time *tmax*
- Pulse shape (when amplitude is normalized) is in fact not distinctly different







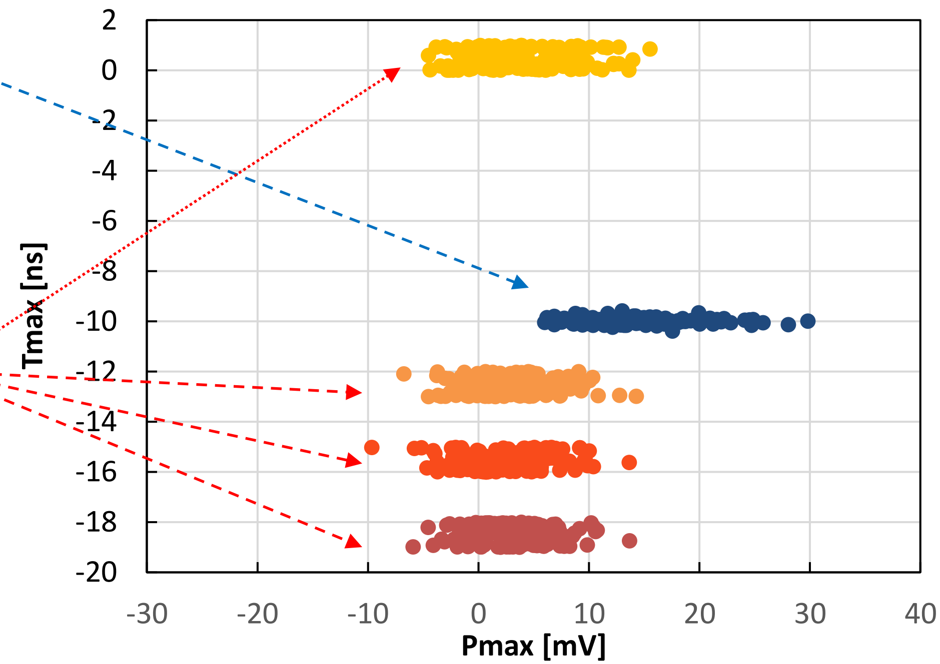
Pmax - tmax

- 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

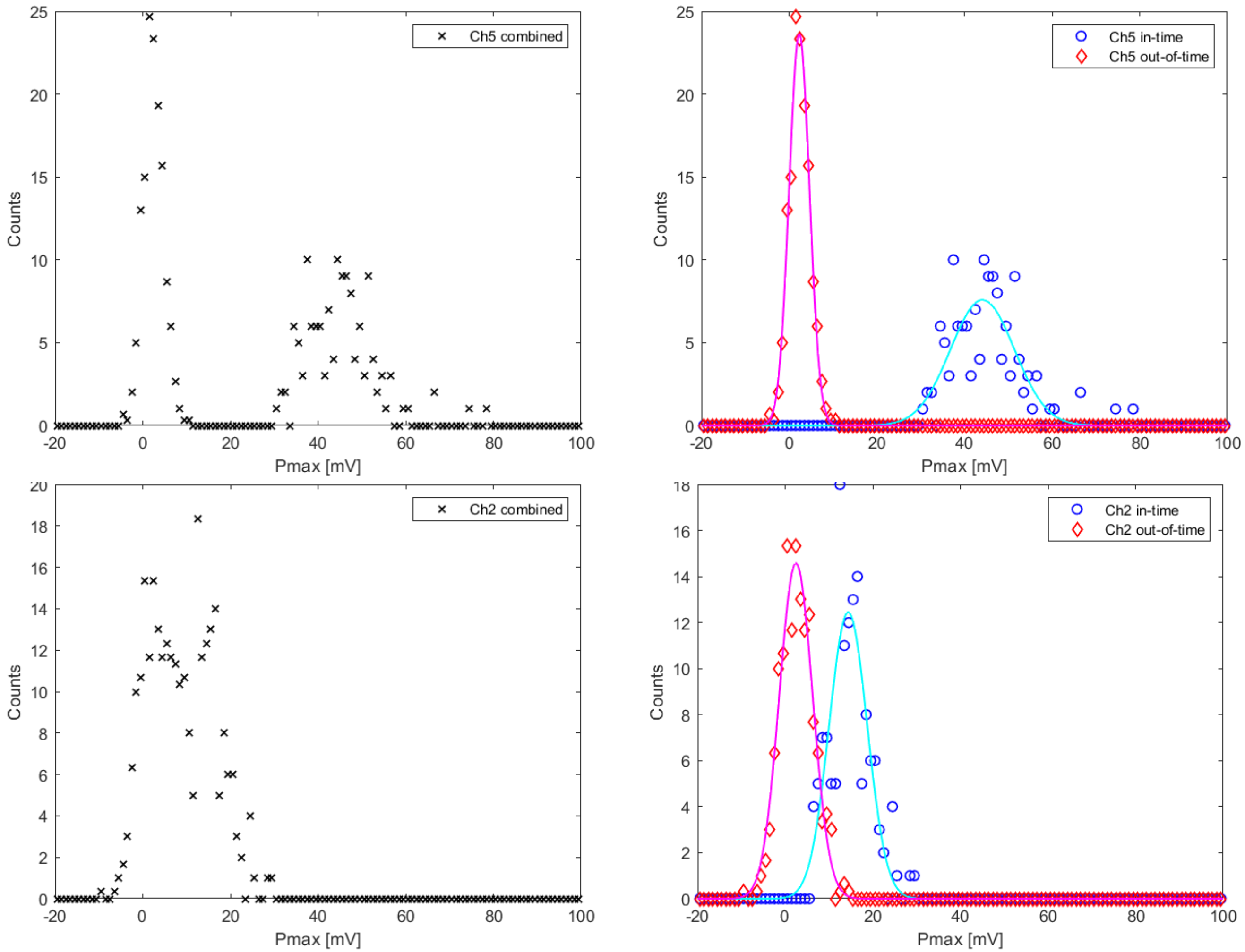
➢ *out-of-time* events: events outside of the decided timeframe

- Out-of-time bin after signal has higher noise: analysis focuses on bins before signal



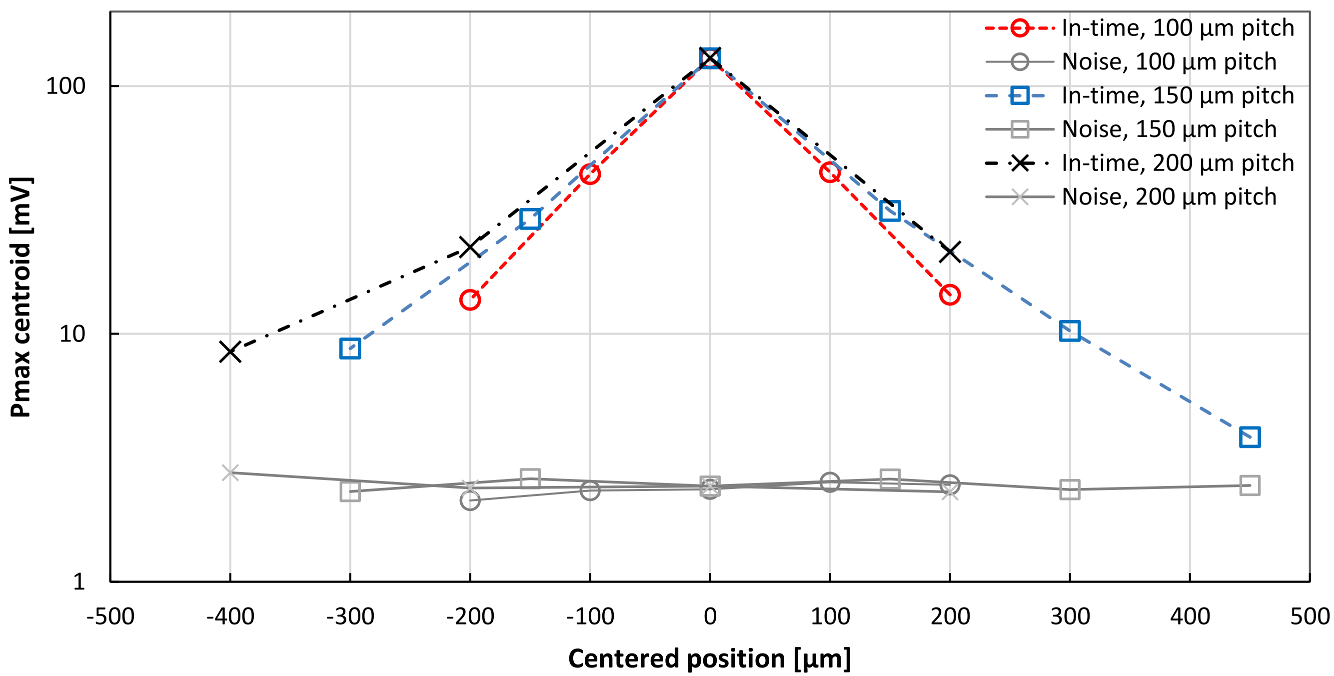
Separation of real signals: In-time vs out-of-time

- 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

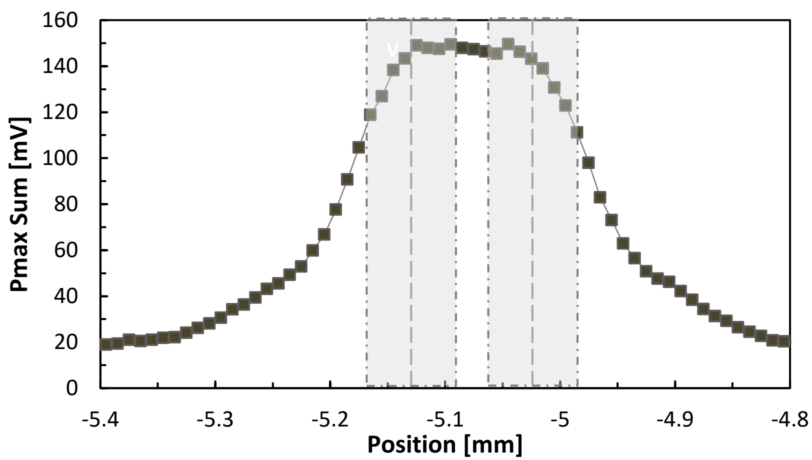
- Smaller time window reduces noise contribution to signal
- The choice of model used to describe the signal (mean, Landau, Gaussian) does not have a strong impact on signal/noise separation
- Even at large distances from the triggered channel, in-time signal pulse heights are above the noise floor



Pulse fraction and position resolution

Case of two adjacent strips

- The pmax sum ist not constant under the strip metal, but fairly constant between strip centers

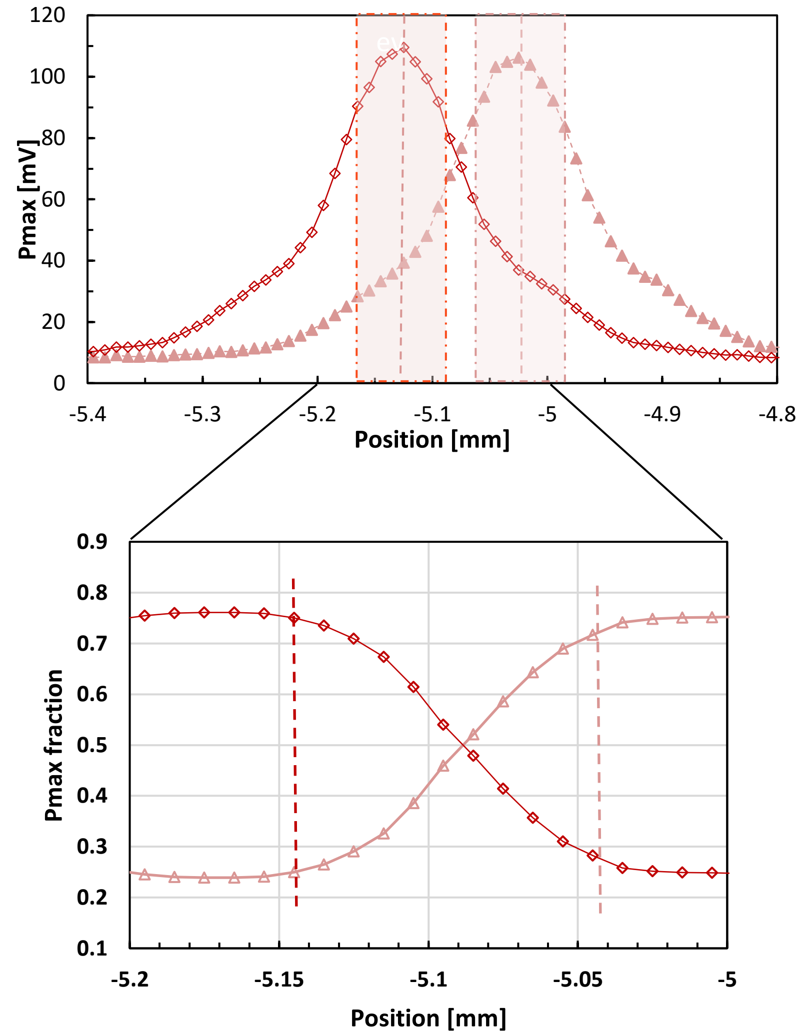


- The pmax fraction of an individual strip is defined as:

$$pmax\ fraction\ (channel) = \frac{pmax\ (channel)}{\sum pmax}$$

- The position resolution can be calculated from the fraction of pmax at a given position (fitted with an error function):

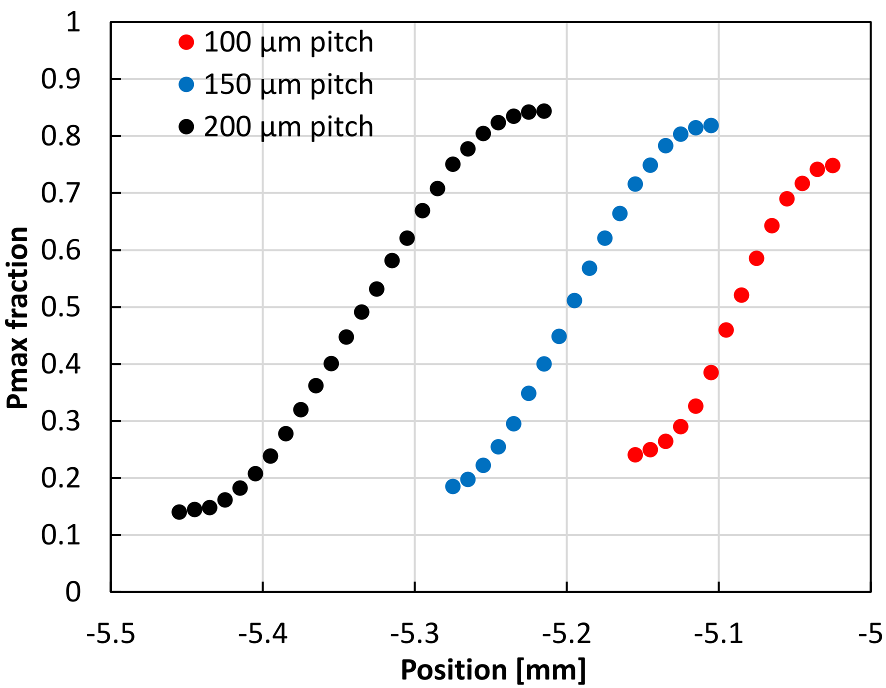
$$position\ resolution\ \sigma_{pos} = \sqrt{2}\,\frac{d(position)}{d(fraction)} / \frac{S}{N}$$

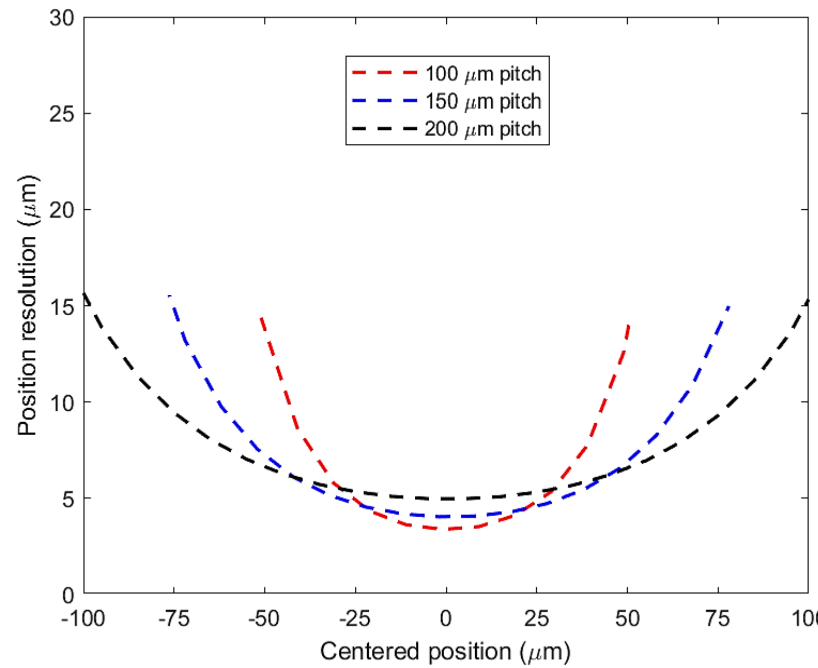


Signal-to-noise ratio is favourable in (AC-)LGADs due to their internal gain

Position resolution in BNL 2021 strips

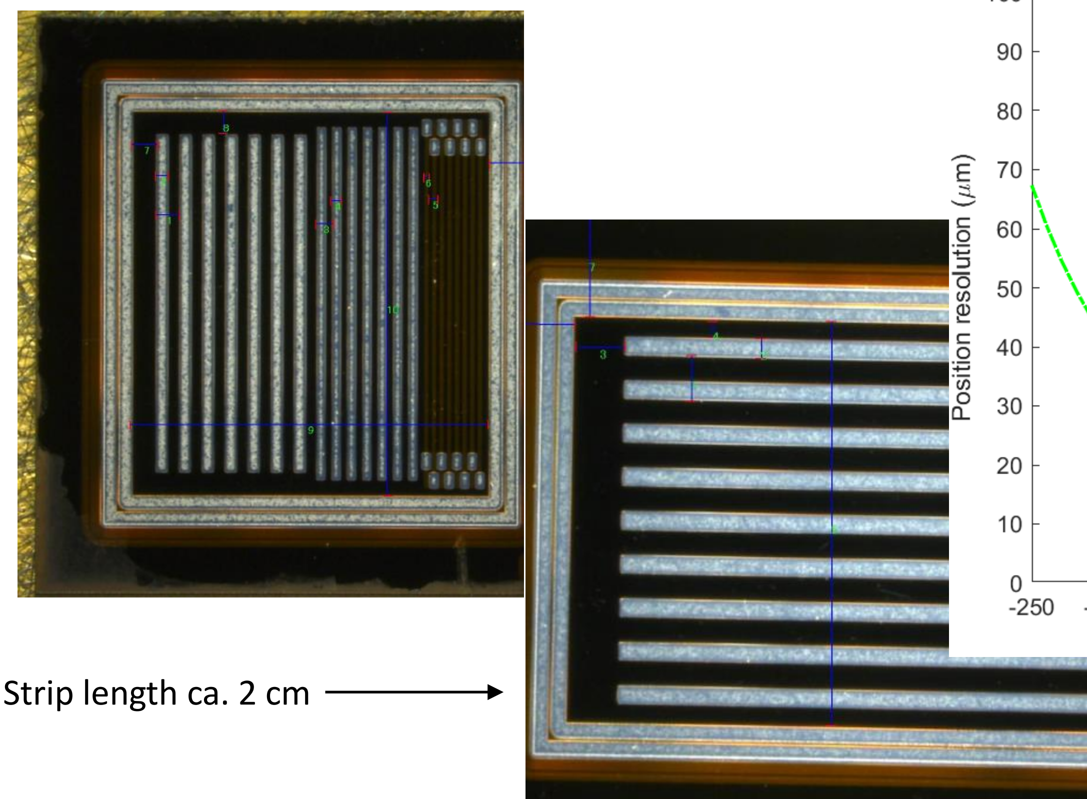
- Strip pitch is expected to - and appears to - have a large impact on charge sharing as seen in the pmax fraction profile …
- … position resolution of ca. 15 µm at the respective strip metal centers (end of the data points in the plot): **in fact very similar for all three pitches**
- Between strips,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



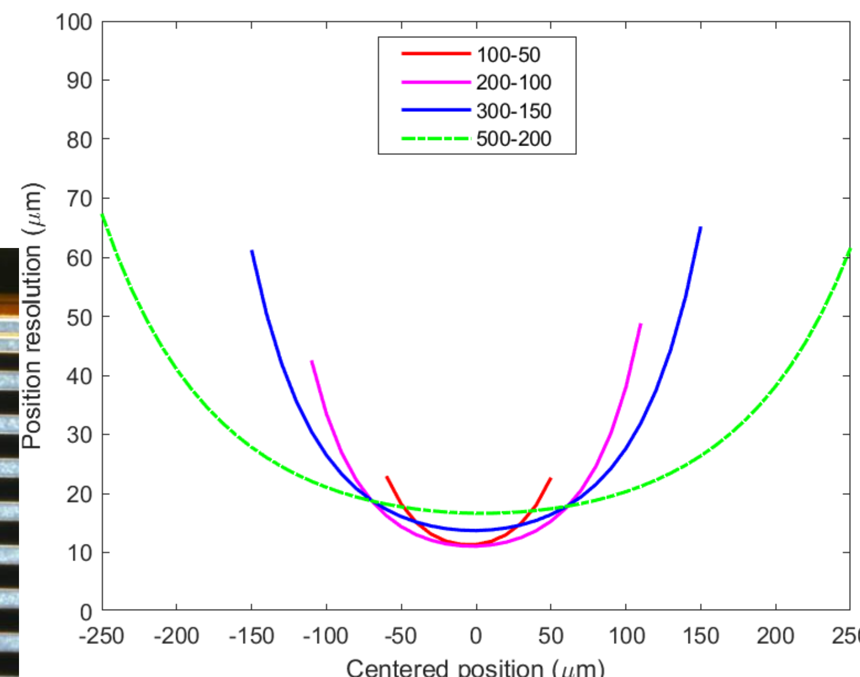


BNL 2021, new production

- Variations in both pitch and metal width
- 500µm-pitch/200µm-metal sensor differs from others in terms of charge sharing, but still provides < 20µm position resolution between metal strips

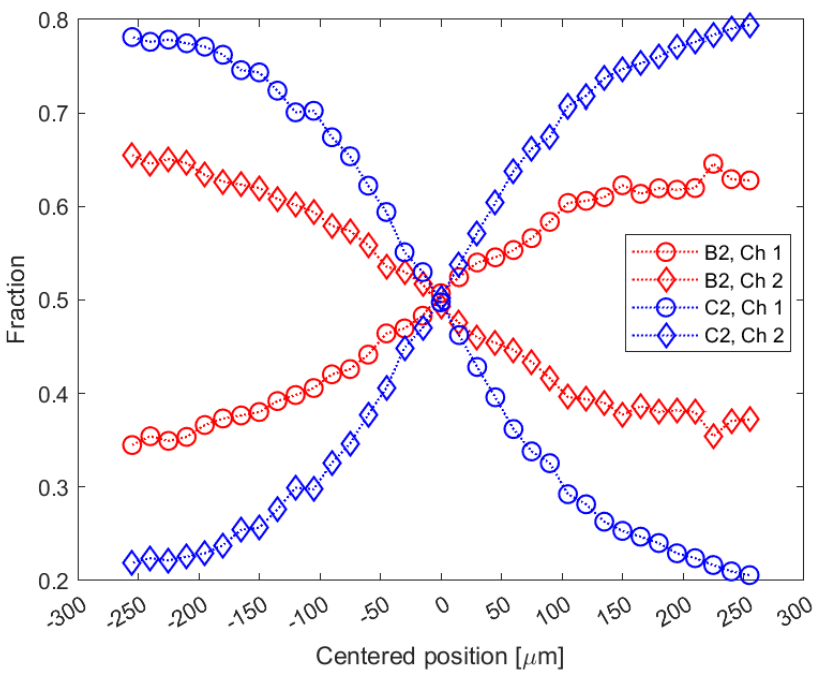


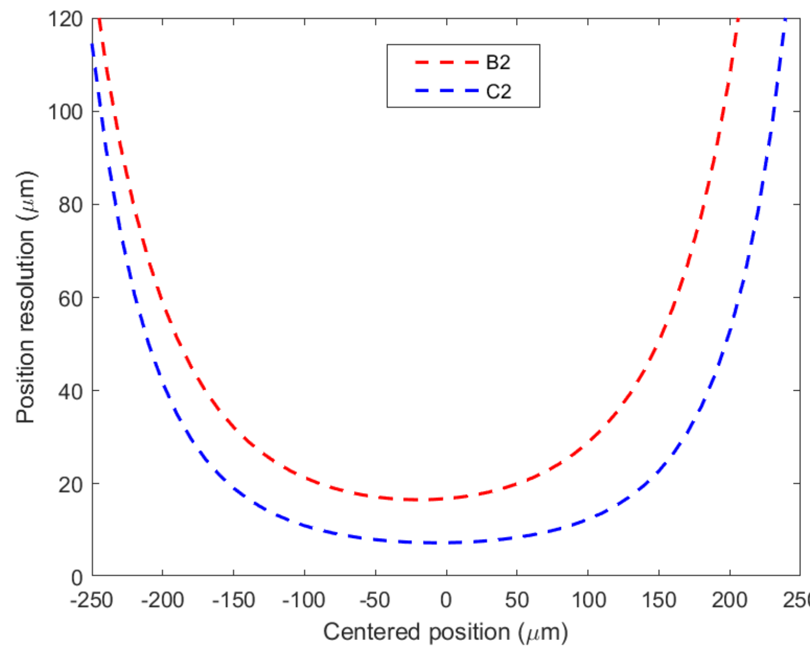
Strip length ca. 2 cm →



Position resolution in HPK pad sensors

- Charge sharing in terms of pmax 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 is significant!**
  - **n^+ resistivity is another parameter to tune charge sharing to the requirements of specific applications**

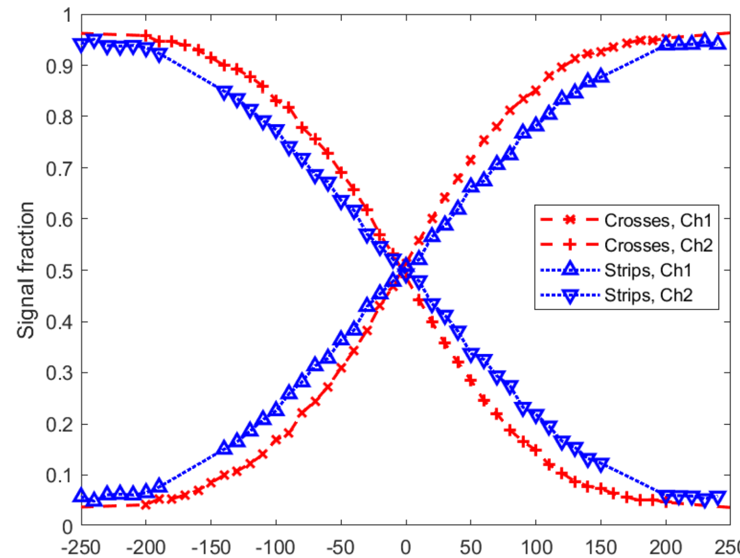




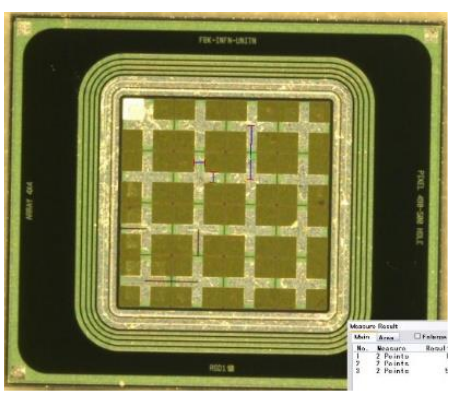
* K. Nakamura *et al*, First Prototype of Finely Segmented HPK AC-LGAD Detectors, JPS Conf. Proc. 34, 010016 (2021)

Electrode shape

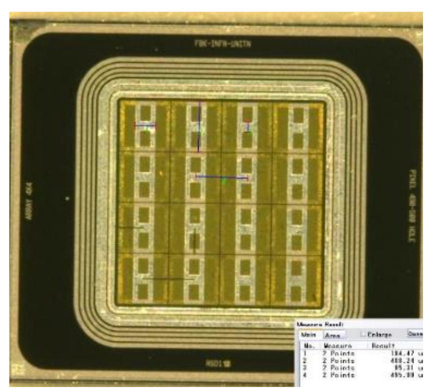
- First proof of concept by etching the electrode metal of FBK RSD1 sensors (at BNL)
- Charge sharing can also be investigated in a laser setup – however, precision close to the strips is limited, since the laser cannot penetrate through metal
  - Results close to the metal differ, depending on if charge injection occurs from the metallized front side or the backside of the sensor

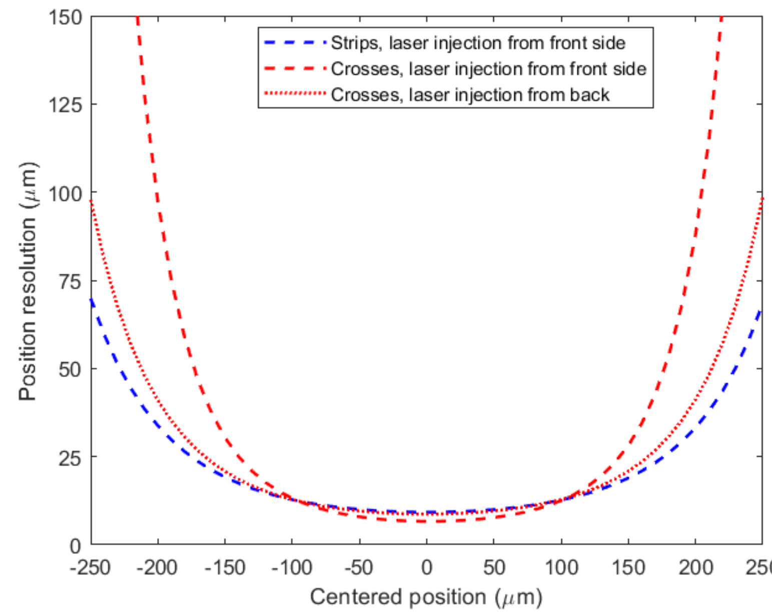


FBK RSD1, etched crosses



FBK RSD1, Etched strips

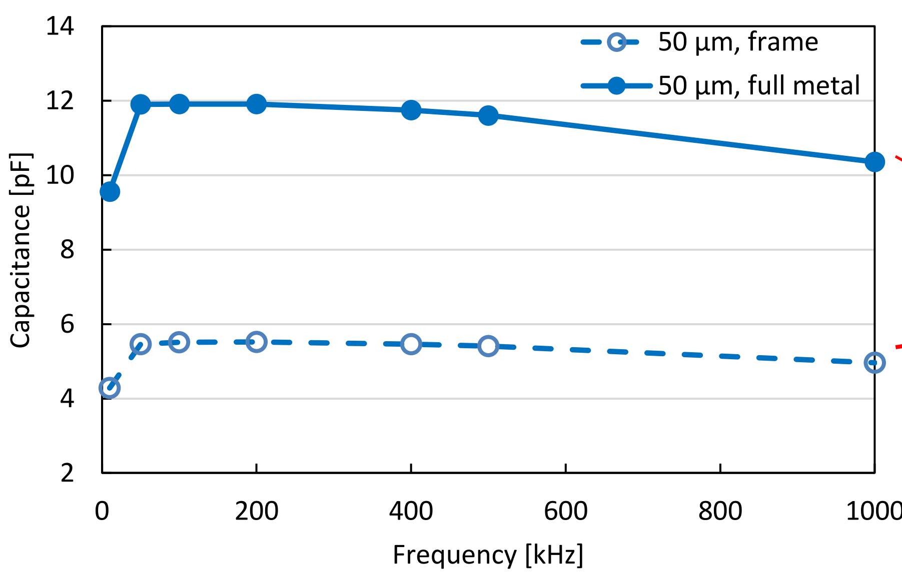


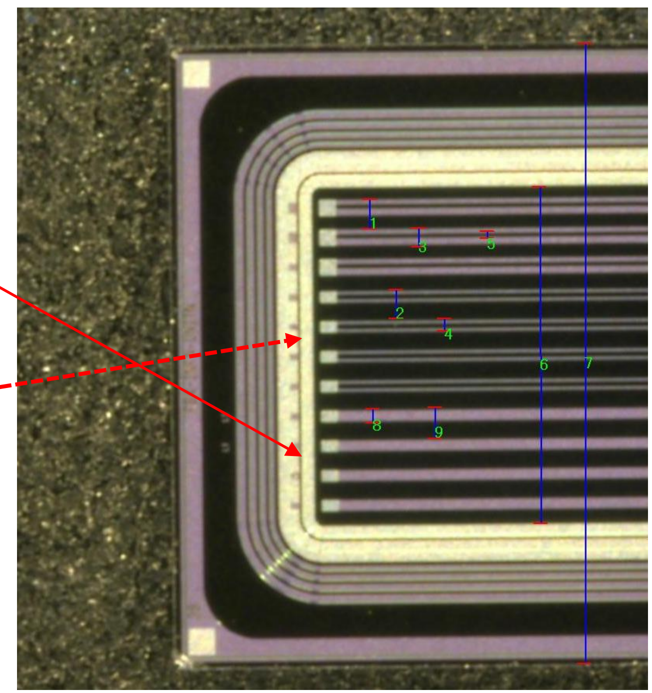


S. M. Mazza *et al*, Development of AC-LGADs for large-scale high-precision time and position measurements, IEEE TNS **2022**, submitted

Electrode shape

- 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?*

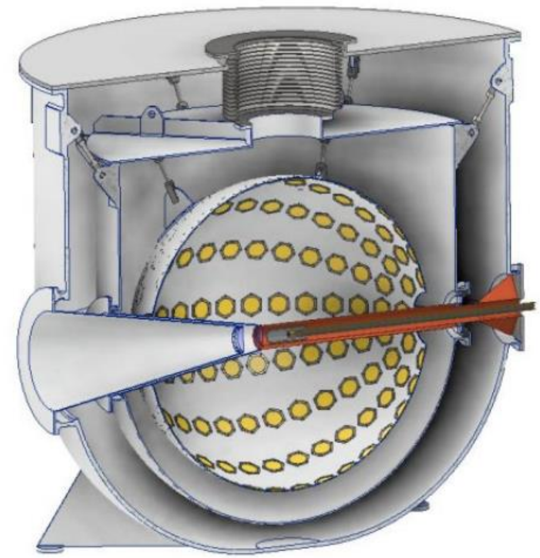


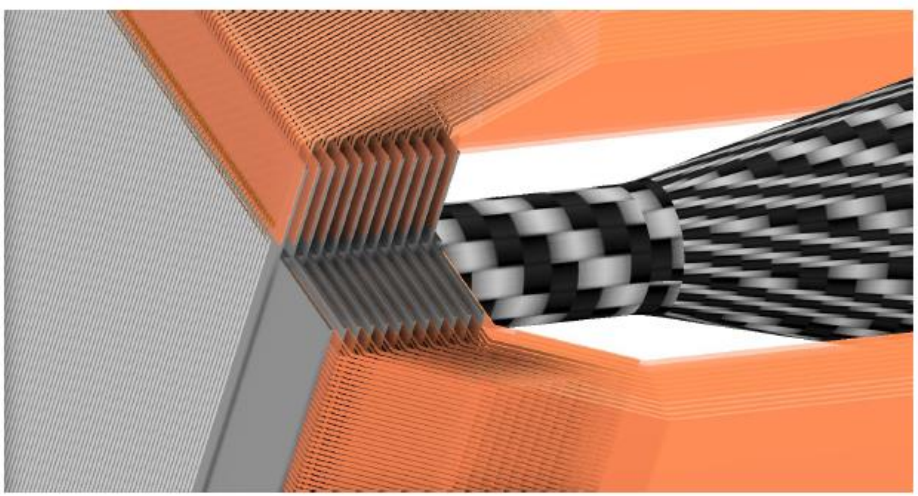


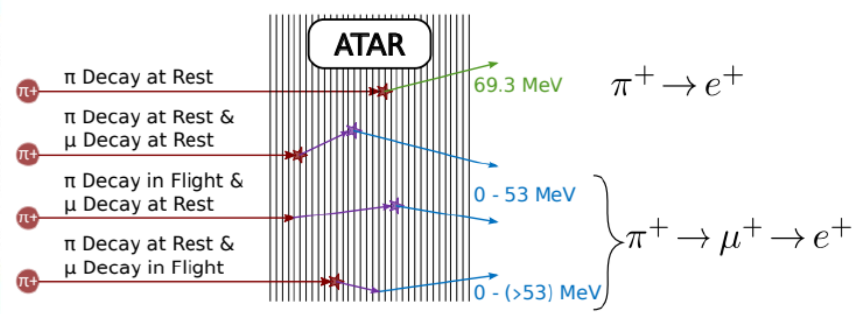
M. Mandurrino et al, 39th RD50 Workshop, November 2021 (https://indico.cern.ch/event/1074989/contributions/4602006/)

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 cm^2 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







PIONEER public webpages: https://pioneer.npl.washington.edu/do/view/TWiki/WebHome

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

Summary

- 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

- AC-LGADs can achieve remarkable position resolution even with large and widely spaced electrodes
    - Less than 1/20 of the pitch

- Studies can be conducted with a laser, but for precise investigation including signals under the metal, particle beam tests are essential

➢ **Continued investigation of charge sharing, and hence improved position (… and timing) resolution, will provide valuable information for adjusting the properties of future AC-LGAD sensors to their targeted applications**

➢ **Comparison of experimental data with TCAD simulation is important for understanding the charge sharing and to facilitate the design of sensors for future applications**

Thank you!

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

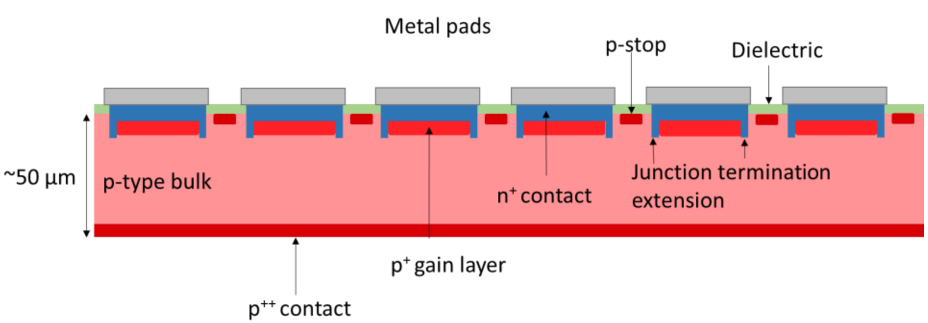
- special thanks to the FNAL Test Beam Facility and the beam test crew!

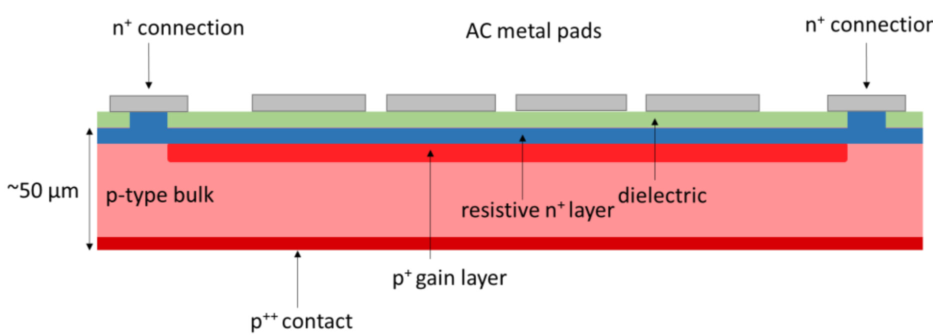
Finnish Cultural Foundation

BACKUP

Low gain avalanche diodes

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





H. F.-W. Sadrozinski et al, 4D tracking with ultra-fast silicon detectors, Reports on Progress in Physics 2018, 81, 026101
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

Charges on neighboring strips

- Contributions from neighboring strip depend (weakly) on pitch