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SUOMEN KULTTUURIRAHASTO

AC-coupled Low Gain Avalanche Diodes for 4D tracking: impact of electrode geometry on charge sharing

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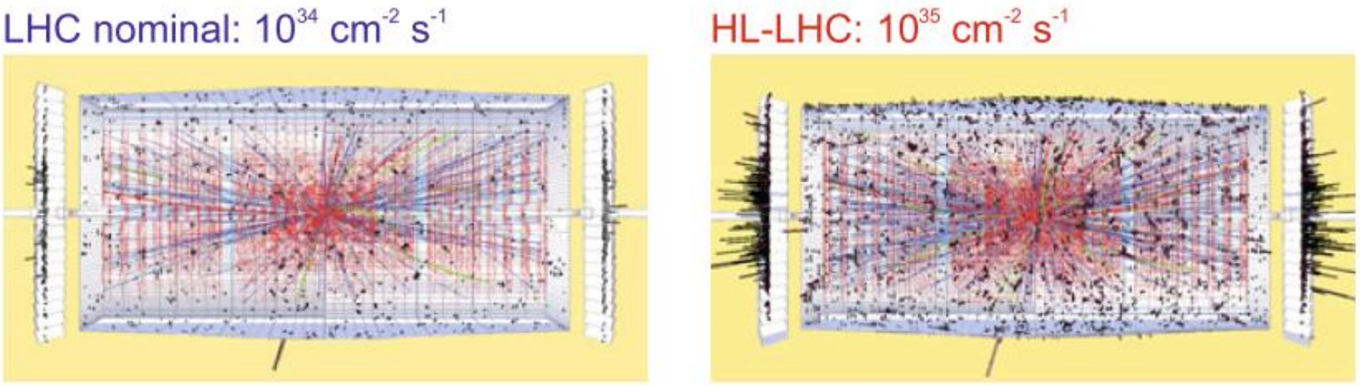
Precision tracking and timing

- 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

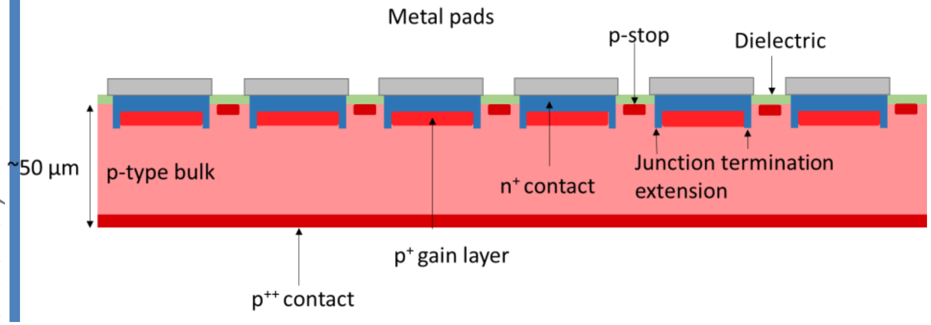


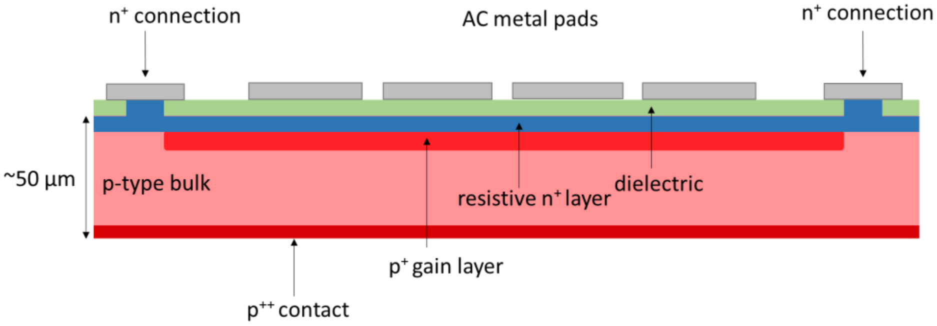
- 4D tracking is going to be essential in future high-energy physics experiments to mitigate effects of higher luminosity and pile-up and to improve tracking, vertexing and timing precision

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
D. Berry et al, *Snowmass White Paper: 4-Dimensional Trackers*, https://arxiv.org/abs/2203.13900, 2022

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**

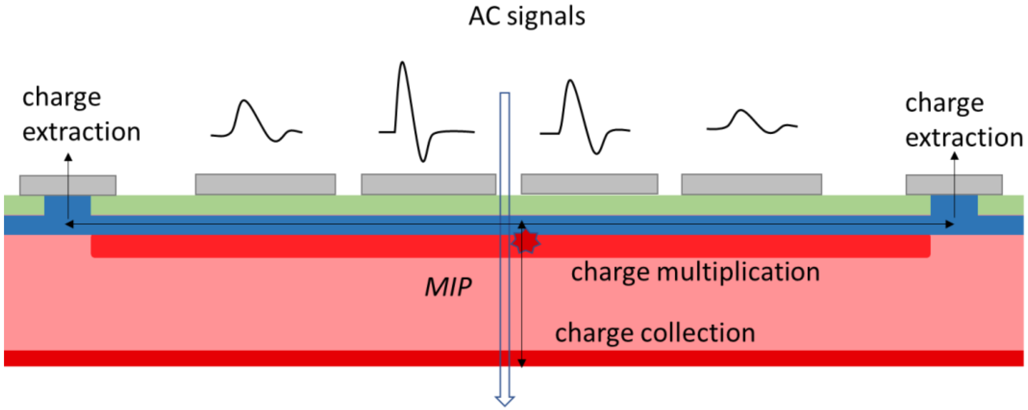




H. F.-W. Sadrozinski et al, *4D tracking with ultra-fast silicon detectors*, Reports on Progress in Physics 2018, 81, 026101
CMS Collaboration, *A MIP Timing Detector for the CMS Phase-2 Upgrade*, CERN-LHCC-2019-003, 2019
ATLAS Collaboration, *A High-Granularity Timing Detector for the ATLAS Phase-II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

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
  - No junction termination extension: fill factor ~100
- 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
  - **Extrapolation of position based on signal sharing – finer position resolution for larger pitch, also allowing for more sparse readout channels**



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**

J. Ott et al, AC-LGAD 4D tracking and electrode geometry, Pixel2022

AC-LGAD strip sensors

Brookhaven National Laboratory

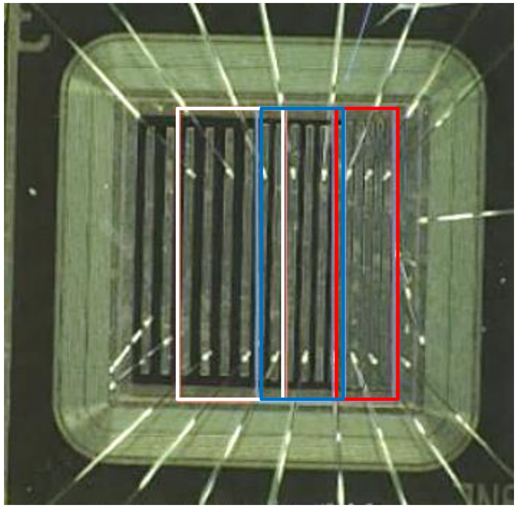
*120 GeV proton beam at the Fermilab test beam facility**

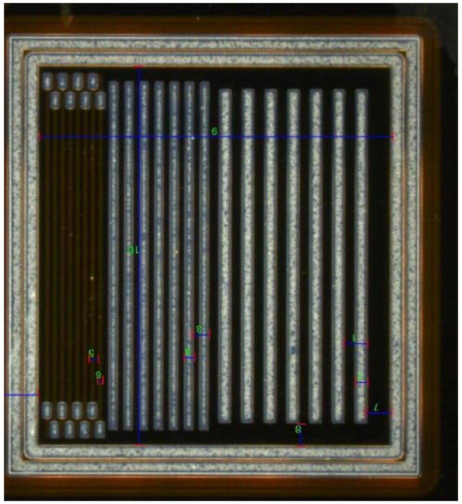
BNL 2021 Strip sensor
Metal width 80 µm, three different pitches:
Narrow, 100 µm
Medium, 150 µm
Wide, 200 µm

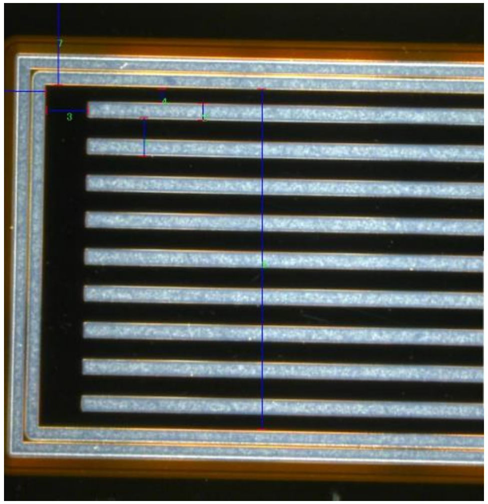
IR Laser TCT

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

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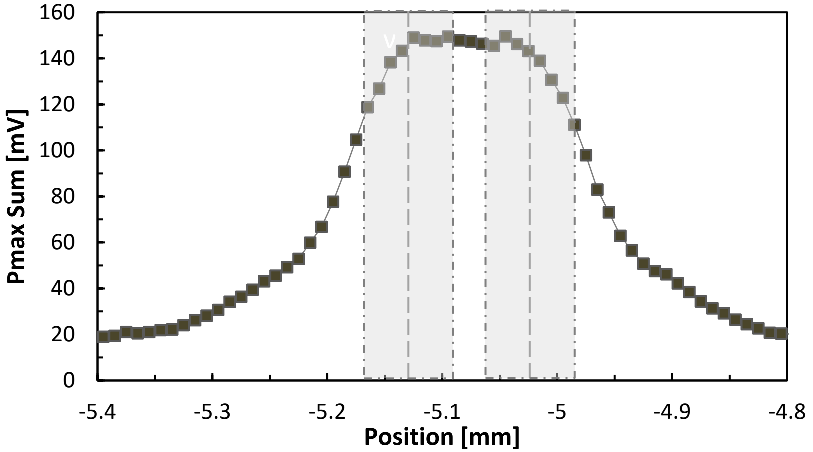
* C. Madrid, 39th RD50 Workshop, November 2021, https://indico.cern.ch/event/1074989/contributions/4602013/, R. Heller et al, https://arxiv.org/abs/2201.07772)

Position resolution by signal sharing

Case of two adjacent strips

- Averaged maximum pulse height (*pmax*): The pmax sum ist not constant under the strip metal, but fairly constant between strip centers

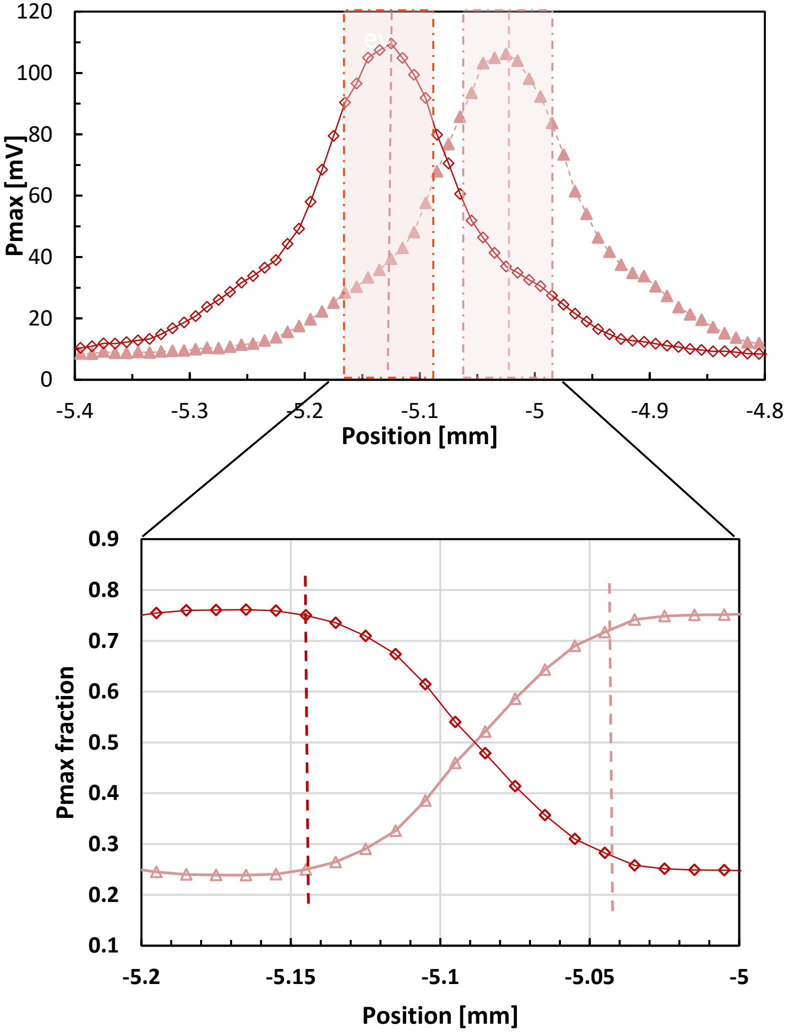


- The pmax fraction of an individual strip is defined as:

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

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

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

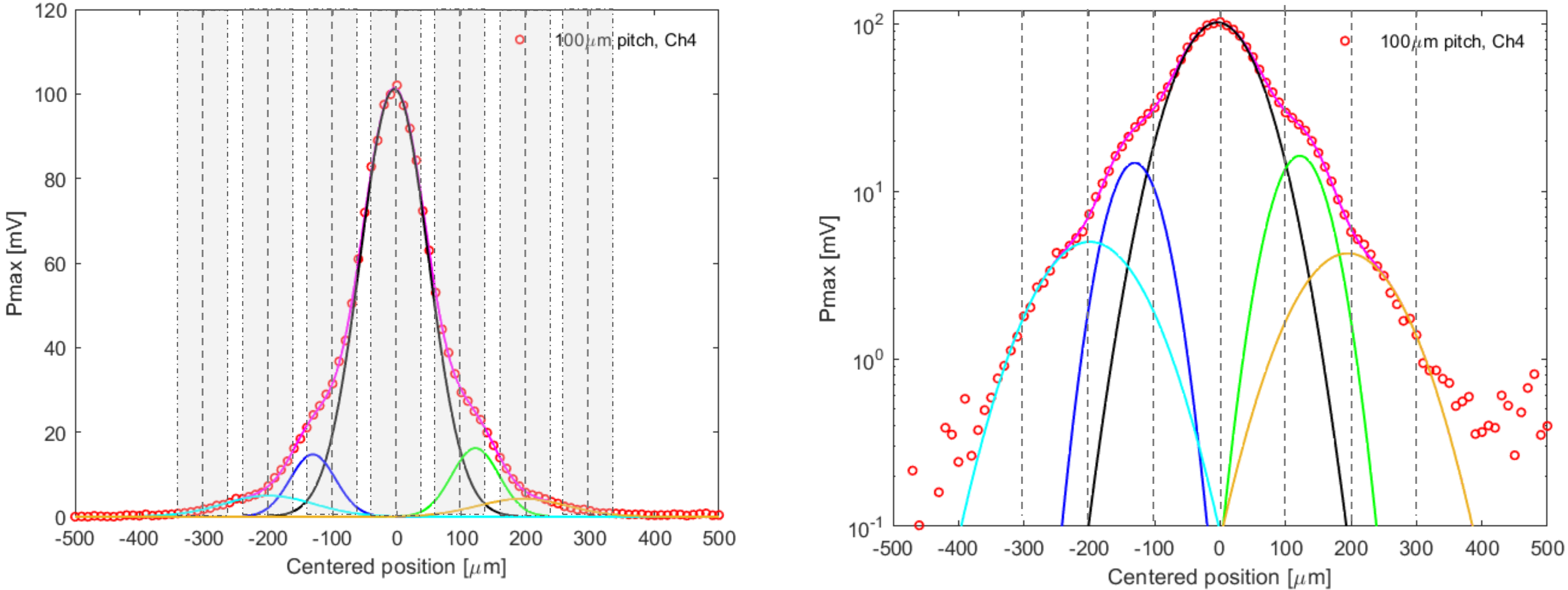


Signal-to-noise ratio is favoring sensors with higher gain

Charge on neighboring strips

J. Ott et al, AC-LGAD 4D tracking and electrode geometry, Pixel2022

- 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

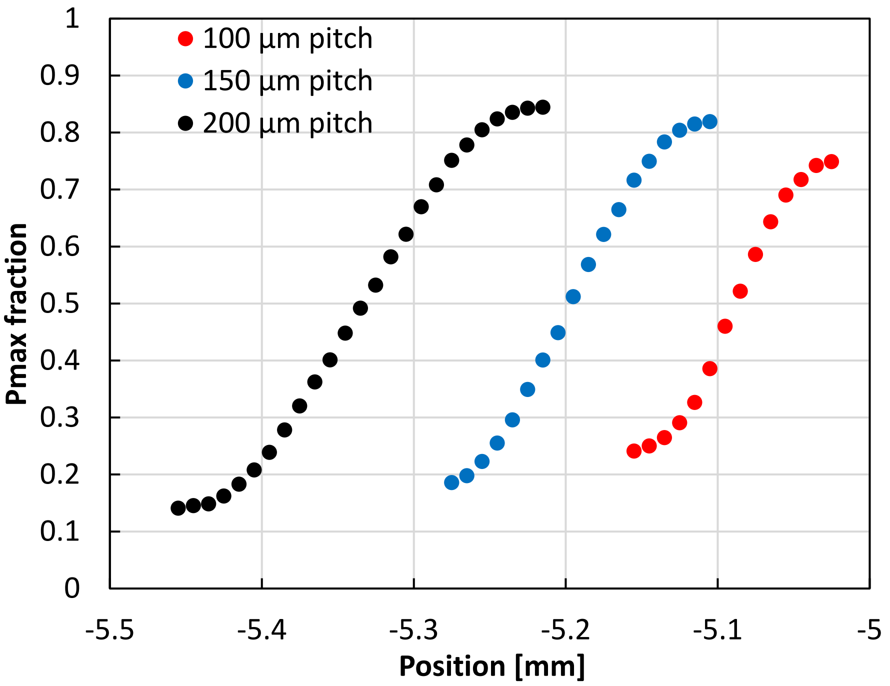


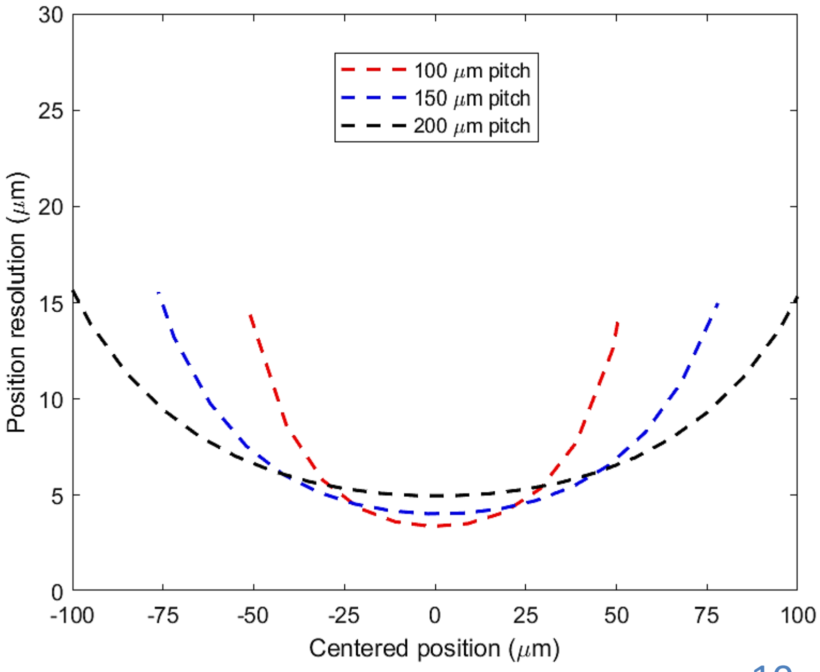
Narrow, 100 μm pitch

J. Ott et al, https://doi.org/10.1016/j.nima.2022.167541

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**

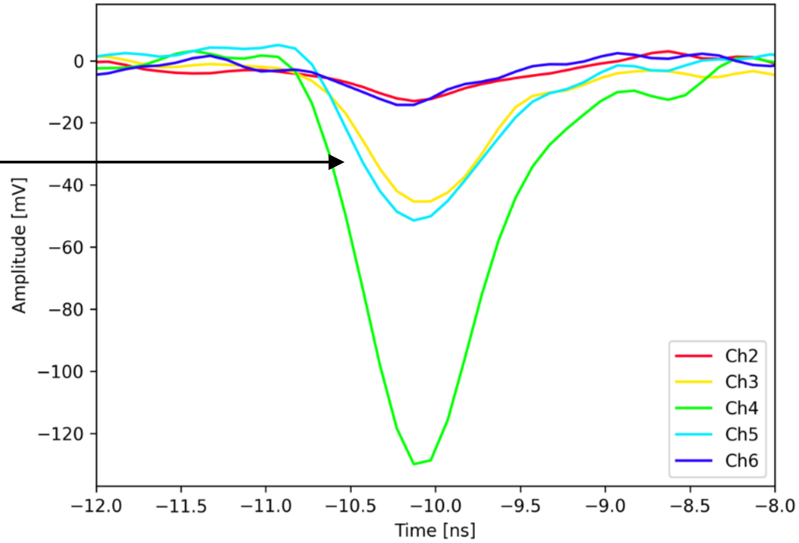




Timing resolution

$$\boldsymbol{\sigma_t^2} = \boldsymbol{\sigma_{Landau}^2} + \boldsymbol{\sigma_{Jitter}^2} + \sigma_{TimeWalk}^2 + \sigma_{TDC}^2 + \sigma_{Distortion}^2$$

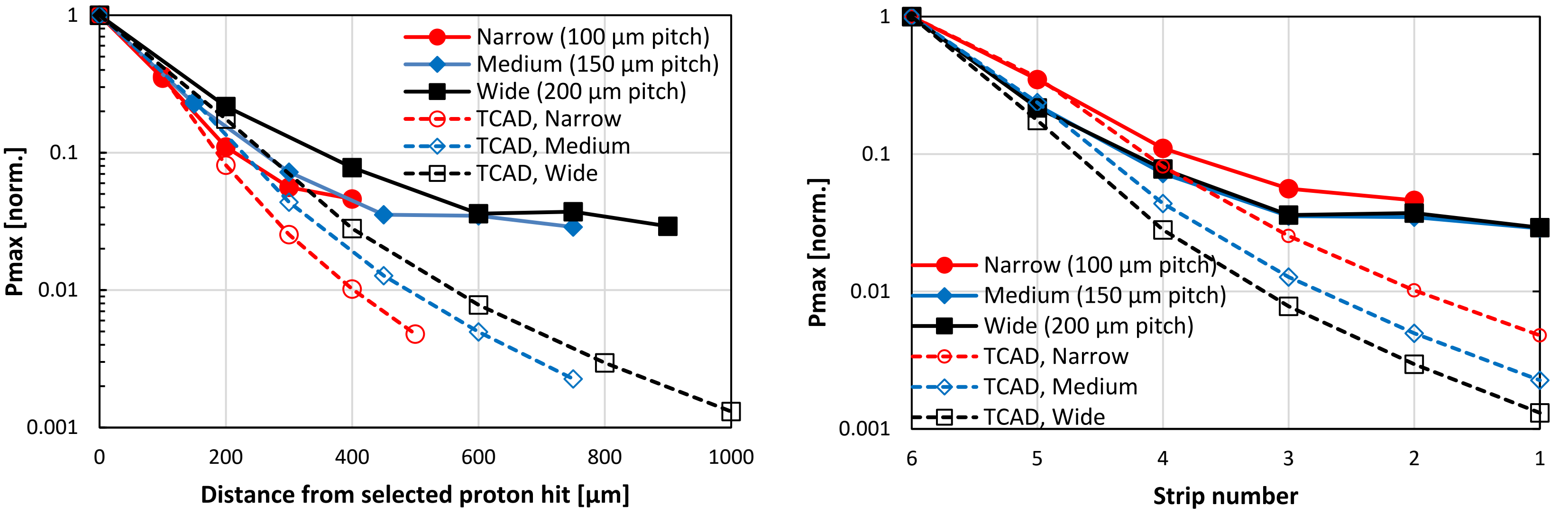
- AC-LGADs provide comparable performance to conventional LGADs, determined by largely by the gain layer: < 40 ps established, 20 ps reachable
- Impact of signal sharing on timing resolution:
  - Weighted reconstruction of several contributions can improve timing resolution
  - But: lower signal in individual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



J. Ott et al, AC-LGAD 4D tracking and electrode geometry, Pixel2022

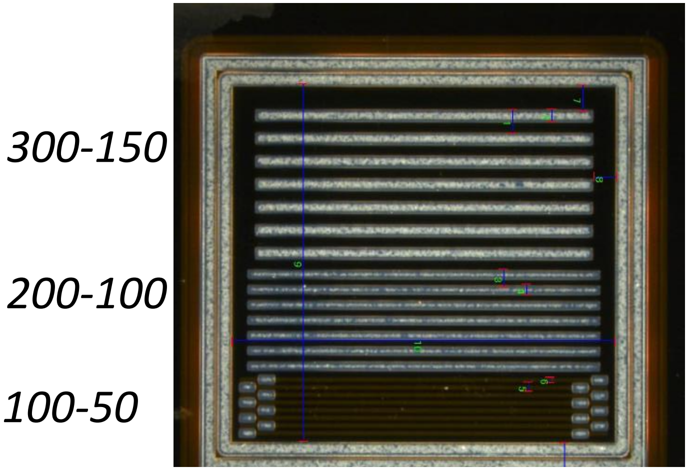
Charge sharing at long distances

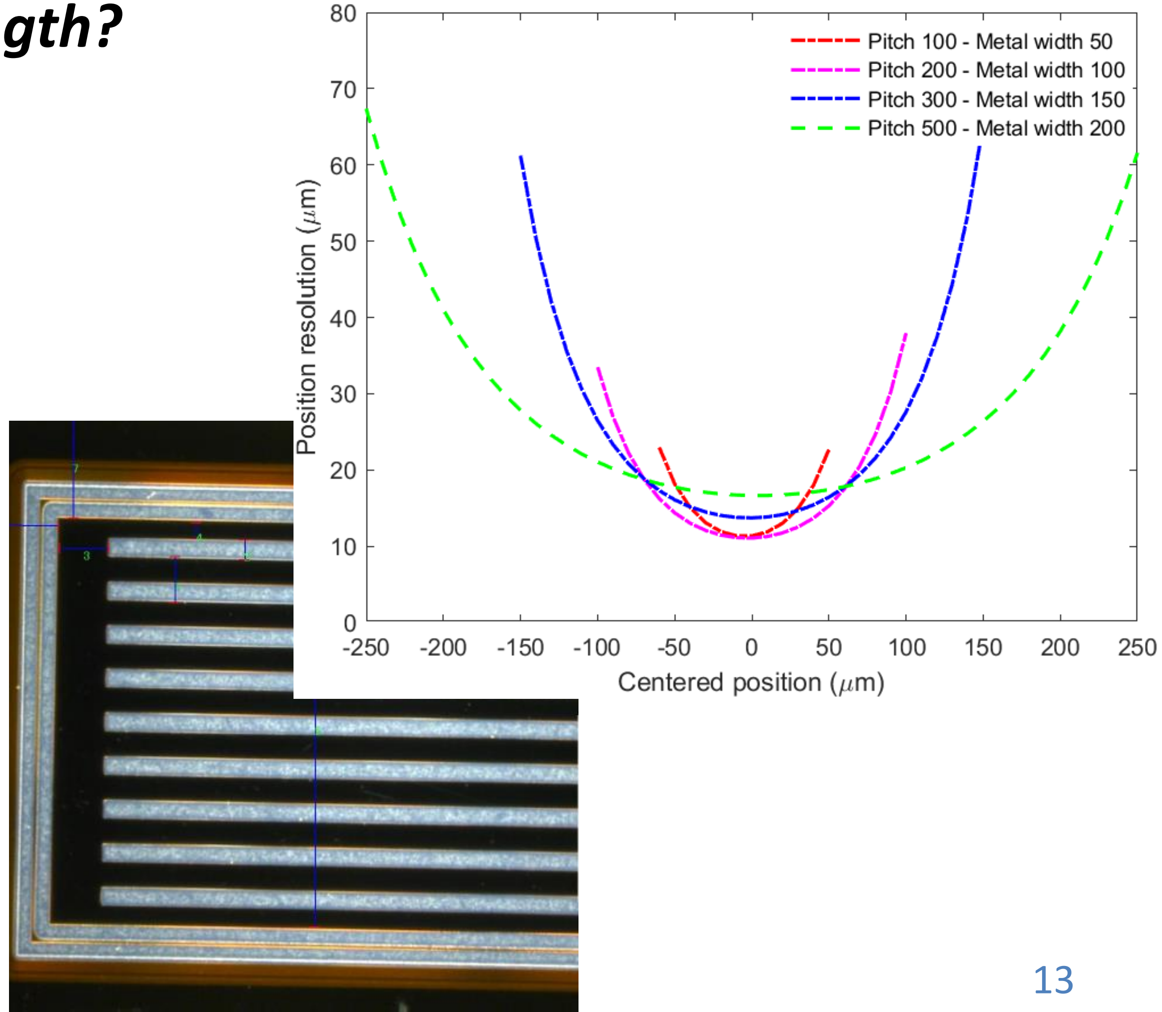
- Selection: proton track on strip #6, “in-time” data within 1 ns time window of the main signal
- Constant, position-independent pmax (above noise) at longer distance from hit – not predicted by 2D simulations
  - **Sharing or pick-up from the n$^+$ layer? Or cross-talk with other strips?**



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
- **Impact of strip *length?***

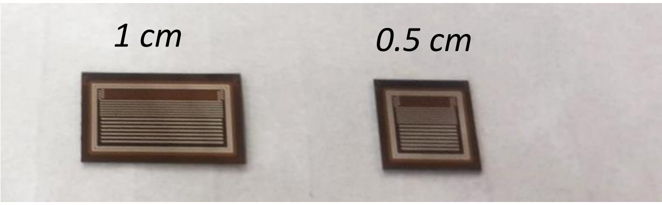




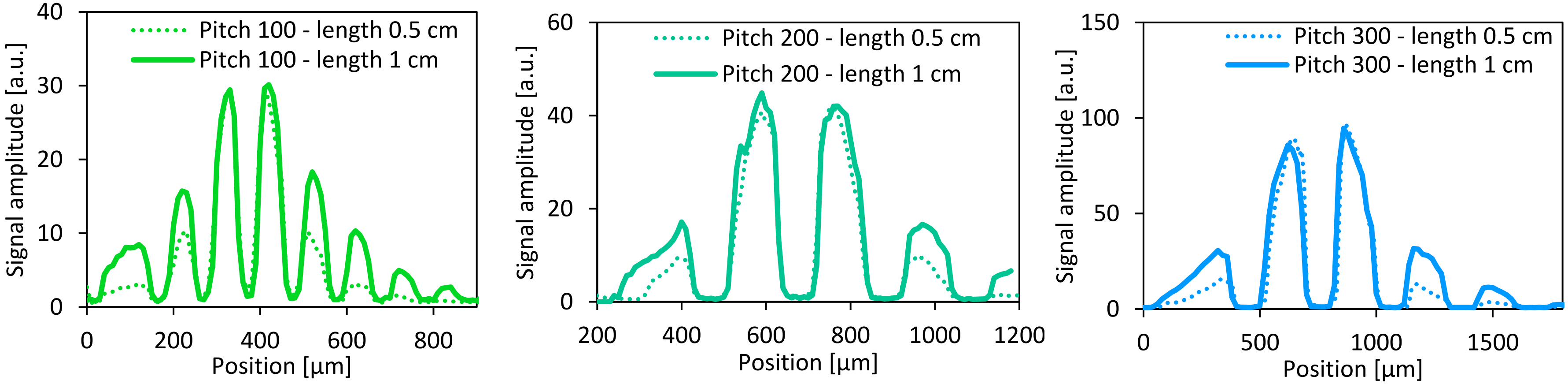
Strip length ca. 2.5 cm →

Role of strip length in charge sharing

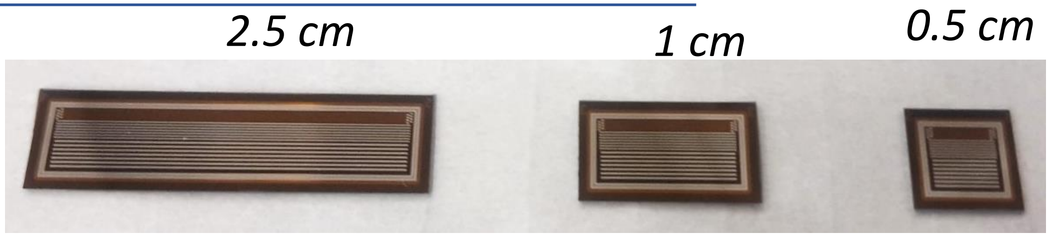
J. Ott et al, AC-LGAD 4D tracking and electrode geometry, Pixel2022



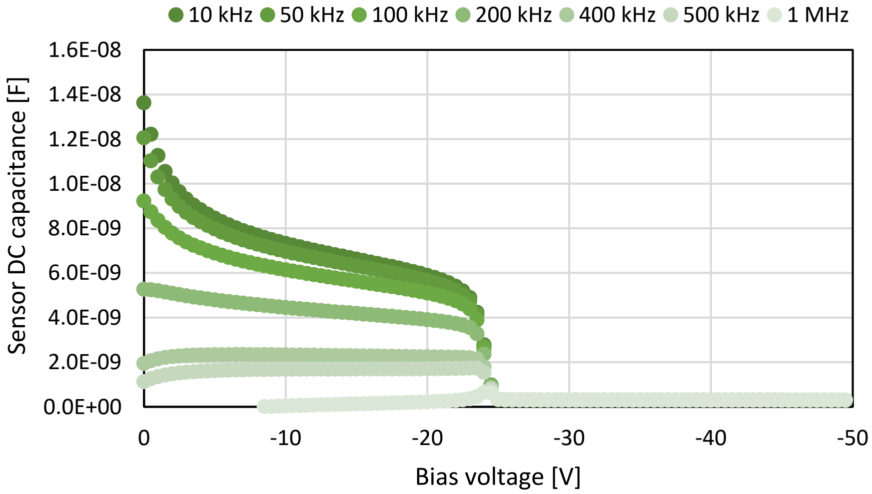
- Traditionally, research focus lies on identifying and optimal strip pitch and metal width
- Strip **length** also affects charge sharing
  - Not detectable in 2D or quasi-3D simulations - preliminary 3D simulations appear to be able to replicate higher sharing for longer strips
  - Longer strips exhibit 80-140 % higher amplitude in the next neighbor and almost 200 % more sharing to the second neighbor
  - **Strip length correlates with (inter)strip resistance and (inter)strip capacitance**

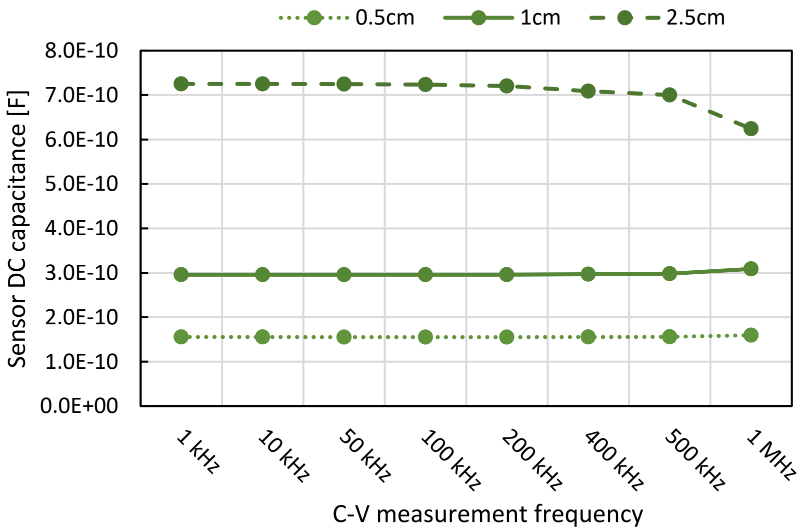


Multipitch strips: sensor capacitance



- For reference: capacitance of the full sensor, n^+ to backplane (‘DC configuration’)
  - ➢ No dependence on measurement frequency after bulk has been depleted of charge carriers



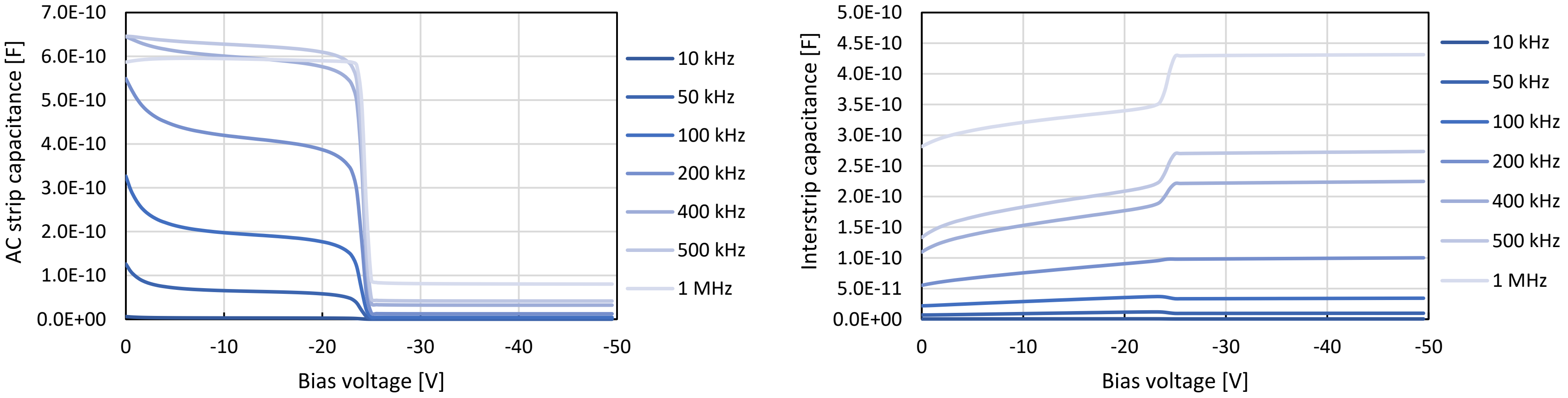


J. Ott et al, AC-LGAD 4D tracking and electrode geometry, Pixel2022

AC strip and interstrip capacitances

- Very different picture when measuring AC component(s): AC strip electrode to backplane, or between AC strips
    - ➢ Frequency dependence, and inverse correlation of frequency and capacitance

- Depletion is still observed: contribution to these capacitances not only by surface, metal or dielectric
- Interstrip capacitance is larger than strip capacitance itself



1 cm strip length; 200 um pitch = 100 um metal

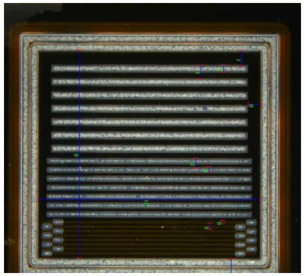
Capacitances as function of strip length and width

J. Ott et al, AC-LGAD 4D tracking and electrode geometry, Pixel2022

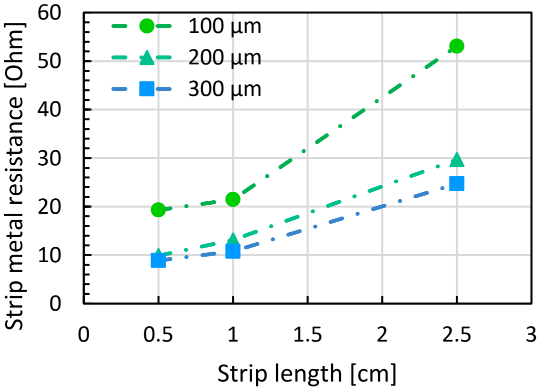
300-150

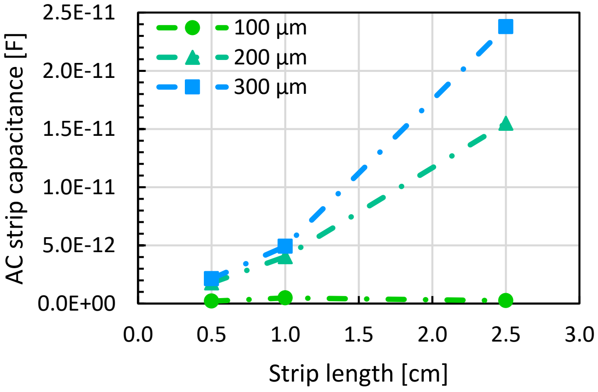
200-100

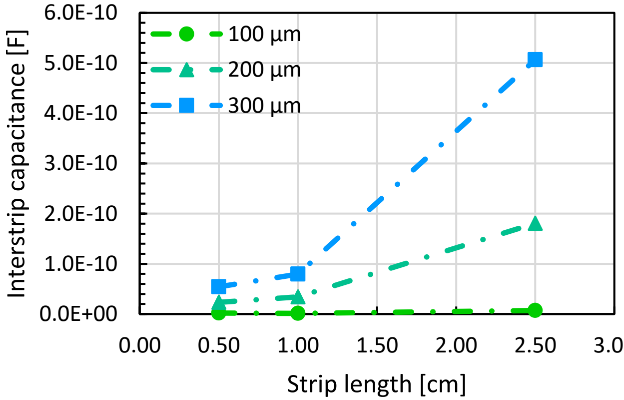
100-50

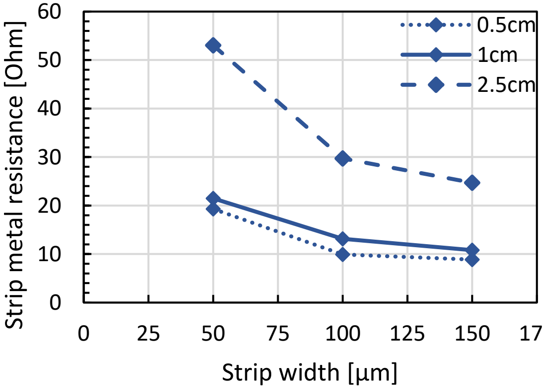


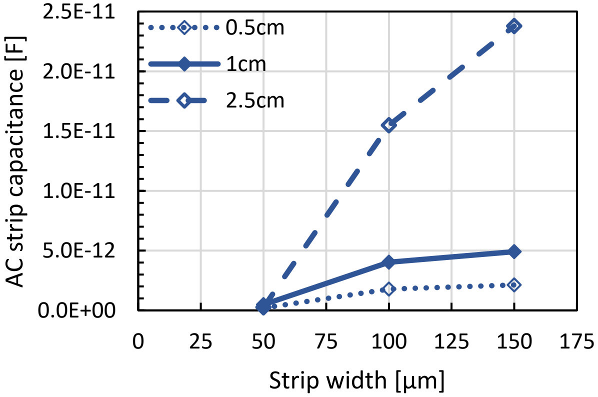
2.5 cm *1 cm* *0.5 cm*

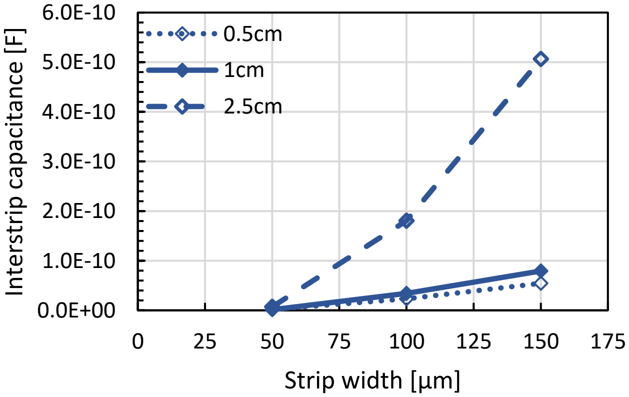












100 kHz

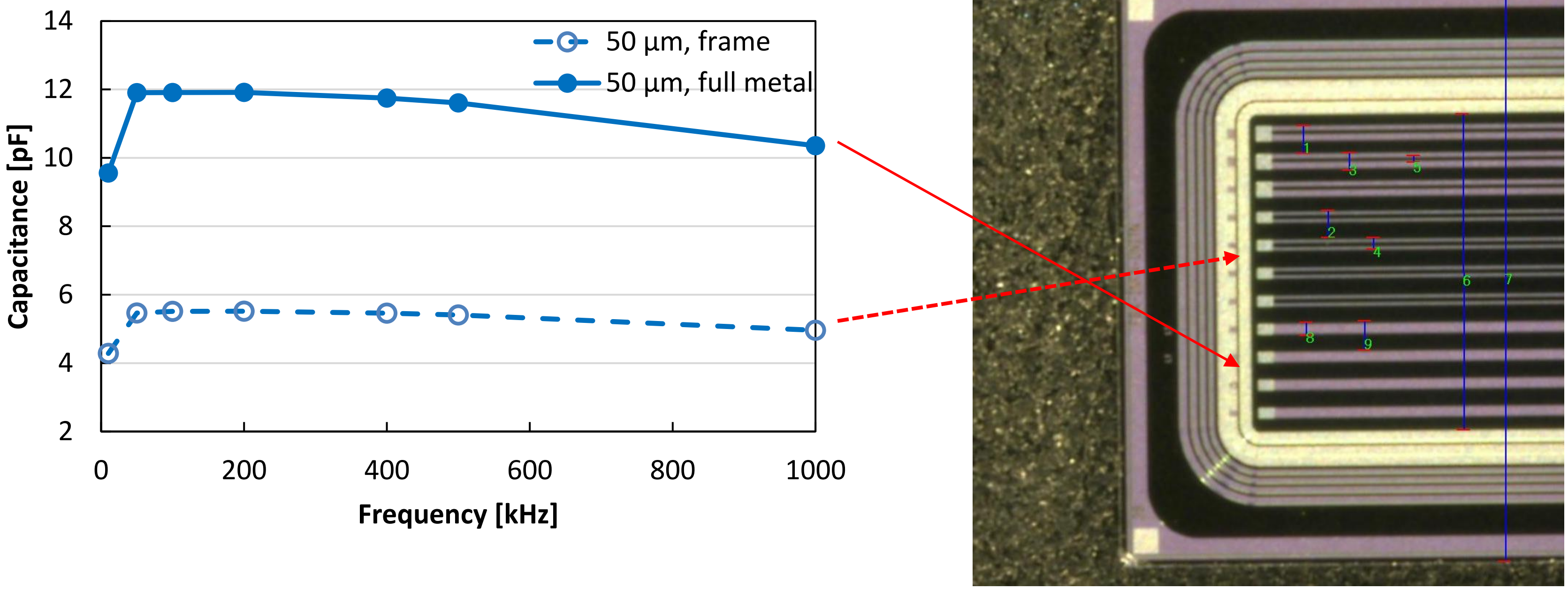
Capacitances as function of strip length and width

- Strip length and width increase both strip and interstrip capacitances
  - Nearly exponential increase with strip length
    - Strip resistance increases with length as well
  - Impact of strip width (in this case, directly connected to the pitch) less extreme
    - Strip resistance is reduced for wider metal
- Interpretation of the obtained resistances corresponding to a C_p-R_p / C_s-R_s model is not well understood yet
- Increased strip capacitance seems to correlate with higher position-independent response – potentially cross-talk and pick-up are increased in larger strips *

* C. Madrid et al, https://arxiv.org/abs/2211.09698 and data shown in conversation

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***



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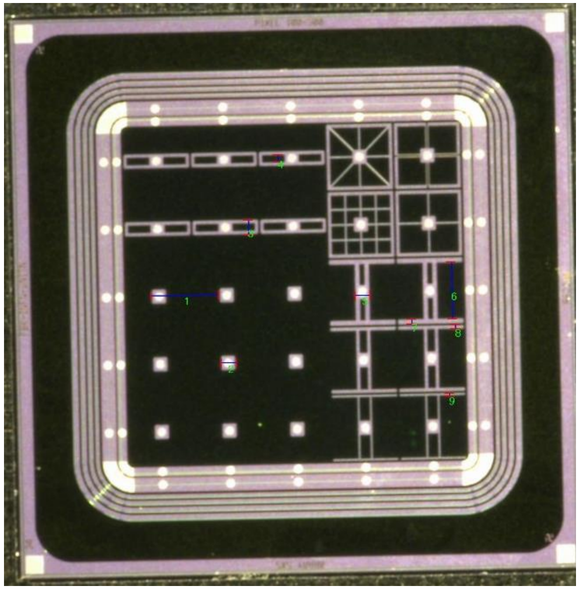
*M. Mandurrino et al, 39th RD50 Workshop, November 2021 (https://indico.cern.ch/event/1074989/contributions/4602006/)

FBK RSD2 exotic geometries

- 500 µm pitch pad array with unconventional metal shapes
  - Reduction of AC pad capacitance by using metal lines instead of full metallization?
  - Impact on signal?
  - Exploration of asymmetric metal (microstrips, H-bars) for enhanced resolution in one dimension

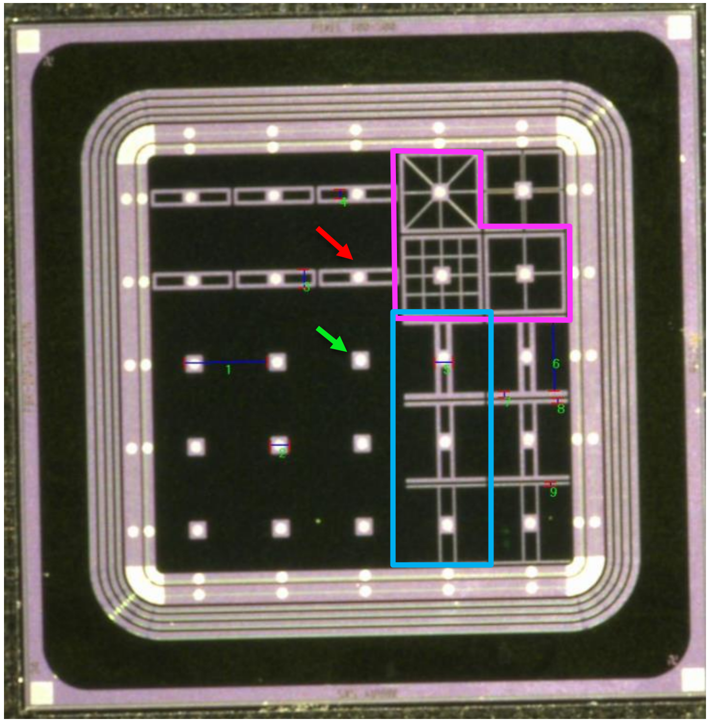


J. Ott et al, AC-LGAD 4D tracking and electrode geometry, Pixel2022

FBK RSD2 exotic geometries

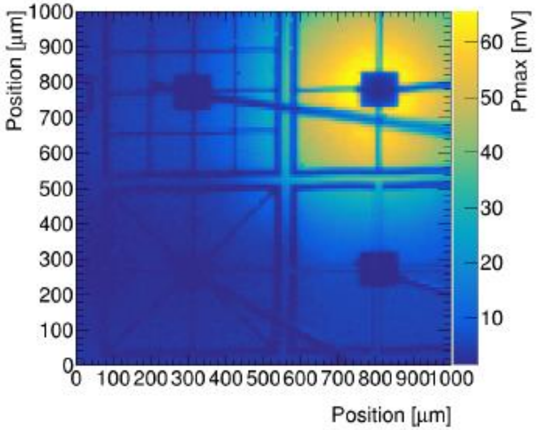
- Capacitances scale well with metal area
- Already small change in metal line width affects the measured capacitance

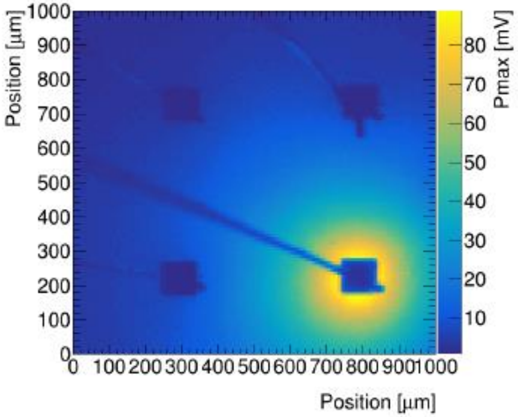
Pad shape	Capacitance [fF]
Square	94
Microstrip	299
Cage 1	726
Cage 2	801
Cage 3	621
H-bar 1	639
H-bar 2	493
H-bar 3	329

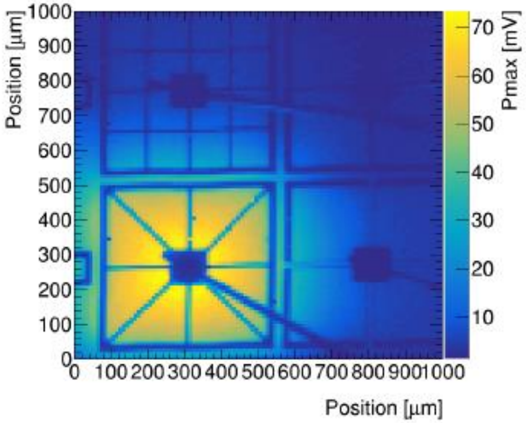


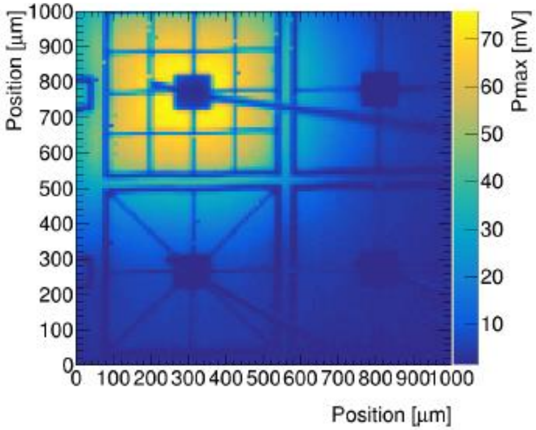
FBK RSD2 exotic geometries

- Square pads: uniform response in x and y
- Cages: uniform response in x and y as well, but
  - … broader maximum amplitude profile
  - … cage outer lines contain the (large) signal
  - … reduced capacitance by a factor of ~2-2.5 compared to fully metallized pad





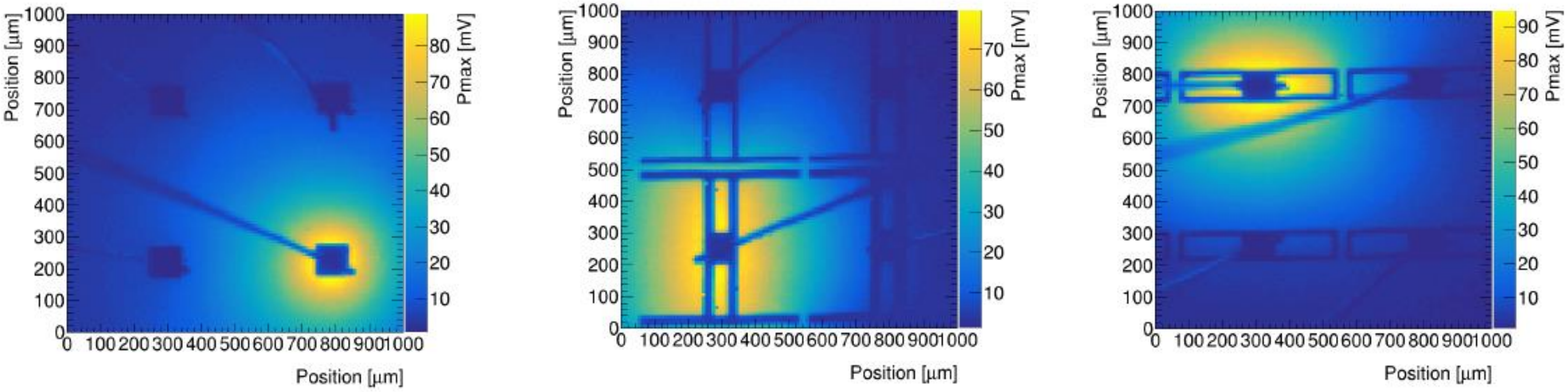




S. Mazza et al, https://indico.cern.ch/event/1157463/contributions/4922739/

FBK RSD2 exotic geometries

- Microstrips and H-bar pads: broader maximum amplitude profile along the elongated dimension
- Additional metal line ‘cap’ provides more homogeneous signal along H-bar pads!
    - Similar to cages, but visible also in one dimension



S. Mazza et al, https://indico.cern.ch/event/1157463/contributions/4922739/

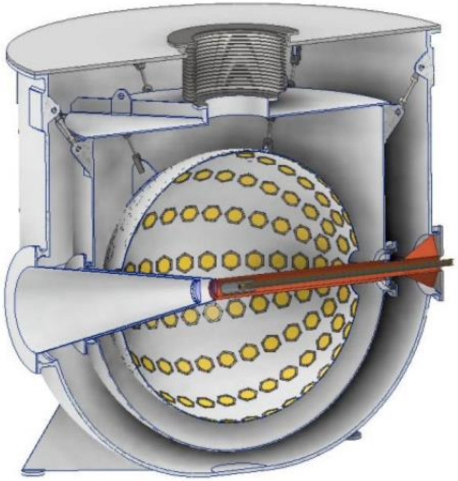
Summary I

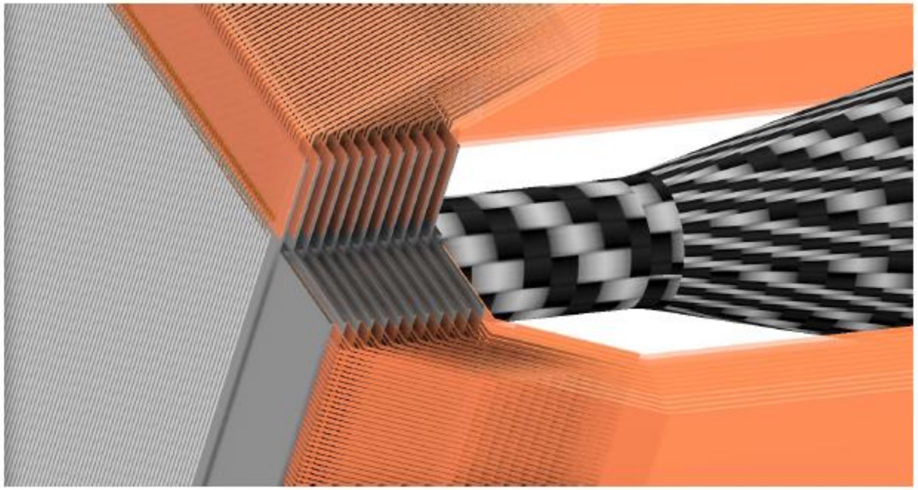
- Thanks to signal sharing, AC-LGADs can achieve remarkable position resolution even with large and widely spaced electrodes
  - ➢ Less than 1/20 of the pitch – e.g. ~20 µm at 500 µm pitch
  - ➢ Simultaneously, 25-35 ps timing resolution
- Reconstruction with multiple strips beneficial for position resolution, but is not preferred for timing

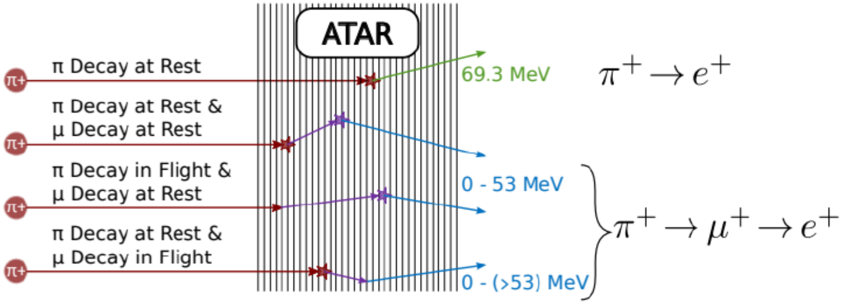
- Charge sharing in AC-LGADs is influenced by several factors:
- **Metal electrode**:
  - Induction of signal on neighboring electrodes is observed
  - Strip length and width affect charge sharing – pitch appears less critical
  - Understanding of the interaction of various capacitances and resistances in the sensor to be improved, drawing also on circuit and 3D sensor simulations
  - “Advanced manipulation” of the electrode shape may be interesting for targeted application
- Dielectric: not well quantified, capacitance is dominated by the Si area and volume
- n^+ layer resistivity (cf. backup slide): higher resistivity reduces sharing
  - ➢ Limited by feasible implantation dose, avoiding depletion of the n+ layer

Example of future experiments: PIONEER

- New pion decay experiment approved at PSI, data taking to be started in 2028 - first beam time completed in May-June 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 too much in order not to occupy large areas of the sensor from a single hit





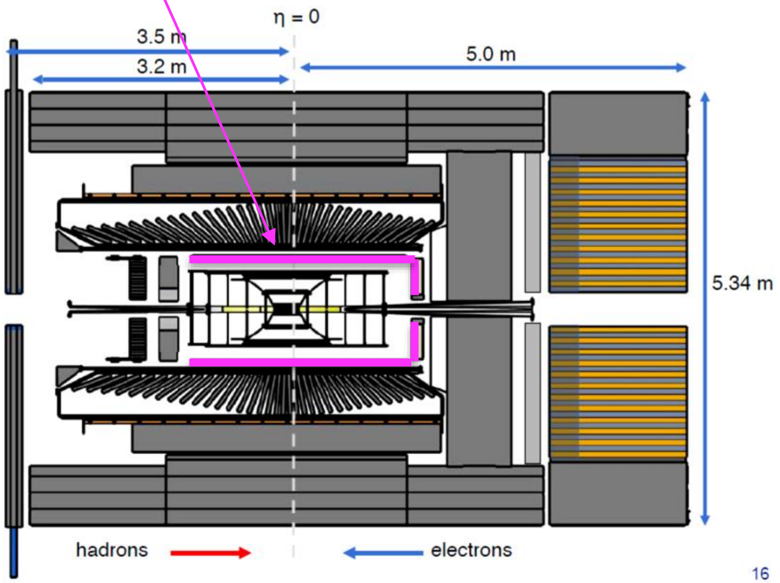


PIONEER: Studies of Rare Pion Decays, https://arxiv.org/abs/2203.01981 (2022)
S. M. Mazza, An LGAD-Based Full Active Target for the PIONEER Experiment, *Instruments* **2021**, *5*(4), 40

EPIC detector at the Electron-Ion Collider

- EIC Detector 1: recently issued recommendation, based on two proto-collaborations
  - ➢ Emerged as EPIC Detector collaboration in summer 2022

- Design includes AC-LGADs for time-of-flight particle ID, t_0 determination and timing, and serving as additional layer in Tracking
  - ➢Efforts organized in the TOF-PID working group, and eRD112/LGAD consortium



https://indico.bnl.gov/event/17072/contributions/68825/
https://indico.bnl.gov/event/17072/contributions/70500/

EPIC detector at the Electron-Ion Collider

- EIC Detector 1: recently issued recommendation, based on two proto-collaborations
    - Emerged as EPIC Detector collaboration in summer 2022
- Design includes AC-LGADs for time-of-flight particle ID, t_0 determination and timing, and serving as additional layer in Tracking
    - Efforts organized in the TOF-PID working group, and eRD112/LGAD consortium

- Radiation hardness of timing detectors not very challenging - more important:
    - **Combination of precise temporal and spatial resolution: 25 ps and 30 µm / hit**
    - Low material budget
- Current sensor design baseline:
    - Barrel: **strips, 500 µm pitch and 1 cm length**
    - Hadronic endcap (and Roman Pots): **pads, 500 x 500 µm**

Summary II

- **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!

- Strip sensors are more sought after for larger areas: understanding the mechanisms and limiting the charge sharing in long strips is important for both aforementioned projects

- Pad sensors: reconstruction more complex; tradeoff between larger signal on one hand, and reduced resolution under the metal on the other

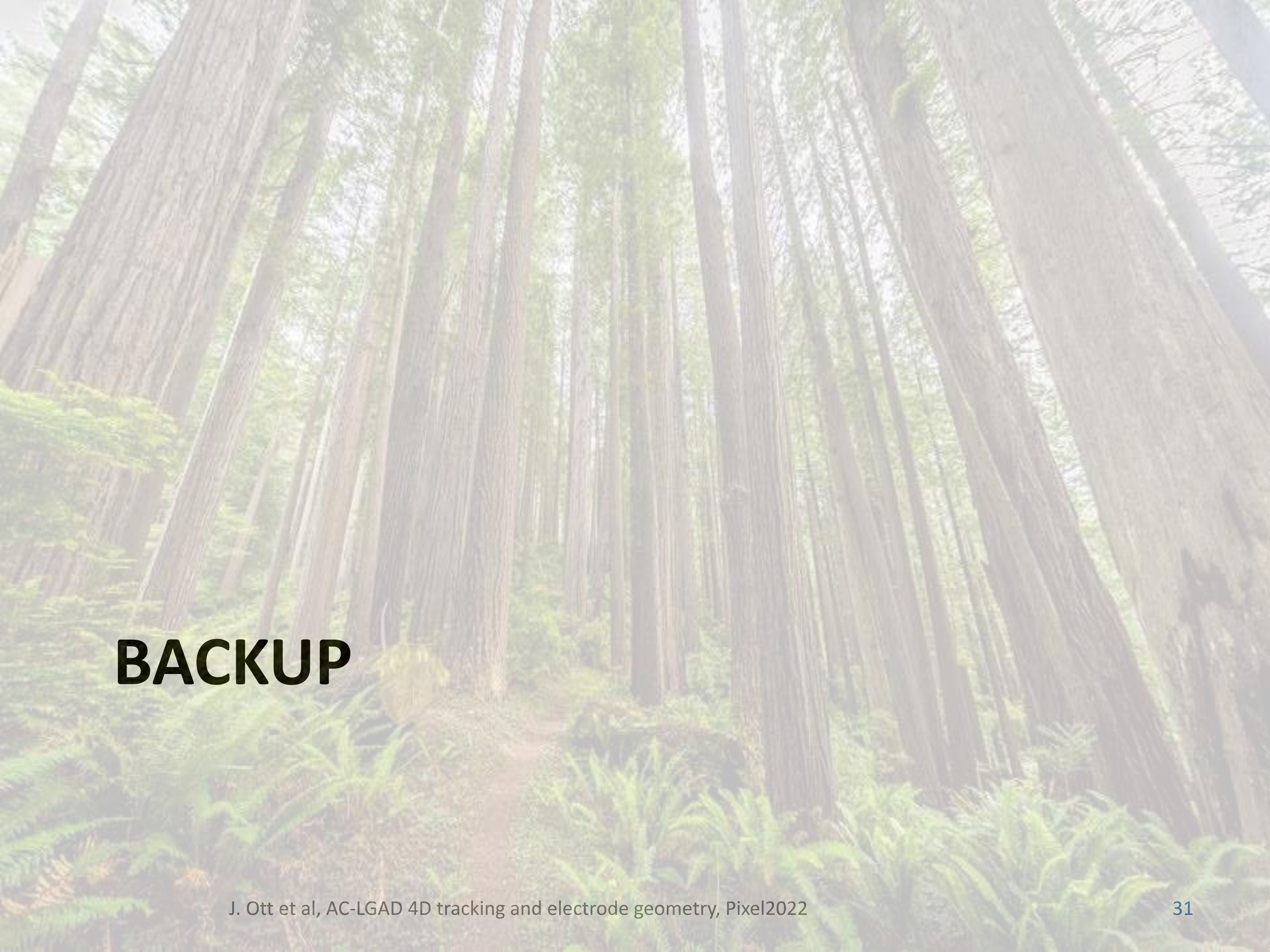
- Precise timing and position resolution and fast charge collection time is also attractive to other fields, such as beam monitoring, photon counting

Thank you!

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

This work was supported by the United States Department of Energy, grant DE-SC0010107-005

Thank you!

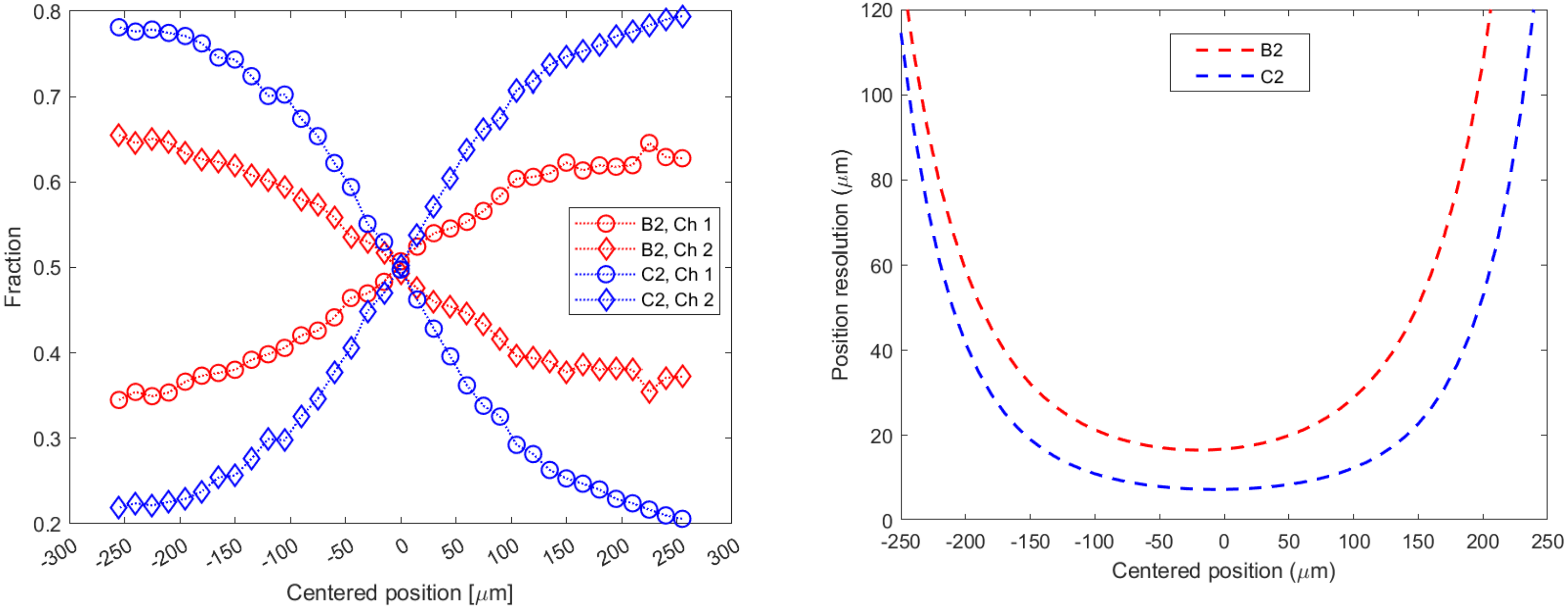


BACKUP

Impact of n$^+$ implant dose on position resolution

Impact of n+

- 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)**



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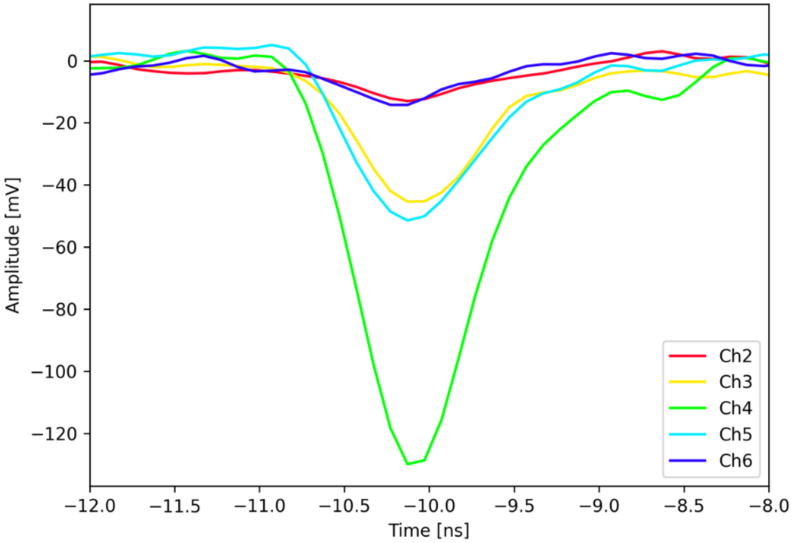
* K. Nakamura *et al*, First Prototype of Finely Segmented HPK AC-LGAD Detectors, JPS Conf. Proc. 34, 010016 (2021)

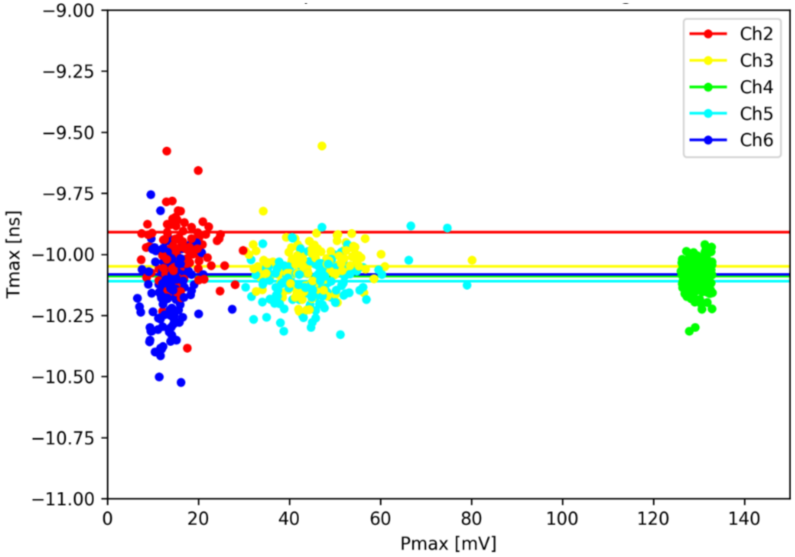
J. Ott et al, AC-LGAD 4D tracking and electrode geometry, Pixel2022

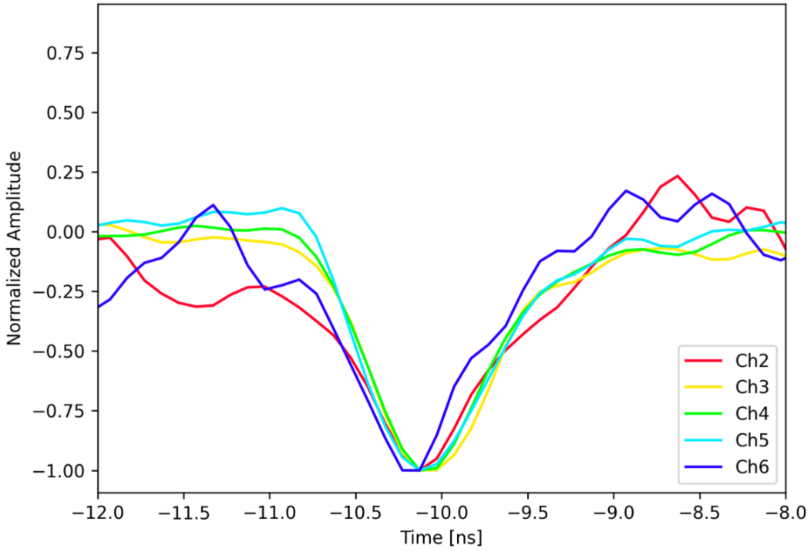
Signal pulse shapes

Continuation to slide 10 with normalized pulses and tmax-pmax plot

- 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

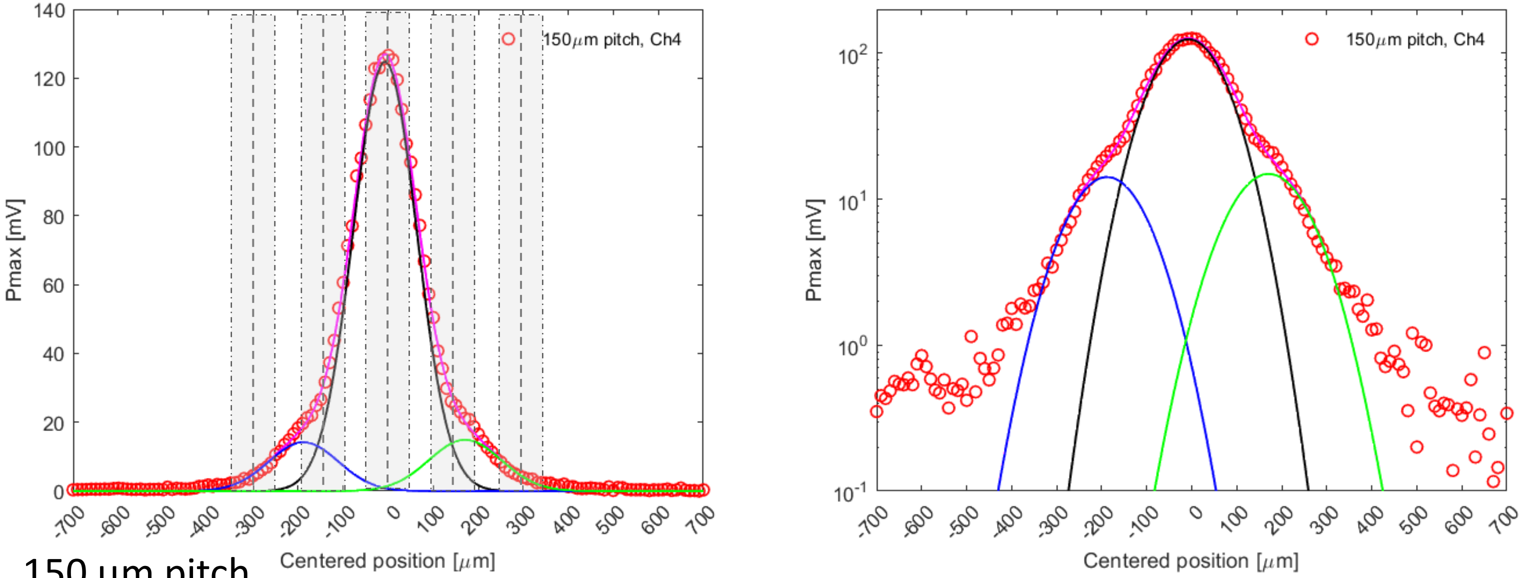




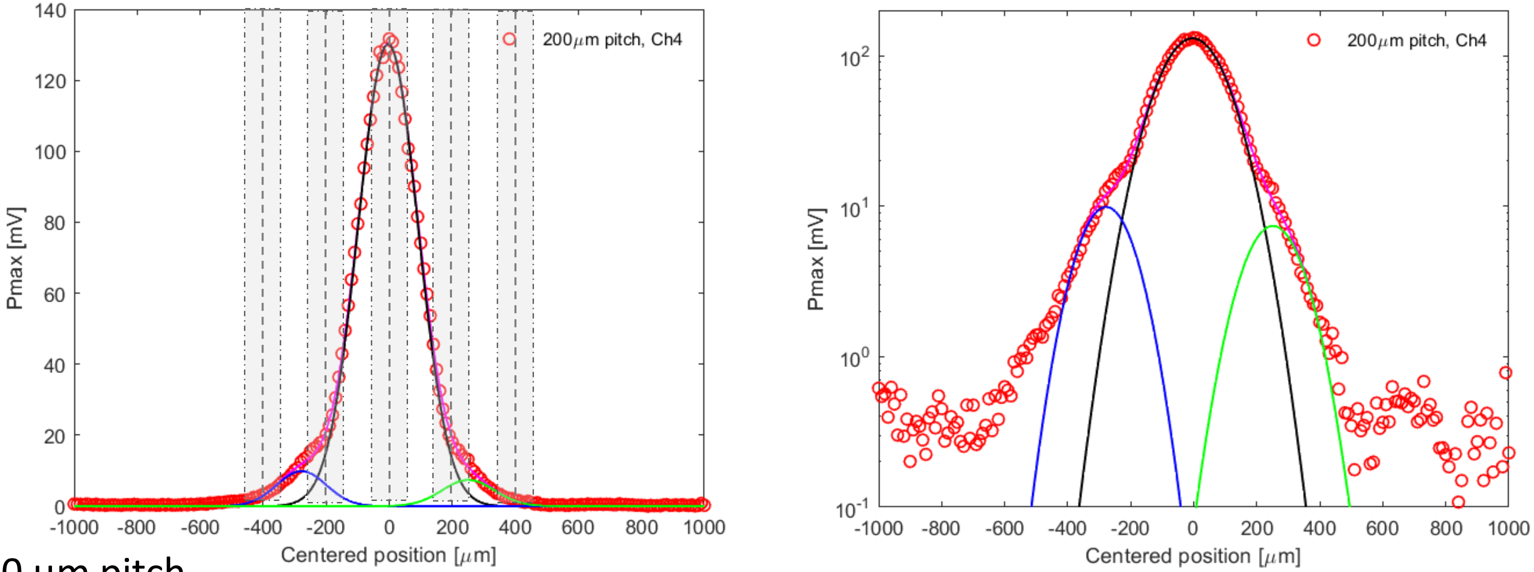


Charge on neighboring strips

Continuation to slide 9 with larger pitches



Medium, 150 µm pitch



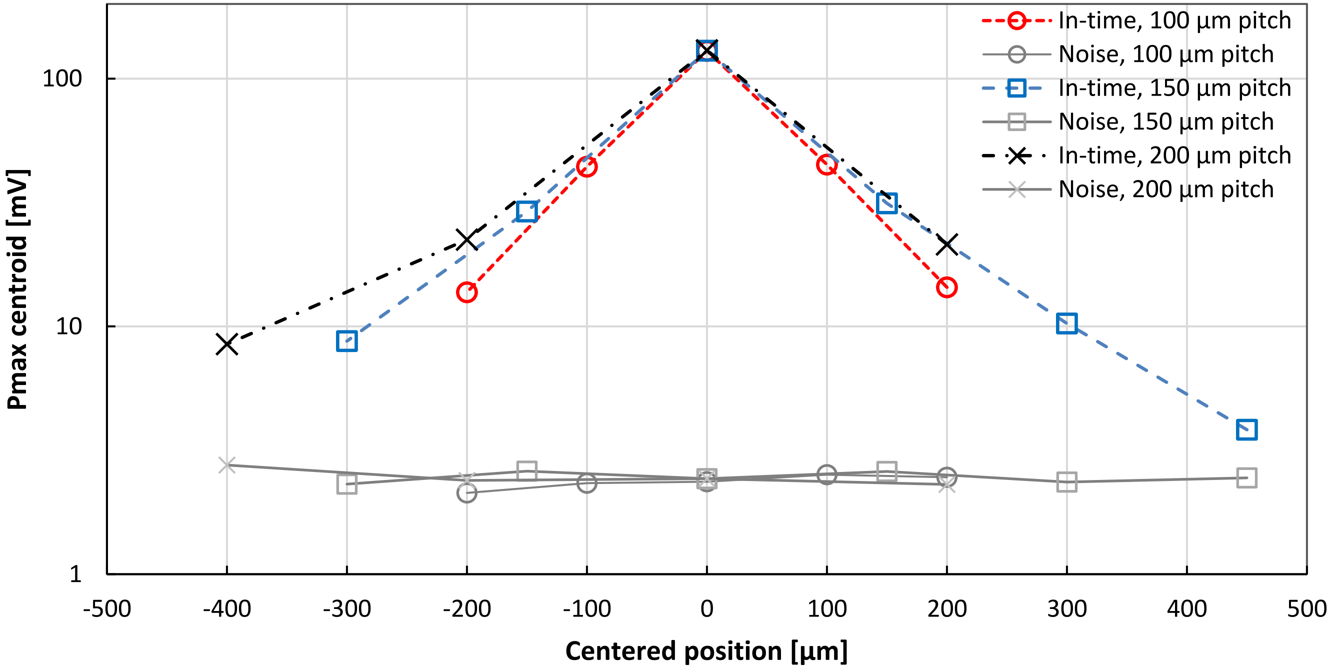
Wide, 200 µm pitch

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

Addition on in-time/out-of time plot, slide 12

- Smaller time window reduces noise contribution to signal

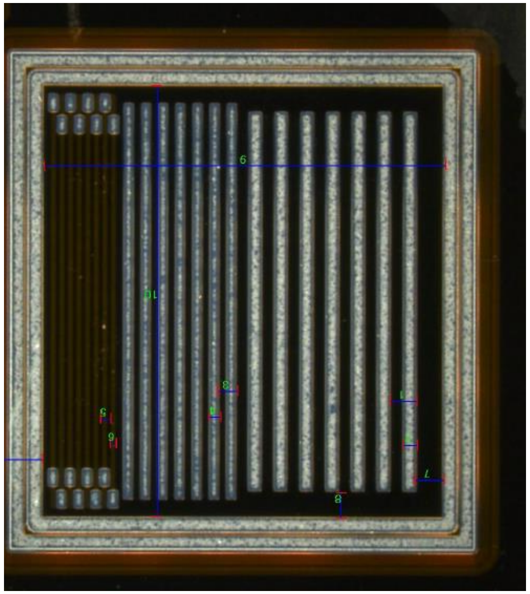
- The choice of model used to describe the signal (mean, Landau, Gaussian) does not have a strong impact on signal/noise separation
- Even at large distances from the triggered channel, in-time signal pulse heights are above the noise floor

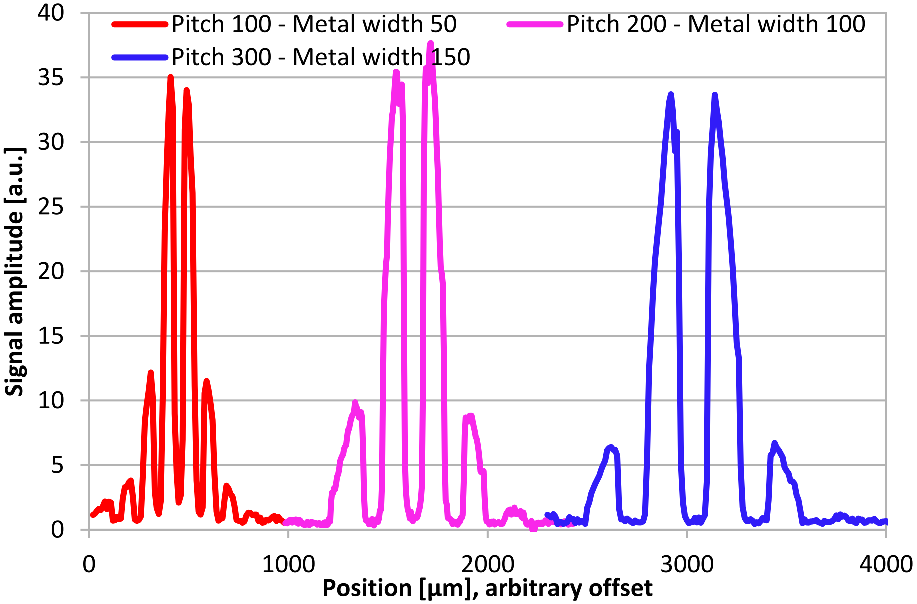


Laser study of charge sharing

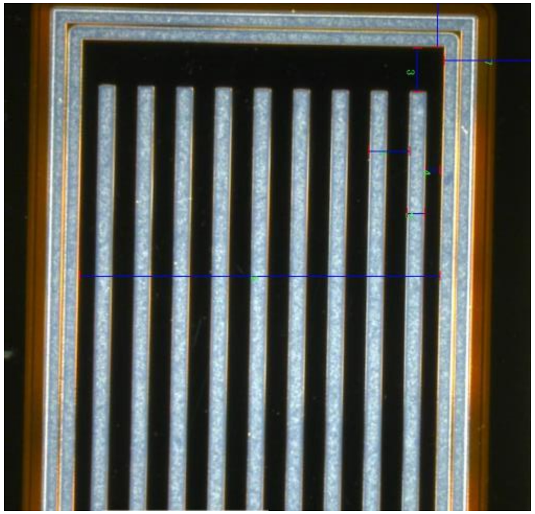
Alternative to slides 13 and 14

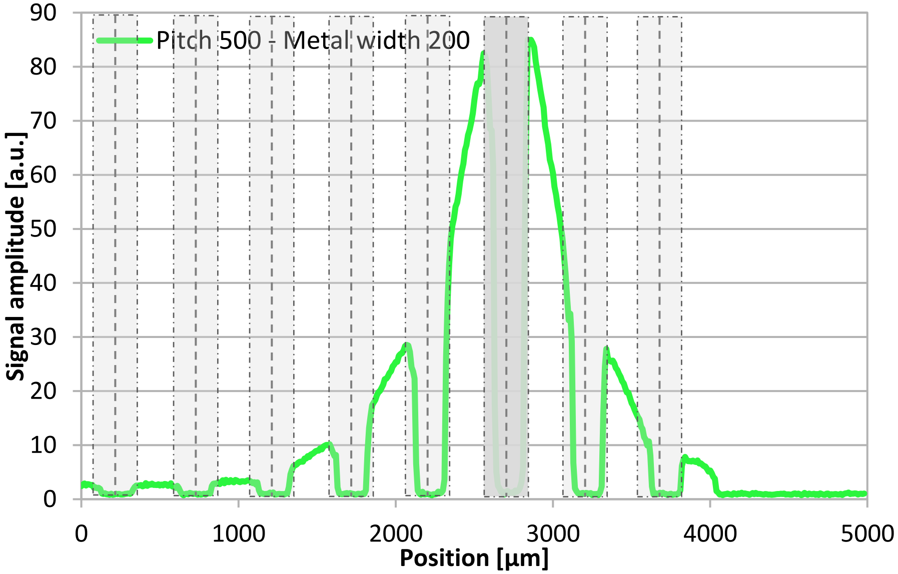
~0.5 cm





~2.5 cm





Strip length and width

Same as slide 17, just log-y axis