Developments in AC-LGADs for future colliders and nuclear physics experiments

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CPAD Workshop

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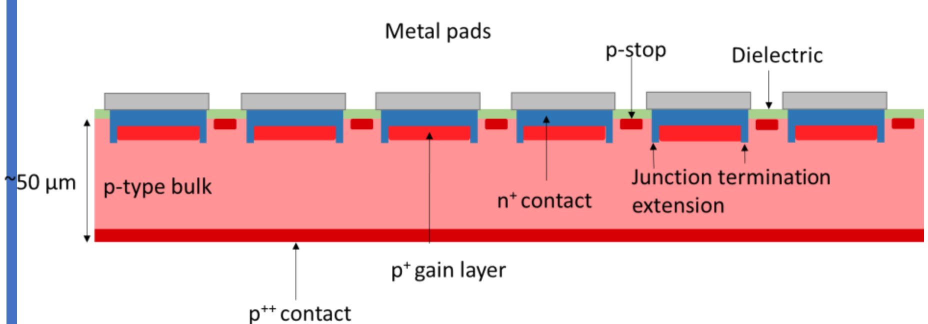
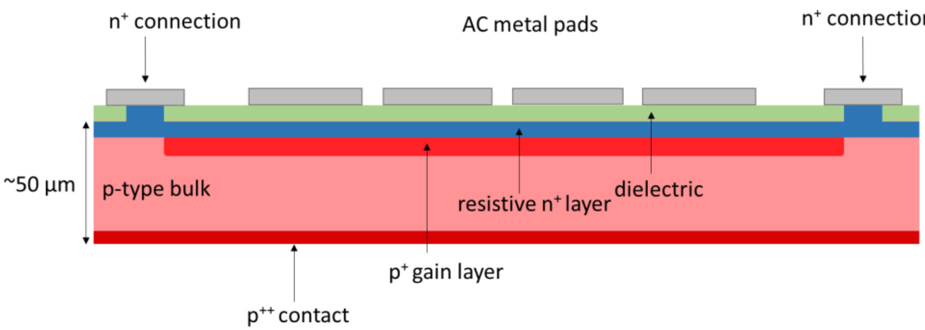
Low gain avalanche diodes

- 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**

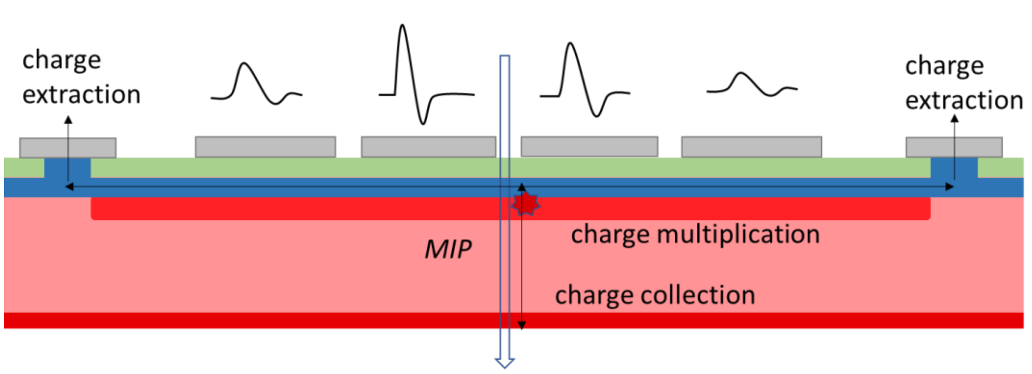




H. F.-W. Sadrozinski et al, *4D tracking with ultra-fast silicon detectors*, Reports on Progress in Physics 2018, 81, 026101
CMS Collaboration, *A MIP Timing Detector for the CMS Phase-2 Upgrade*, CERN-LHCC-2019-003, 2019
ATLAS Collaboration, *A High-Granularity Timing Detector for the ATLAS Phase-II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

AC-coupled low gain avalanche diodes

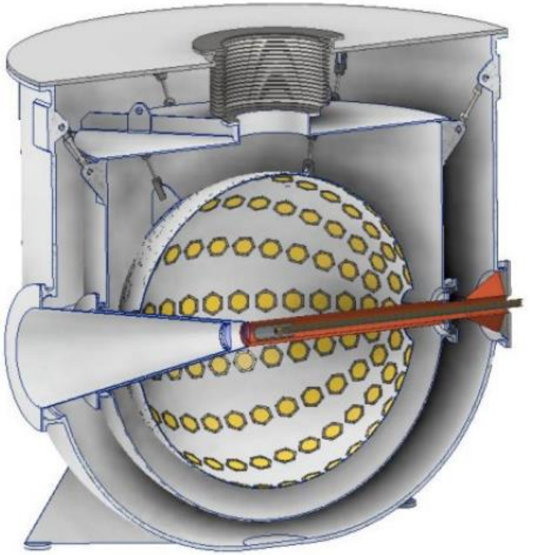
- In AC-coupled LGADs, also referred to as Resistive Silicon Detectors (RSD), the multiplication layer and n^+ contact are continuous, only the metal is patterned:
  - The signal is read out from metal pads on top of a continuous layer of dielectric
  - The underlying resistive n^+ implant is contacted 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**

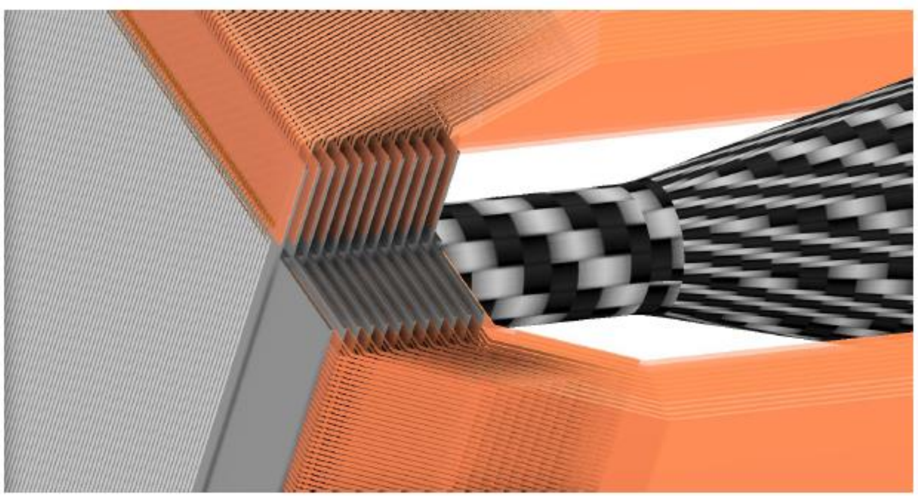


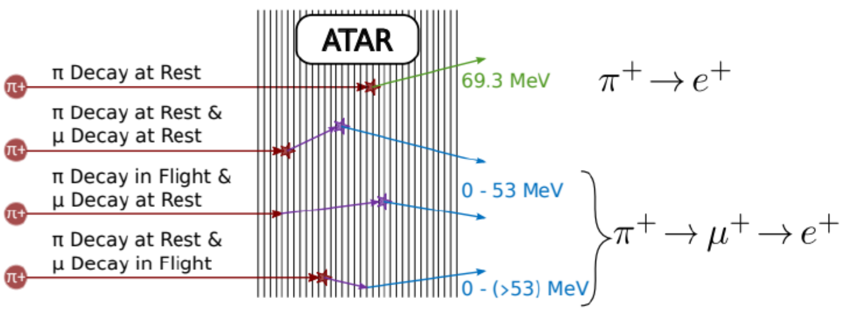
G. Giacomini *et al.,* Fabrication and performance of AC-coupled LGADs, *JINST* **2019**, 14, P09004
A. Apresyan *et al.,* Measurements of an AC-LGAD strip sensor with a 120 GeV proton beam**,** *JINST* **2020**, 15, P09038
S. M. Mazza, An LGAD-Based Full Active Target for the PIONEER Experiment, *Instruments*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

PIONEER Experiment

- New pion decay experiment approved at PSI, data taking to be started in 2028 - first beam time assigned in May 2022, next November 2023
- 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







Cf. Adam's talk

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

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EPIC detector at the Electron-Ion Collider

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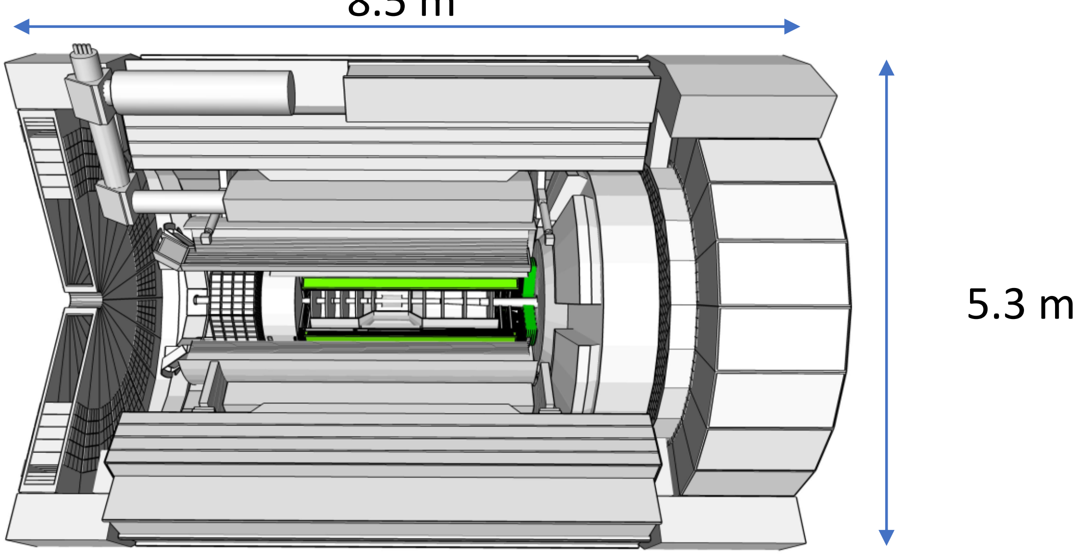
- EIC Detector 1: recently issued recommendation, based on two proto-collaborations
  - ➢ Emerged as ePIC Detector collaboration in summer 2022

- 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/

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- 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**

ePIC TOF-PID sensor development

- First design plans based on earlier generic AC-LGAD productions by FBK, BNL, HPK
  - Various electrode geometries, typically smaller sizes
  - Resistive n-layer and dielectric capacitance variation by HPK and FBK

- More targeted production(s) by BNL to evaluate strip pitch and width
- Beginning to fabricate 20 µm sensors in addition to the standard 50 µm

Cf. Artur's talk

- Recent (2023) production by HPK aimed at EIC sensor specifications
- Focusing on 500 µm pitch baseline
- BNL productions focusing on gain layer engineering

HPK sensor production for the EIC

HPK production splits:

- E and C type n-layer (E resistivity higher, C lower)
- Dielectric capacitance 240 and 600 pF/mm2
  - 20 and 50 µm bulk thickness for 600 pF/mm2

50 um Thick - E type - 240 pF/mm^2
50 um Thick - C type - 240 pF/mm^2
50 um Thick - E type - 600 pF/mm^2
50 um Thick - C type - 600 pF/mm^2
20 um Thick - E type - 600 pF/mm^2
20 um Thick - C type - 600 pF/mm^2

- Strips:
  - 2, 5, 10, 20, 25 mm length
  - 50, 100 µm width
- Pixels:
  - 150, 300, 450 µm pixel size

- Breakdown voltages ca. 210 V for 50 µm, 120 V for 20 µm thicknesses; gain layer depletion at ca. 50 V

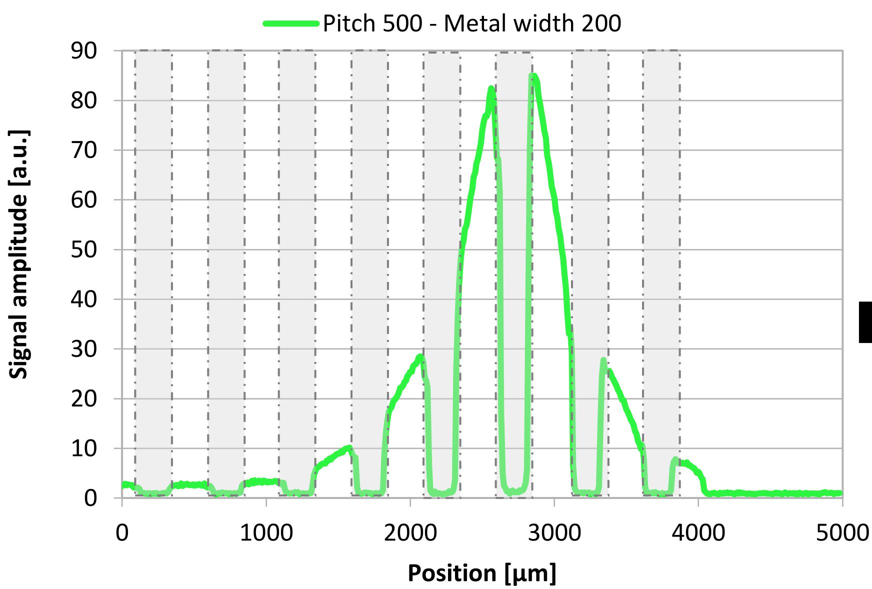
Irradiation campaign for AC-LGADs

- Radiation hardness: has not been extensively studied specifically for AC-LGADs
- Subset of HPK (and BNL) sensors were sent to Los Alamos National Lab for irradiation with 800 MeV protons in August
  - Focus on E type
  - Focus on 600 pF/mm^2 dielectric capacitance
  - Focus on 1cm strip length, 100 µm strip width, 150 µm pad size
- Total fluences between 1e13 and 2e14 p/cm^2 – higher than envisioned at the EIC over the full time of life,
- Including attempts at **graded irradiation of strip sensors to study the effects of non-uniform degradation of the gain layer and n-layer** within a long sensor

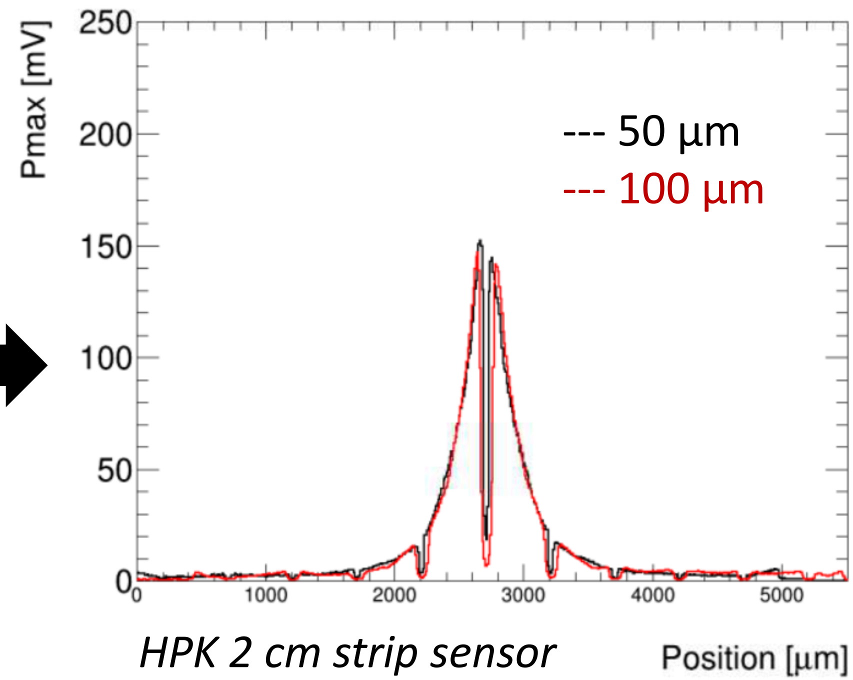
Characterization of AC-LGADs: signal sharing

- **Impact of sensor geometry, coupling dielectric, and n+ layer resistivity on signal sharing:** essential question for any AC-LGAD detector

- Charge sharing to far-away strips has been the main problem in long strip sensors in the past
- Significant improvement in recent sensors



Older 2.5 cm strip sensor



HPK 2 cm strip sensor
Amplitude normalized

HPK strip sensors: laser studies

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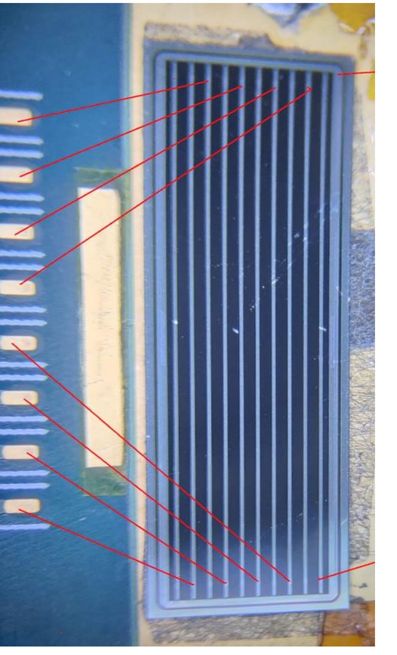
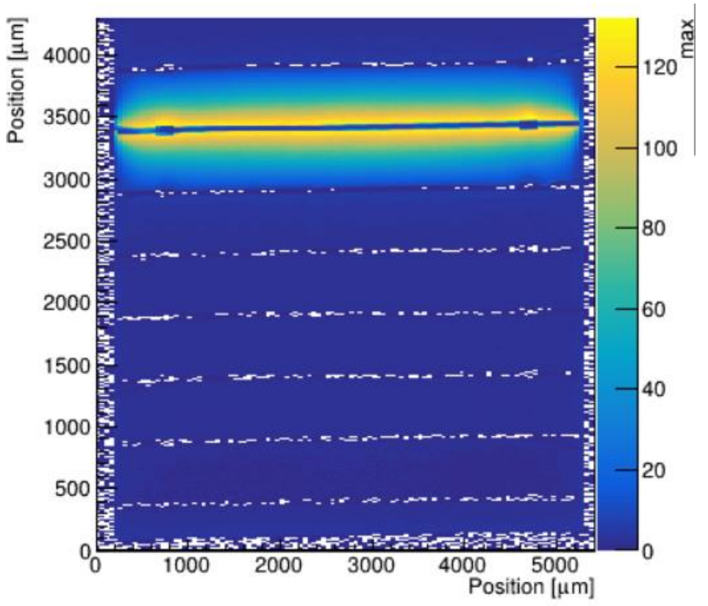
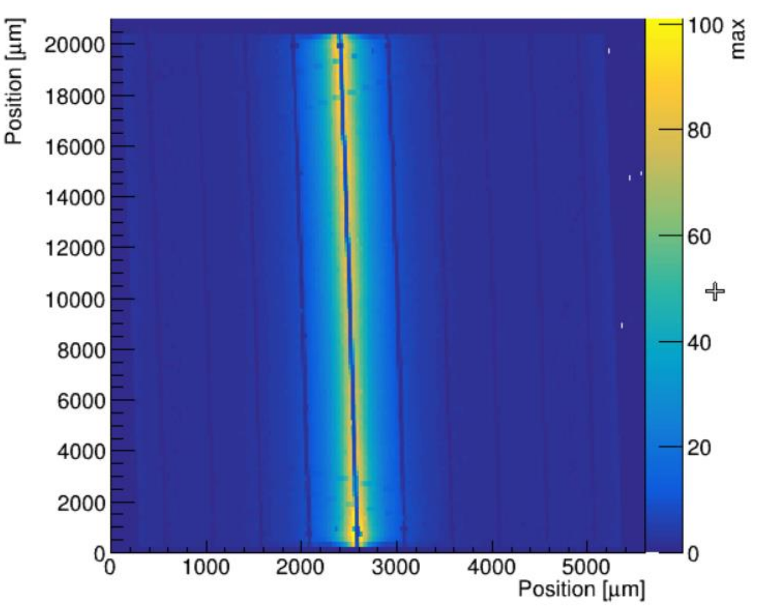
- Set of sensors at UCSC which have not been sent to LANL for irradiation: measured by infrared laser scanning TCT
  - Focus on 50 µm strip width
- Averaged waveform at each x-y point
- Time-of-arrival information and jitter based on laser reference
- Monitoring of sensor response uniformity, gain ‘hotspots’



5 mm length, 50 µm thickness, E600



20 mm length, 20 µm thickness, E600



HPK strip sensors: laser studies

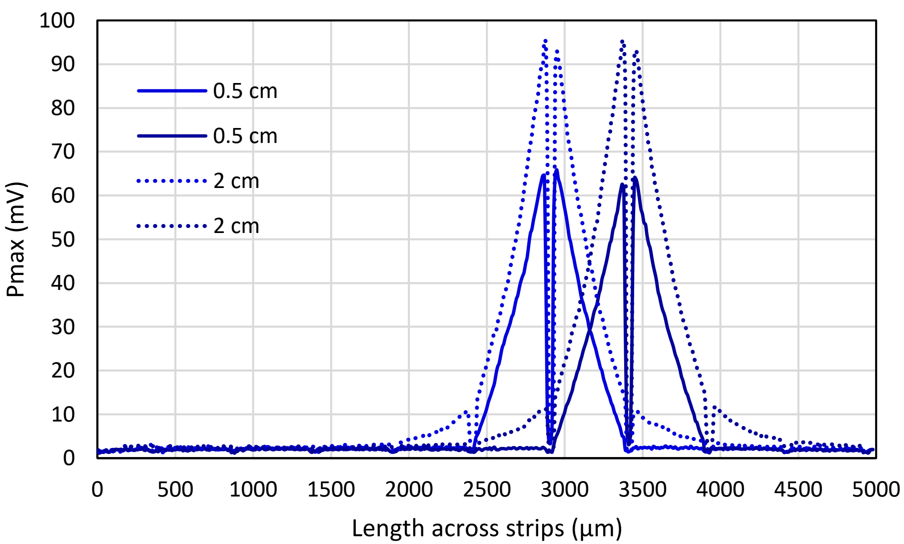
- Selection for comparison:

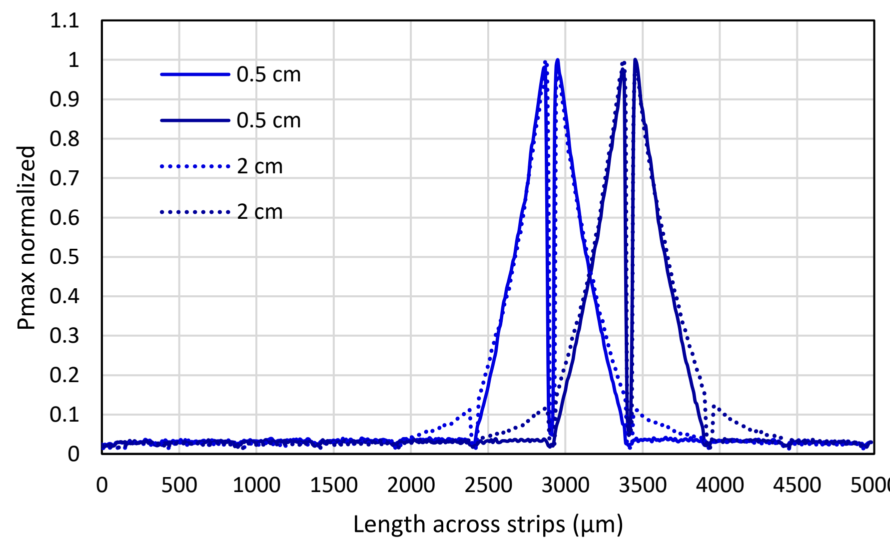
HPK ID	Geometry	wafer	position	size	HPK n+ layer doping	Nominal dielectric C (pF/mm2)	thickness	lenght (mm)	pitch (um)	width (um)
HPK29	Strip	W09			E	600	20	20	500	50
HPK35	Strip	W09			E	600	20	20	500	100
HPK8	*Strip*	*W04*			*C*	*240*	*50*	*5*	*500*	*100*
HPK4	Strip	W08			C	600	50	5	500	50
HPK4	Strip	W08			C	600	50	5	500	50
HPK3	Strip	W05			E	600	50	5	500	50
HPK8	*Strip*	*W04*			*C*	*240*	*50*	*5*	*500*	*100*
HPK1	Strip	W02			E	240	50	5	500	50
HPK27	Strip	W05			E	600	50	20	500	50
HPK21	Strip	W05			E	600	50	10	500	100
HPK3	Strip	W05			E	600	50	5	500	50
HPK27	Strip	W05			E	600	50	20	500	50
HPK3	Strip	W05			E	600	50	5	500	50
HPK27	Strip	W05			E	600	50	20	500	50
HPK29	Strip	W09			E	600	20	20	500	50

https://indico.bnl.gov/event/20784/contributions/81807/attachments/50296/86020/JOtt_HPK_EIC_strips_Oct10.pdf

HPK strip sensors: strip length

- Larger signal sharing has been observed in longer strips – was not considered a factor originally
- Promising efforts to replicate this in TCAD simulation and correlate it to strip capacitances and resistances
- For E600 type sensors, strip length is indeed confirmed to increase charge sharing with the neighboring strip, however likely **not to a detrimental degree (< 15 % at the next strip) even for 2 cm long samples**
- **Encouraging to consider longer strips than the baseline design: would reduce number of readout channels**

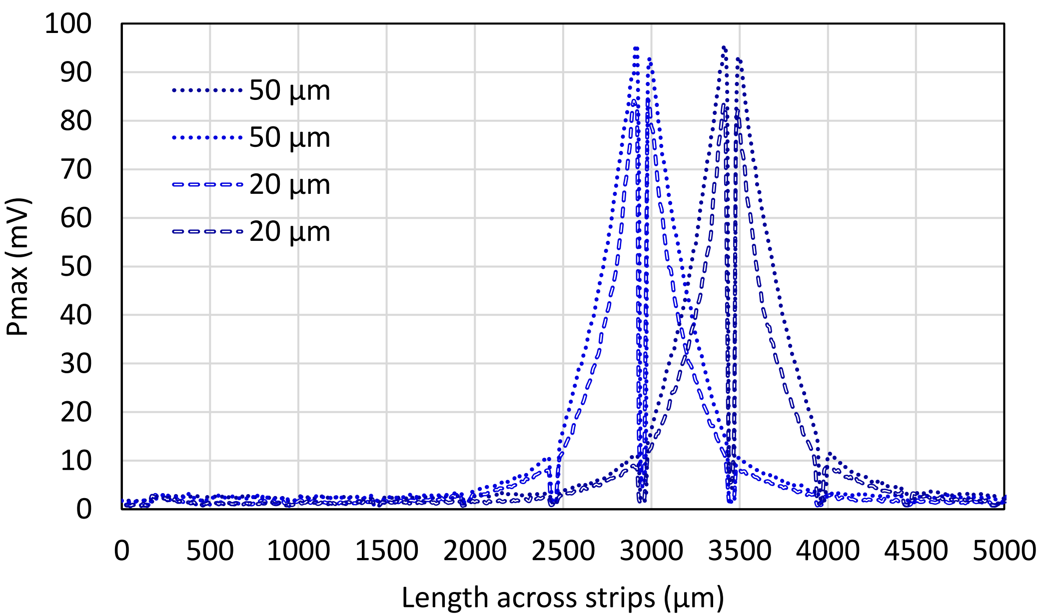




HPK strip sensors: sensor thickness

- 50 µm has been a standard active thickness for LGAD sensors
- To lower the contribution of Landau fluctuations in charge deposition and signal induction, thinning of the sensor bulk (20 µm ~established, in the future even further) is desirable
  - Cons: smaller intrinsic signal; lower breakdown voltage = carrier drift velocity does not saturate unless gain layer is modified

- In 2 cm sensors, at comparable gain, the bulk thickness does not have a significant impact on the signal sharing
- Signal amplitude profile between main strips differs: quantification of expected spatial and timing resolution to be investigated



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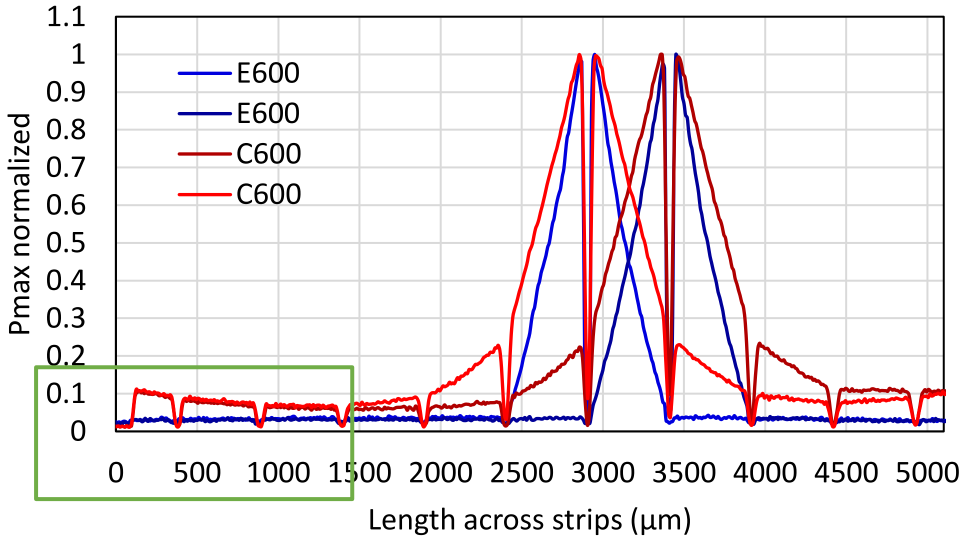
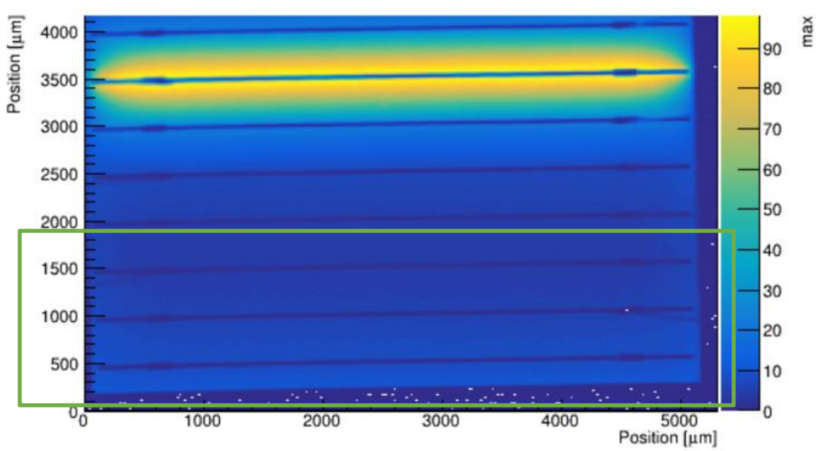
HPK strip sensors: n-layer resistivity

- Expected to be one of the most important parameters in AC-LGADs
- Not fully conclusive results in earlier sensors

- Effect very clearly visible in the HPK production: show-stopper for strip sensors, however increased sharing may be needed in small pad sensors in order to not lose efficiency at the relatively large 500 µm pitch
- Significant long-distance sharing in the C type sensor, increasing towards the edge n-layer contact: how would this affect larger – in this case wider – sensors even if strip length is restricted?





HPK strip sensors: laser studies

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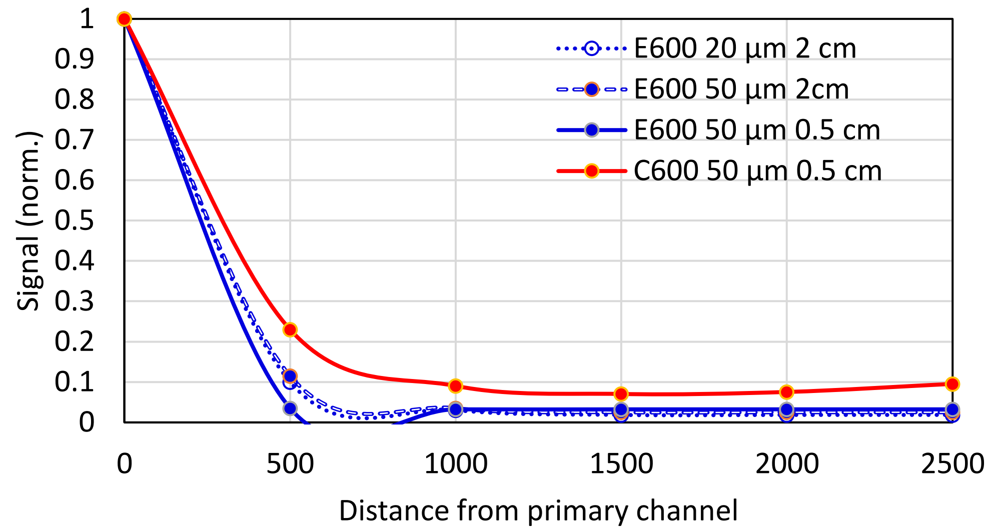
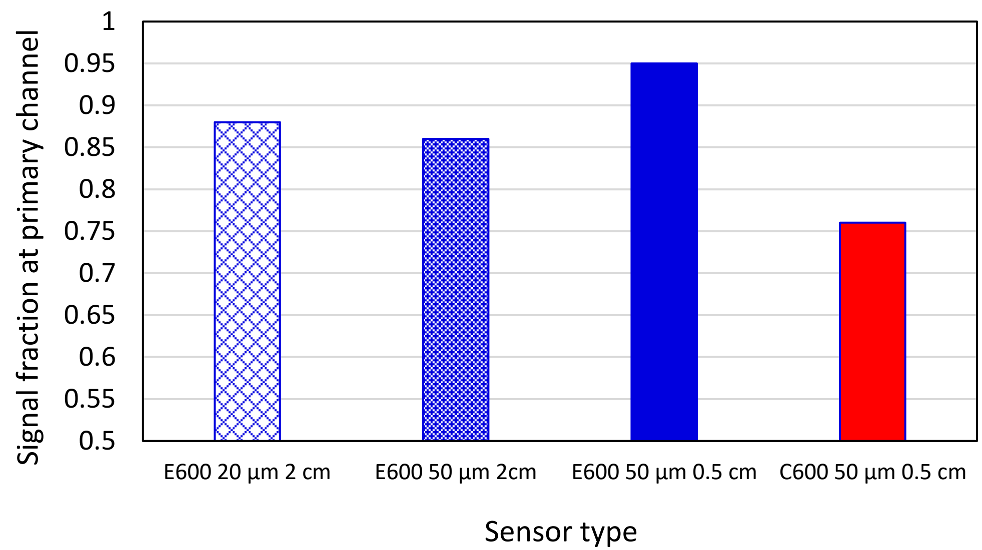
In terms of signal sharing / signal amplitude:

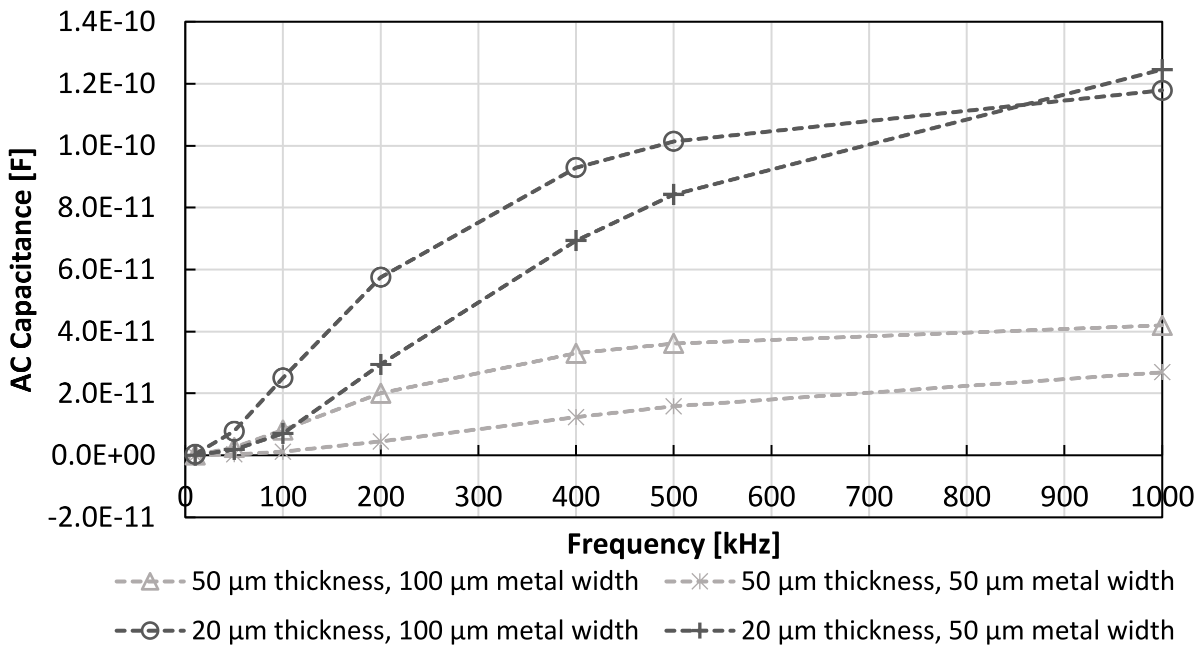
- Signal sharing is strongly impacted by the n-layer resistivity – almost 20 % more for lower resistivity, as well as different long-range behavior
- Strip length increases signal sharing, but signal from primary channel decreases down to ~10% at the next neighbor
- Roles of sensor bulk thickness, strip width, dielectric capacitance are less significant





Characterization of AC-LGADs: capacitances

- Ongoing effort to link signal sharing to capacitances – stay tuned!



More details:
https://indico.cern.ch/event/829863/contributions/5061072/attachments/2564834/4422979/JOtt_Pixel2022.pdf
https://indico.bnl.gov/event/20281/contributions/79620/attachments/49124/83705/JOtt_eRD112_CV_update_Aug23.pdf

Near-future sensor R&D questions

- Quantification of reduced signal amplitude and timing delay in long strips
- Charge sharing along (parallel to) the strip
- Time-of-arrival and timing resolution parallel to a strip
- Systematic studies on pad sensors, intrinsic position reconstruction based on charge sharing

- **Angular dependence of abovementioned properties**

➢ **Identify optimal parameters for strip and pad sensors for specific applications**

Near-future challenges on the detector and project level

- Large-scale sensor productions
  - Uniformity of gain implantation
  - ‘Large’ sensors (e.g. 2x4 cm strips)
  - Fabrication, yield
  - Vendor qualification
- Readout electronics
  - Electronics for precision timing are being developed
  - Sensor size and input capacitances need to be specified
- Detector system integration
  - Assembly into modules: glueing, mechanics
  - Profit from previous experiences in strip detectors as well as ATLAS/CMS endcap timing layers, but timelines of developments overlap

Considerations regarding future colliders

- Standalone timing layers or integration into 4D (5D) Trackers?
  - Integration of gain layer in CMOS sensors…
- Occupancy:
  - Challenging for resistive layers
  - AC-coupling may not be ideal or necessary: DC-coupled resistive detectors? (in production at FBK)
- Radiation hardness: similar problems related to gain layer radiation hardness as other LGADs, potentially additional features
  - Partially compensated boron doping
- Segmentation
  - AC-LGADs can achieve better position resolution through charge sharing – may come at expense of timing performance
  - Deep-junction LGAD or deep gain layer