Laboratory measurements on AC-LGADs

Jennifer Ott on behalf of the SCIPP team

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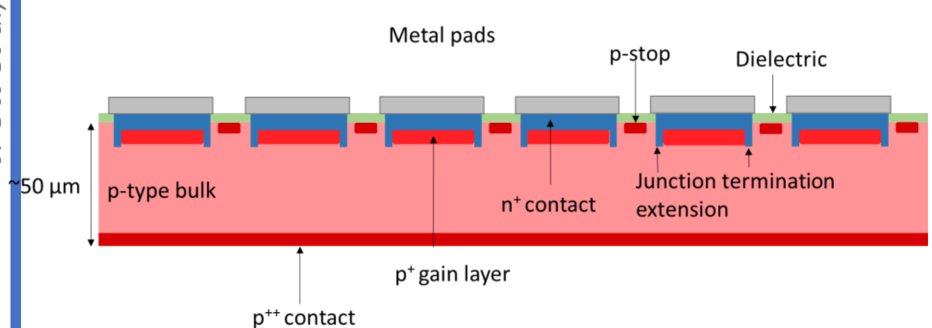
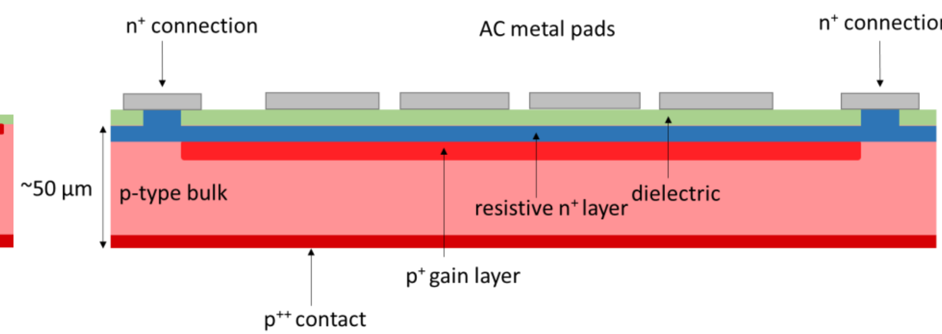
*jeott@ucsc.edu

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**



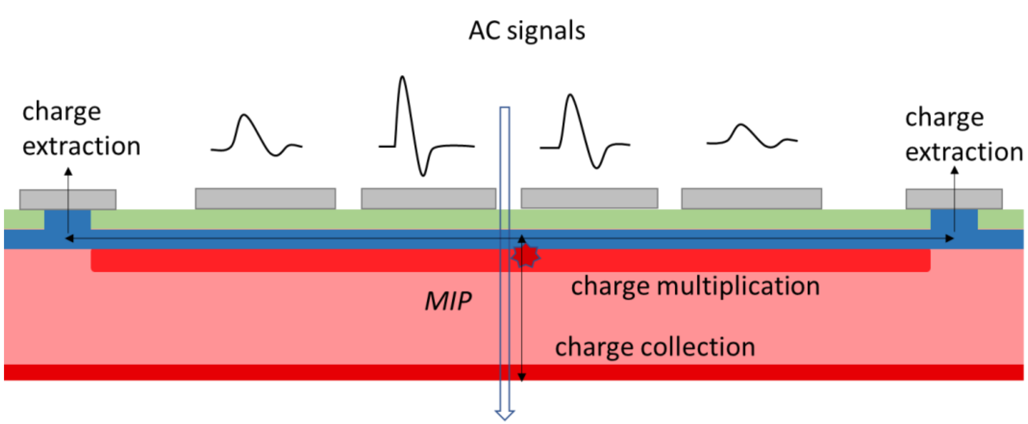


J. Ott et al, AC-LGAD lab measurements

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

ePIC TOF-PID sensor development

- Current sensor design baseline:
  - Barrel: **strips, 500 µm pitch and 1 cm length**
  - Forward (and Roman Pots): **pads, 500 x 500 µm**

- 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

- Recent (May 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:

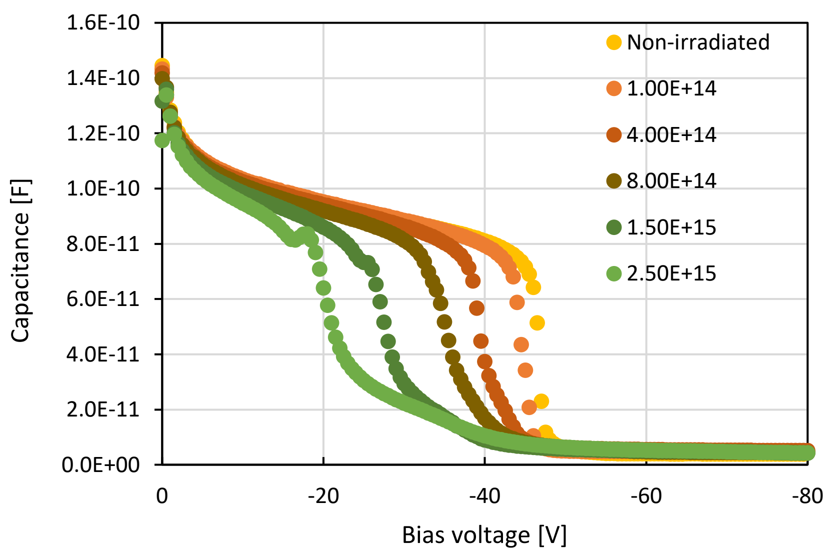
- E and C type n-layer (E resistivity higher, C lower)
- Dielectric capacitance 240 and 600 pF/mm2
    - 20 and 50 µm bulk thickness for 600 pF/mm2

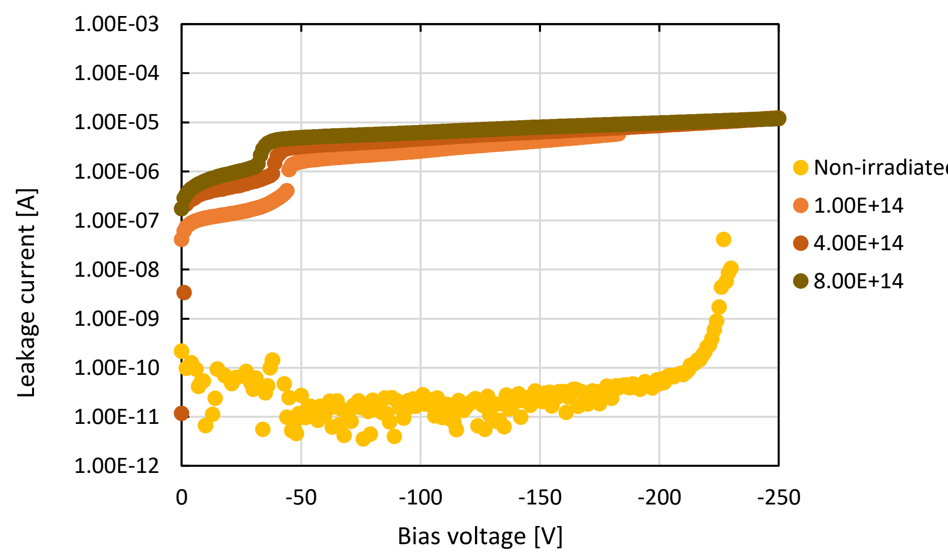
Wafer	N+	Dielectric C	Thickness
W02	E	240	50
W04	C	240	50
W05	E	600	50
W08	C	600	50
W09	E	600	20
W11	C	600	20

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

IV and CV measurements

- Current-Voltage
  - Breakdown voltage
  - Leakage current at operating bias voltage
- Capacitance-Voltage
  - Depletion voltage of gain layer
  - Gain layer doping
  - Sensor capacitance(s)
- Both: spread in properties over wafer / sensor production, radiation damage
  - ➢ Decrease of gain layer doping = gain; increase in leakage current

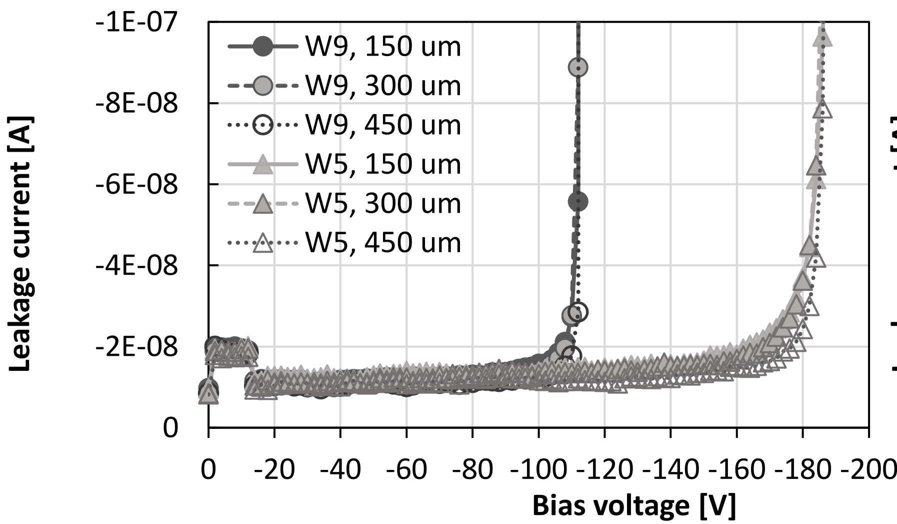


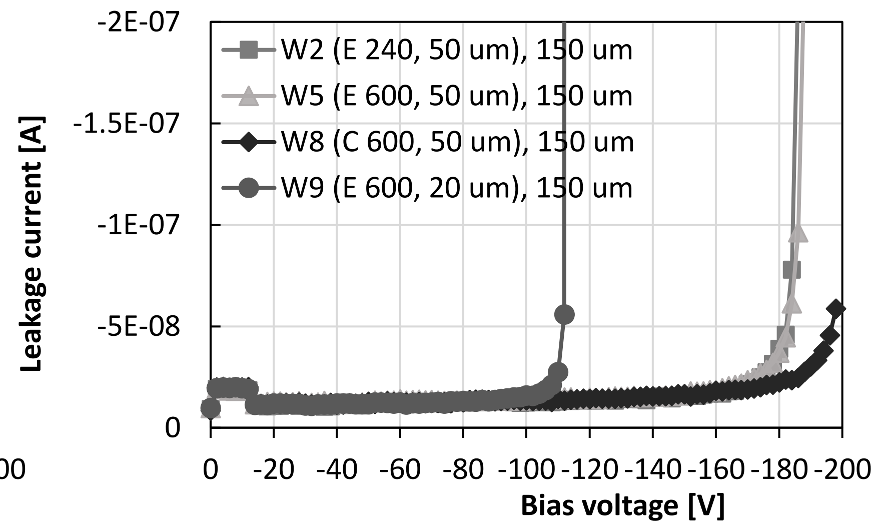


Example: irradiated pad DC-LGADS

IV measurements

- Leakage current of unirradiated sensors is < 20 nA before breakdown
- Consistent over different samples of the same wafer (different AC metal size should not impact)
- Breakdown voltage ca. 120 V for 20 µm-thick sensors, 210 V for 50 µm-thick sensors
- Slightly higher breakdown voltage for C-type n+ layer



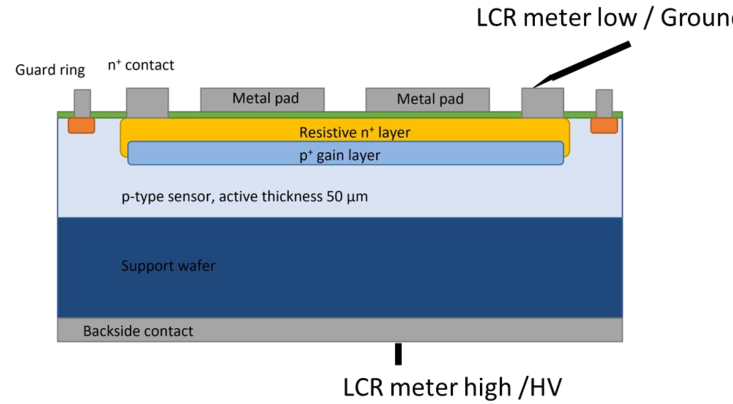


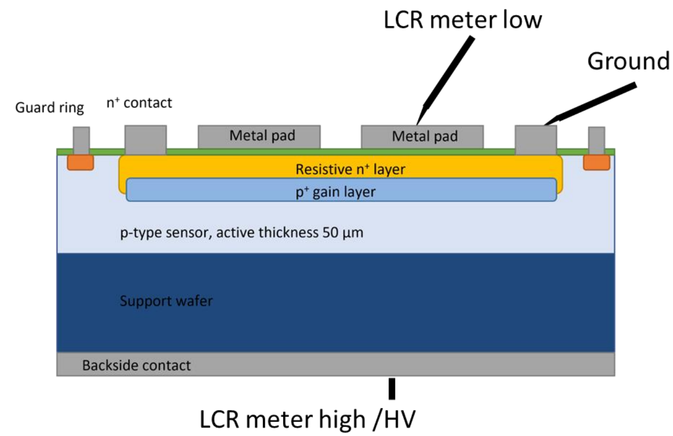
HPK AC-LGAD pad array sensors

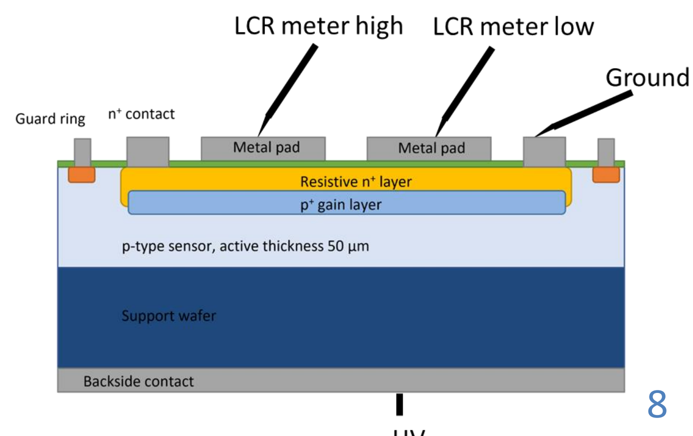
J. Ott et al, AC-LGAD lab measurements

CV measurements

- Different capacitances in sensors:
  - n+ electrode to backplane (standard, ‘DC’ capacitance measurement)
  - AC pad or strip to backplane
  - Interpad or interstrip capacitance
  - Dielectric capacitance



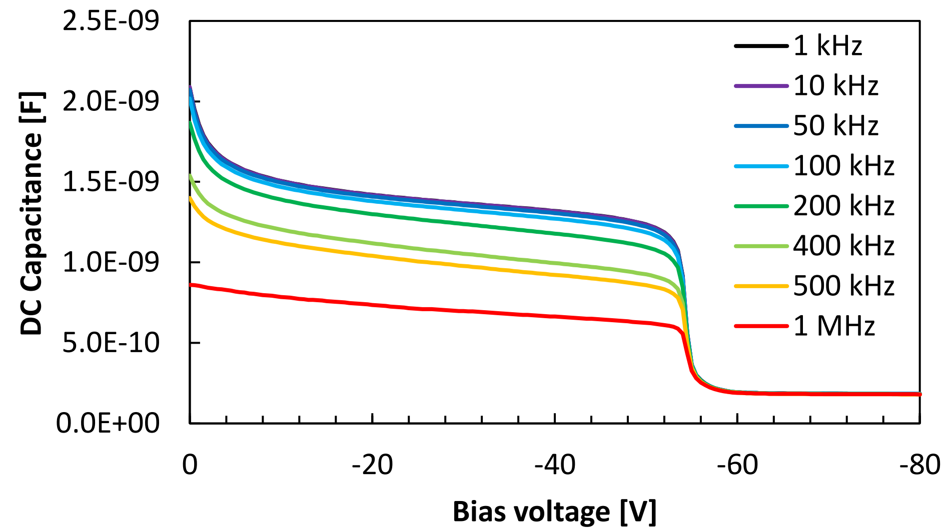


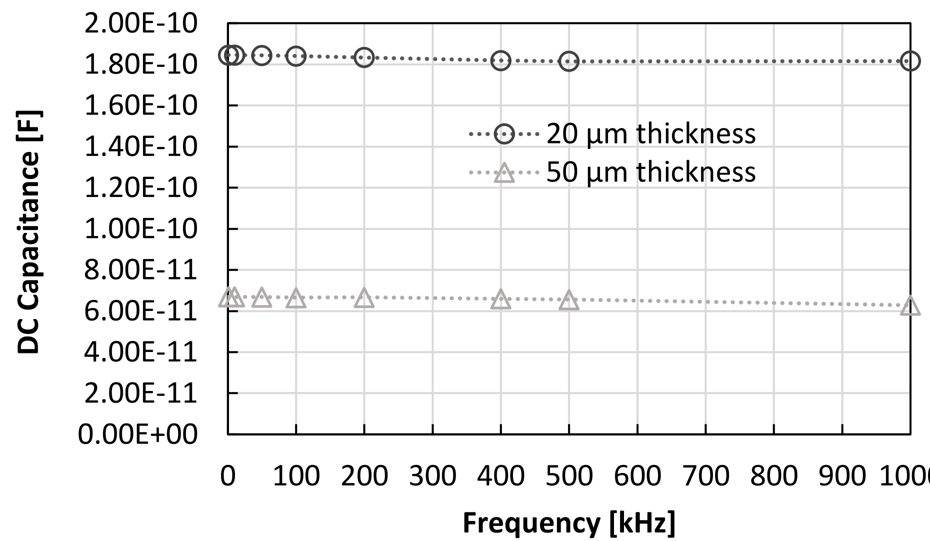


CV measurements

- Depletion voltage of gain layer: ca. 48 V
- Relatively highly doped gain layer: in BNL sensor productions, typically around 25 V

- Sensor capacitance scales with Si thickness (by geometry)





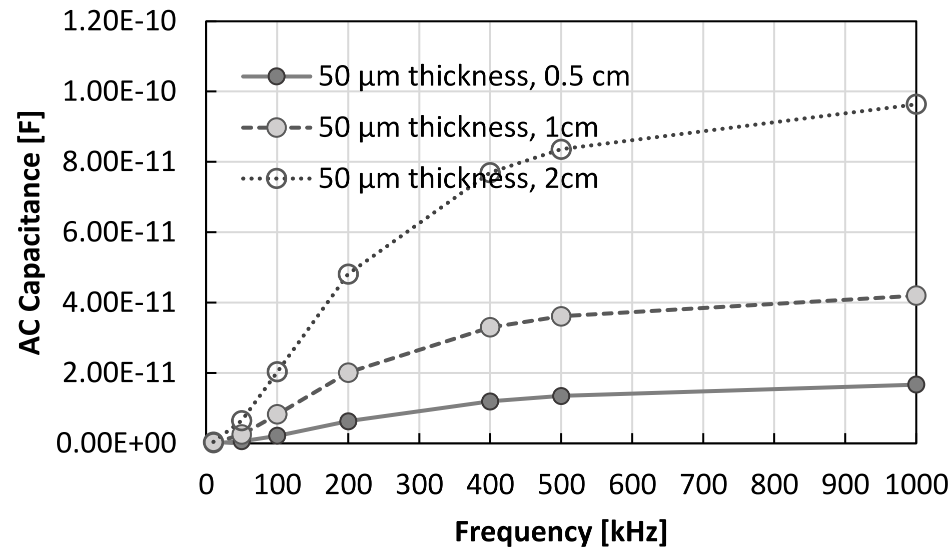
HPK 0.5 cm, 50 µm AC-LGAD strip sensor

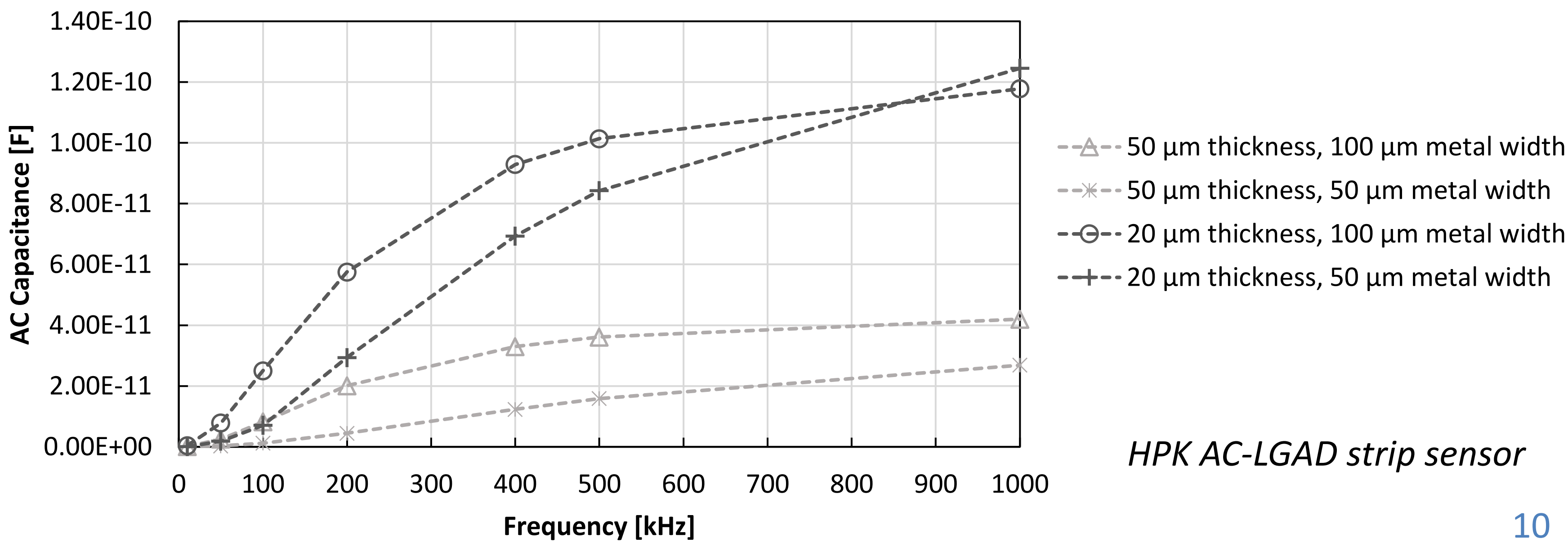
More details:
https://indico.cern.ch/event/829863/contributions/5061072/attachments/2564834/4422979/JOtt_Pixel2022.pdf
https://indico.bnl.gov/event/20281/contributions/79620/attachments/49124/83705/JOtt_eRD112_CV_update_Aug23.pdf

CV measurements

- AC capacitance scales with Si thickness, metal width and strip length

- Frequency dependence of capacitance is observed: **what is the effective input capacitance to the front-end?**





HPK AC-LGAD strip sensor

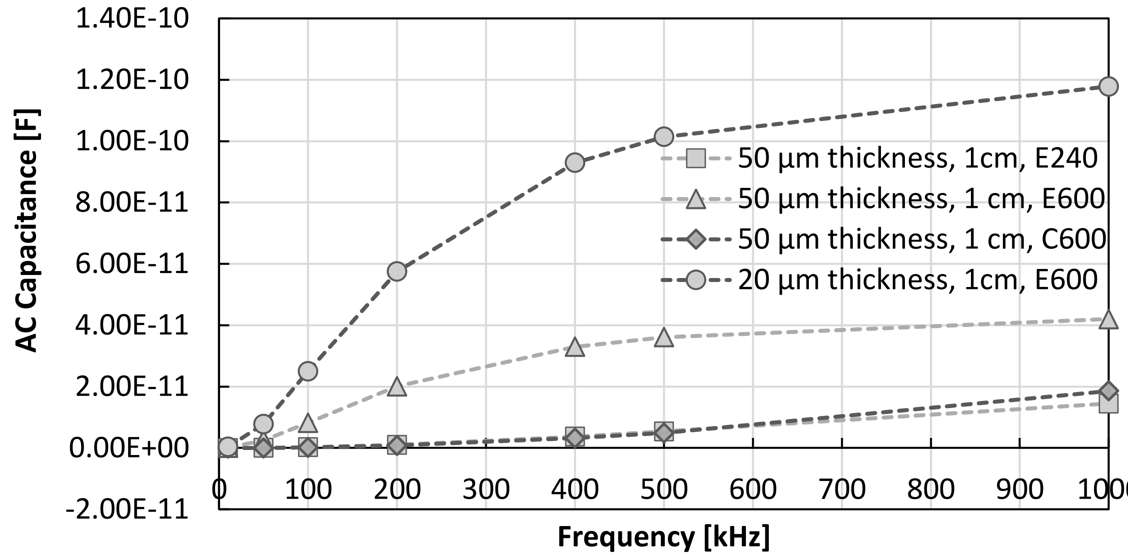
J. Ott et al, AC-LGAD lab measurements

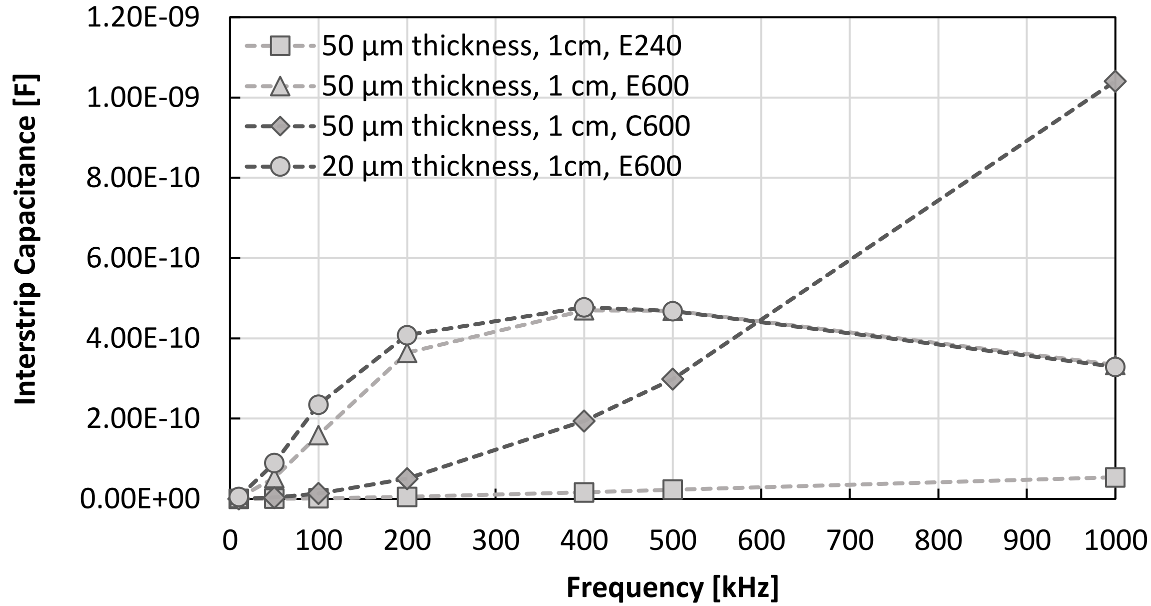
CV measurements

J. Ott et al, AC-LGAD lab measurements

- Interpad/interstrip capacitance scales with strip length and width, but is independent of bulk thickness

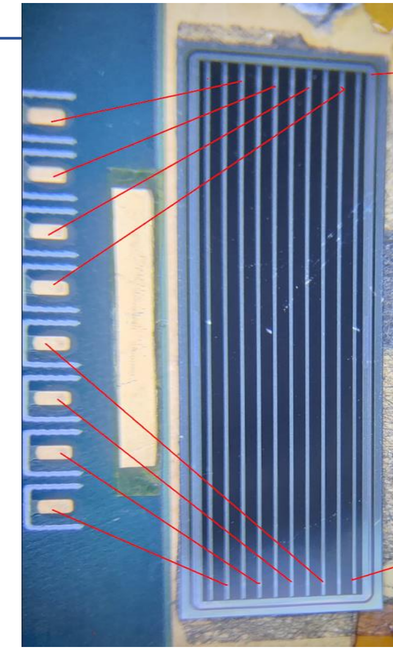
- Dielectric capacitance and n+ resistivity influence AC and interstrip capacitances



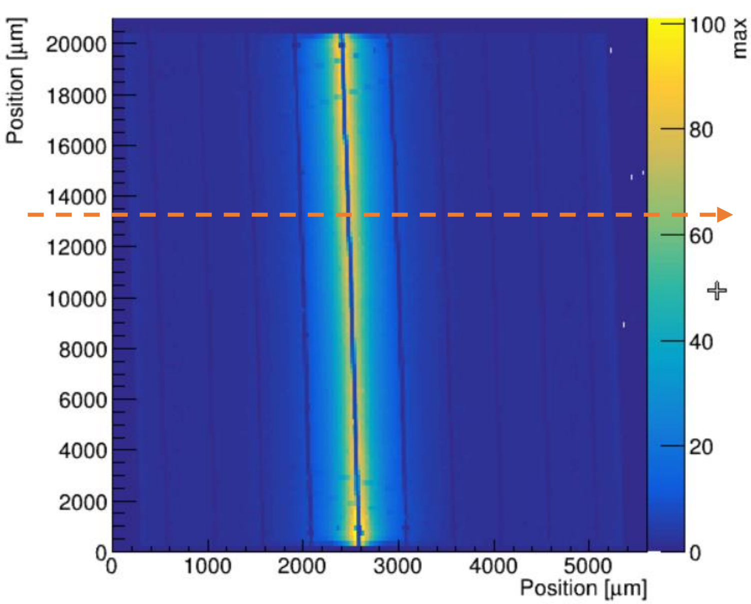


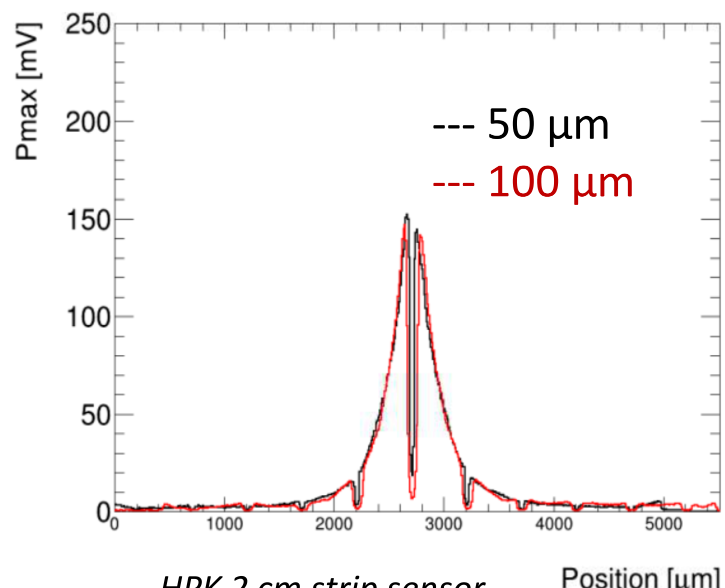
1 cm strip, 100 µm width

Laser studies



- Infrared laser scanning TCT (Transient Current Technique): sensor is illuminated with a focused laser to simulate signal generated by a minimum-ionizing particle
- Averaged waveform at each x-y point
- ➢ Monitoring of sensor response uniformity, gain 'hotspots'
- ➢ Time-of-arrival information and jitter based on laser reference
    - No Landau fluctuations of signal charge as in the case of a charged particle
- ➢ **Impact of sensor geometry, coupling dielectric, and n+ layer resistivity on signal sharing**



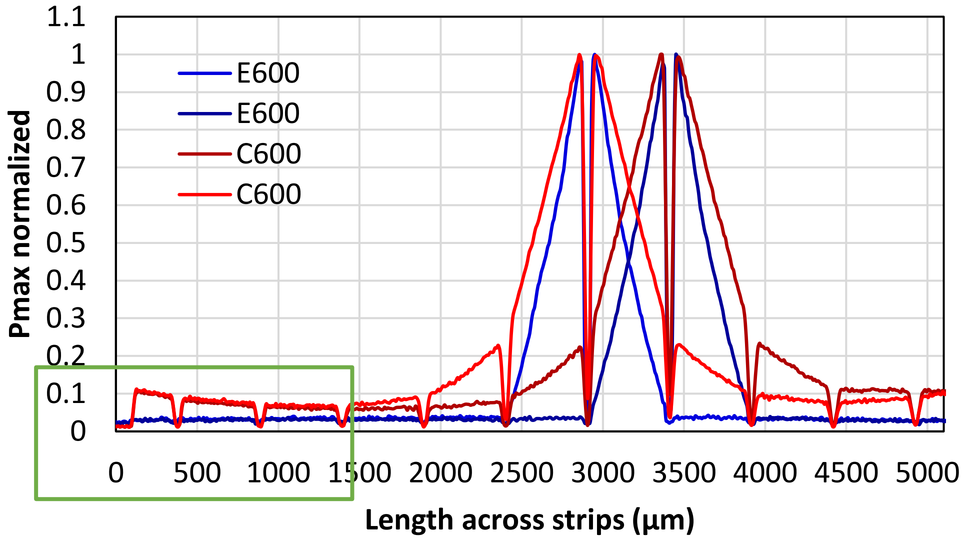


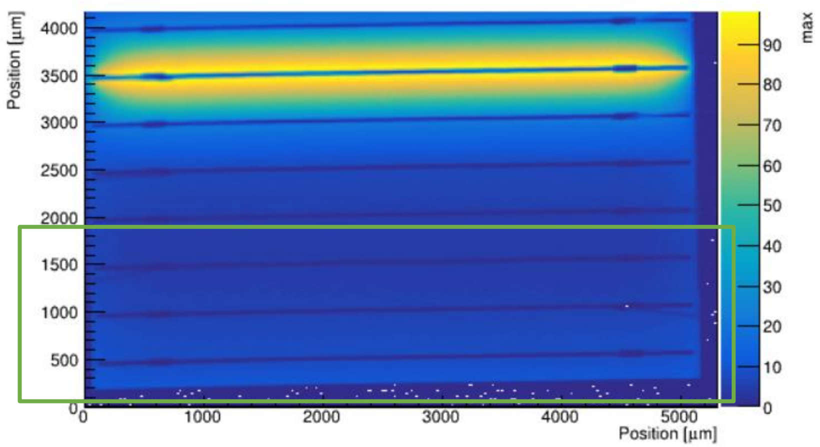
HPK 2 cm strip sensor
Amplitude normalized

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?



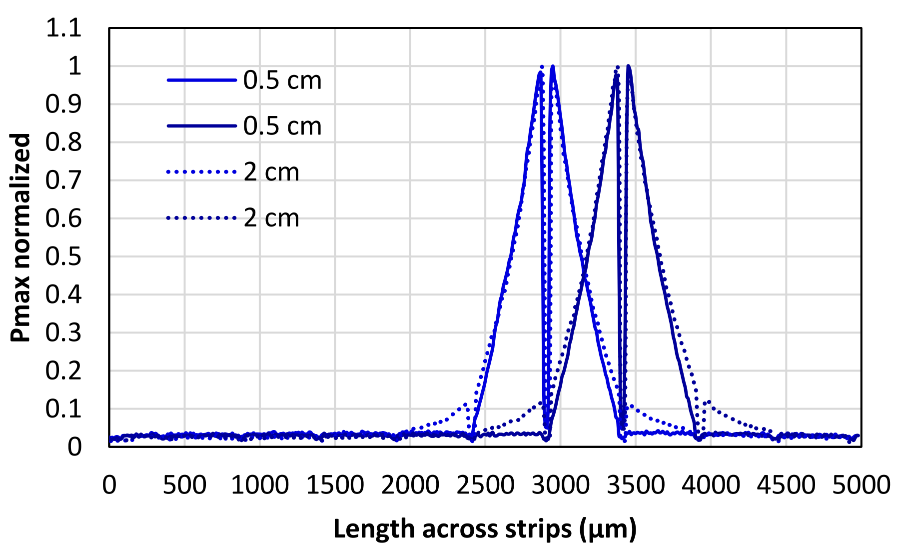


https://indico.slac.stanford.edu/event/8288/contributions/7494/

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**
- From this point of view, it could be considered to use longer strips in the BTOF
  - **Limitation: decrease of amplitude and time delay along the strip**



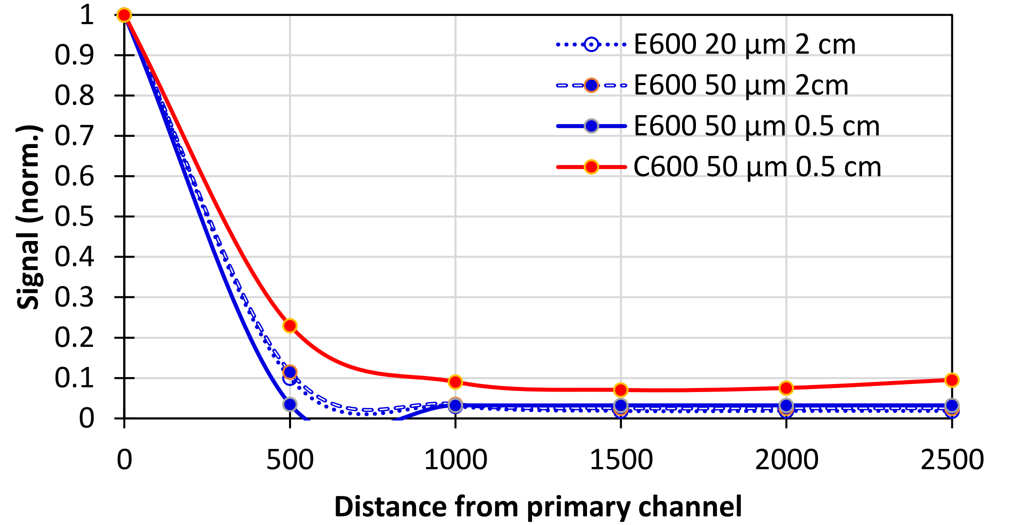
J. Ott et al, AC-LGAD lab measurements

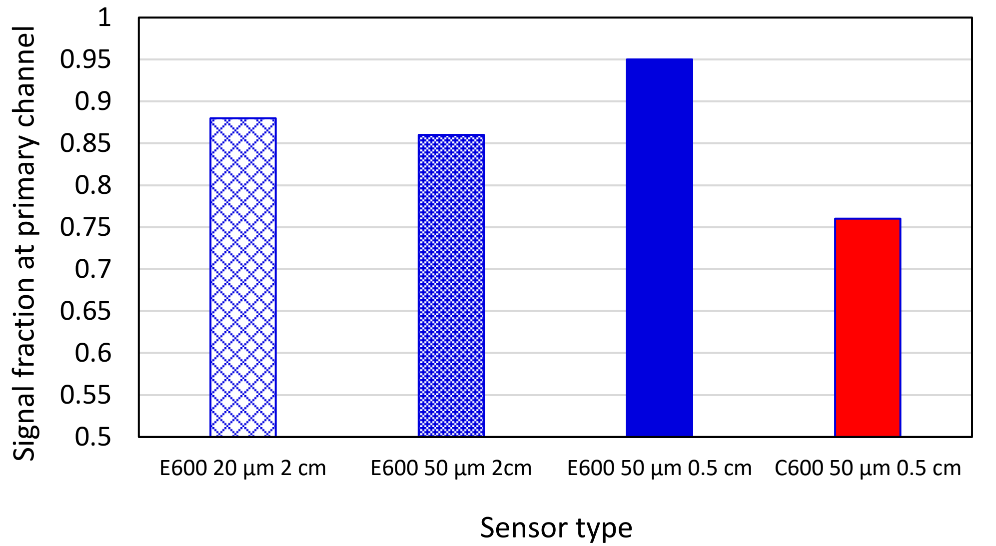
HPK strip sensors: signal sharing

J. Ott et al, AC-LGAD lab measurements

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

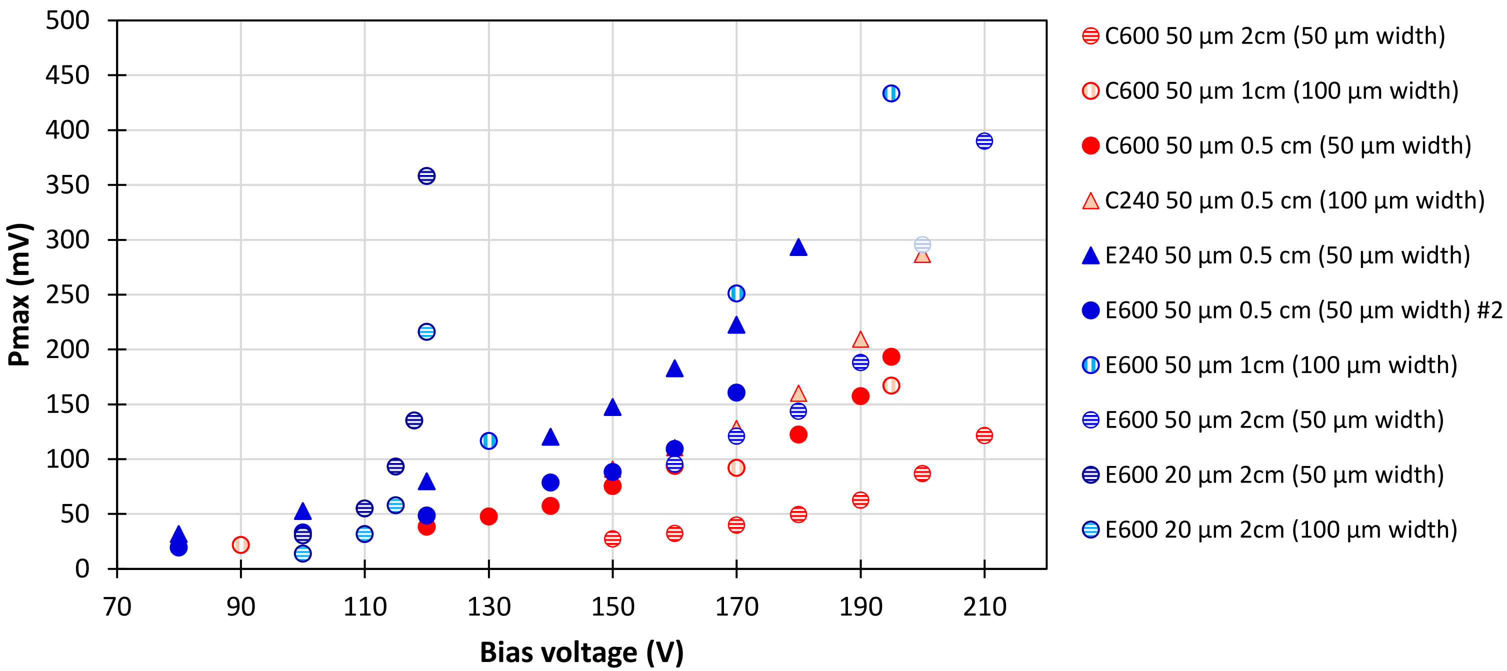




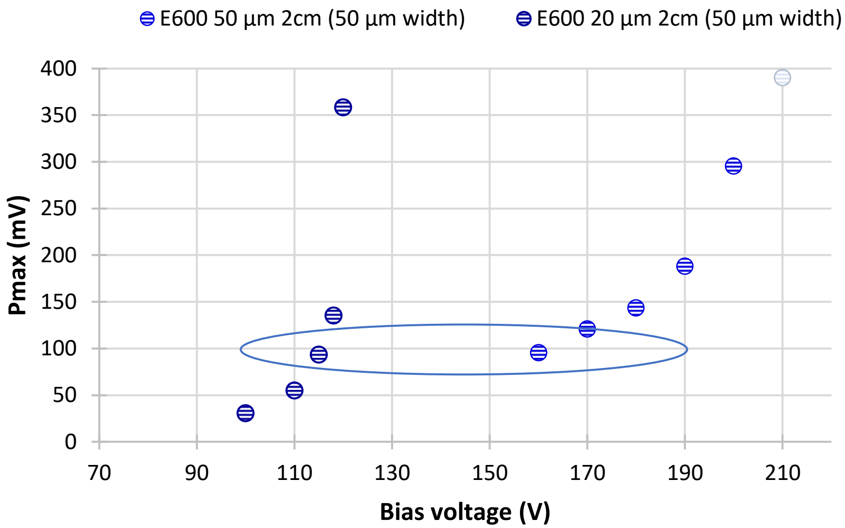
https://indico.slac.stanford.edu/event/8288/contributions/7494/

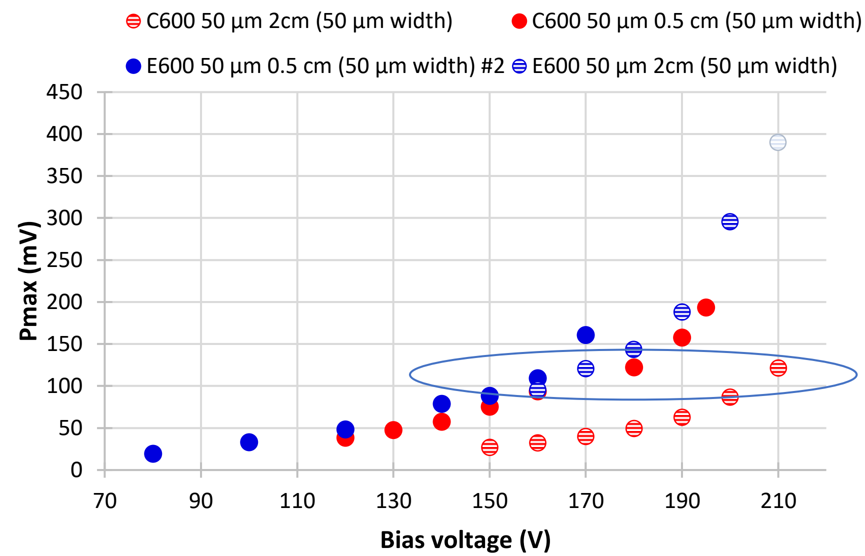
HPK strips pmax summary

- Pulse amplitude is governed by the gain → strongly dependent on bias voltage
- Comparison at the same gain may involve different bias voltages, especially of 20 µm vs 50 µm sensors
- Following and backup slides: showing a few excerpts of the collected dataset below
  - N.B.: laser data does not include data under the metal electrode



Pmax: 20 µm and 50 µm thickness





- Different electric field and gain in 20 µm and 50 µm substrates: steeper gain curve for thinner substrate, signal amplitudes highly depending on bias voltage
- 200+ mV signal can be obtained in 2 cm strip sensors

- Smaller main hit signal amplitude in C type compared to E type
- Impact of strip length less conclusive for E type in our data
- 2 cm strip still provides large signals

Near-future sensor R&D topics

- 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

  - *Also studied in FNAL test beam*

- **Angular dependence of abovementioned properties: BTOF modules have a nominal tilt angle of 18 degrees – impact on hit / cluster signal has not been studied in AC-LGADs**

Pad pitch and size

- In AC-LGADs, the signal is constant in the area under the metal electrode – signal sharing with the next neighboring segments cannot be applied, which limits the position and timing reconstruction
  - Motivates to decrease metal size
  - Additional benefits in terms of reduced AC capacitance

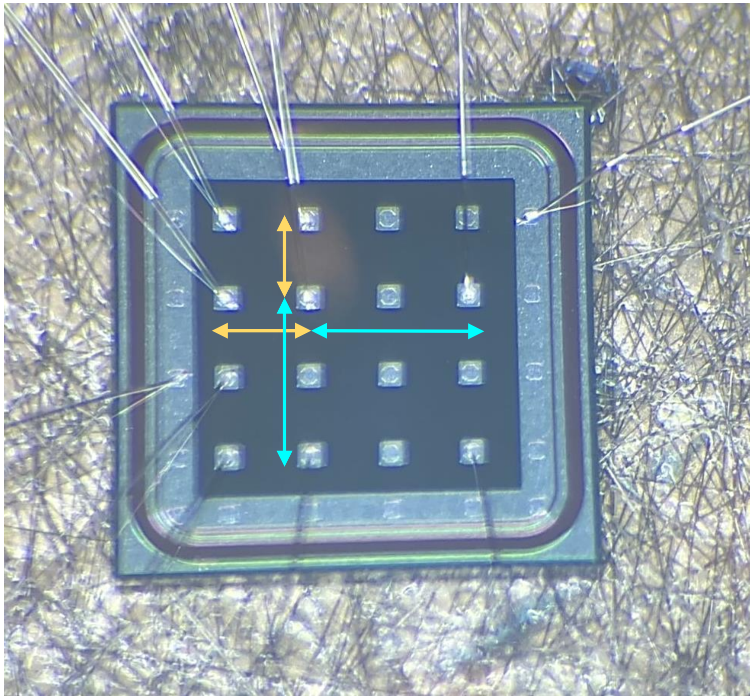
- Increase in pitch would allow a reduction in the number of readout channels

- Concerns: sufficient main hit signal (charge and/or pulse amplitude)? Loss of signal between pads → improvement of reconstruction coming at cost of performance?

Larger pad pitch experiment

- Approach: leave some pads in a 4x4 pad array with 500 µm pitch unbonded and floating to mimic 1000 µm pitch, monitor pulse maximum as function of distance
- Using smallest currently available pad size in the HPK production: 150x150 µm. Here, a C600 sensor (more signal sharing) with bulk thickness 20 µm (faster rise time)

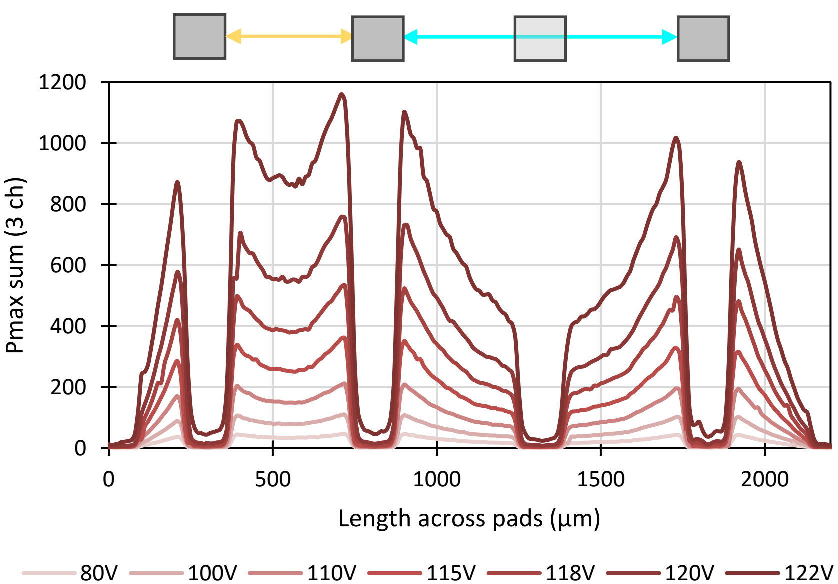
Regular 500 µm pitch

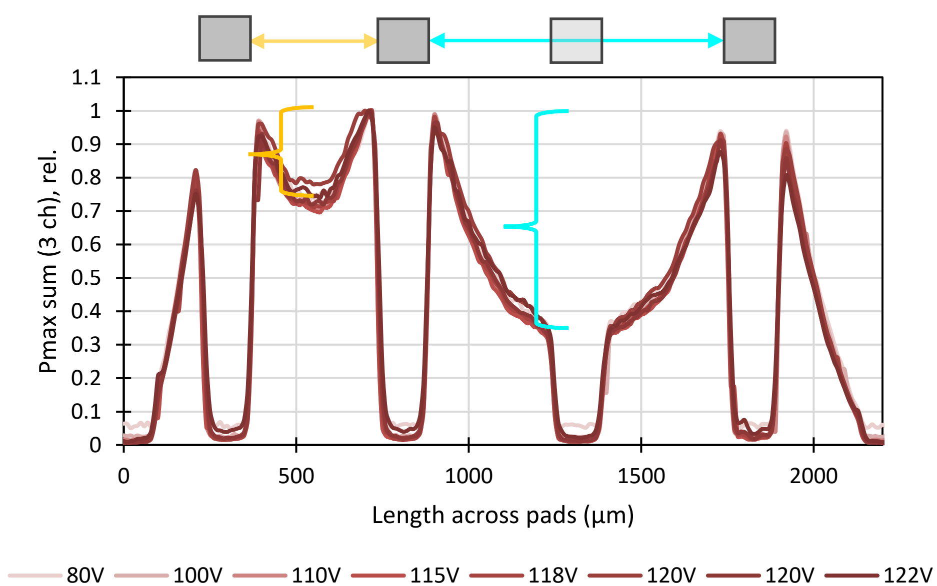


'1000 µm' pitch

Larger pad pitch experiment

- Significant **loss of signal amplitude** between pads at 500 µm, more pronounced for the double distance: in this sensor, ca. 27% at the center point between adjacent pads, **ca. 65% for '1000 µm' pitch**
- The effect of the bias voltage on relative signal sharing is minimal (observed throughout this production)
- Whether smaller signal, worse SNR and jitter are acceptable depends on what gain the sensor is operated at = what absolute signal remains, and how critical the reduction of the metal size or channel count is finally determined to be





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

Thoughts and discussion items

- **Comparability of laser and test beam results**
  - Laser is fast and easy to control; however, does not provide information in areas under metal
  - Calibration to MIP and stability over time need to be verified
  - Close to breakdown and especially for very thin sensors, signal amplitude (gain) is very sensitive to increase in bias voltage – voltage needs to be known when comparing data; sensor-to-sensor variation may play a role as well

- **Thickness**: better timing resolution of 20 µm sensor, but gain is very sensitive to bias voltage: 30 or 35 µm may be an option
  - Was included in previous HPK production; planned for upcoming HPK and BNL productions?

- **Gain**: traditionally determined as Q_LGAD/Q_PIN; first and large-scale LGAD productions were DC-coupled pads
  - ➢ Would it make sense to include some no-gain sensors in AC-LGAD strip and pad fabrication runs to assess the actual signal gain? Cross-check with simulations.

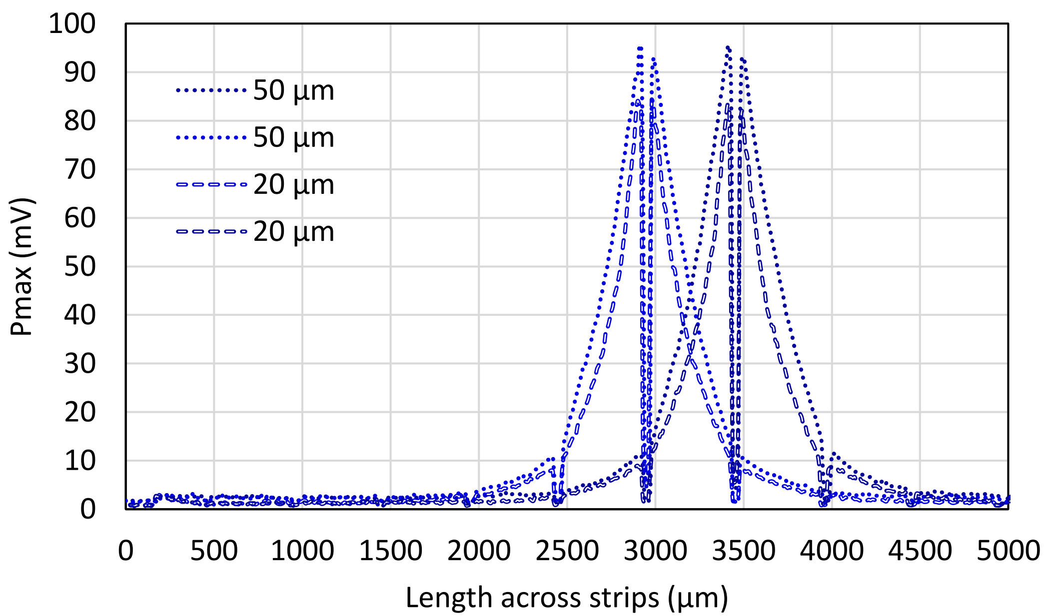
- **Specification of input capacitance**: frequency dependence complicates establishing of a certain number for the strip or pad capacitance
  - ➢ Try to confirm measured capacitance by monitoring the noise levels of inherently low-noise analog preamp chip, e.g. ASROC
  - ➢ Confirm correlation with signal sharing?

Thank you!

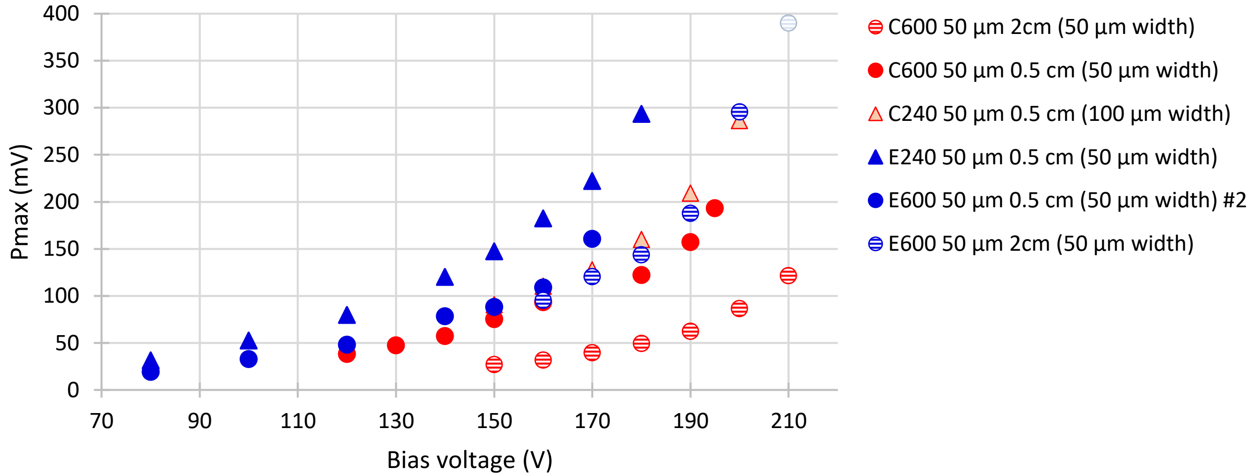
Backup

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 pmax, 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

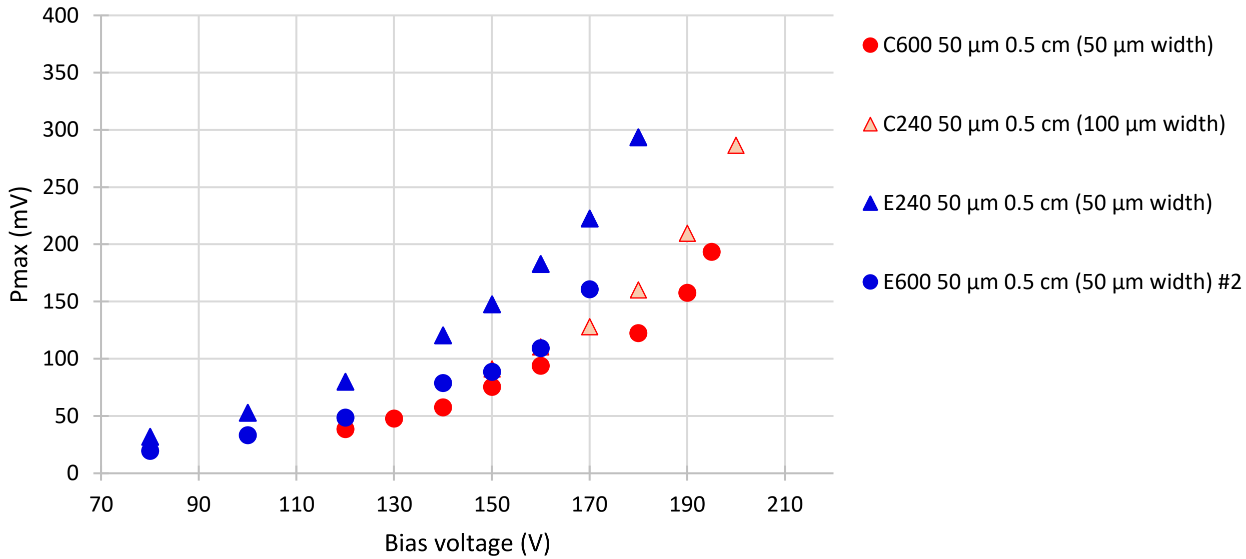


Pmax: C vs E type



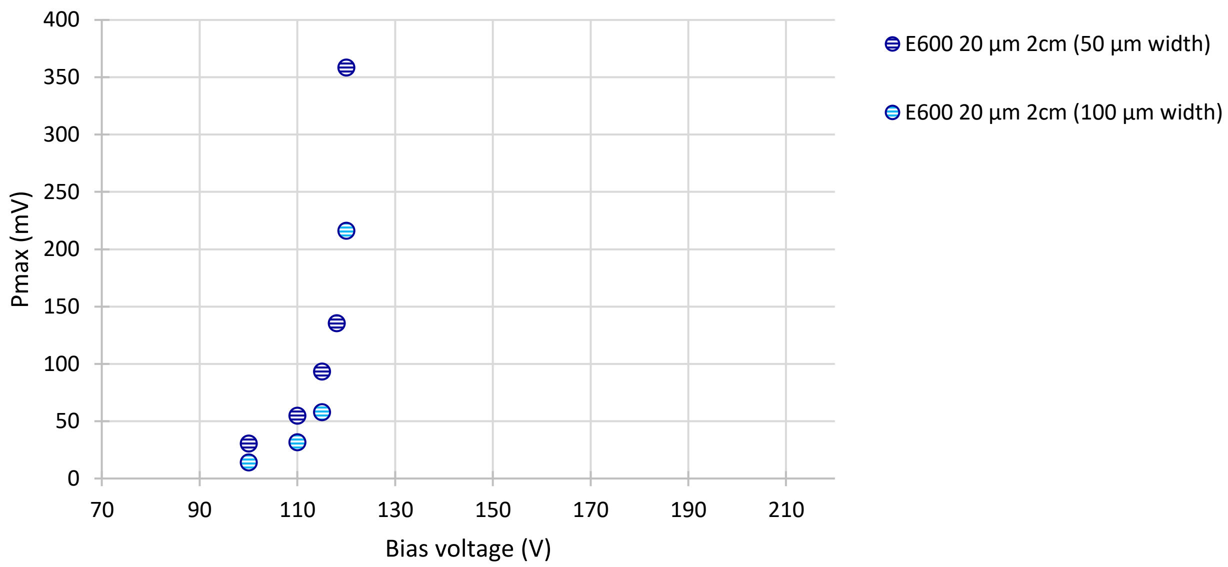
- Throughout, smaller main hit signal amplitude in C type compared to E type

Pmax: 240 vs 600



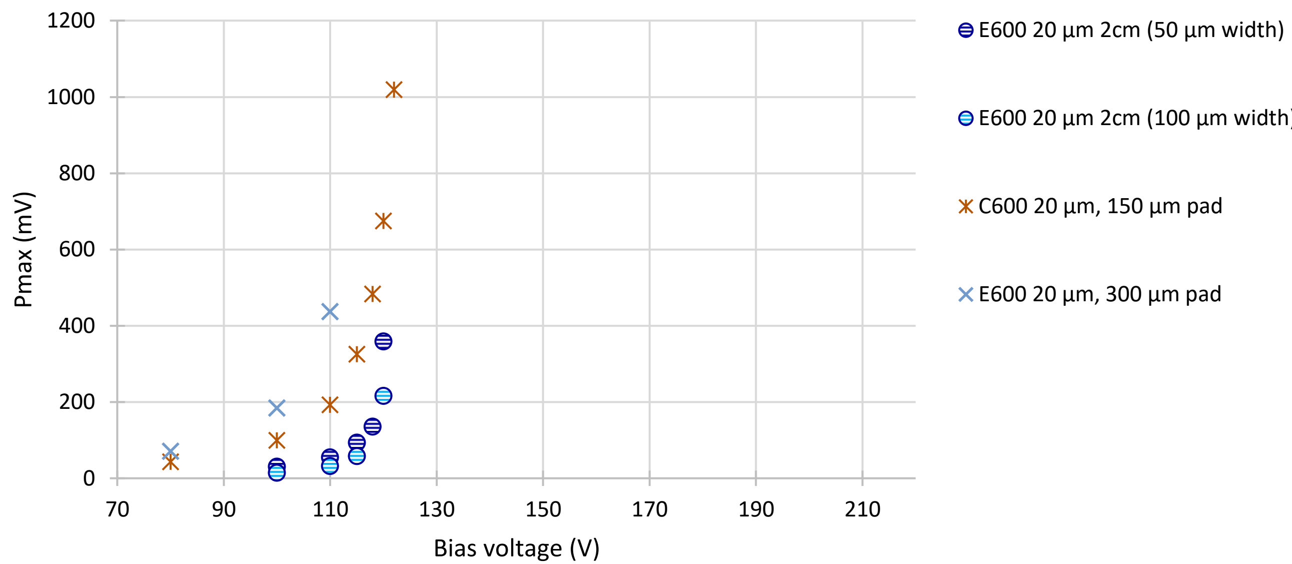
- Larger signal in 240 – contradictory to some earlier results

Pmax: strip width



- Narrower metal seems to achieve higher signal

Pmax: 20 µm sensor strips and pads



- 20 µm: weighting field increases signal in pads (?)

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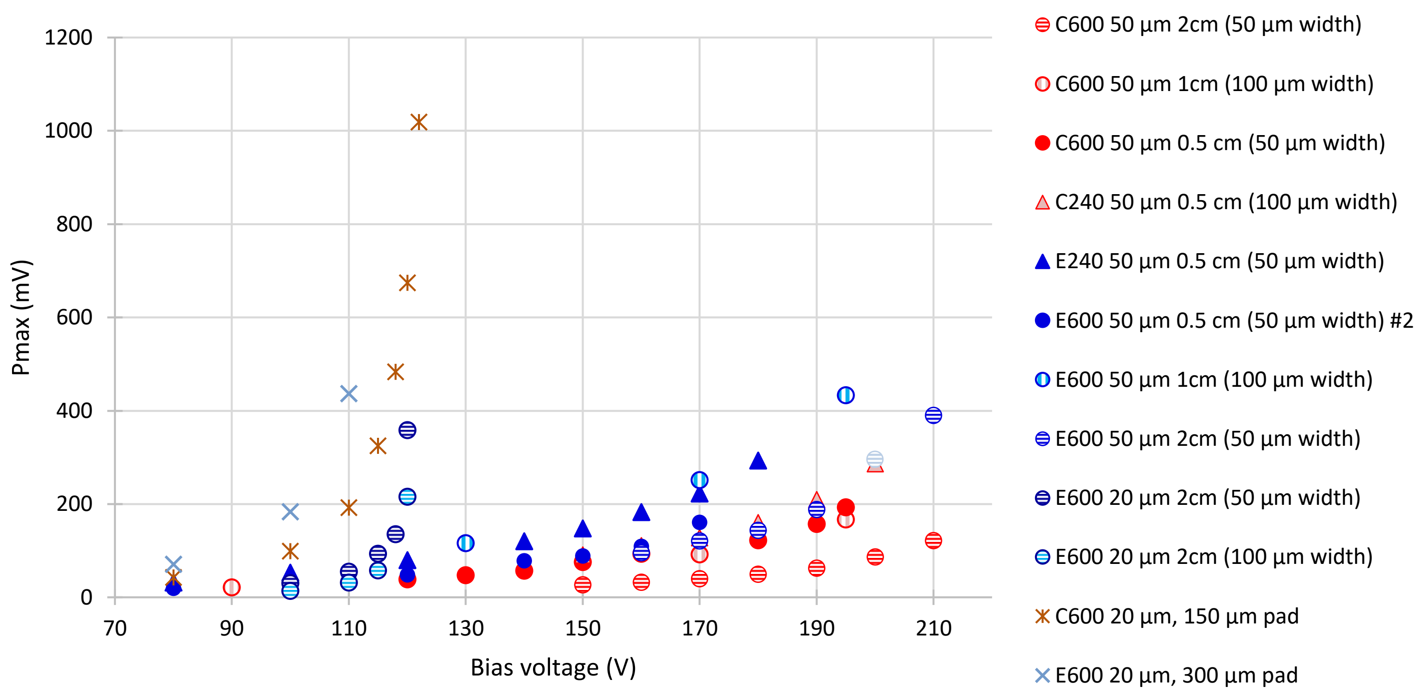
HPK laser Pmax summary



- All data acquired at UCSC/SCIPP to this point