Design characterization of AC-coupled LGADs for high precision 4D tracking

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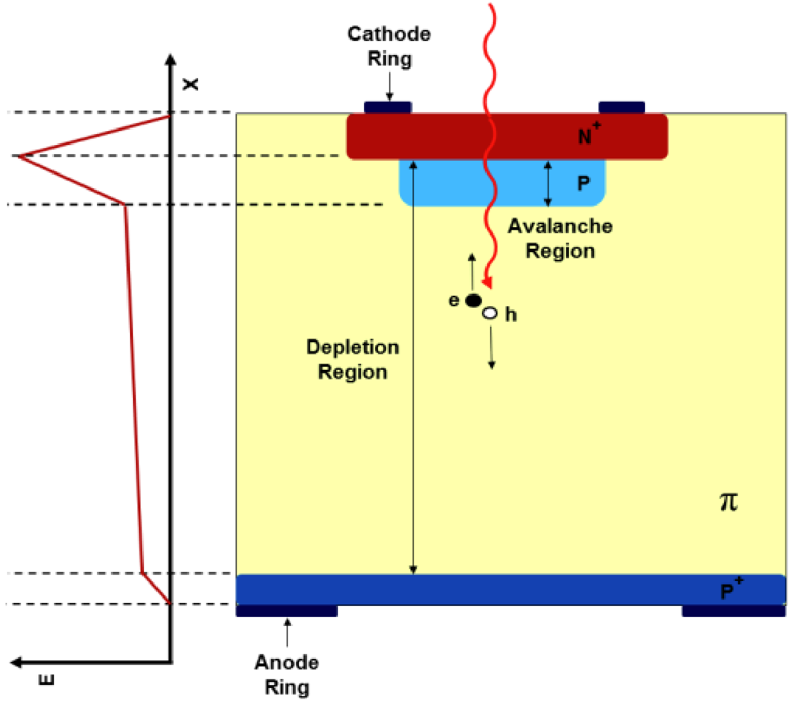
ULITIMA 2023, March 2023, SLAC

Low Gain Avalanche Detectors

- LGAD: silicon detector with a thin (<5 µm) and highly doped (~10^{16} P++) multiplication layer
  - High electric field in the multiplication layer
  - Field is high enough for electron multiplication but not hole multiplication
- LGADs have intrinsic modest internal gain (10-50)
  - Gain $= \frac{Q_{LGAD}}{Q_{PiN}}$ (collected charge of LGAD vs same size PiN)
  - Not in avalanche mode → controlled tunable gain with applied bias voltage
- Great single hit time resolution (down to 20ps)
- The **granularity** of LGADs is **limited to the mm scale**
  - **Solution: high granularity LGAD prototypes**

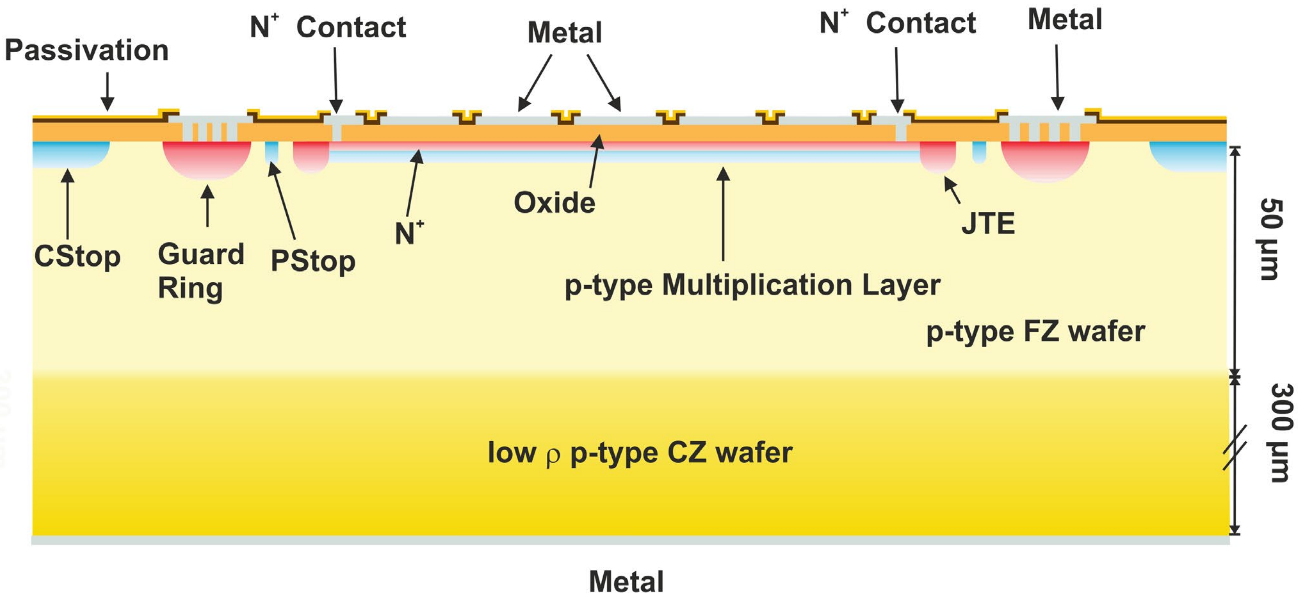
- Several producers of experimental LGADs
  - **HPK (Japan), BNL (USA), FBK (Italy),** CNM (Spain), NDL/IMEI (China), Micron (UK)
  - AC-LGAD produced at HPK and BNL in this study funded by US-Japan grant



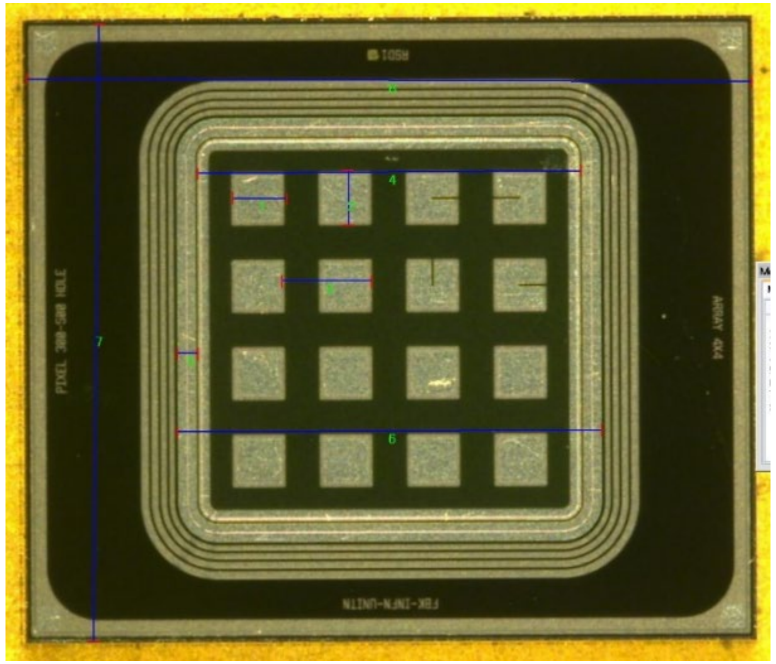
Nucl. Instrum. Meth. A765 (2014) 12 – 16.
Nucl. Instrum. Meth. A831 (2016) 18–23.

AC-LGADs

- Most advanced high granularity LGADs **are AC coupled LGADs**
  - Finer segmentation and easier implantation process
  - (UCSC - US patent N. 9,613,993 B2, granted Apr. 4, 2017)
- Continuous sheets of multiplication layer and N+ layer
  - 100% fill factor
- **N+** layer is **resistive** and grounded through side connections
- **Readout pads are AC-coupled**
  - Oxide insulator layer between N+ and pads



- **The response of the sensors can be tuned** by modifying several parameters
  - Pad geometry and dimension
  - Pad pitch
  - N+ layer resistivity
  - Oxide thickness

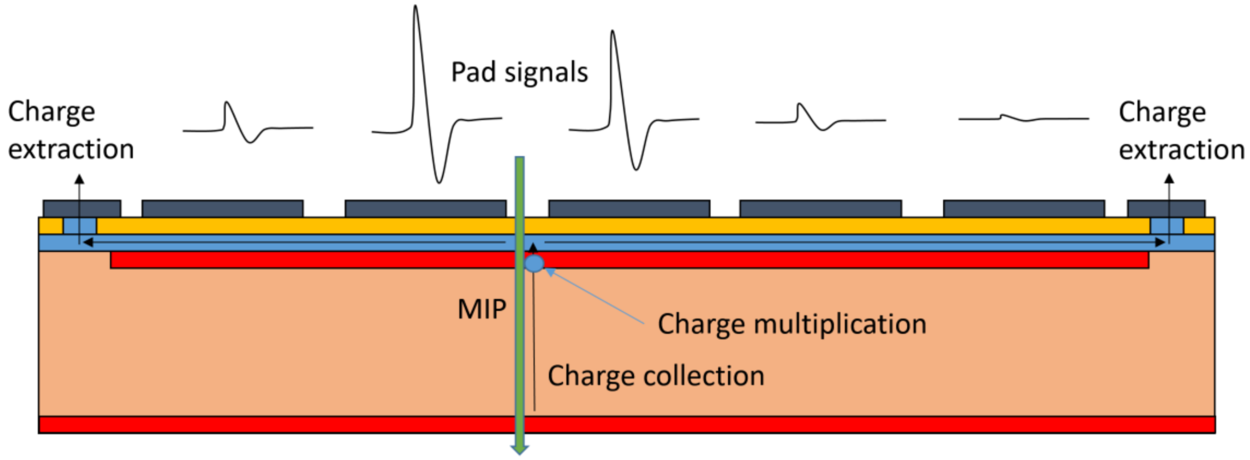


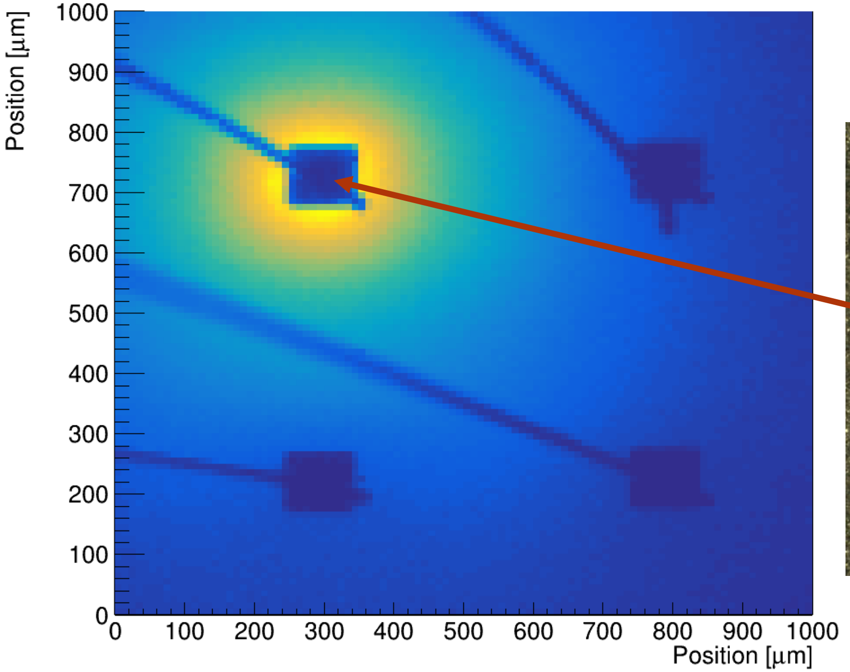
AC-LGAD hit reconstruction

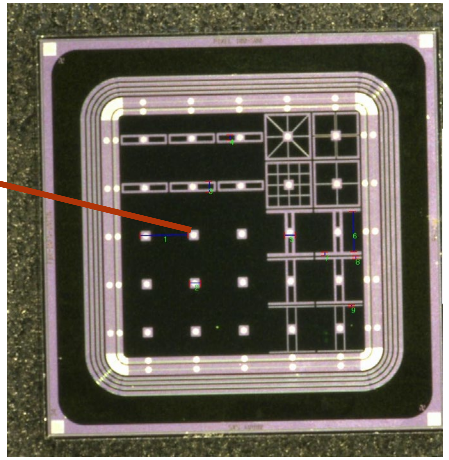
References:
https://indico.physics.lbl.gov/event/1262/
https://indico.cern.ch/event/918298/contributions/3880516/
https://arxiv.org/abs/2006.01999

- AC-LGAD has intrinsic charge sharing between pixels
  - Gain increases the S/N and allows for smaller metal pads
  - Metal pads can have all sort of shapes
- **Charge sharing can be a great feature for low density tracking environment**
  - Using information from multiple pixels for hit reconstruction
- **With a sparse pixelation of 300 um a <10 um hit precision can be achieved!**
  - Better than standard $\sqrt{12}$ detector precision
- Sparse readout is extremely useful for channel density and **power dissipation**

- Technology being developed (examples)
  - For the PIONEER experiment: AC-LGAD strips
  - For EPIC, the detector at the Electron-ion collider (EIC) at BNL: AC-LGAD strips and pixels

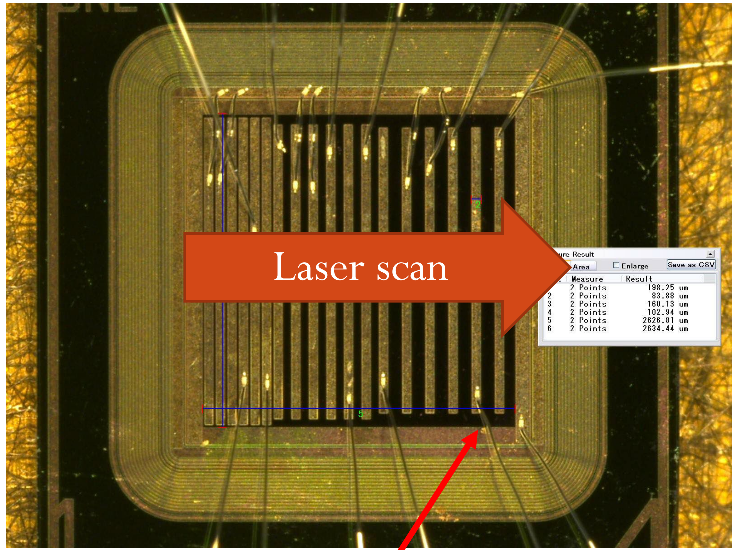


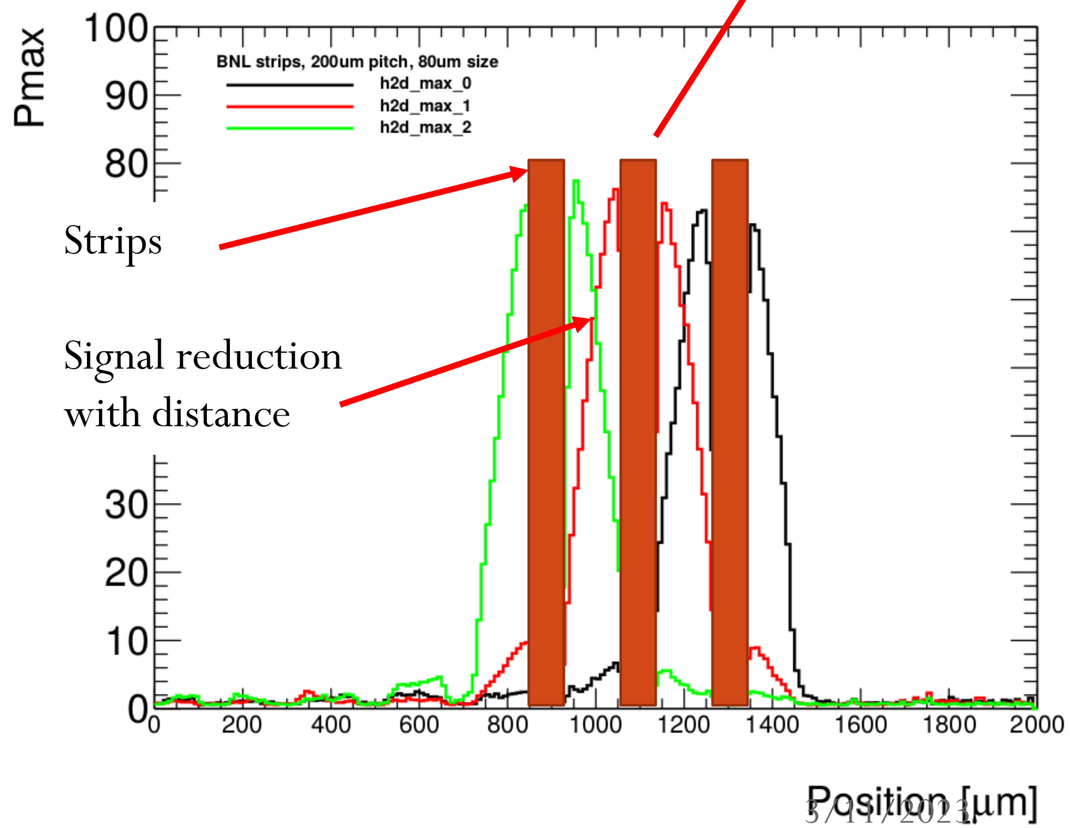




AC-LGAD strip sensors

- Since the signal is AC-coupled the signal goes down with distance
  - For AC-LGAD strips the reconstruction is only in one direction
  - AC-pads need a more complicated reconstruction
- The position of an event can be reconstructed by looking at the fraction in between the strips
  - E.g. when the signal is split 50-50 the event is exactly between strips
  - Next-neighbors can be used to refine the reconstruction
- The position resolution is estimated by looking at the derivative of the fractional charge sharing profile and S/N





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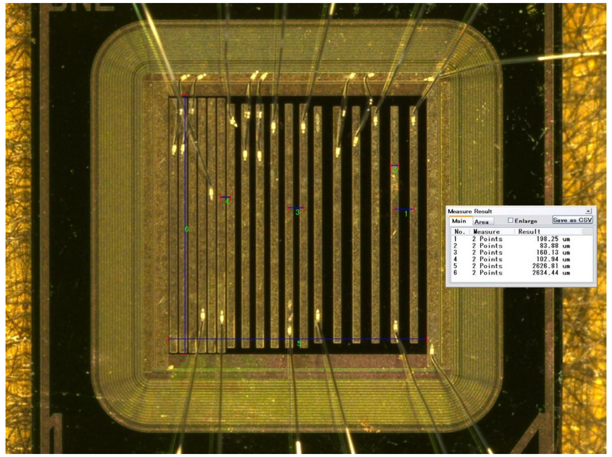
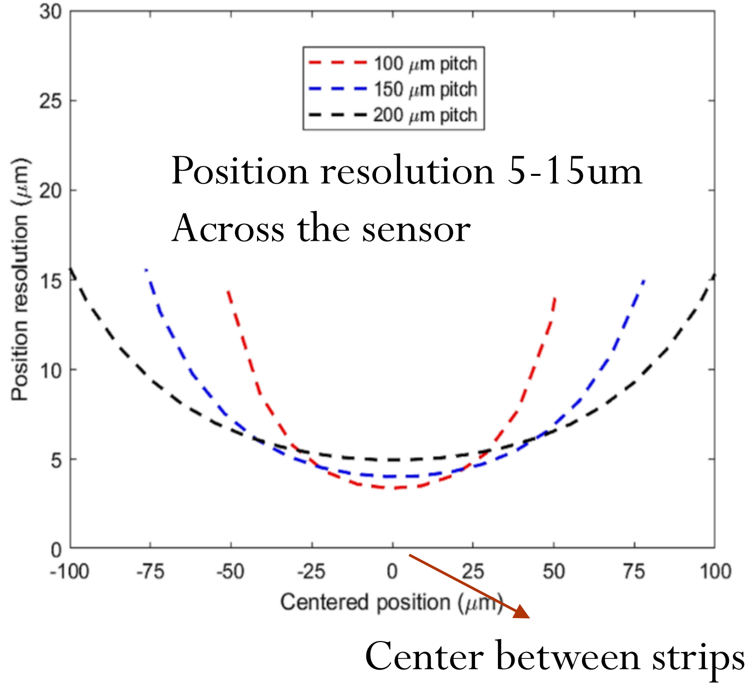
indico.cern.ch/event/1029124/contributions/4411193/attachments/2268966/3852924/RD50.pdf

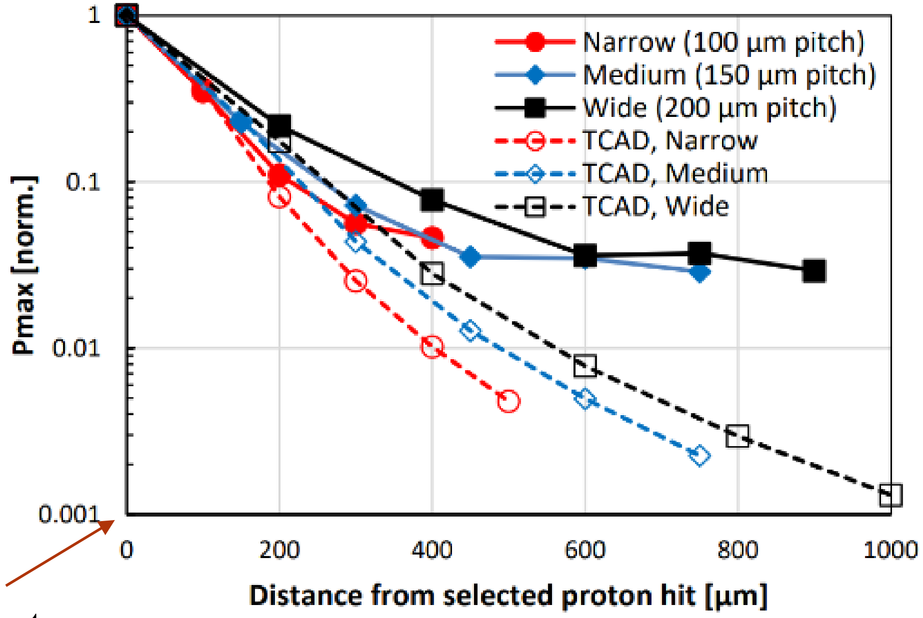
AC-LGAD studies – strip pitch

- Experimental studies on a **BNL AC-LGAD prototype strip sensors** (50 um thick) with many geometries
- First prototype: same strip length (3 mm) and width (80 um), but with different pitches (200 um, 150 um, 100 um)
  - Studies made with FNAL TB data
  - Close strips show a slightly better position resolution, however the channel count increases
- The same sensor was **simulated with TCAD**
  - At short distance (first 1-2 neighbor) the charge sharing is the same between data and simulation
- **At large distances the charge sharing it's still at a few percent level in data** but decreases to zero in the simulation
  - This study is with large signals where at distances of ~1mm the induced charge is still clearly over noise
  - The effect is still to be fully understood, likely from interstrip capacitance





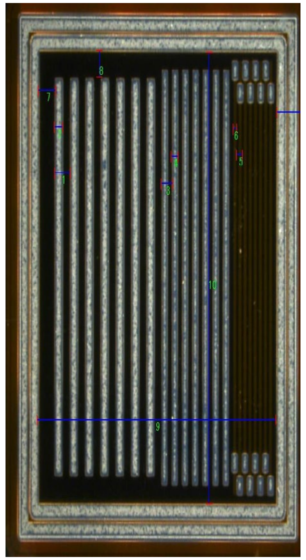
Position resolution vs position
for AC-LGAD strips of different pitch

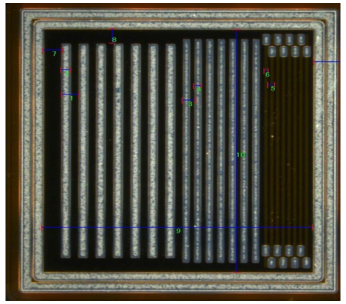


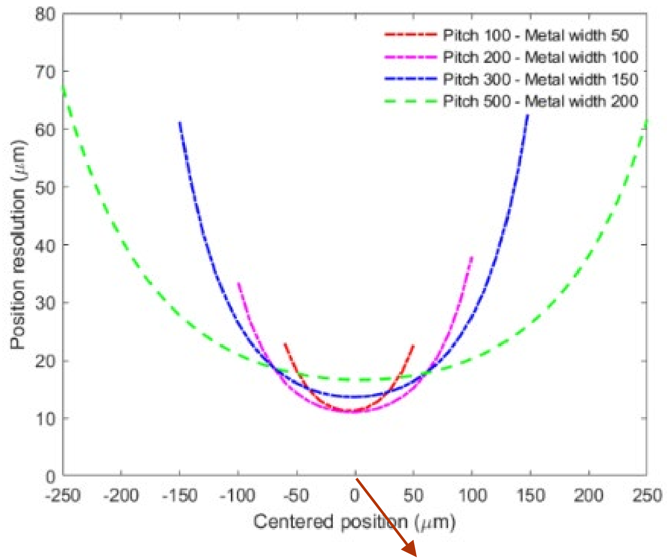
Data by: M. Wong, S. Letts, J. Ott

AC-LGAD studies – strip length

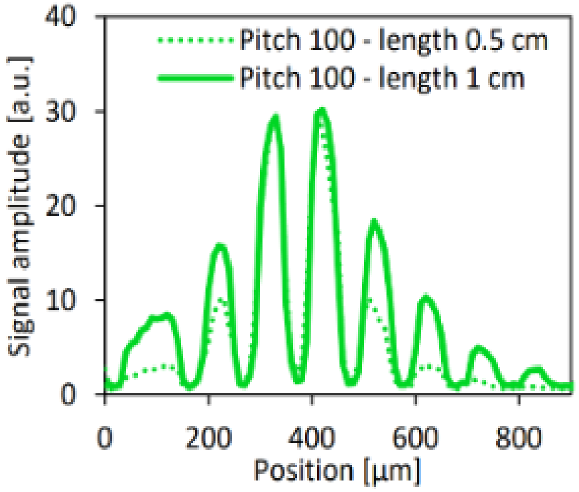
- BNL sensors with same geometry but different lengths
  - Study made with focused IR laser TCT
- Pitch and width in three configurations (width = pitch/2)
  - 300-150 um, 200-100 um, 100-50 um
  - 0.5 cm and 1 cm long sensors
- Direct comparison of geometry shows that **longer strips have increased charge sharing**
- 2.5 cm long sensor with strips of 500-200 um
  - Charge sharing present up to ~2mm
- **Position resolution is similar in the 4 sensors in the center between strips, but increases under the strip**

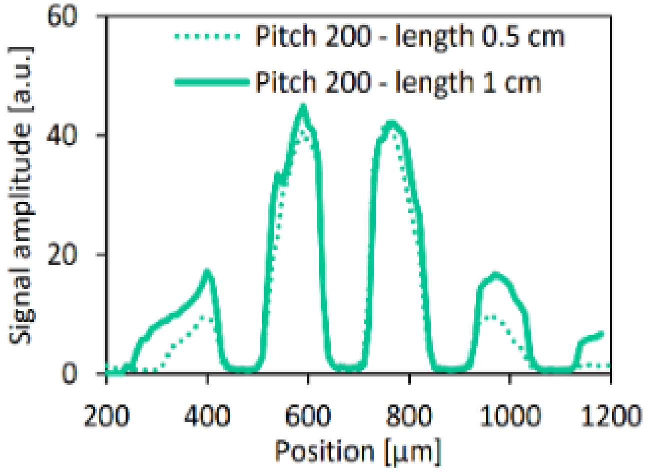


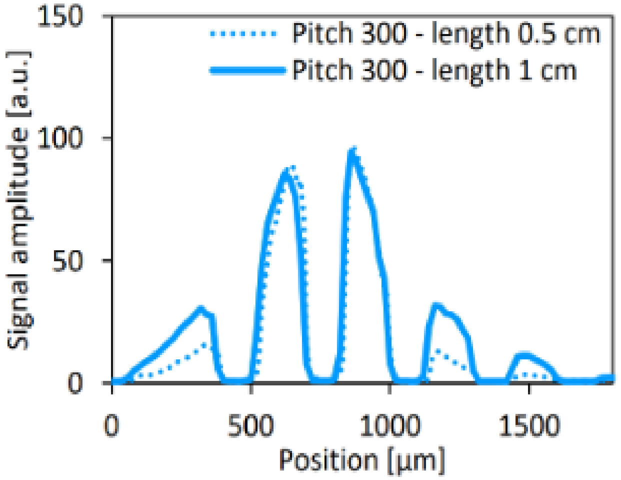


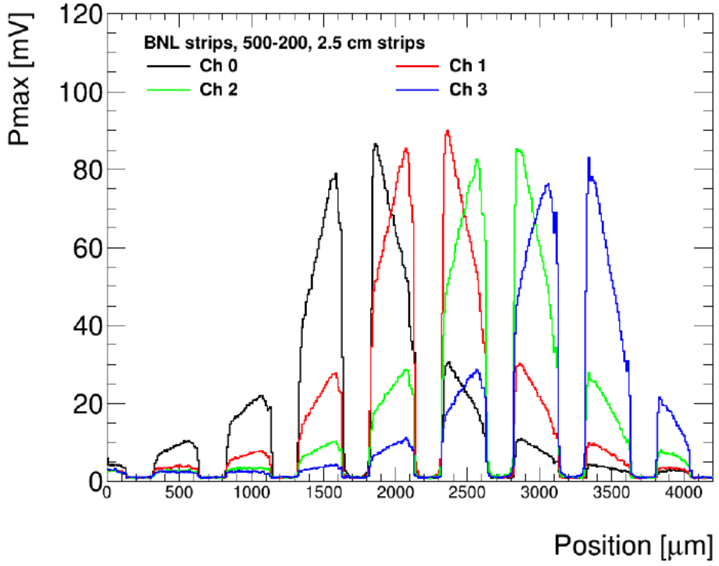


Center between strips





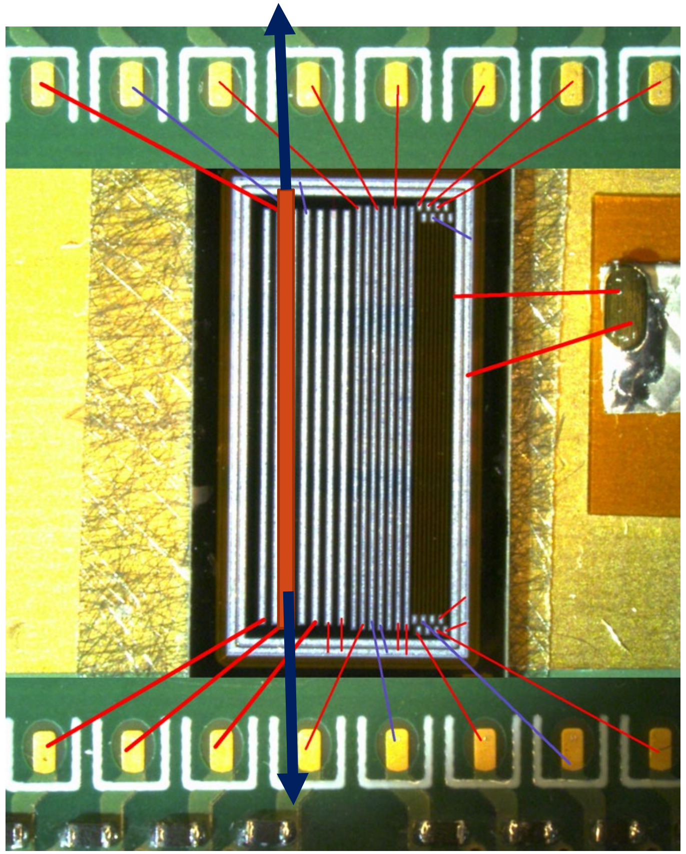


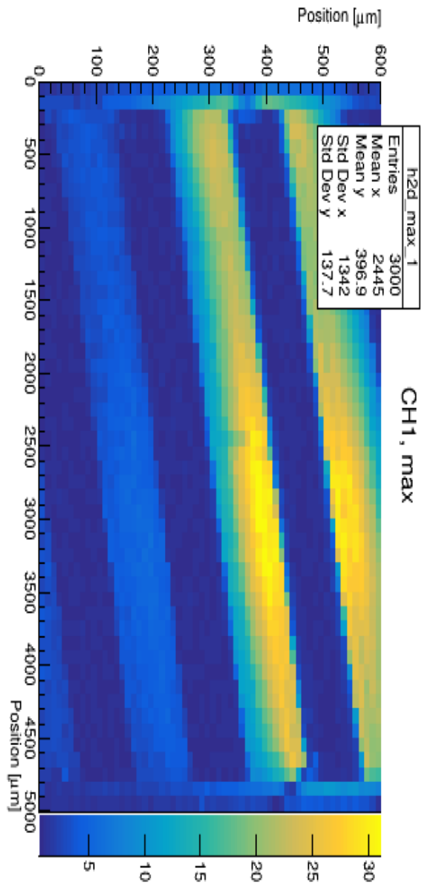


Data by: A. Das, C. Bishop, N. Yoho

AC-LGAD studies – strip readout at both ends

- AC-LGAD strips connected on both sides
  - **Collected charge is split between the two extremes depending on the position**
- Reconstruct event by using charge sharing in the X direction (perpendicular to strips) and charge splitting in the Y direction (parallel to strips)
  - Precision in X is high
  - Precision in Y is limited
    - (for ~2cm strip estimated a few mm)
- **Effect depends on the strip resistance between edges and input impedance**
- Sensor: 1cm long, multi-pitch BNL AC-LGAD
  - Input impedance 50 Ω
  - Measured strip resistance10-30 Ω





BNL AC LGAD Strip W1, 4x4 0.5x1

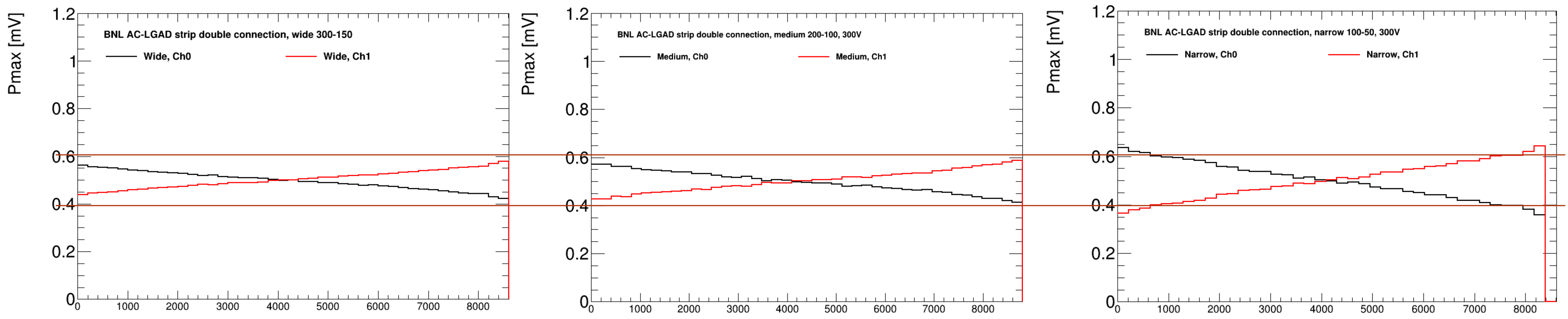
Strip metal resistance

Wide Strip	Medium Strip	Narrow Strip
10.56 Ω	13.5 Ω	27.16 Ω

Data by: A. Das, C. Bishop, N. Yoho

AC-LGAD studies – strip readout at both ends

- Effect is similar in the three cases, more different for the 'narrow' strips
  - Fractions varying between 0.4 and 0.6
- Expected since the strip resistance is similar for 'wide' and 'medium'
- To increase the effect, it's necessary to increase the metal resistance on the strip



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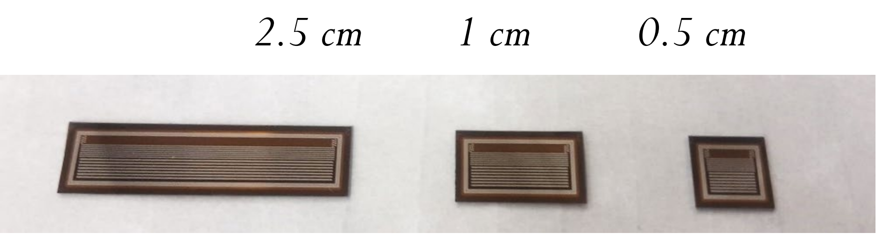
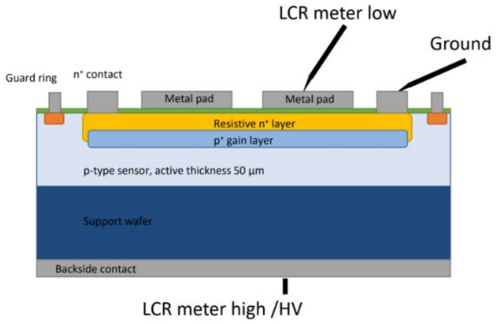
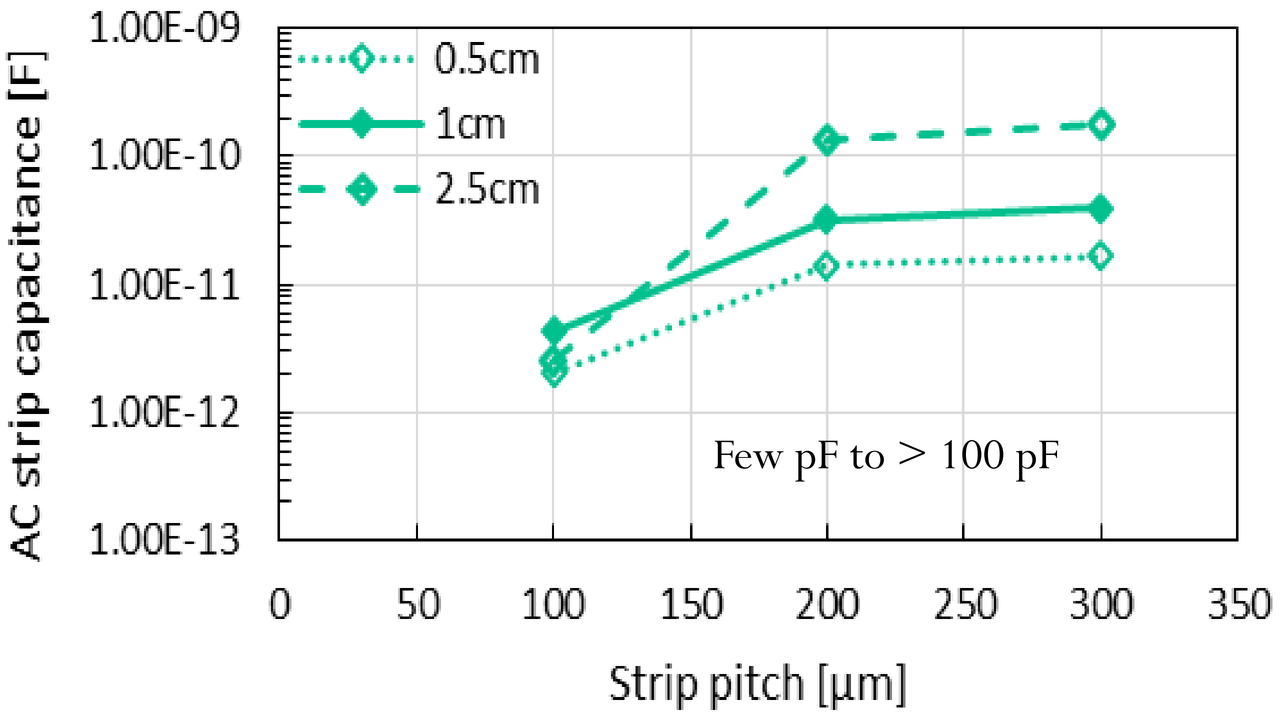
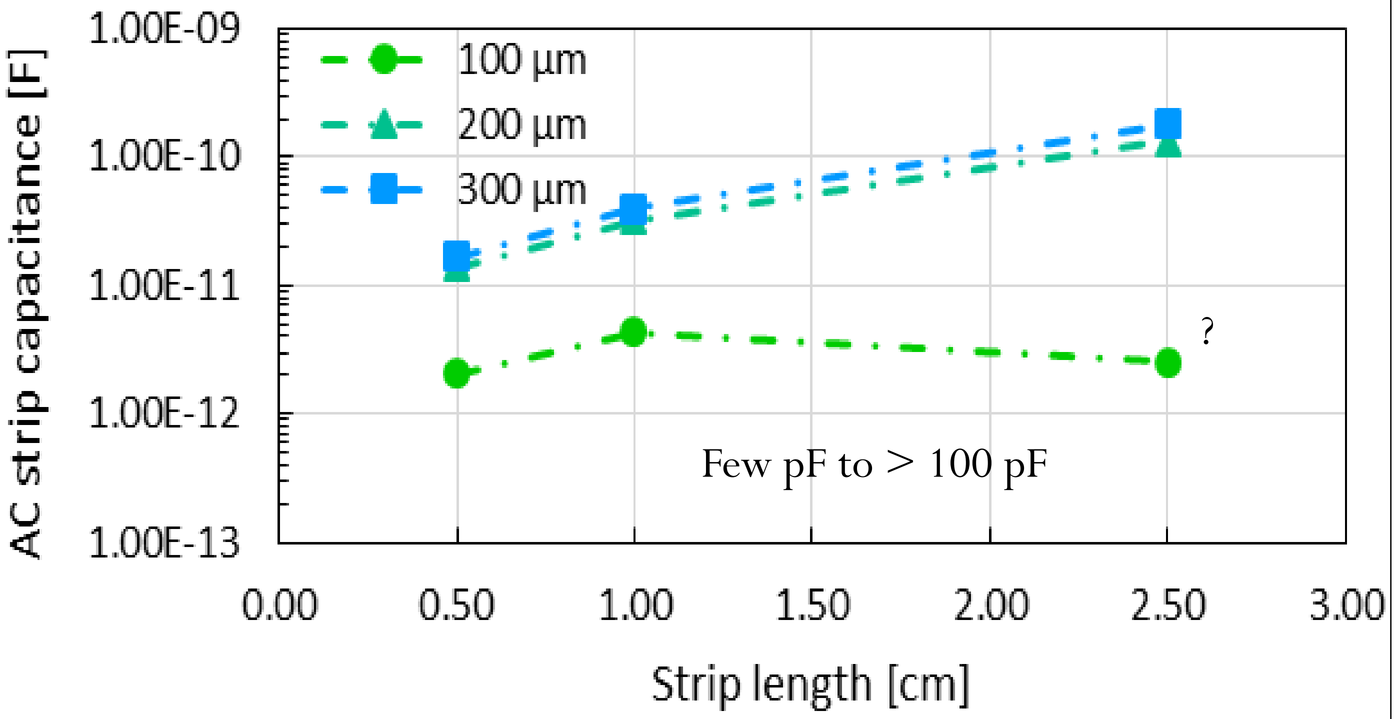
AC-strips capacitance





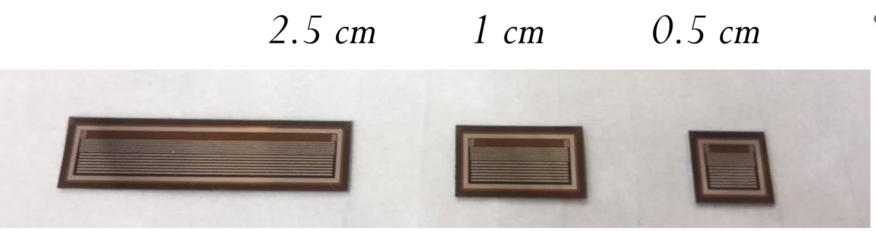
- AC strip capacitance for 2.5 cm, 1 cm and 0.5 cm BNL sensors, width = pitch/2
  - AC capacitance increases with strip length and strip pitch/width as expected
  - Measured at 400 kHz, large dependence on probing frequency for BNL sensors to be understood

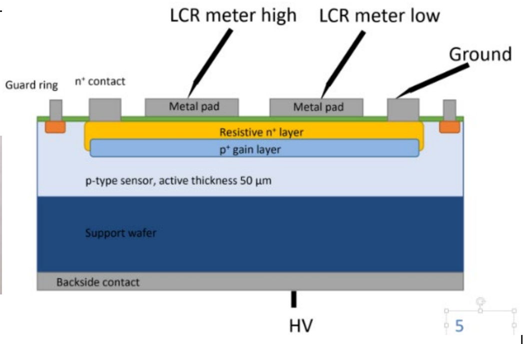




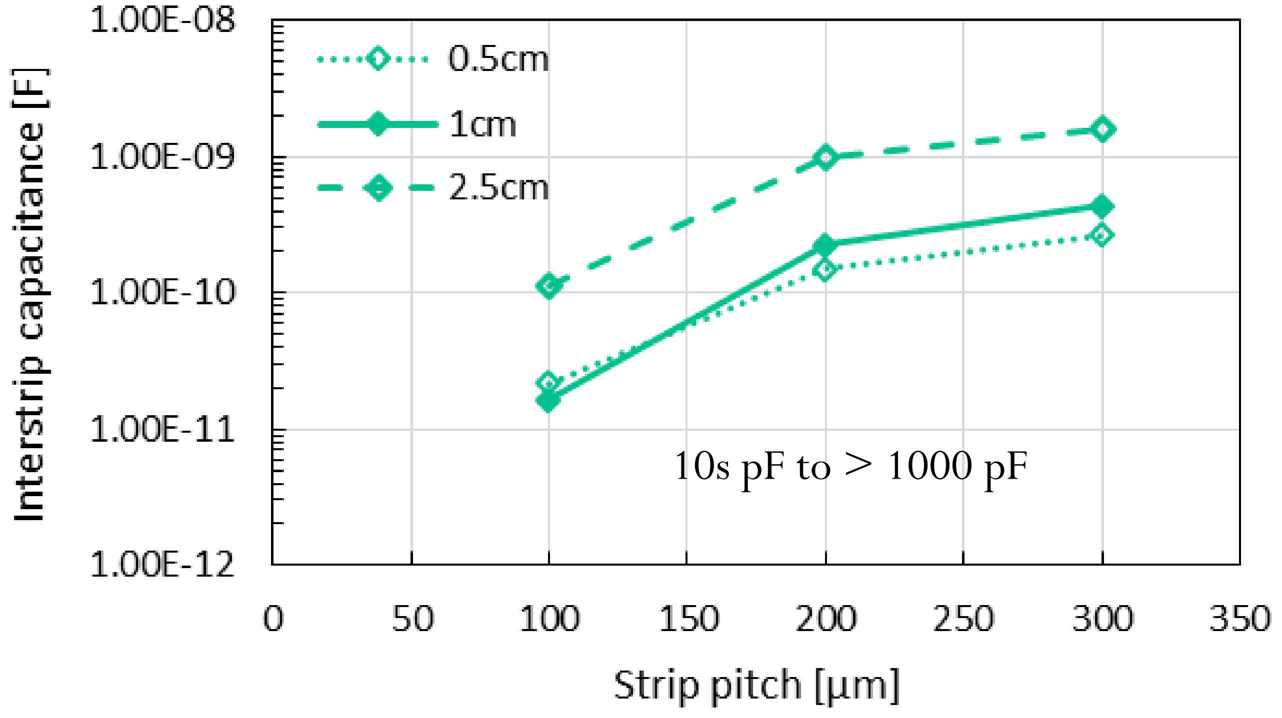
Data by: J. Ott

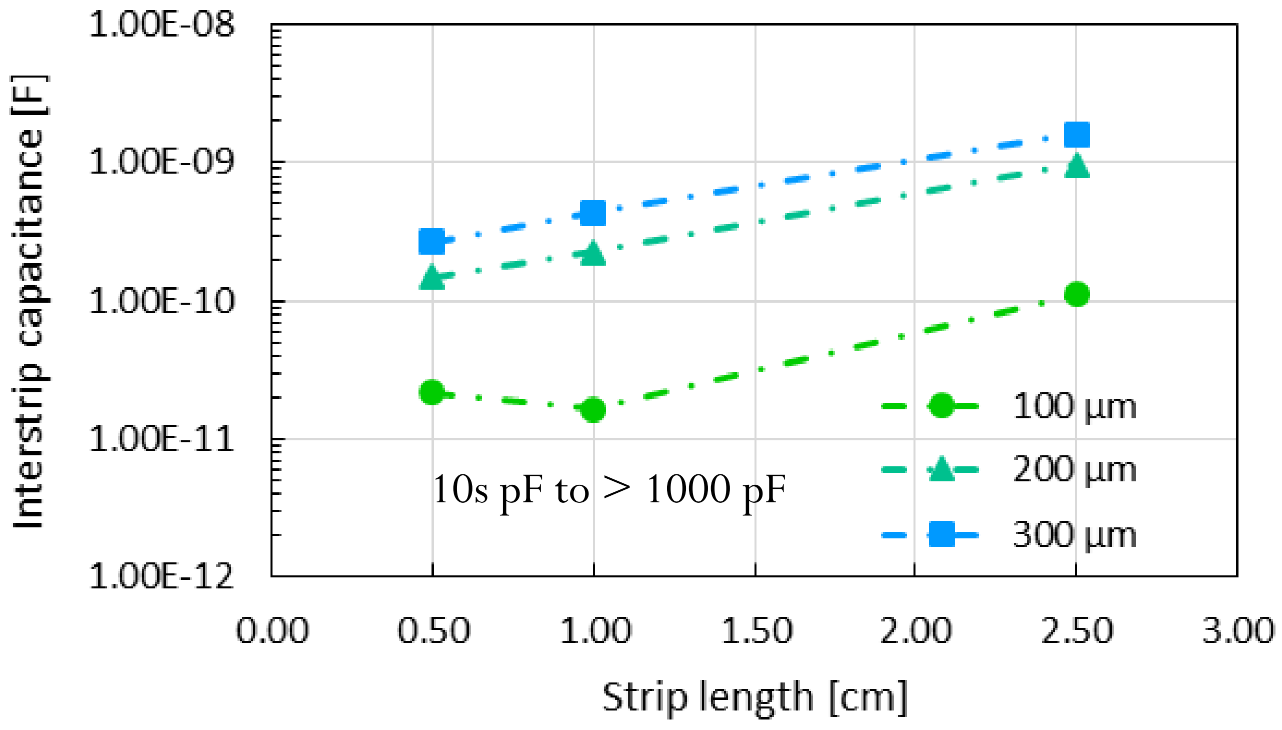
AC-strips capacitance





- AC inter strip capacitance for 2.5 cm, 1 cm and 0.5 cm BNL sensors, width = pitch/2
  - Interstrip capacitance increases with strip length as expected and strip pitch/width
  - Measured at 400 kHz, large dependence on probing frequency for BNL sensors to be understood

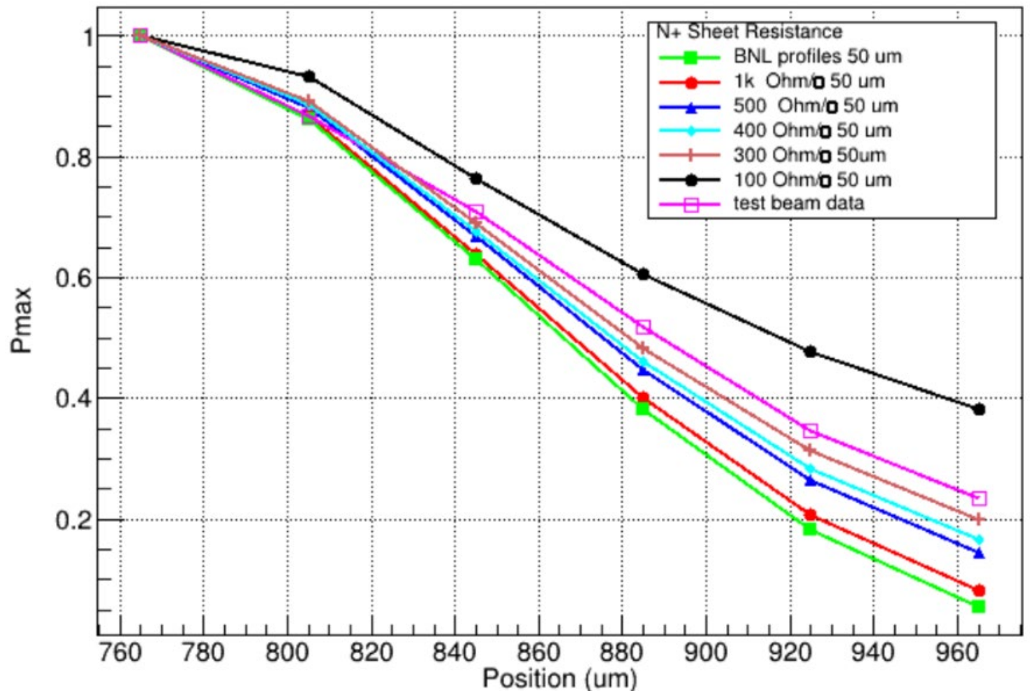


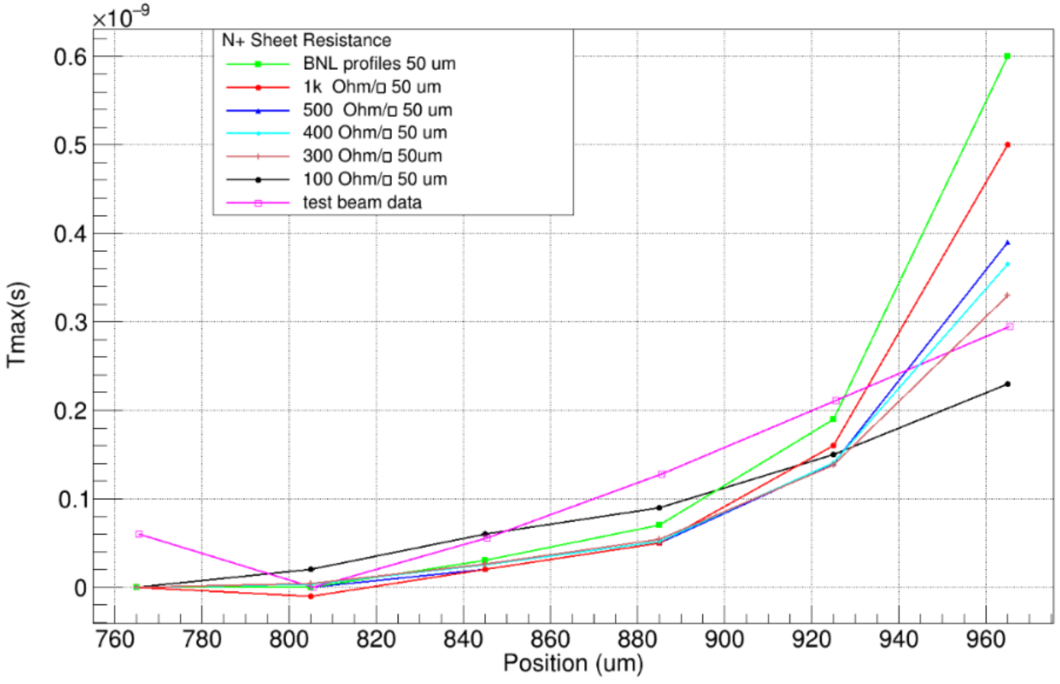


Data by: J. Ott

AC-LGAD device simulation

- **TCAD simulations to study AC-LGAD parameters variations**
  - Studies done with TCAD Silvaco and Sentaurus simulation software
- Study the effect of the N+ doping concentration to the charge sharing profile
  - Matching of profile with test beam data
- **Increased resistance in the N+ reduces the charge sharing**
  - **Need a factor of 10 to see a significant difference (100 Ω vs 1kΩ)**
- Signal induced away from the electrode has a delay (both in data and simulation)
  - **N+ resistivity also influences the time of arrival of signal** especially at large distances



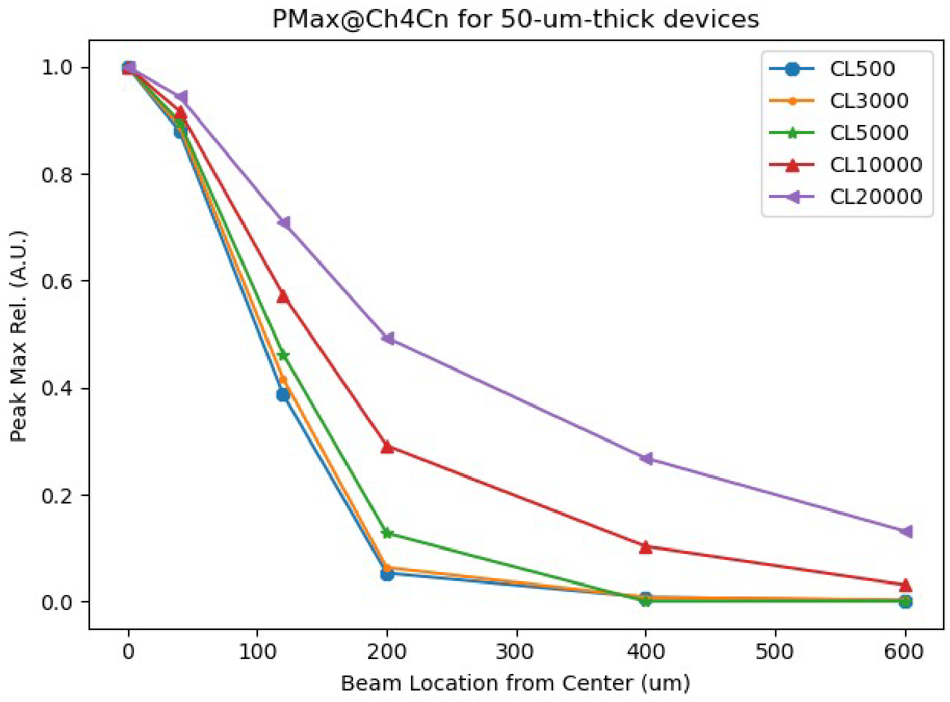


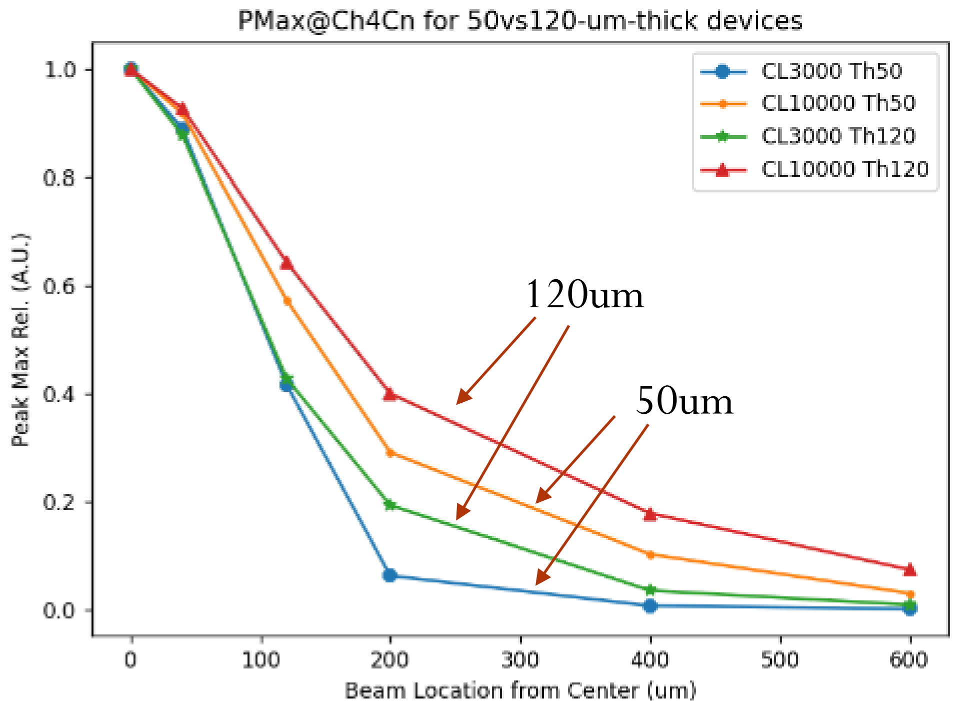
Data by: M. Nizam

AC-LGAD device simulation

- Investigate strip geometry (pitch, length, width) effect on charge sharing
  - **As seen in the data longer strip increase the charge sharing**
  - Effect start to be significant at 1cm of length for this geometry
- Sensors studied are 50um thick, simulation can help understand the behavior of thicker or thinner sensors
  - 120um thick LGADs simulated, the increased thickness increases the charge sharing effect
- For most simulations TCAD in 3D mode is necessary to have realistic results (2D approximation is not enough)

TCAD Sentaurus
50um thickness
different strip lengths



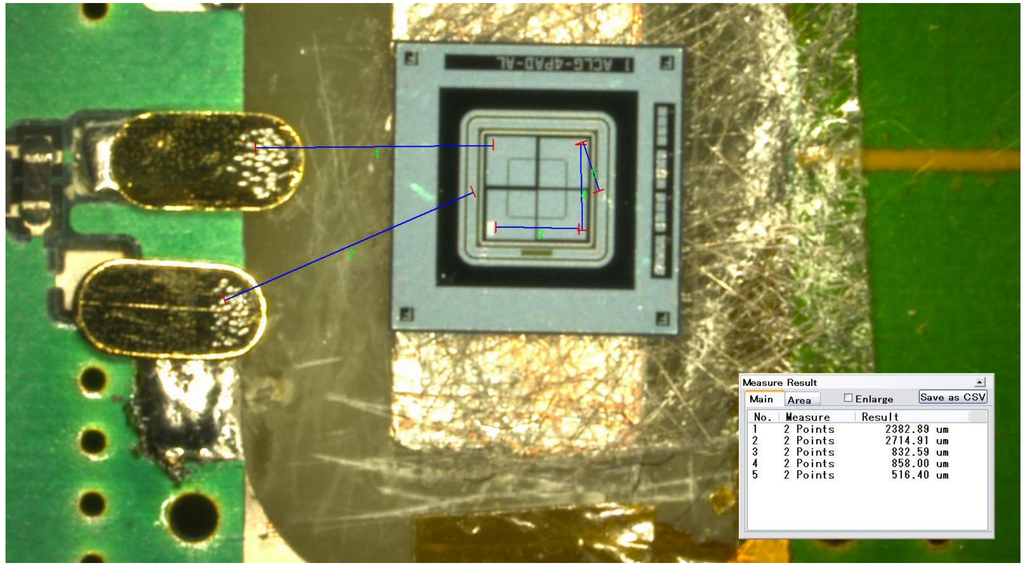


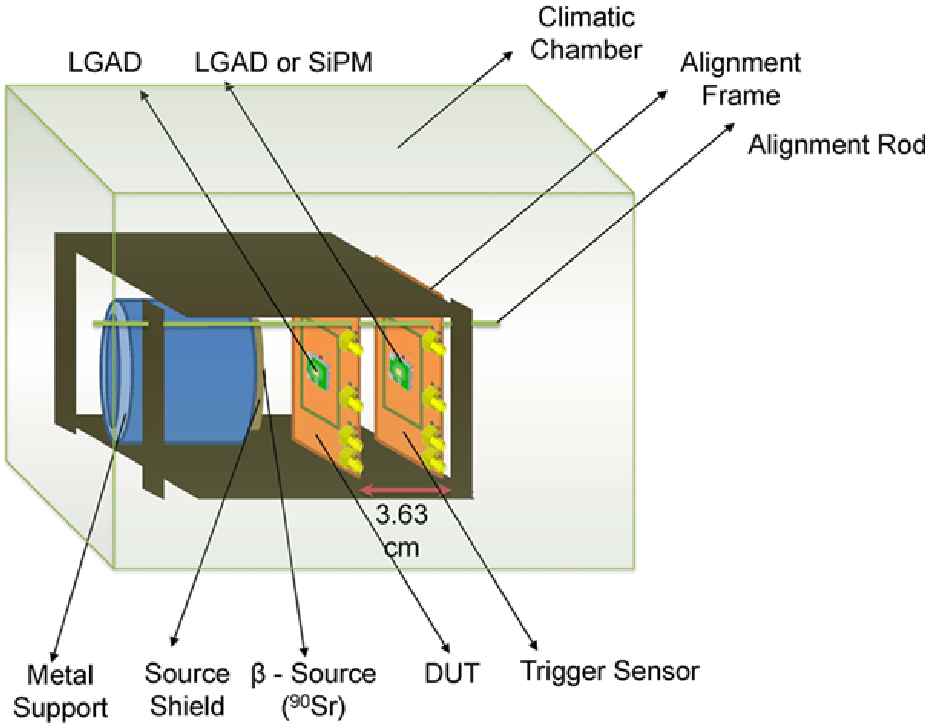
TCAD Sentaurus
different thicknesses
Different strip lengths

Data by: T. Shin

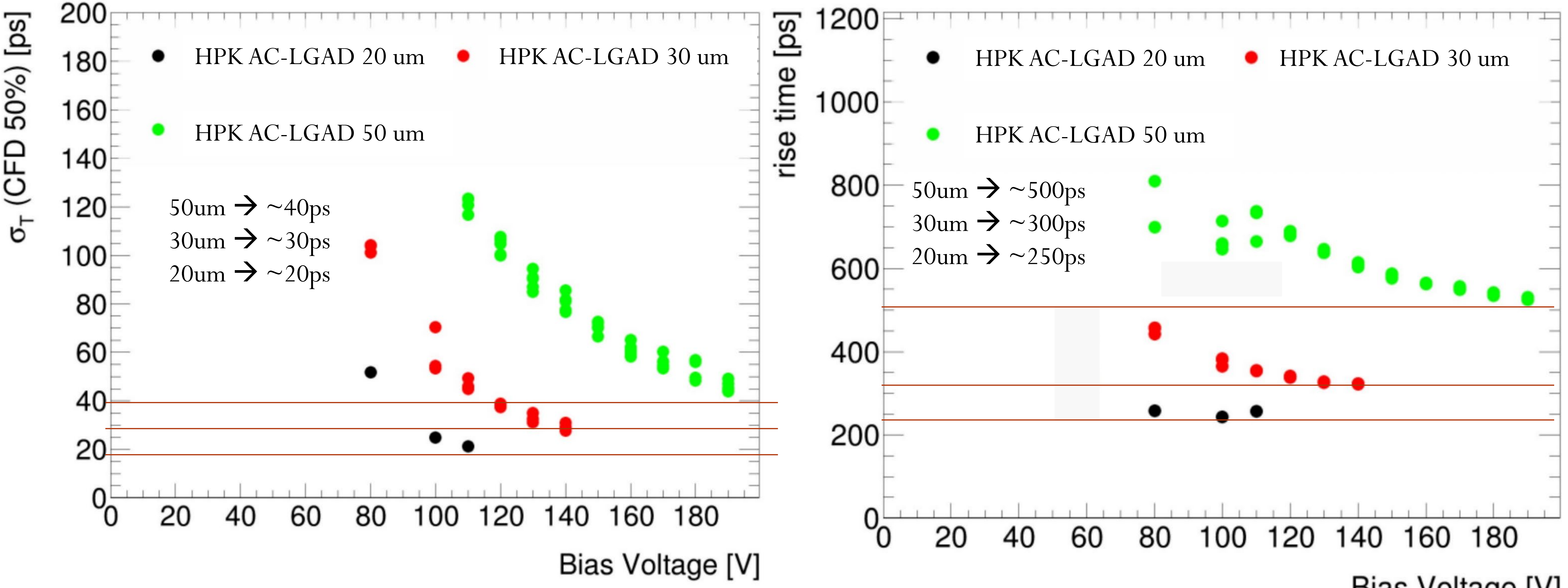
20/30/50um HPK device

- HPK AC-LGAD production with 20/30/50 um of active thickness
  - AC-LGAD array 2x2
  - 500um pitch and ~500um pad size
- Tested with Sr90 source on UCSC 1ch boards
  - Results likely very similar to a DC-LGAD since the response under the metal pad is roughly constant
- Fast trigger LGAD to provide time reference and measure the time resolution
  - Time resolution measured with CFD algorithm, trigger contribution is subtracted
- Digitized with fast (2Ghz) oscilloscope and analyzed offline





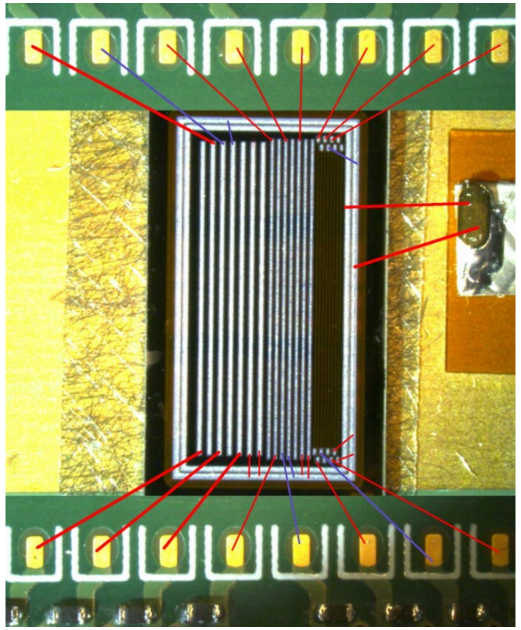
20/30/50um HPK device

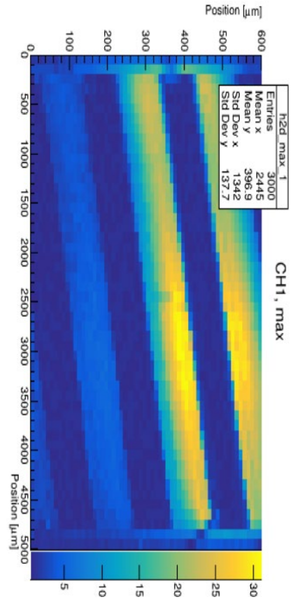


Data by: J. Ding

Conclusions

- **AC-LGADs** are an innovative high density LGAD technology
  - Maintain fast pulses (~1ns), internal gain of 20-50 and exceptional time resolution of LGADs but allow dense LGAD pixelation
  - **Charge sharing mechanism reduces the channel count in low pileup environment**
- Future AC-LGAD applications in many fields
  - PIONEER (**AC-LGAD strips**)
  - EIC (**AC-LGAD strips** and pixels)
- **Charge sharing depends on many parameters**
  - N+ resistivity, strip geometry, strip length, sensor thickness
  - Behavior observed in prototypes and simulated with TCAD software
  - Strips as 2D sensors? Using charge splitting in the strip
  - Strip AC capacitance and inter-strip capacitance measured for several geometries
- Measurement of time resolution in thin AC-LGADs from HPK
  - **Time resolution of 20ps for 20um devices**





Thanks for the attention

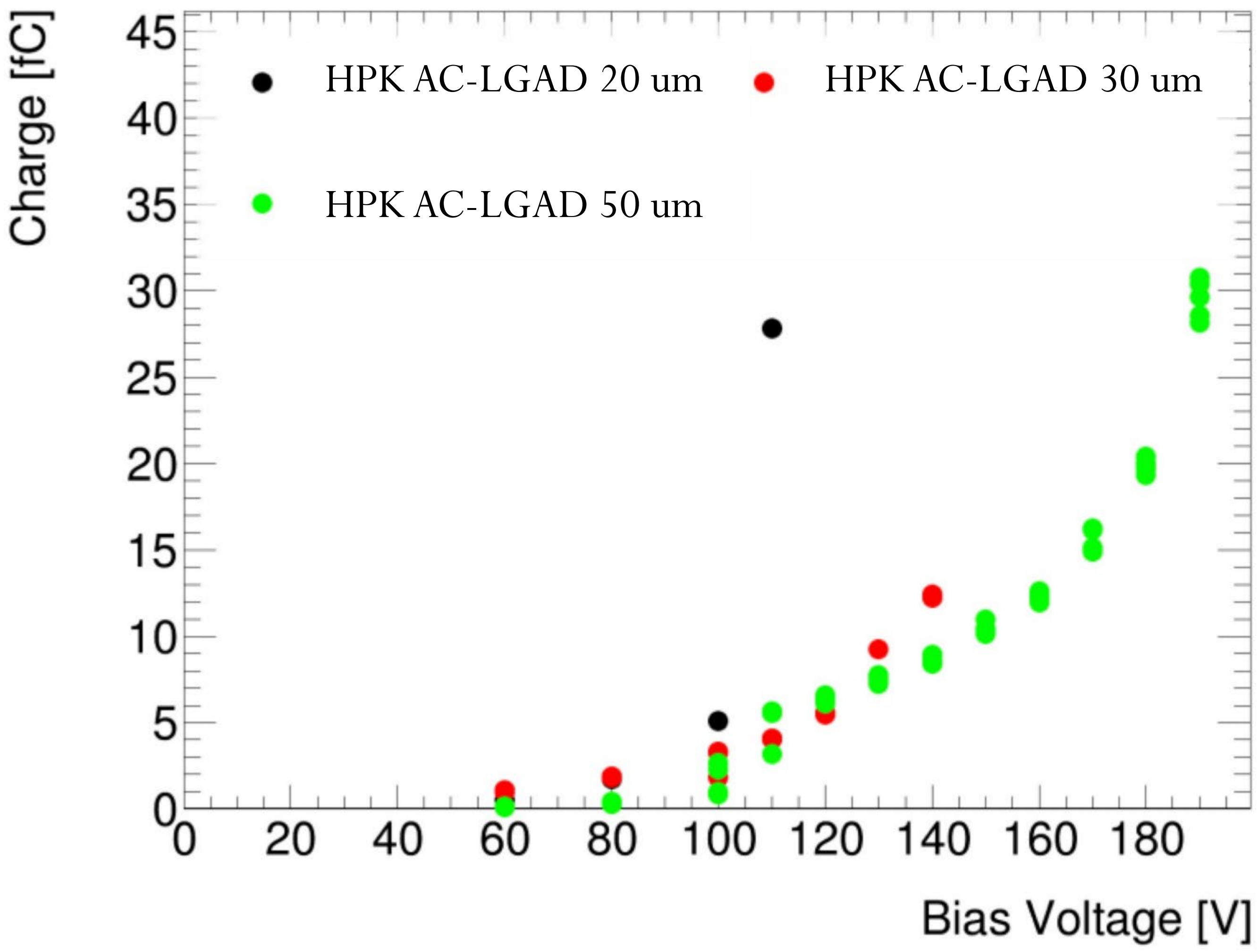
Many thanks to the SCIPP group students and technicians!

Thanks to the HPK and BNL teams for producing and providing the sensors for this study

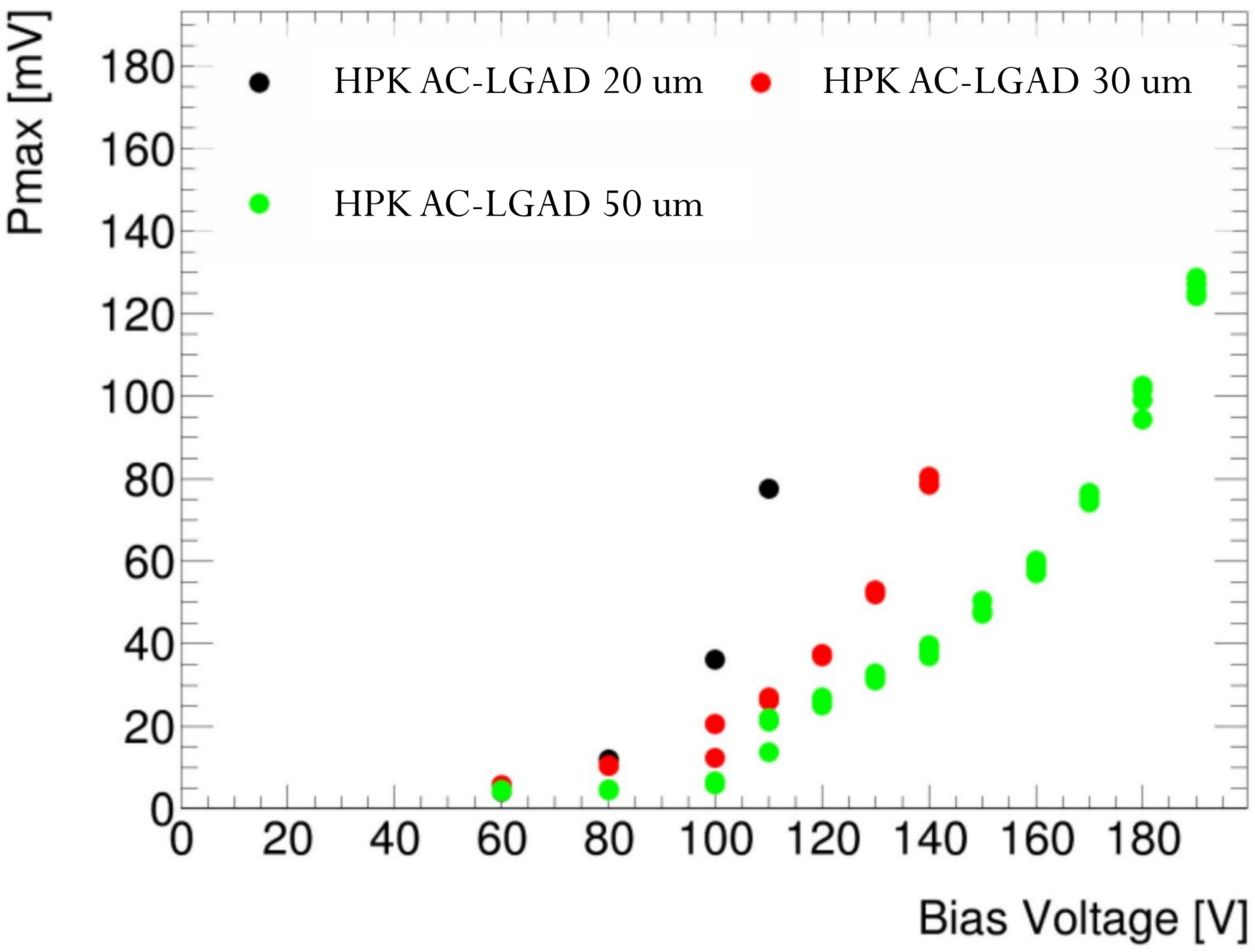
This work was supported by the United States Department of Energy, grant DE-SC0010107

This work was supported by a US-Japan grant

Charge/Pmax



Charge [fC]
HPK AC-LGAD 20 um
HPK AC-LGAD 30 um
HPK AC-LGAD 50 um
45
40
35
30
25
20
15
10
5
0
0
20
40
60
80
100
120
140
160
180
Bias Voltage [V]



Pmax [mV]
HPK AC-LGAD 20 um
HPK AC-LGAD 30 um
HPK AC-LGAD 50 um
180
160
140
120
100
80
60
40
20
0
0
20
40
60
80
100
120
140
160
180
Bias Voltage [V]