BNL AC-LGAD strips laboratory testing and TCAD simulation

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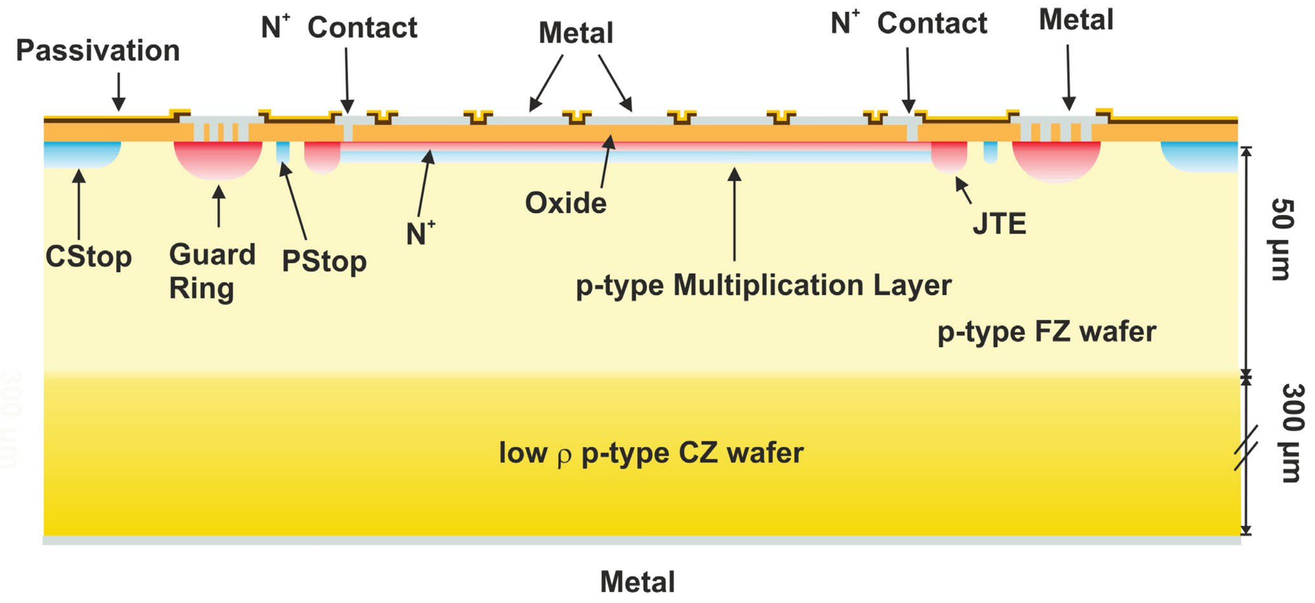
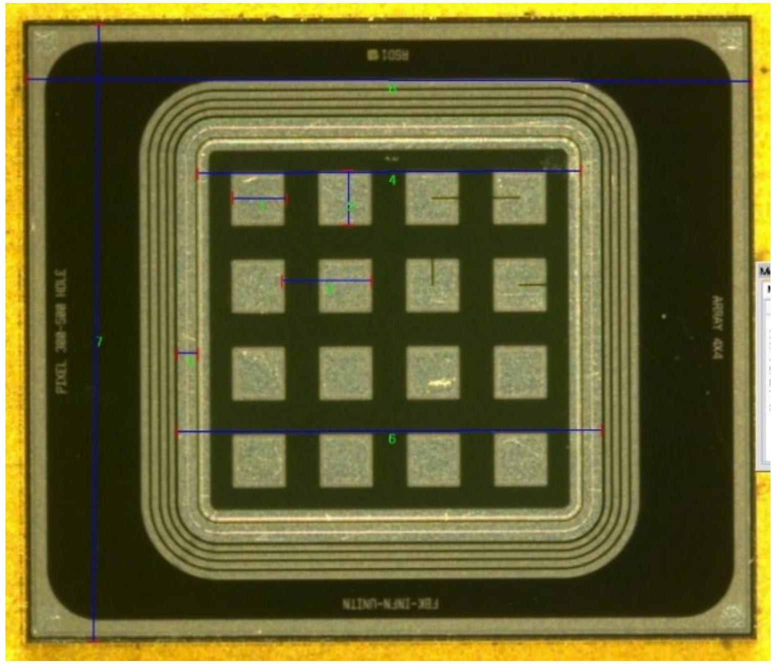
AC-LGADs

- 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



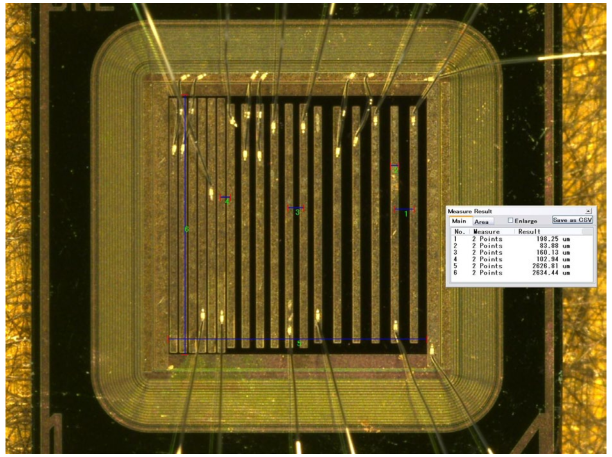
- **The response of the sensors can be tuned** by modifying several parameters
  - Pad geometry and dimension
  - Pad pitch
  - N+ layer resistivity
  - Oxide thickness

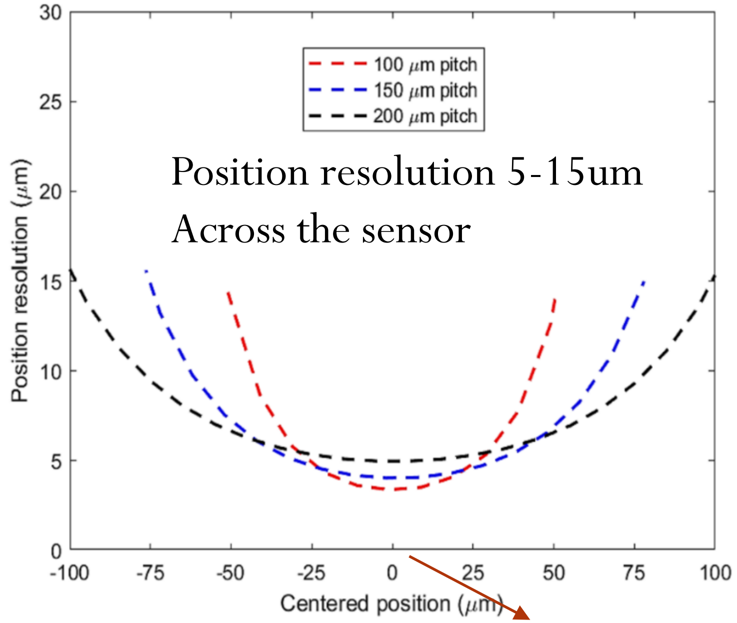


BNL strips

First AC-LGAD studies

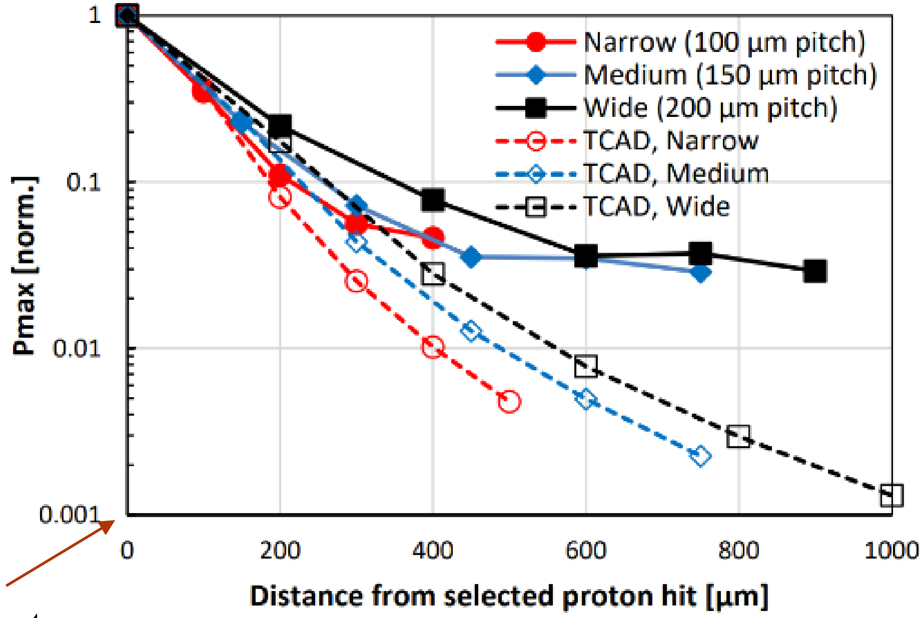
- Experimental studies on a **BNL AC-LGAD prototype strip sensors** (50 um thick) with many geometries
- First prototype: same strip length (3 mm) and width (80 um), but with different pitches (200 um, 150um, 100 um)
  - Studies made with FNAL TB data
  - Close strips show a slightly better position 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

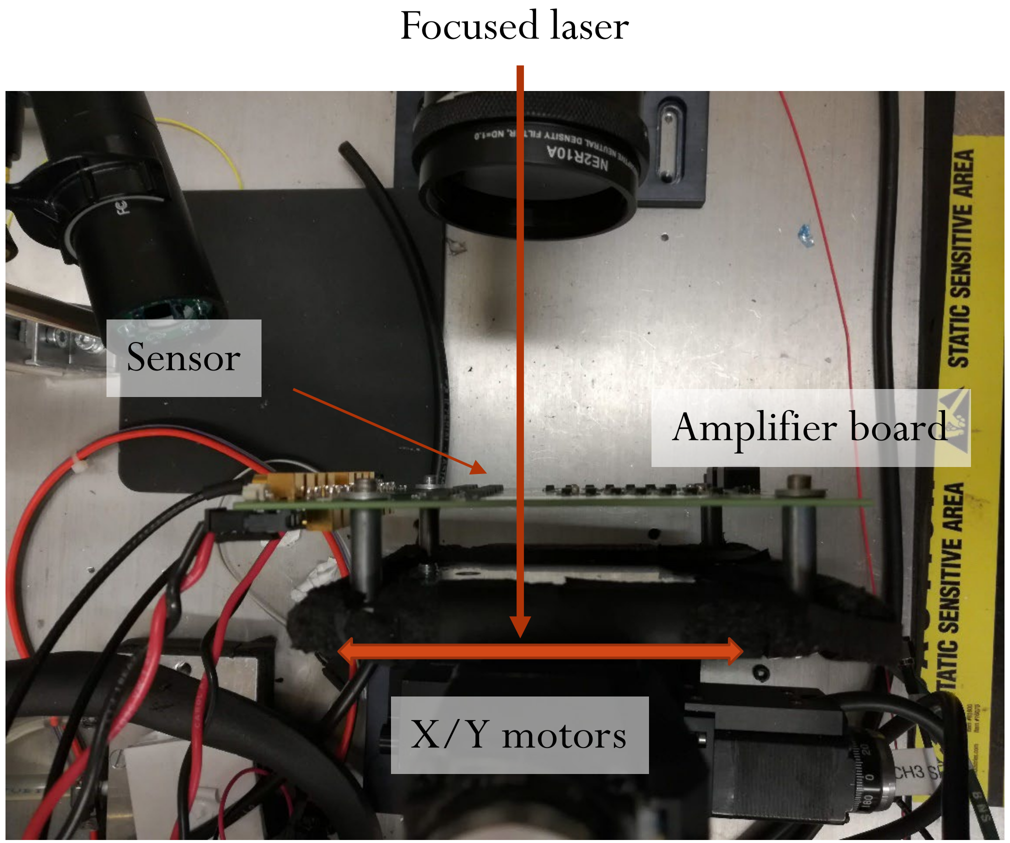
Center between strips

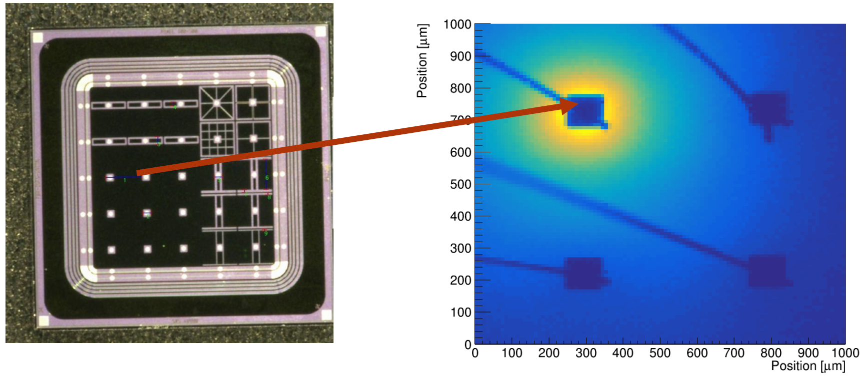


Strip center

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

Sensor testing –Laser TCT setup



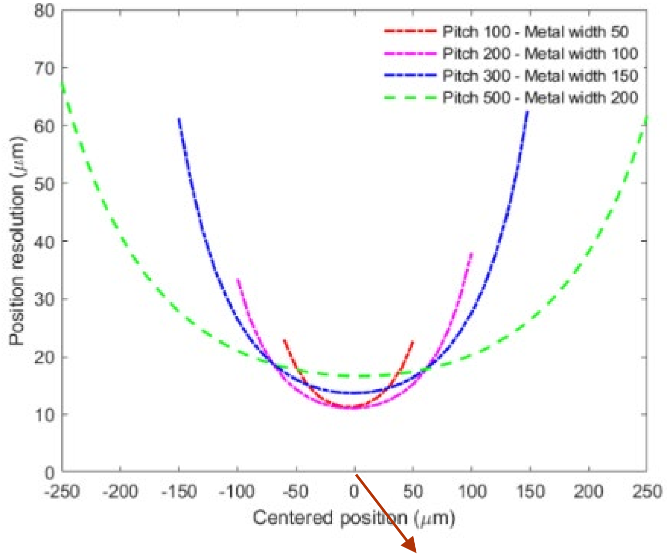


- Sensors are mounted on a multi-channel analog amplifier board with bandwidth ~1 GHz
  - Response is readout by a fast oscilloscope (2 GHz/20 Gs)
- **IR laser (1064 nm)** mimics charge deposit of a MIP
  - Focused beam spot width of < 20 um
  - Metal structures of the sensors are not transparent to IR so no response can be seen when laser is on top of metal
- Amplifier board is mounted on X/Y moving stages
  - **Charge injection as a function of position**

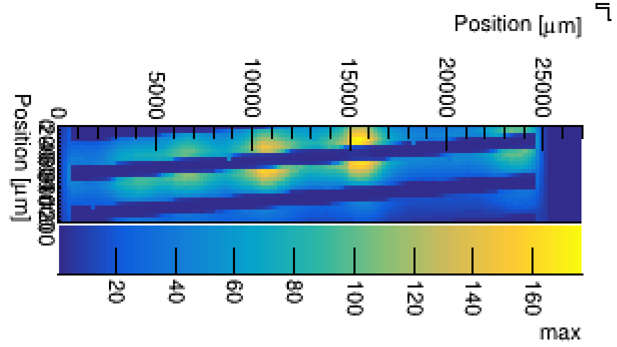
- Test LGADs performance quickly (although as accurately as a source)
- Test the inter pad gap of LGAD arrays
- Probe the response of the sensors as a function of position

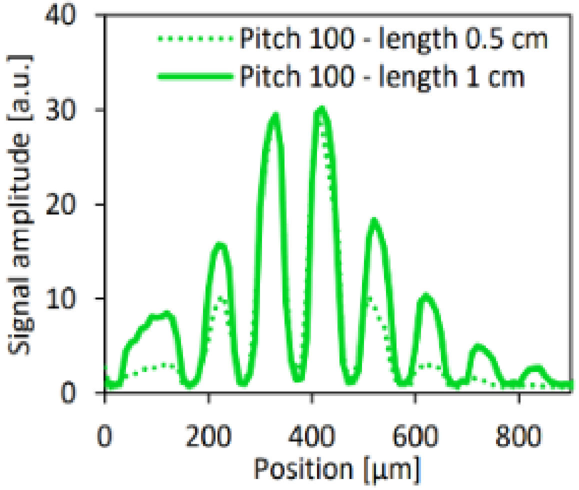
Sensor tested – W1

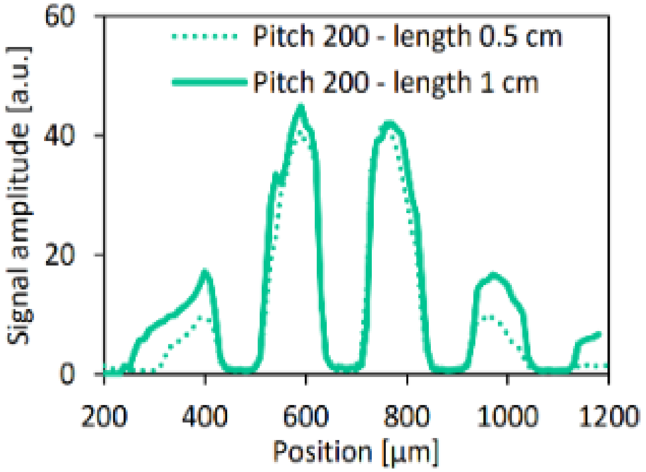
- BNL sensors with same geometry but different lengths
- Pitch and width in three configurations (width = pitch/2)
  - 300-150 um, 200-100 um, 100-50 um
  - 0.5 cm and 1 cm long sensors
- 2.5 cm long sensor with strips of 500-200 um
  - Charge sharing present up to ~2mm
- Direct comparison of geometry shows that **longer strips have increased charge sharing**
- Position resolution is similar in the 4 sensors in the center between strips, but increases under the strip
- **Issue to be solved: gain not uniform**
  - Should be solved in newest wafers

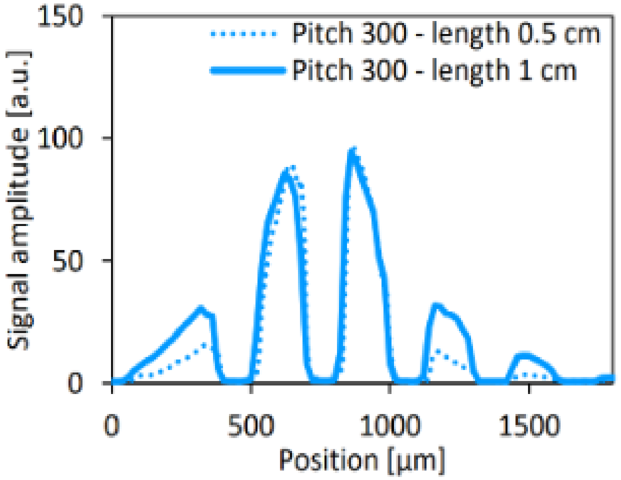


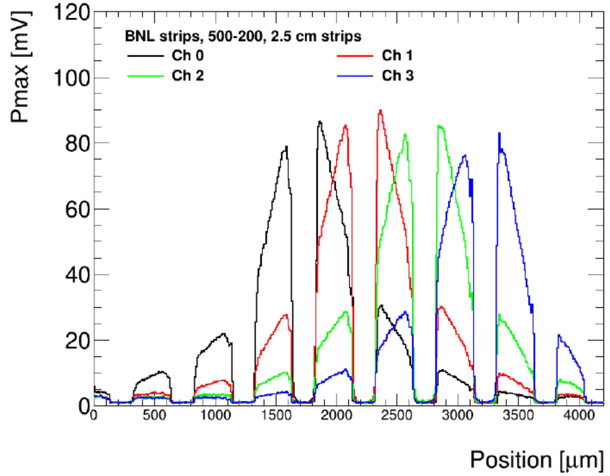
Center between strips









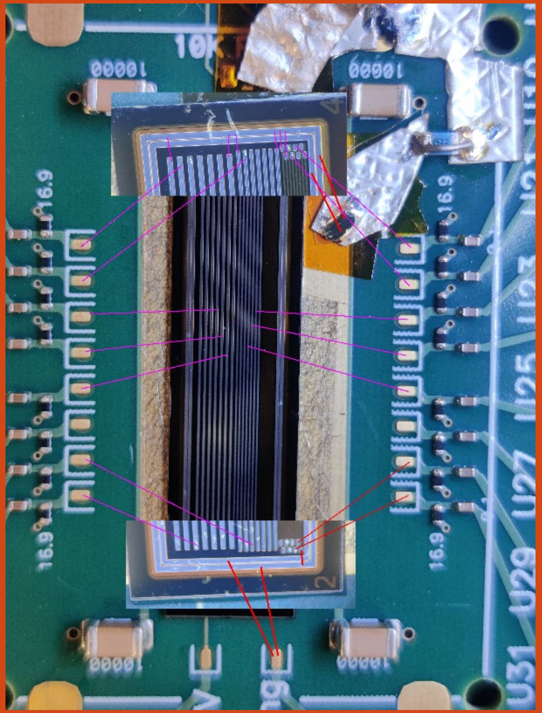


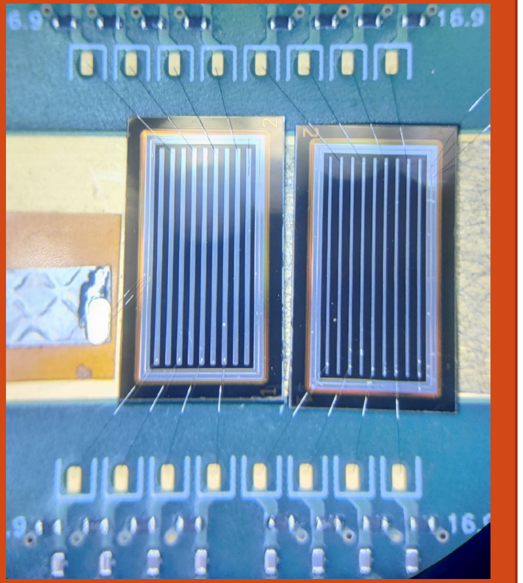
Data by: A. Das, C. Bishop, N. Yoho

Sensor tested – W30XX

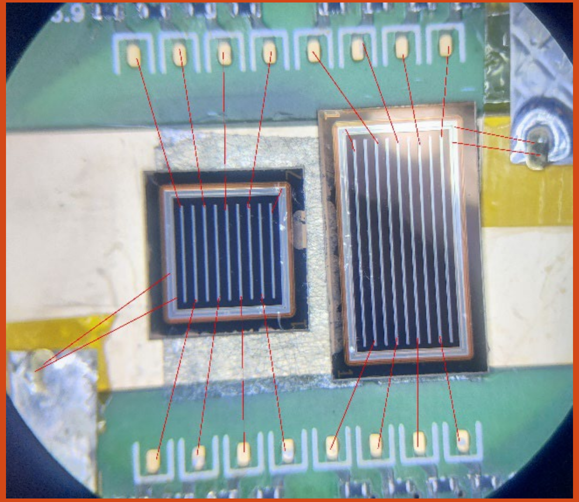
- All sensors have pitch of 500um
  - (except W3072 2.5cm)
  - Strip width, length and bulk thickness vary
- W3049, 50um, 1cm and 0.5 cm
- W3072, 20um, 1cm and 2.5cm
- W3074, 20um, 1cm, 0.5cm, 2.5cm

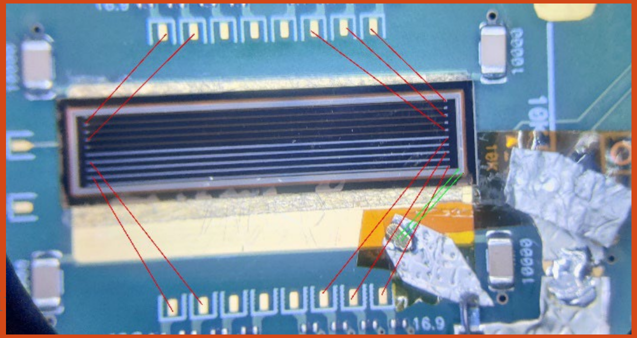
W3072 – 20um

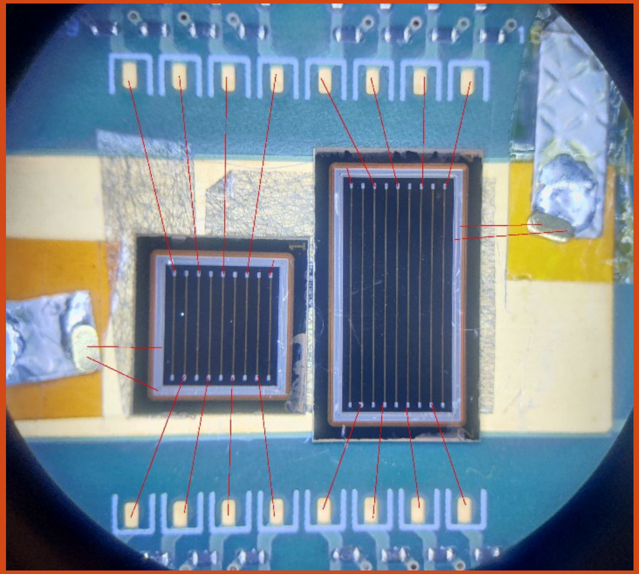




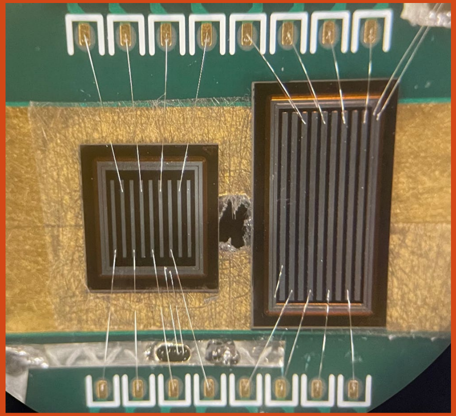
W3074 – 20um





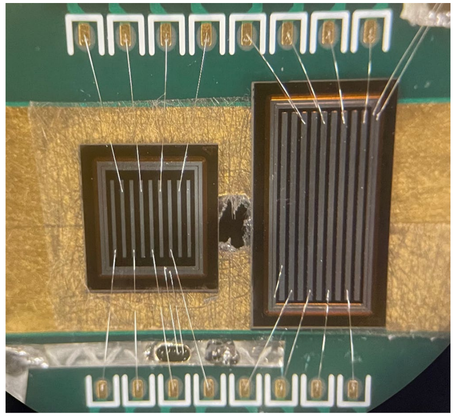


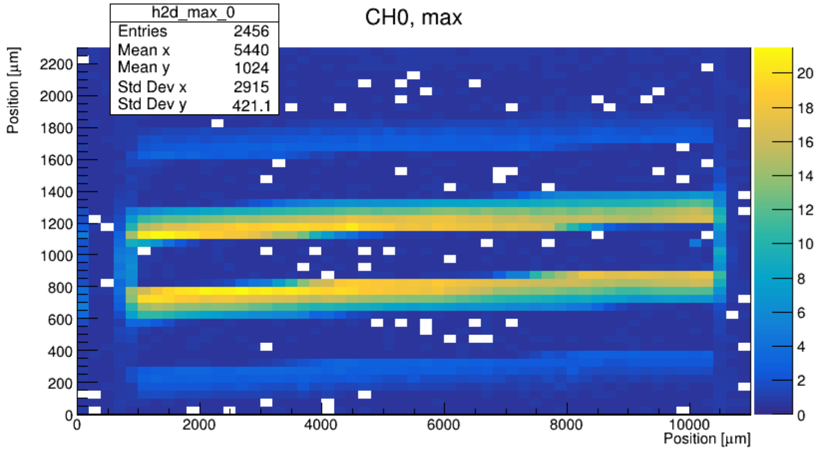
W3049 – 50um

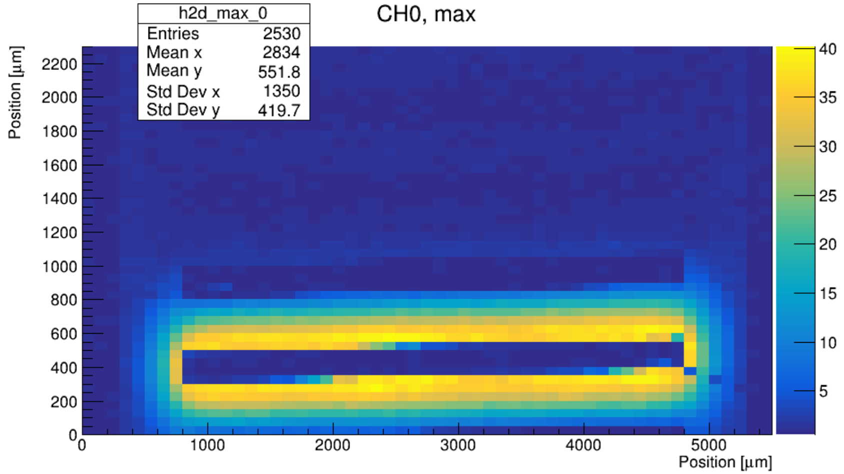


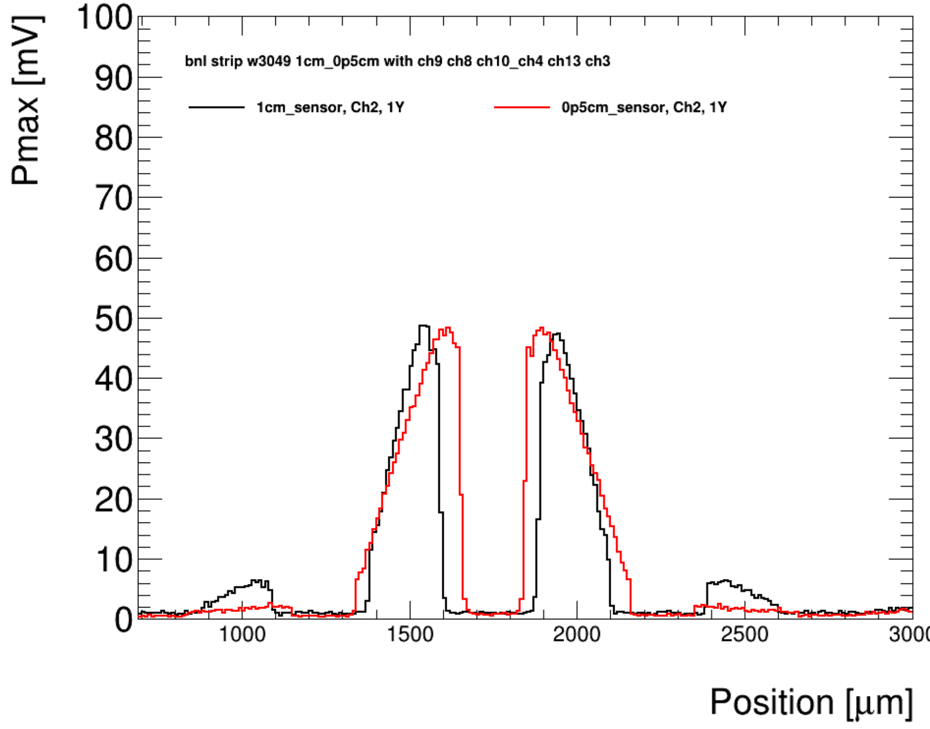
W3049

- 500um pitch, 50 um sensors
  - 1cm length, 300um width strips
  - 0.5cm length, 200um width strips
- Can't go to very high gain, minor gain dis-homogeneity
- Charge sharing for 0.5cm up to first neighbor, for 1cm up to second neighbor
  - Large effect by the strip length



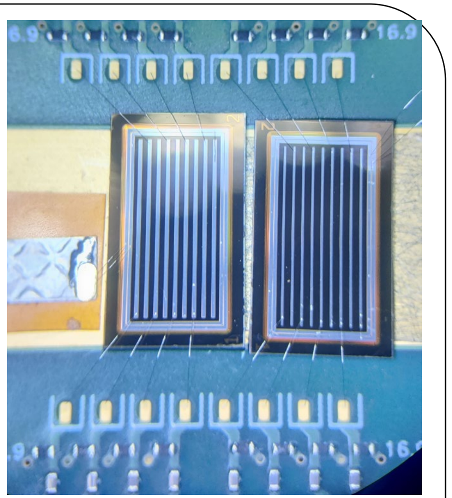


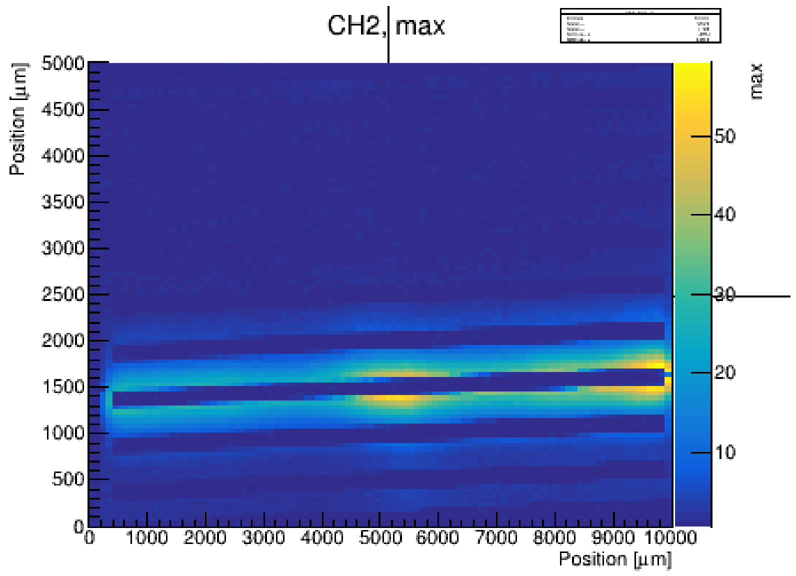


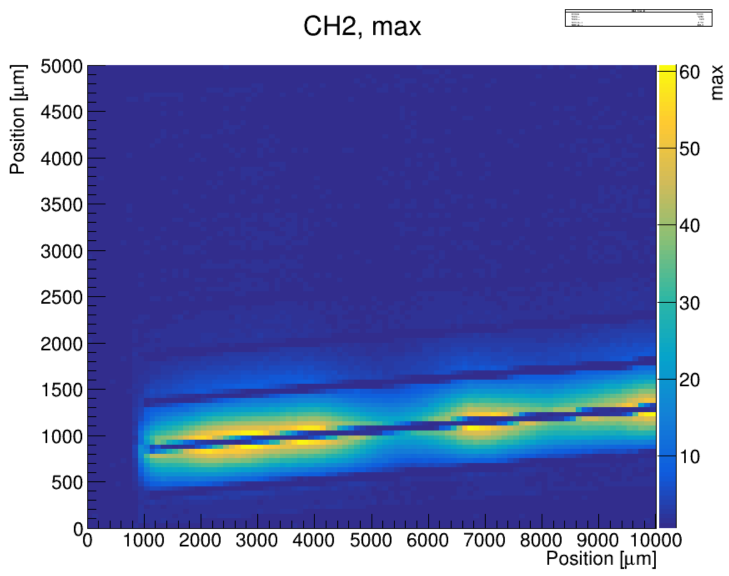


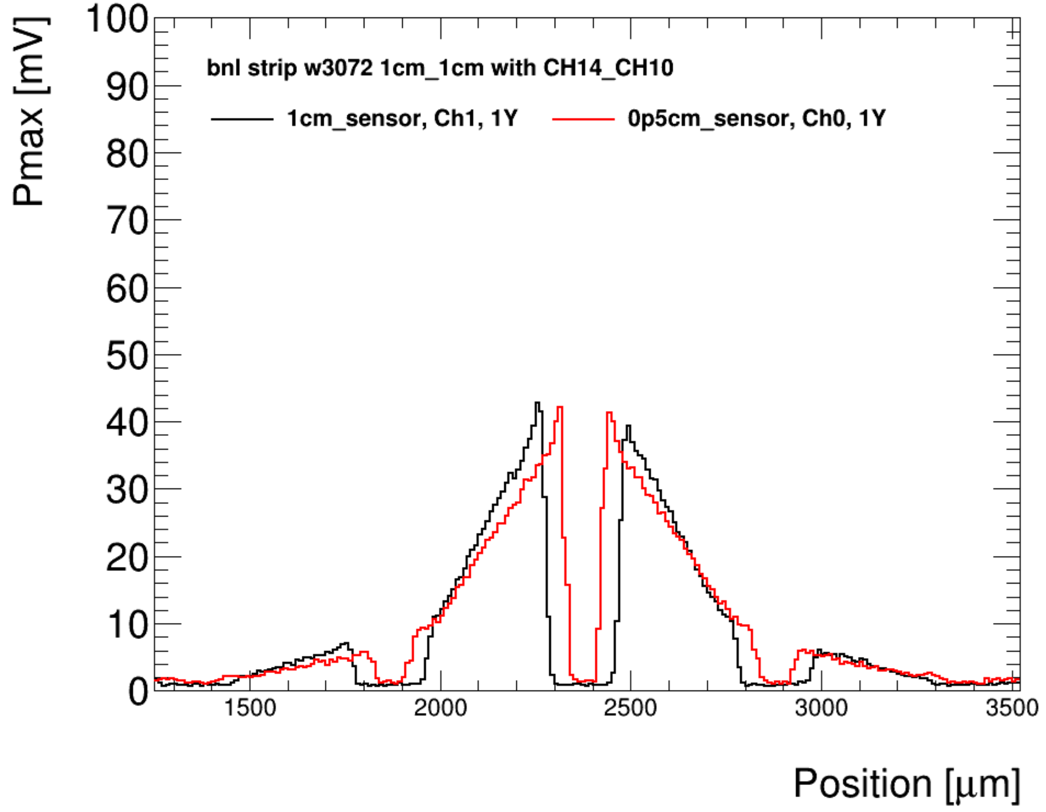
W3072

- 500um pitch, 20 um sensors
  - 1cm length, 200um width strips
  - 1cm length, 100um width strips
- Can't go to very high gain, gain dis-homogeneity observed
- Charge sharing very similar with the two strip widths



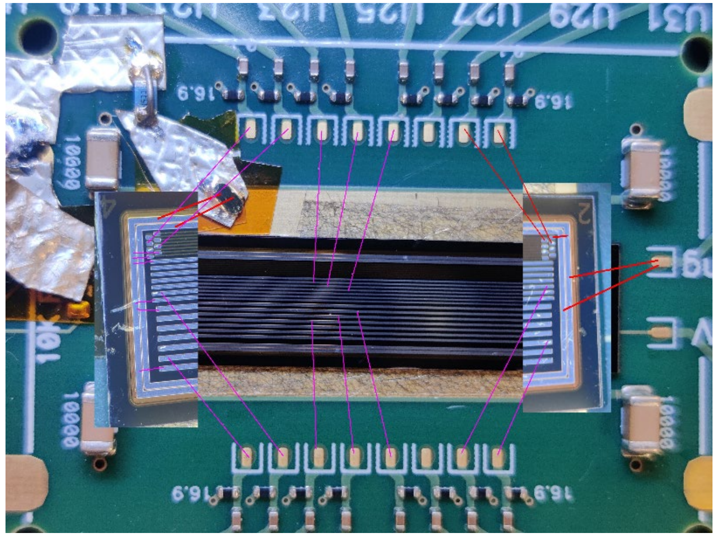


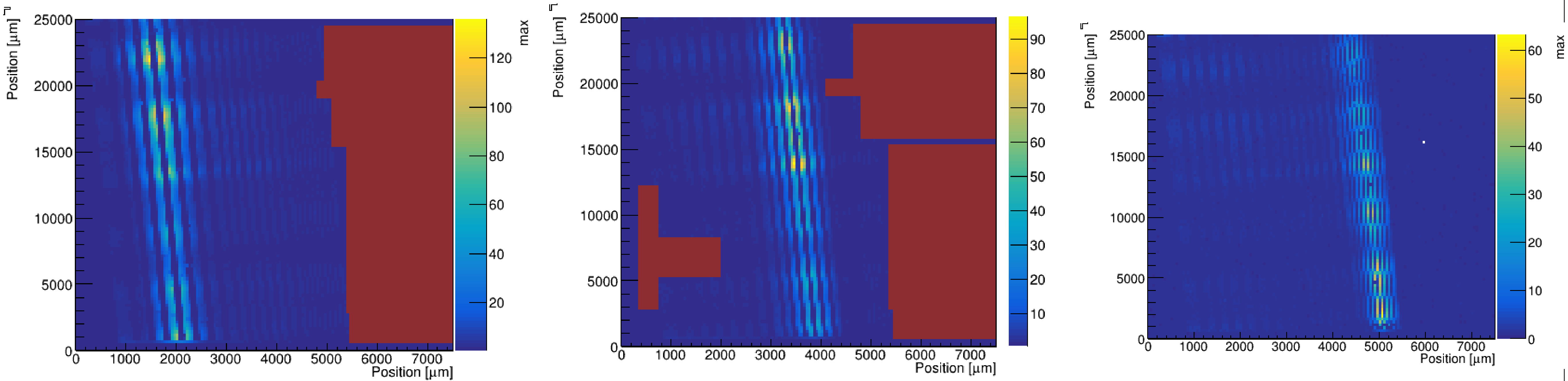




W3072 “long”

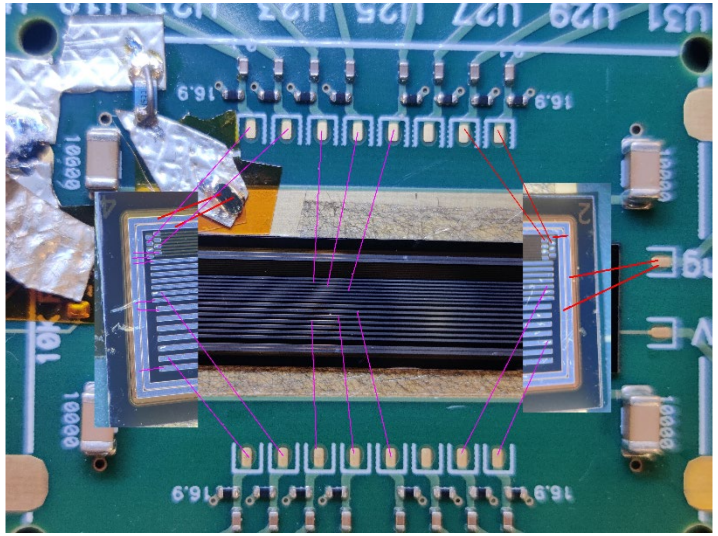
- 2.5cm, 50 um sensors
  - Pitch/width 300/150, 200/100, 100/50
- Gain very low (had to increase laser power to see something)
- Gain dis-homogeneity observed

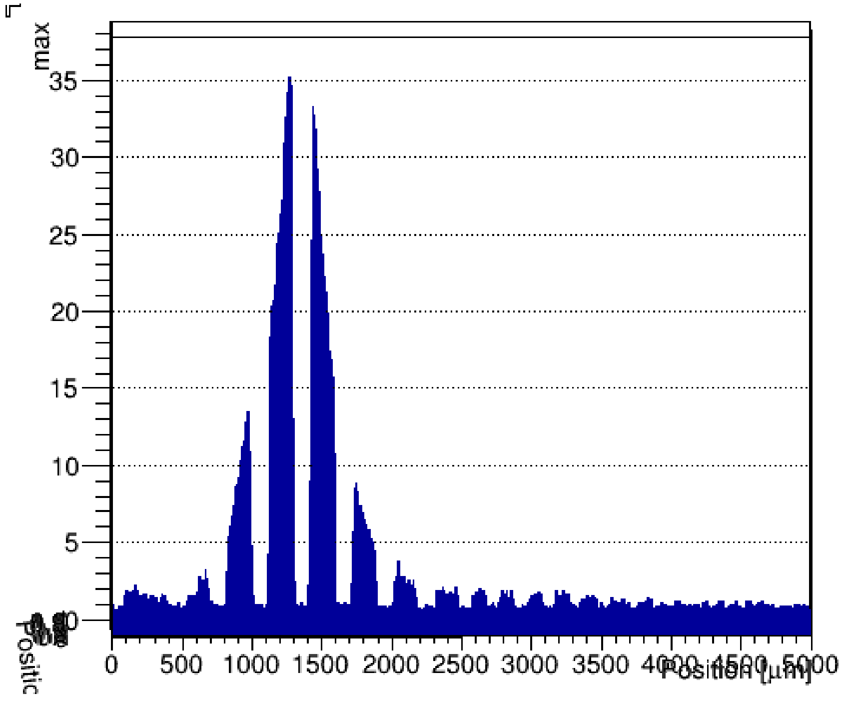


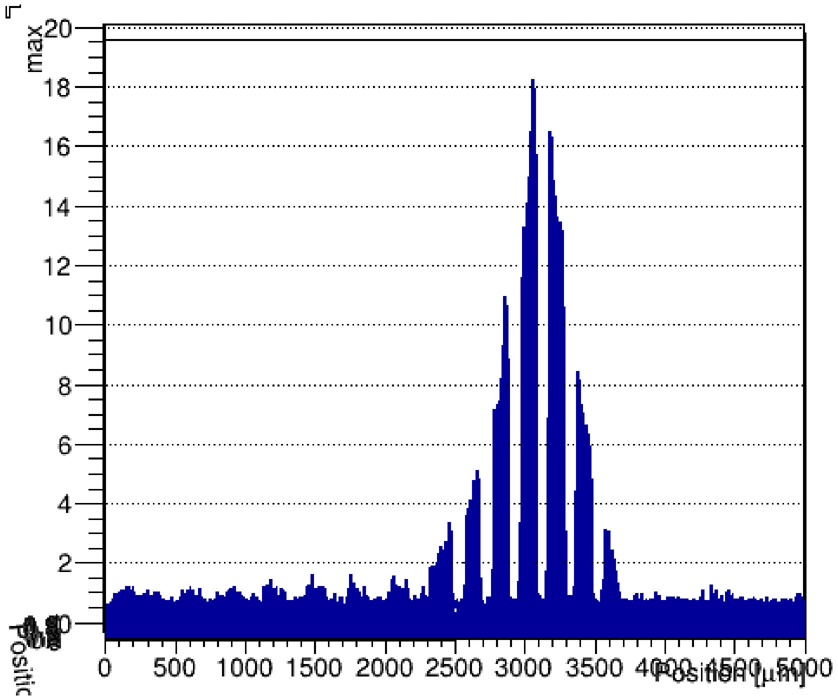


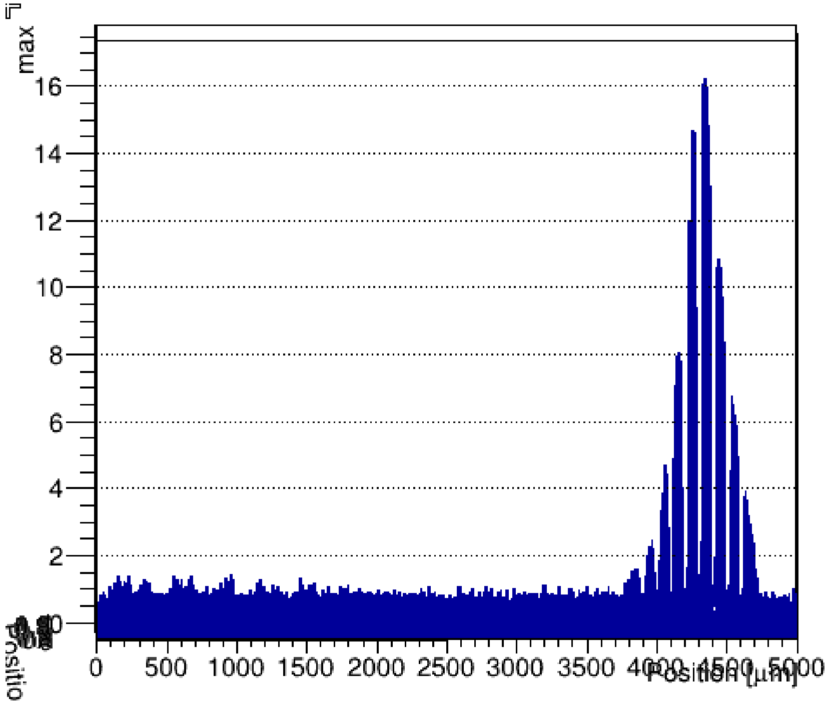
W3072 “long”

- 2.5cm, 20 um sensors
  - Pitch/width 300/150, 200/100, 100/50
- Large charge sharing (up to 5 neighbor for small strips)

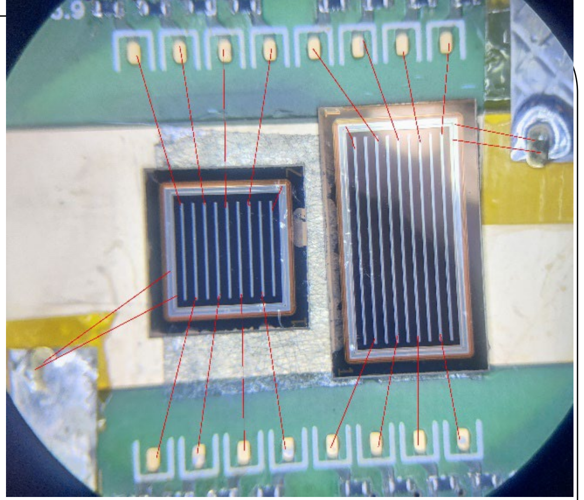






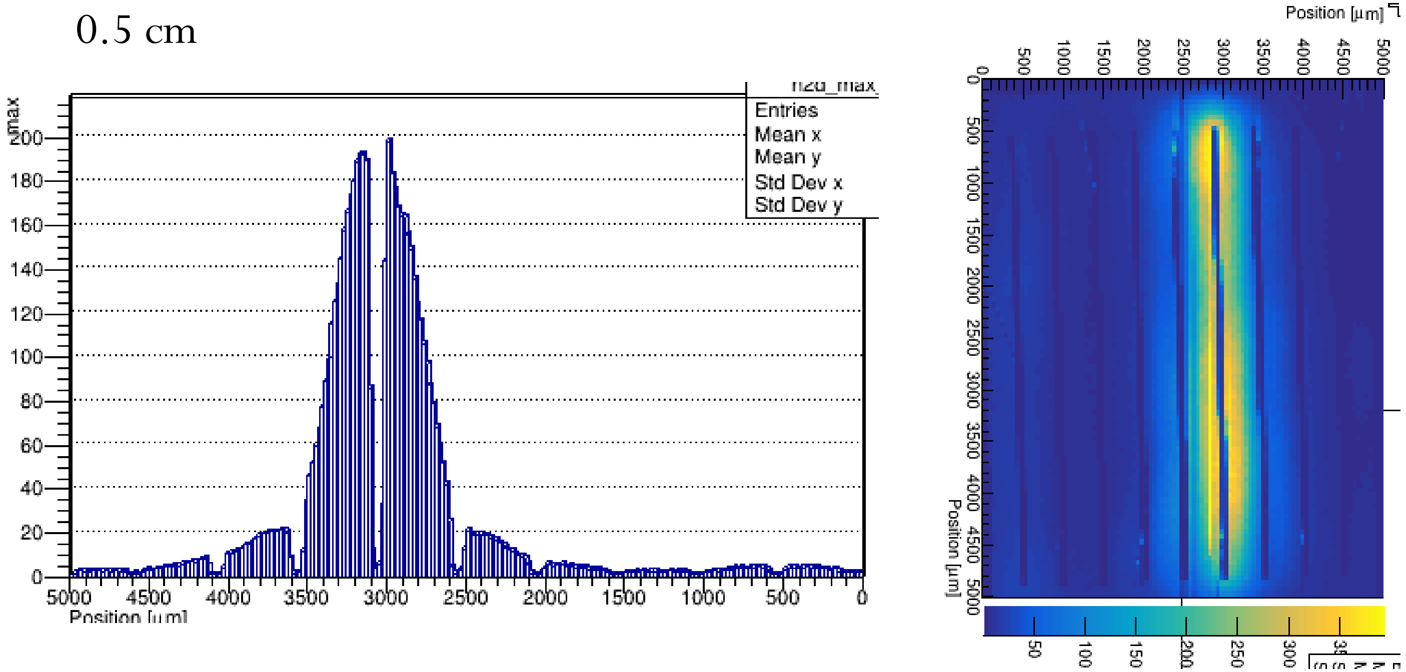


W3074 “wide”

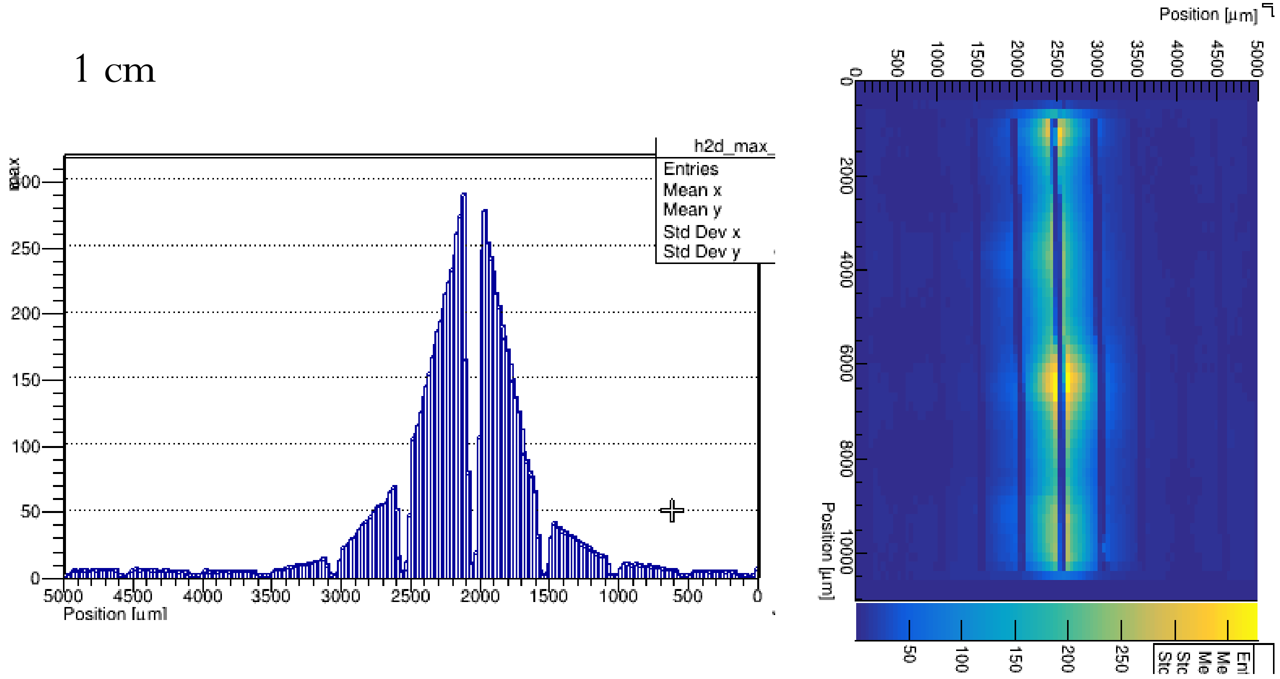


- 500um pitch, 20 um sensors
  - 1cm length, 100um width strips
  - 0.5cm length, 100um width strips
- Good gain, gain dis-homogeneity observed
- Charge sharing larger with longer strips (as expected), up to second neighbor

0.5 cm

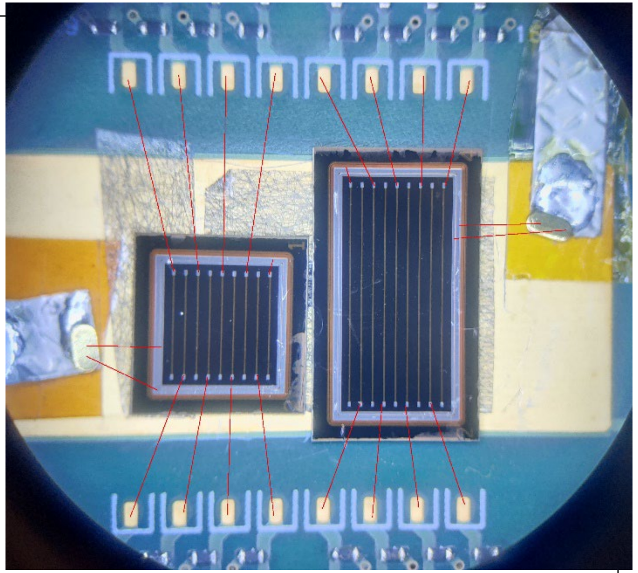


1 cm

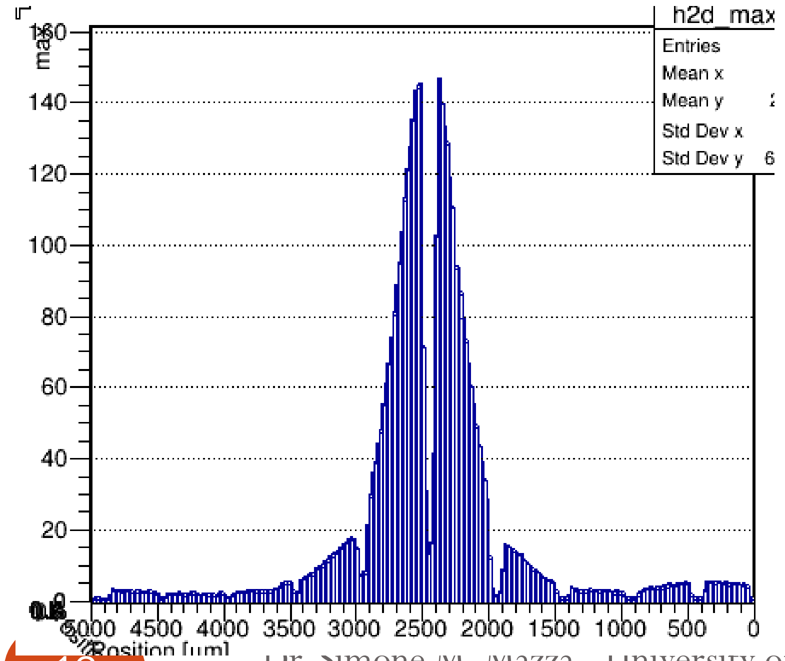


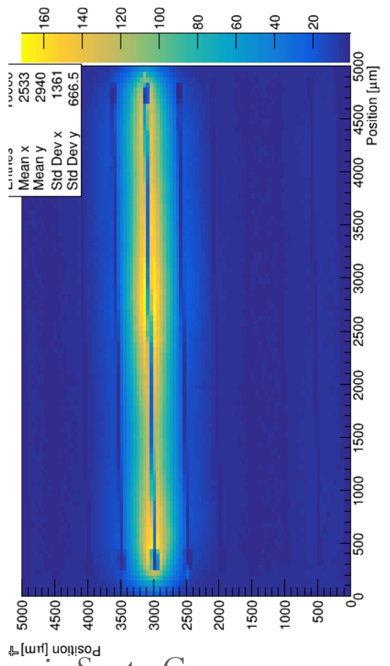
W3074 “narrow”

- 500um pitch, 20 um sensors
  - 1cm length, 50um width strips
  - 0.5cm length, 50um width strips
- Gain dis-homogeneity observed, extreme gain for 1cm sensor >105V
- Charge sharing larger with longer strips (as expected), in general up to second neighbor

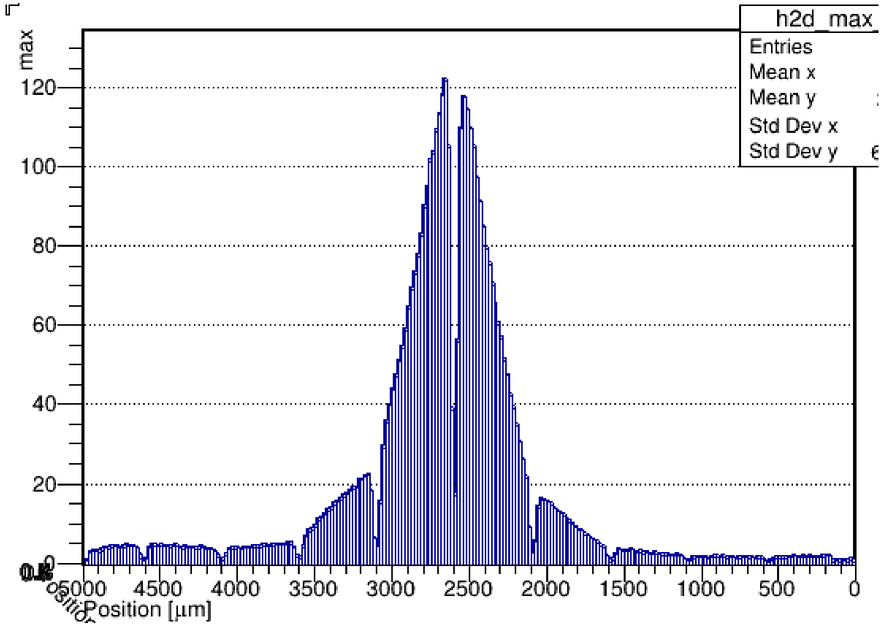


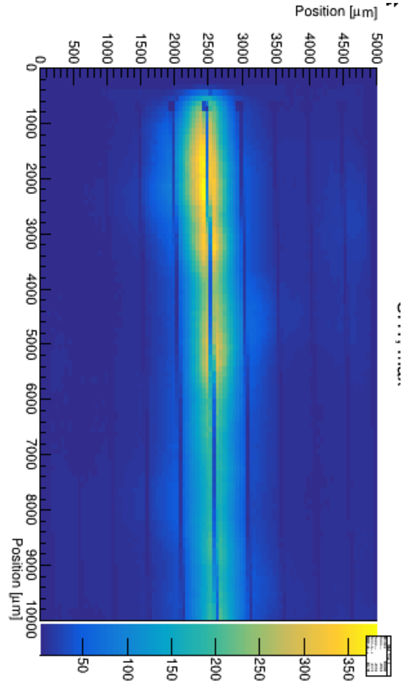
0.5 cm





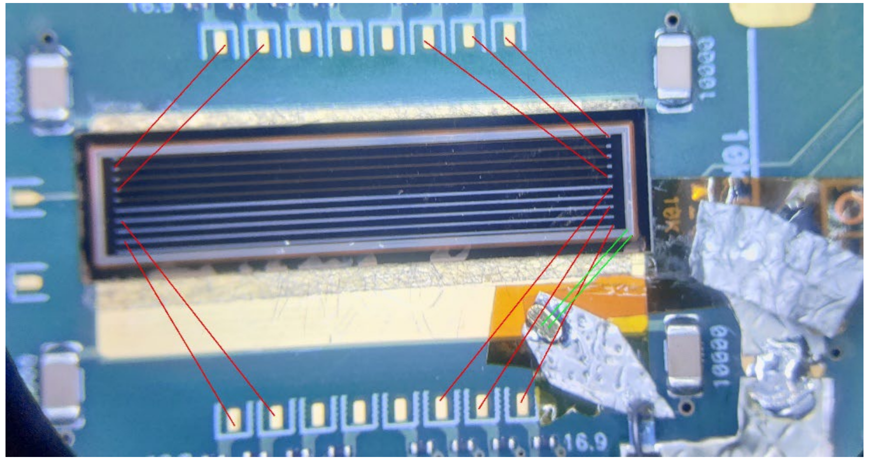
1 cm

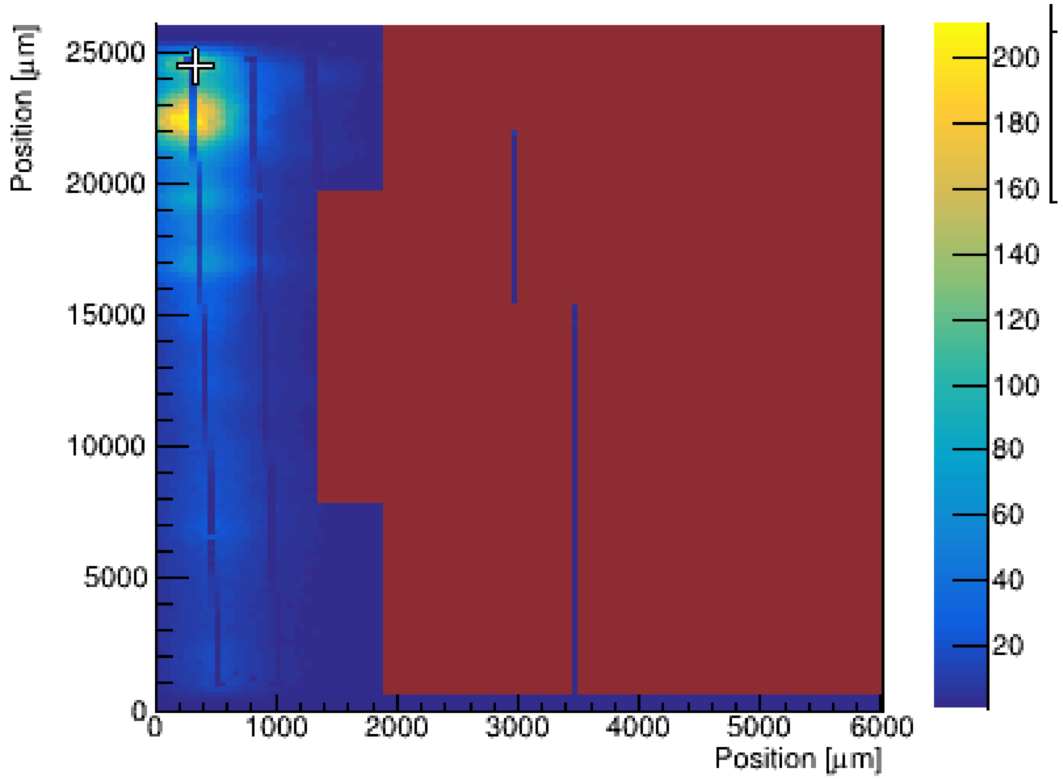


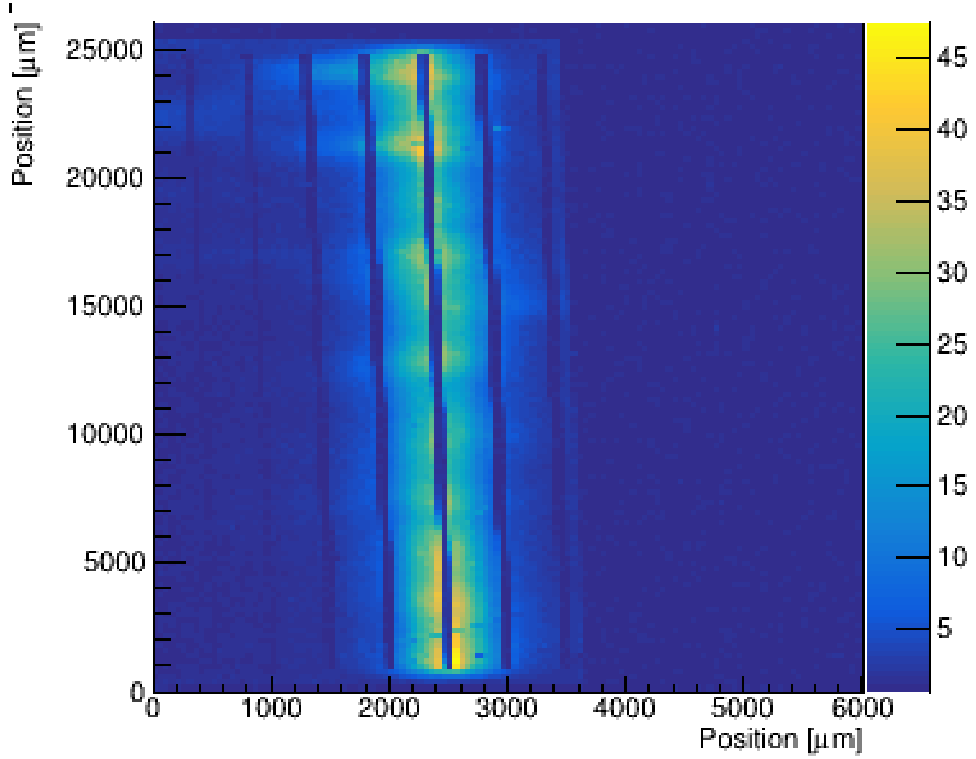


W3074 "long"

- 2.5cm, 500um pitch, 50 um sensors
  - 100um and 200um width
- Good gain
- Large gain dis-homogeneity observed

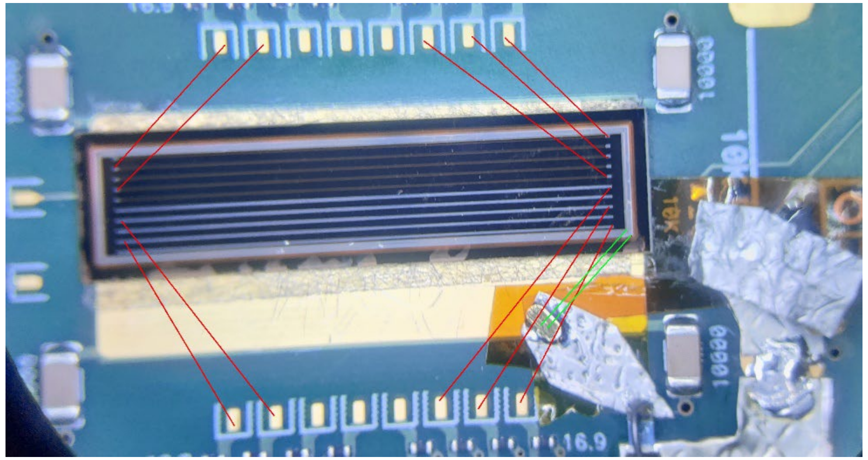


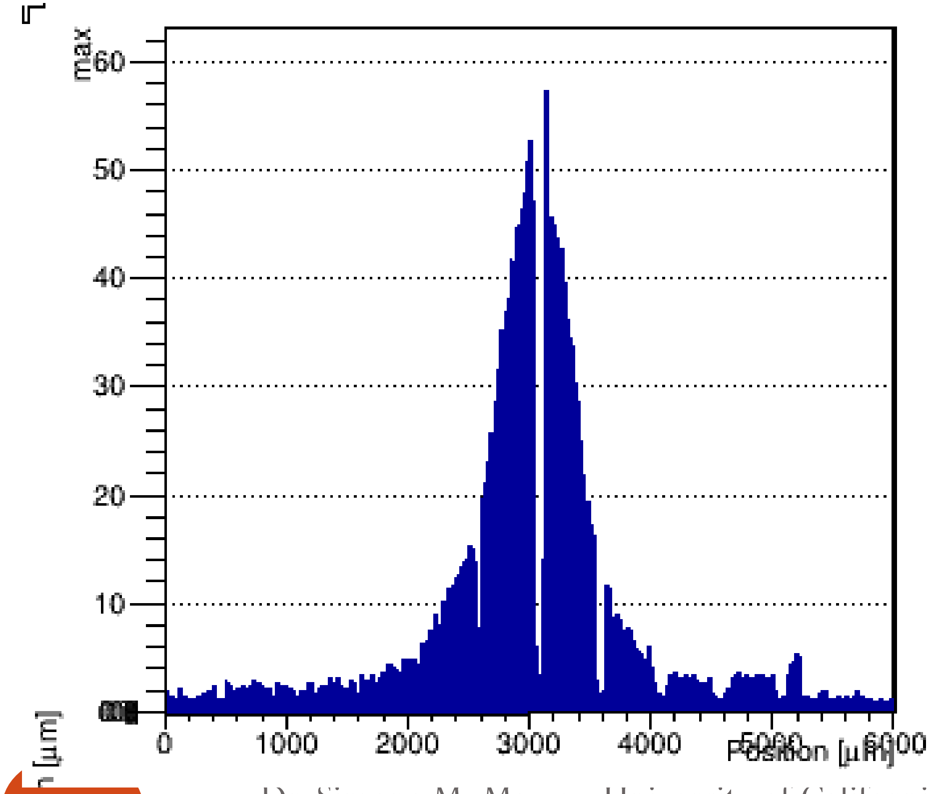


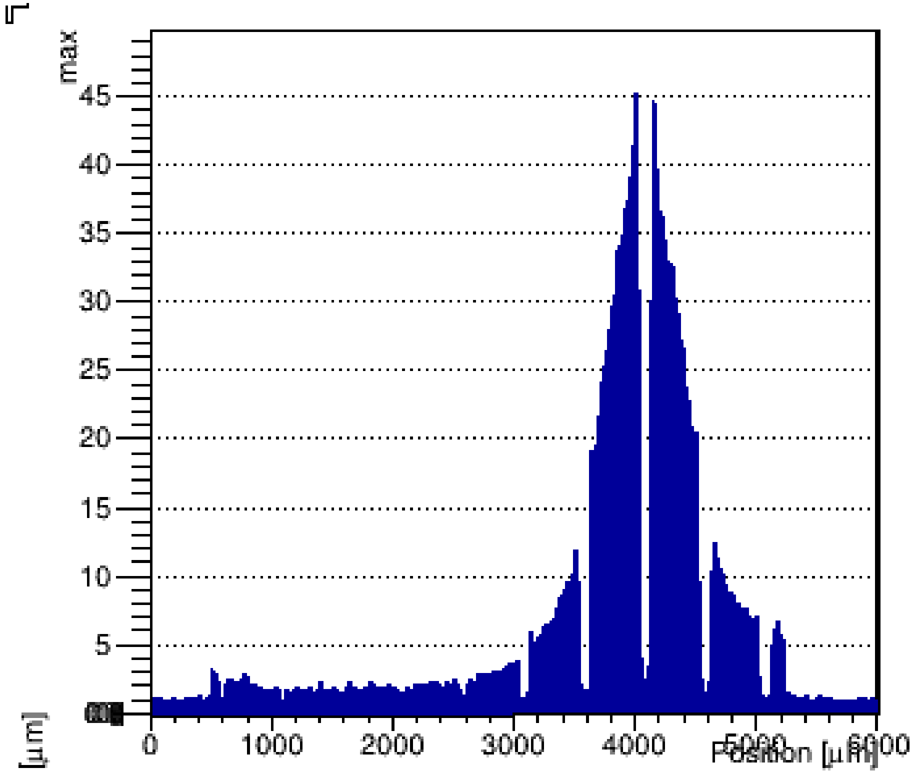


W3074 long

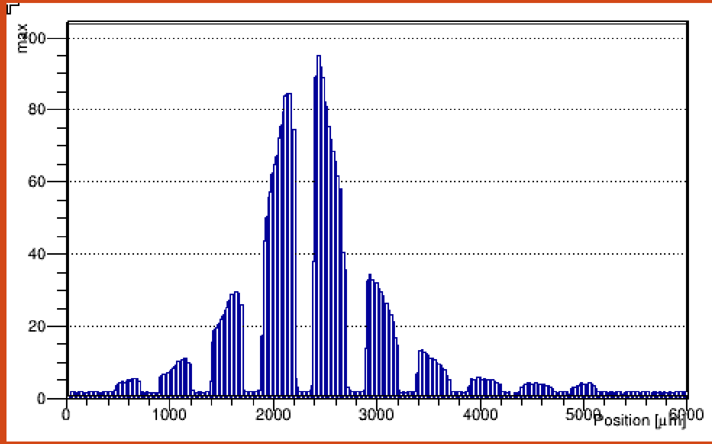
- 2.5cm, 500um pitch, 50 um sensors
  - 100um and 200um width
- Charge sharing up to second neighbor
  - Compared to 50um device the charge sharing profile is less
  - Expected: charge sharing is higher for thicker sensors from TCAD







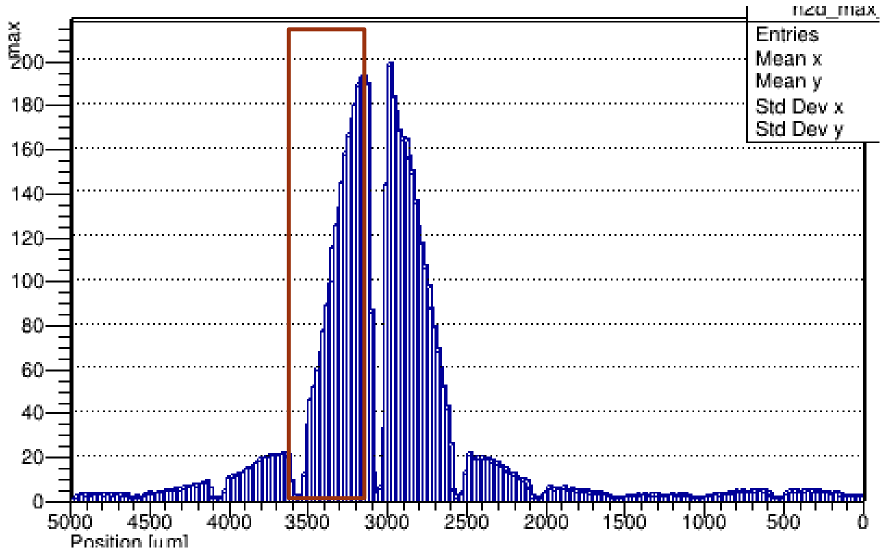
2.5cm, 50um, 500um pitch



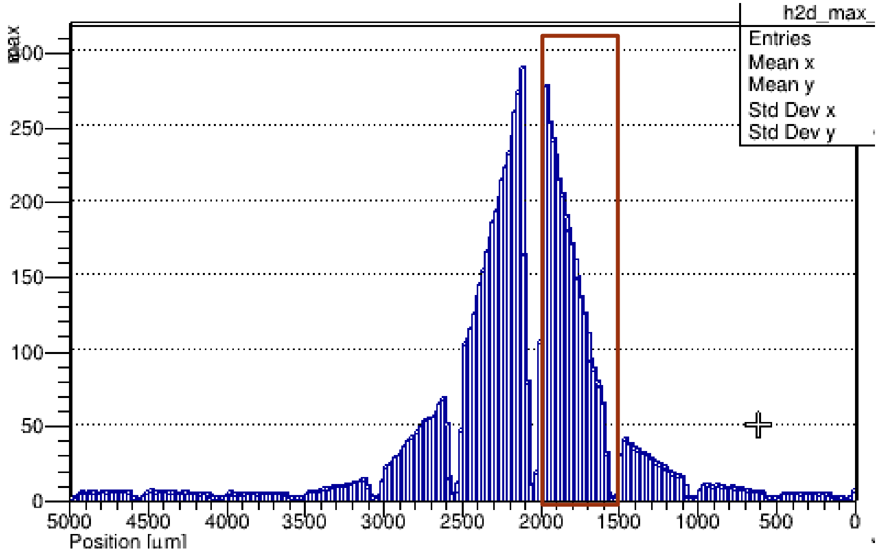
Charge sharing comparison

- Measure charge sharing as signal at the outside edge of first neighbor over the signal at the edge of the readout strip
- Example W3074: 500um pitch, 100um width (Charge sharing after fist neighbor %)

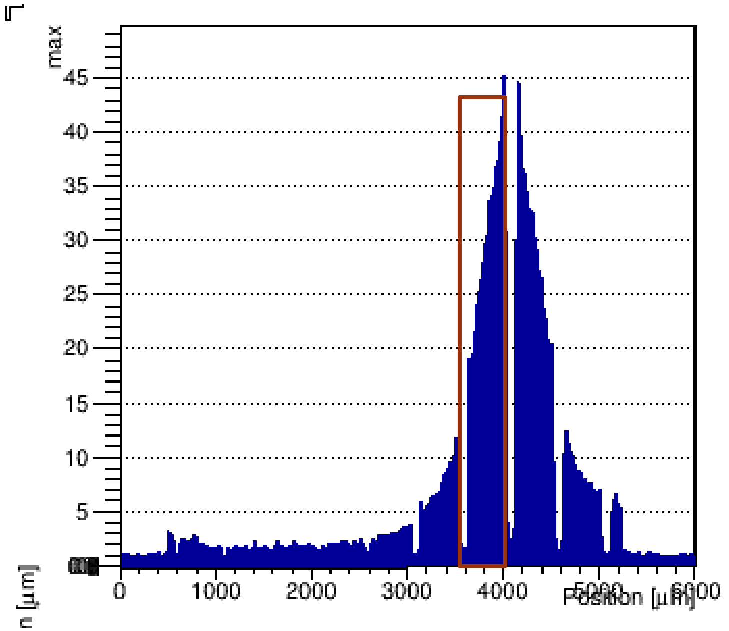
0.5 cm (10.5%)



1cm (15%)

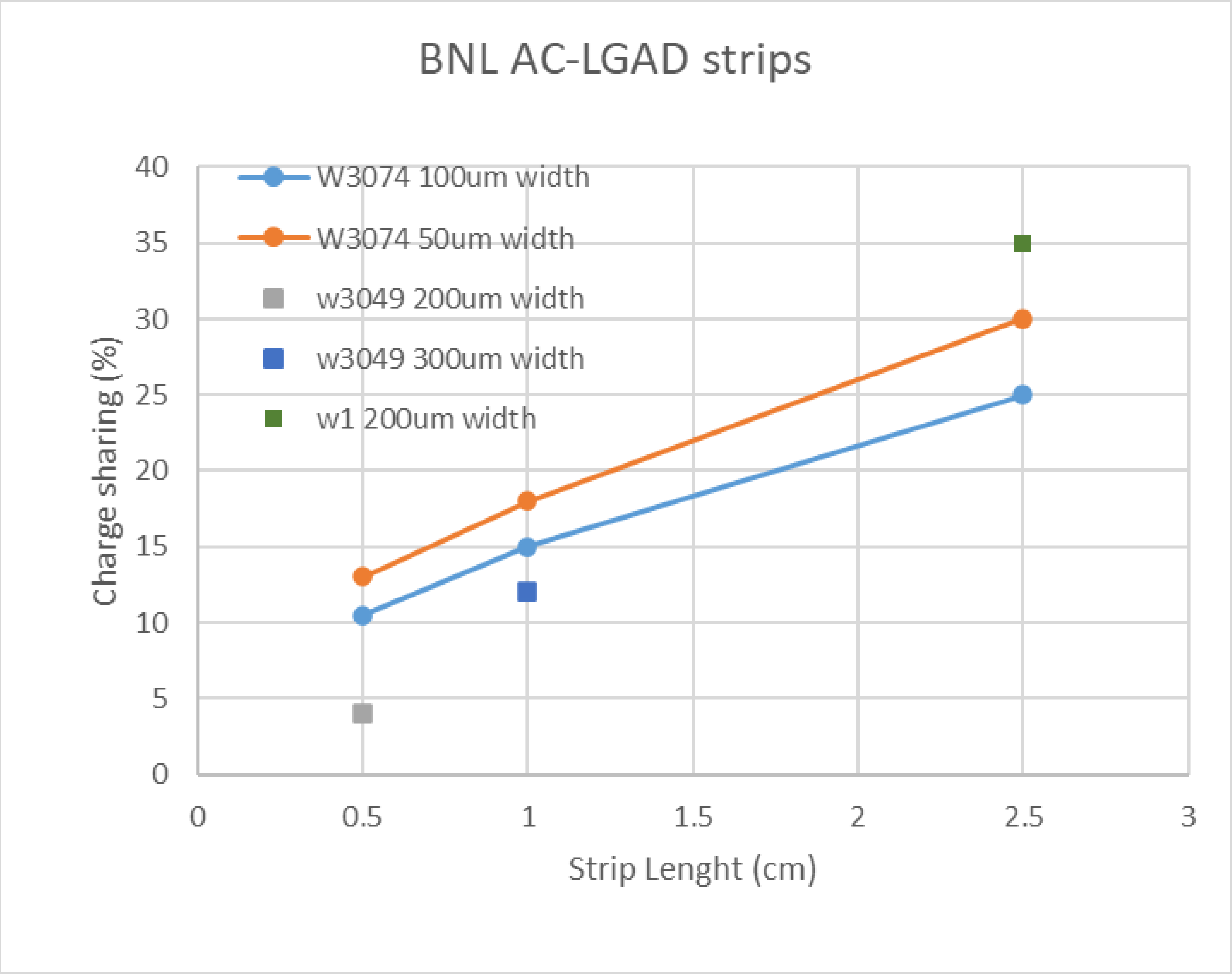


2.5cm (25%)



Charge sharing comparison

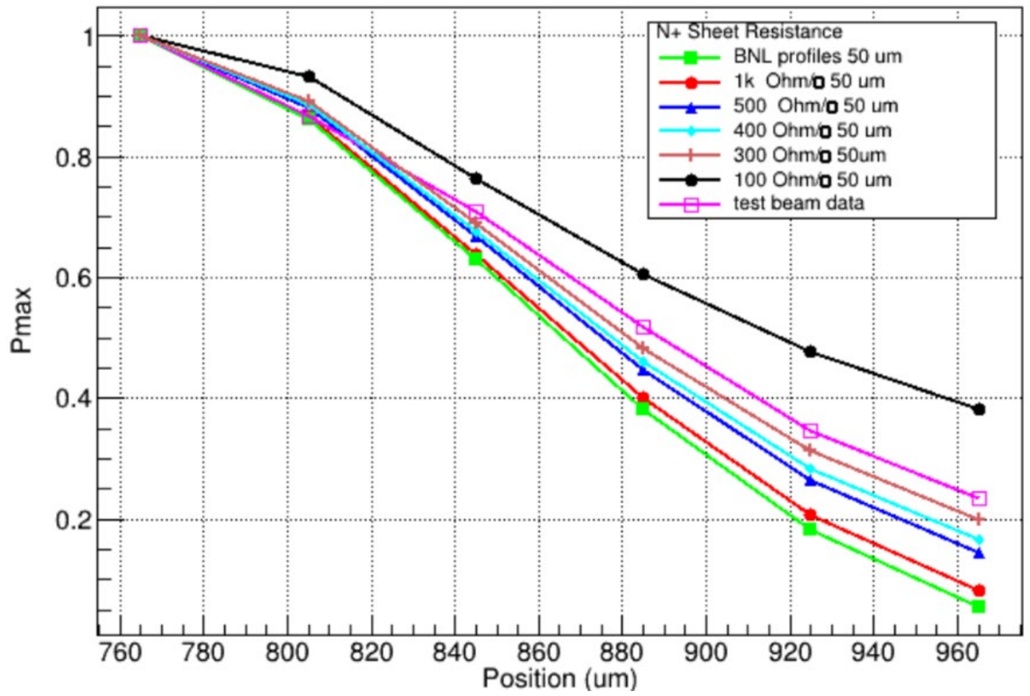
- Charge sharing % after second neighbor for different sensors width and width but same pitch (500um)
- Some preliminary conclusions
  - With larger strips the charge sharing is less
  - Charge sharing increases with strip length
  - Thicker sensors (W3049) increase charge sharing
- **Plots to be refined and completed!**
  - Work on the same plot for time/position resolution and rise/fall time

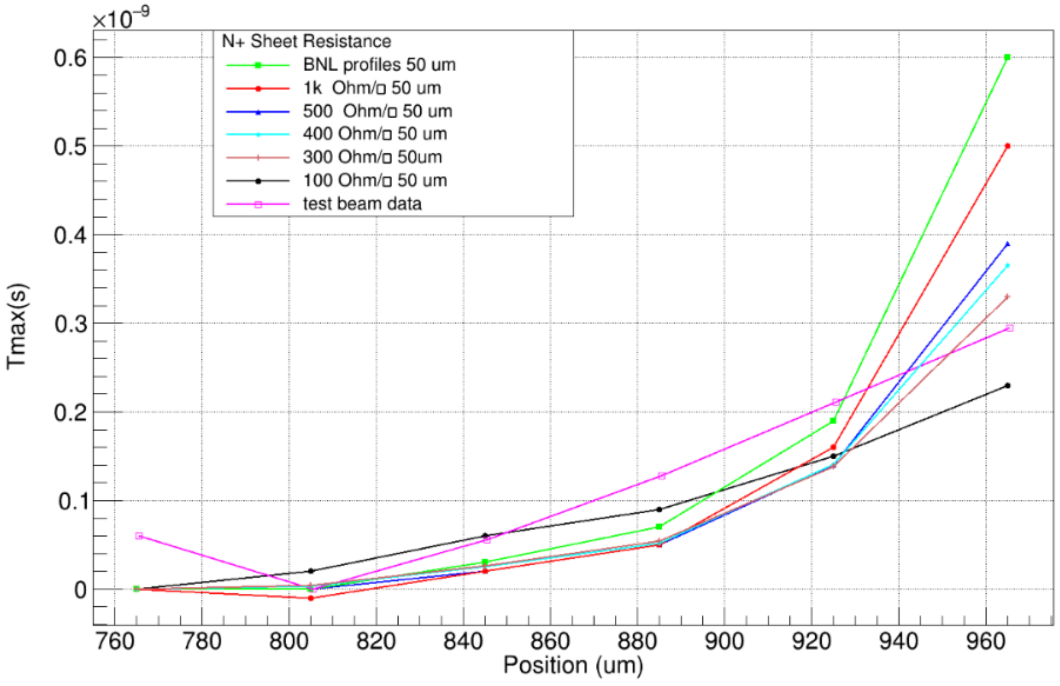


TCAD simulation

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

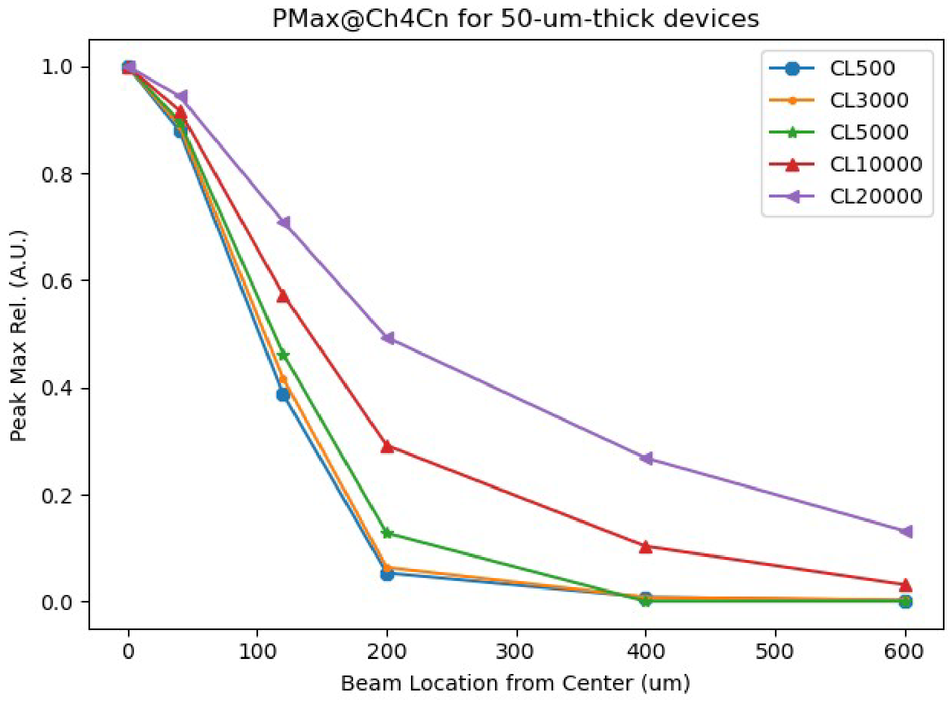
AC-LGAD device simulation

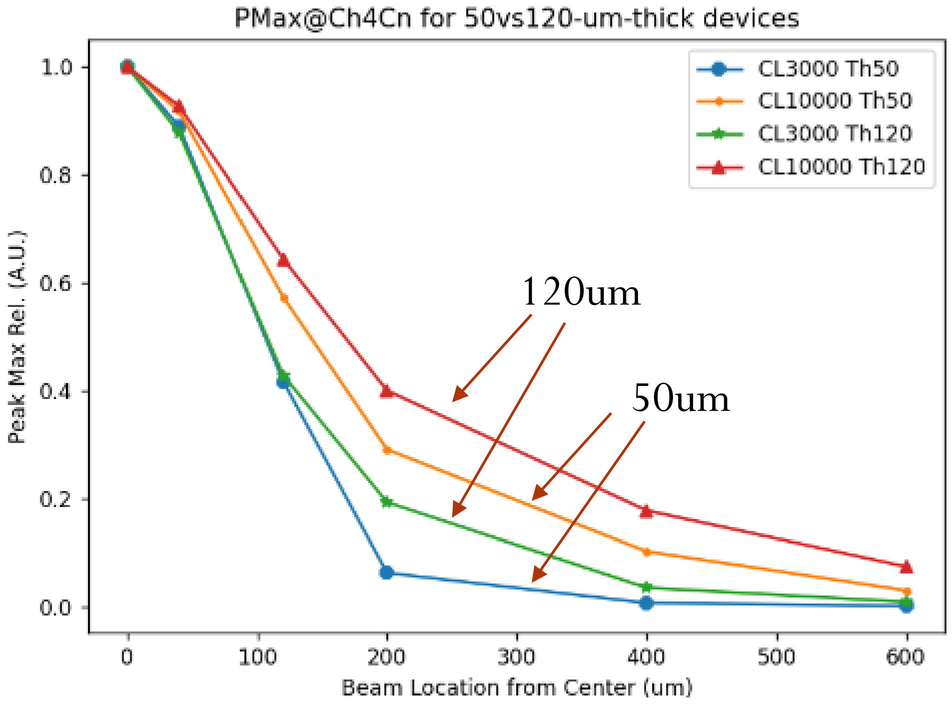
- Investigate strip geometry (pitch, length, width) effect on charge sharing
  - **As seen in the data longer strip increase the charge sharing**
  - Effect start to be significant at 1cm of length for this geometry

- 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
  - (120um because of PIONEER, will try 20um)

- For most simulations TCAD in 3D mode is necessary to have realistic results
  - (2D approximation is not enough)
- **Paper being prepared on AC strips TCAD simulations**

TCAD Sentaurus
50um thickness
different strip lengths





TCAD Sentaurus
different thicknesses
Different strip lengths

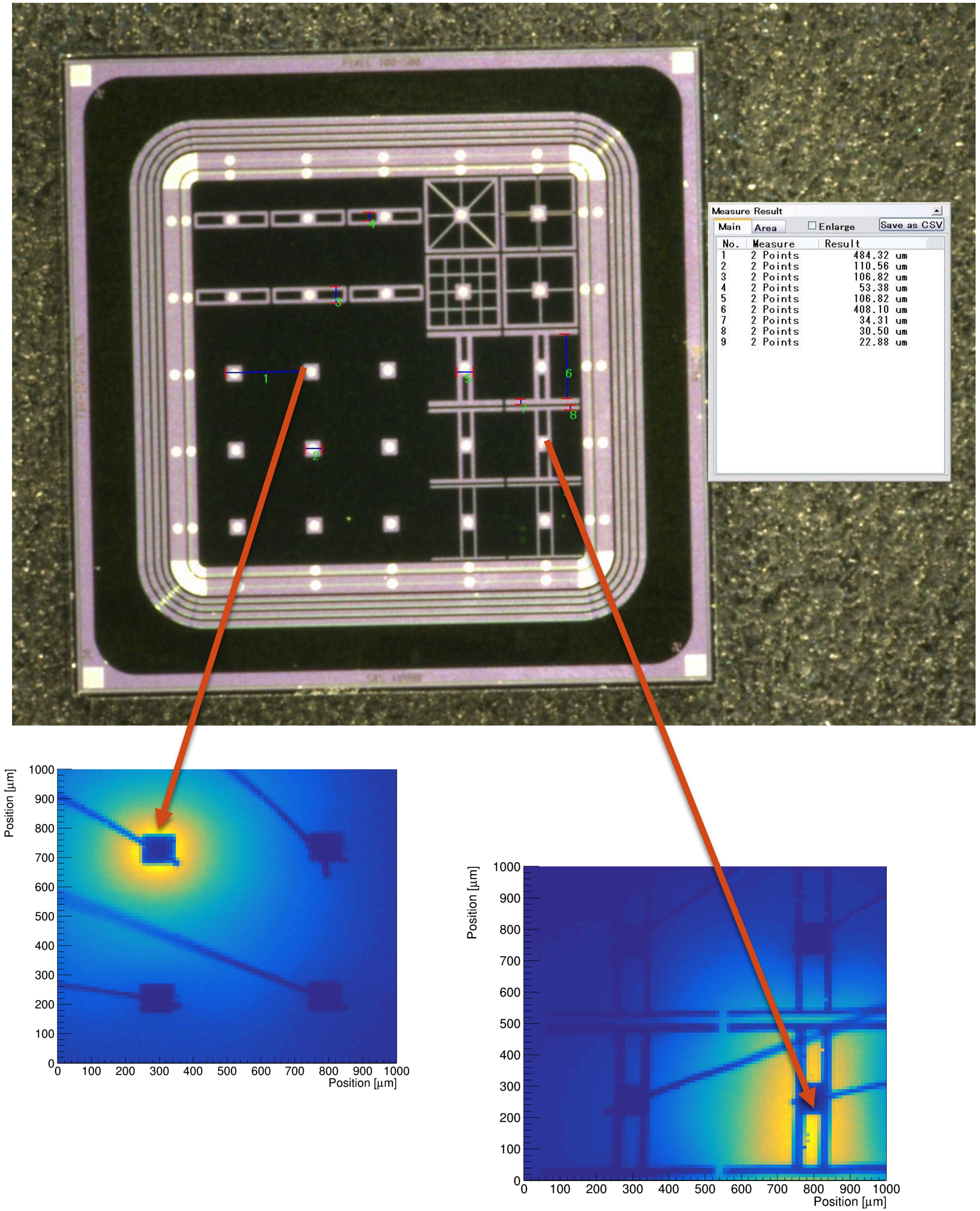
Data by: T. Shin

FBK RSD pads

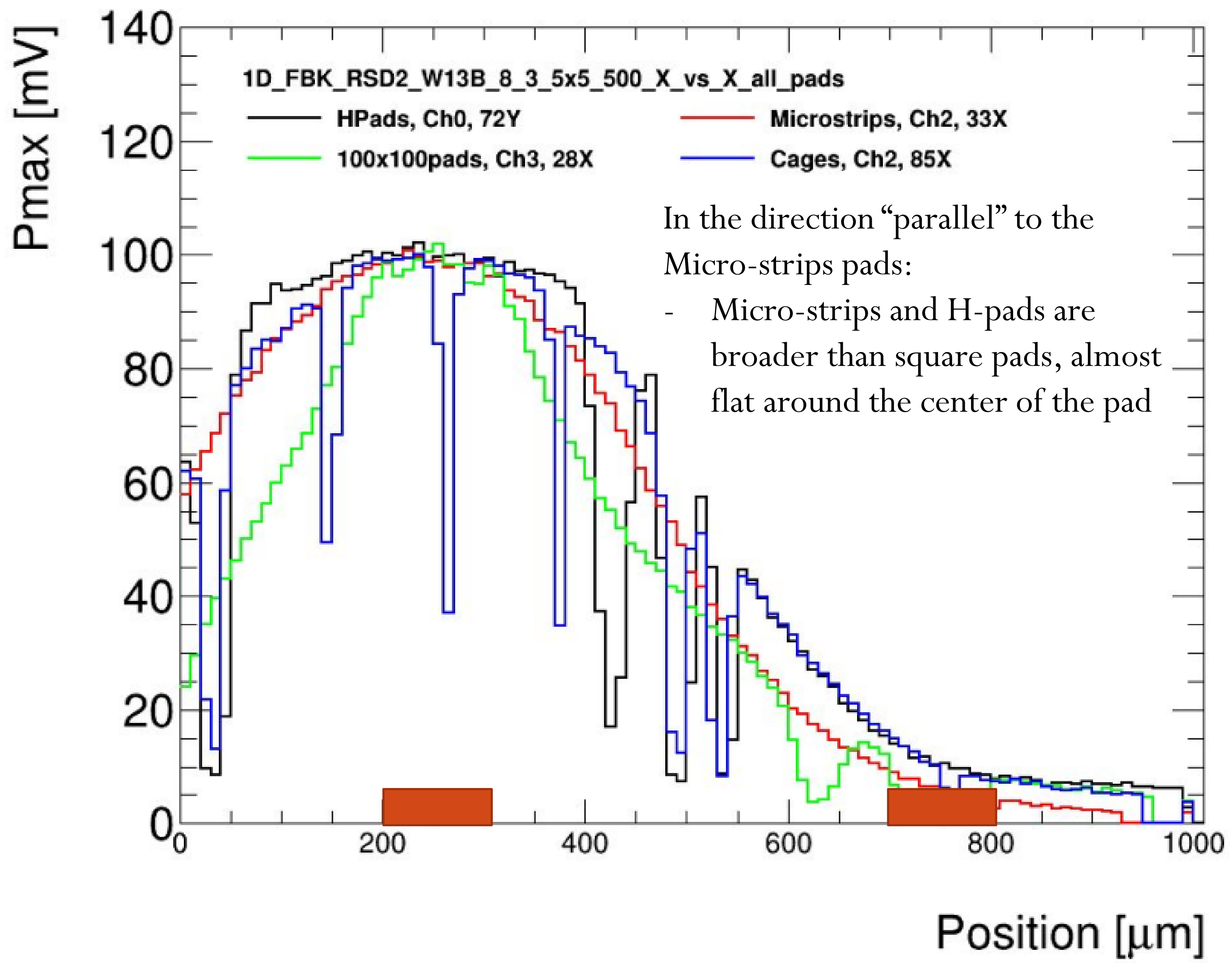
See: https://indico.cern.ch/event/1157463/contributions/4922739/

AC-LGAD geometry - pads

- With AC metal it is possible to create non conventional geometries
  - Simple metal pattern on top, no underlying structures
  - **Allowing to optimize sensor metal shape for the specific application**
- Studies done on a **AC-LGADs** from FBK RSD2 production
  - Pad sensor featuring non conventional geometries, pitch of 500µm
  - FBK RSD2 W13B 8-3 5X5 500 µm
  - Geometries: 100x100um pads, microstrips, H-pads, cages. All have a 100x100um “core” for wire bonding.
- **We also have “cross” sensors, ready to be tested**

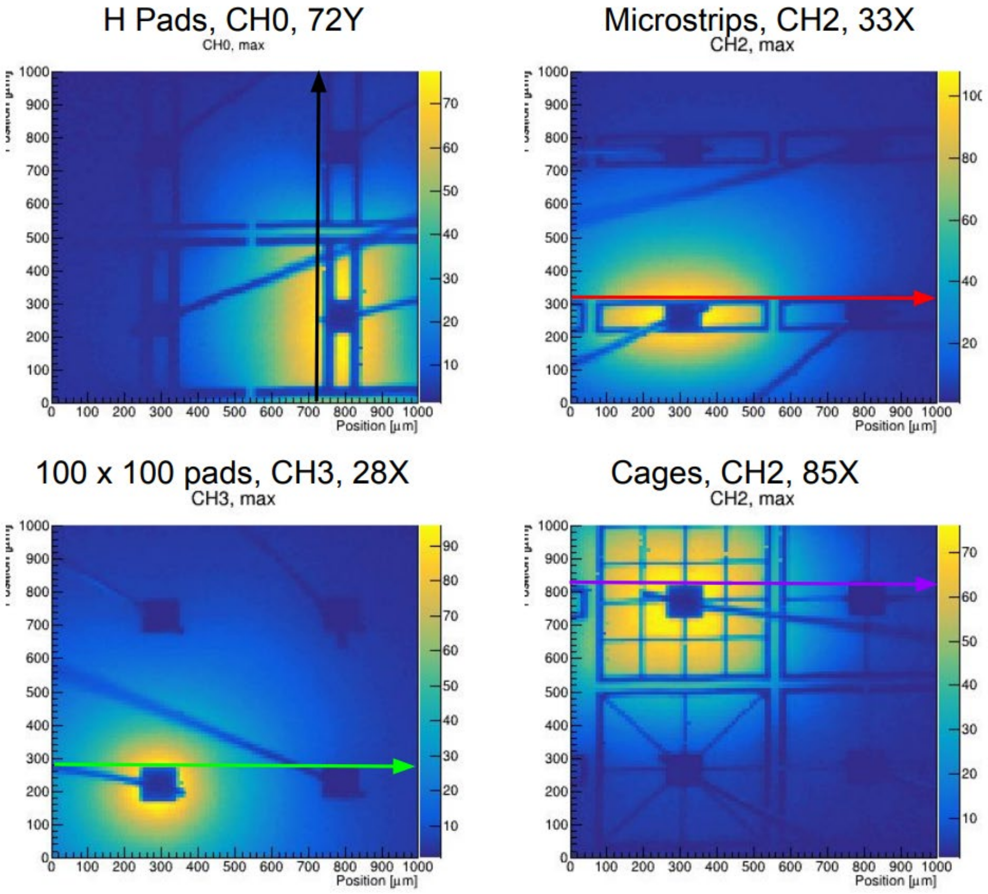


Comparison of 1D profiles, all pads - X

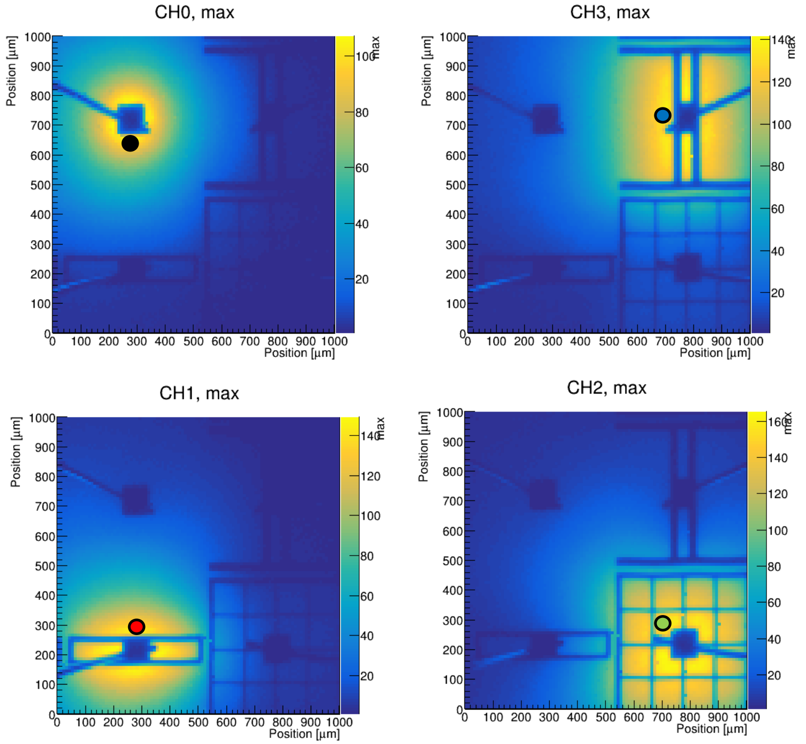


In the direction "parallel" to the Micro-strips pads:

- Micro-strips and H-pads are broader than square pads, almost flat around the center of the pad



Signal from all types of pads

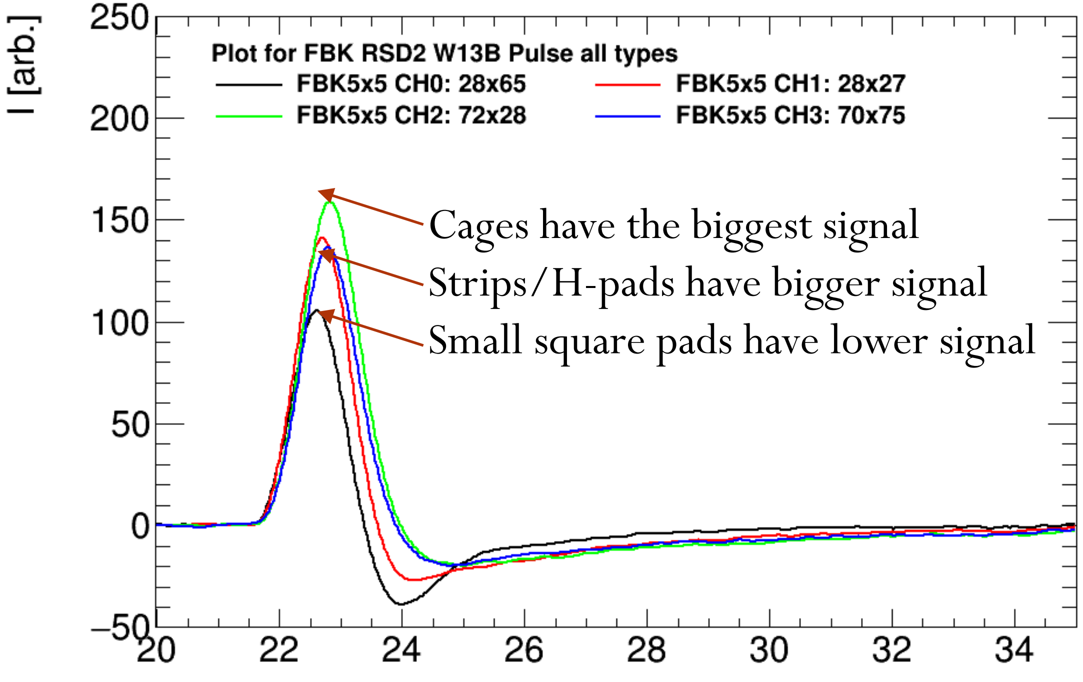


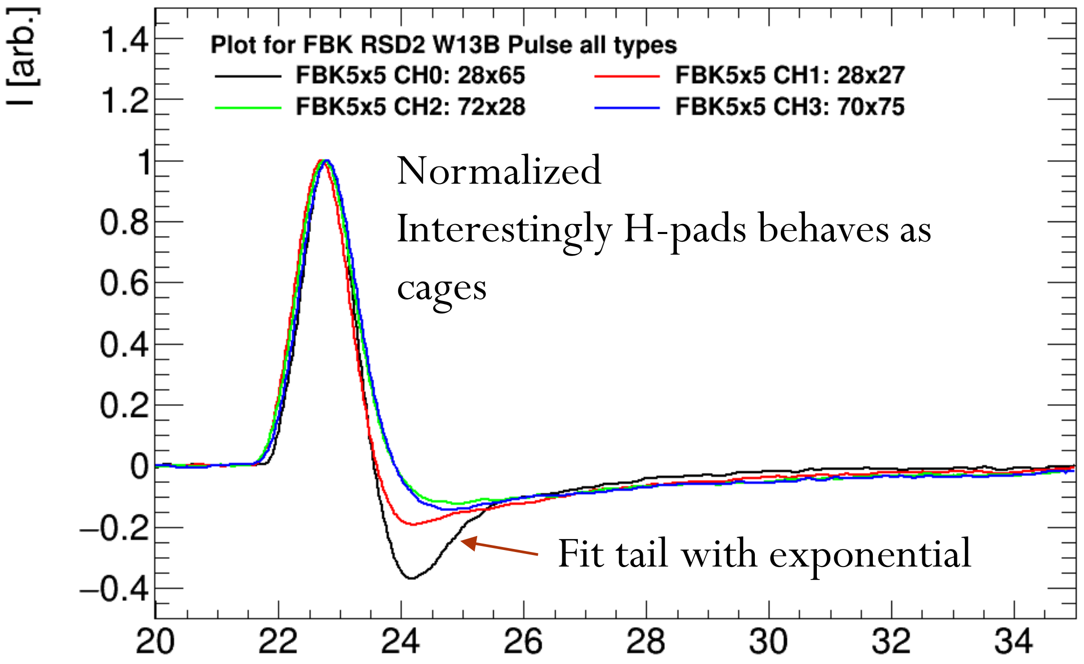
Positive pole of the signal is the same for all pad types

However they have different RC constant and return to baseline

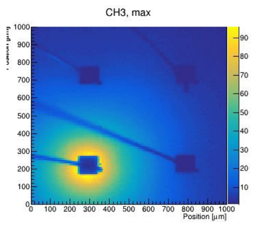
Unclear why it doesn't scale directly with the capacitance of the pad

Pad type	Exponential RC constant	Capacitance
Square pads	0.61	94 fF
Micro-strips	0.28	299 fF
H-pads	0.19	639 fF
Cage	0.19	801 fF

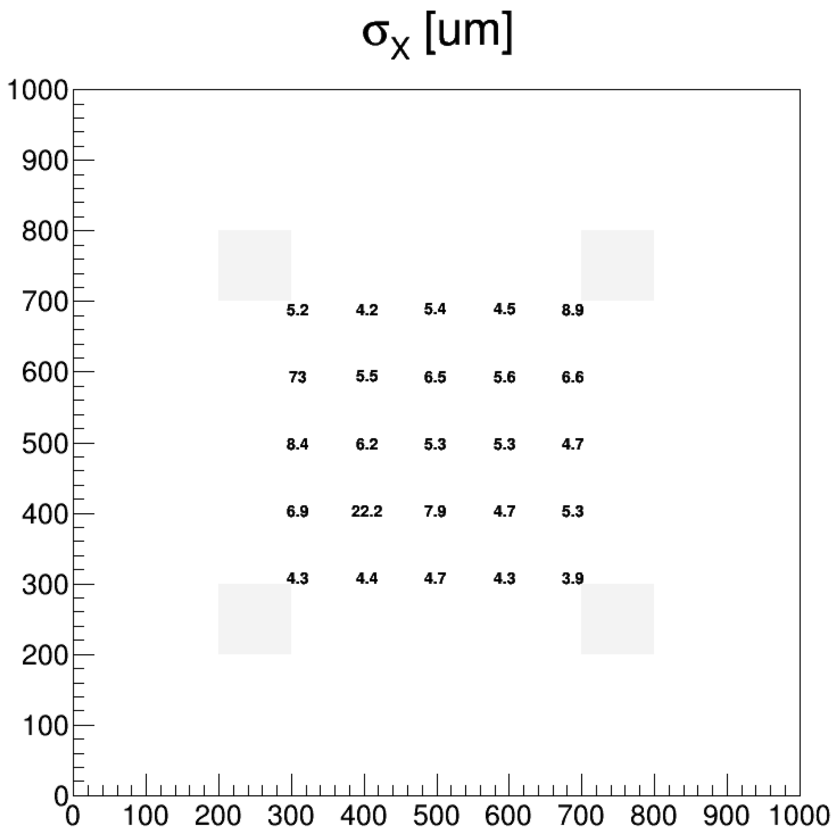


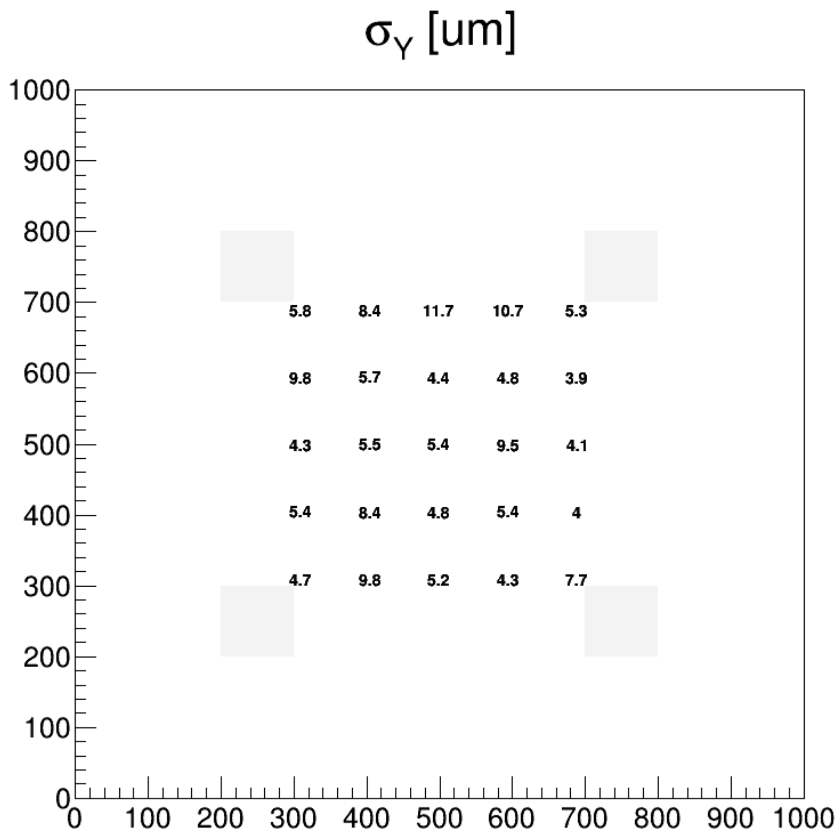


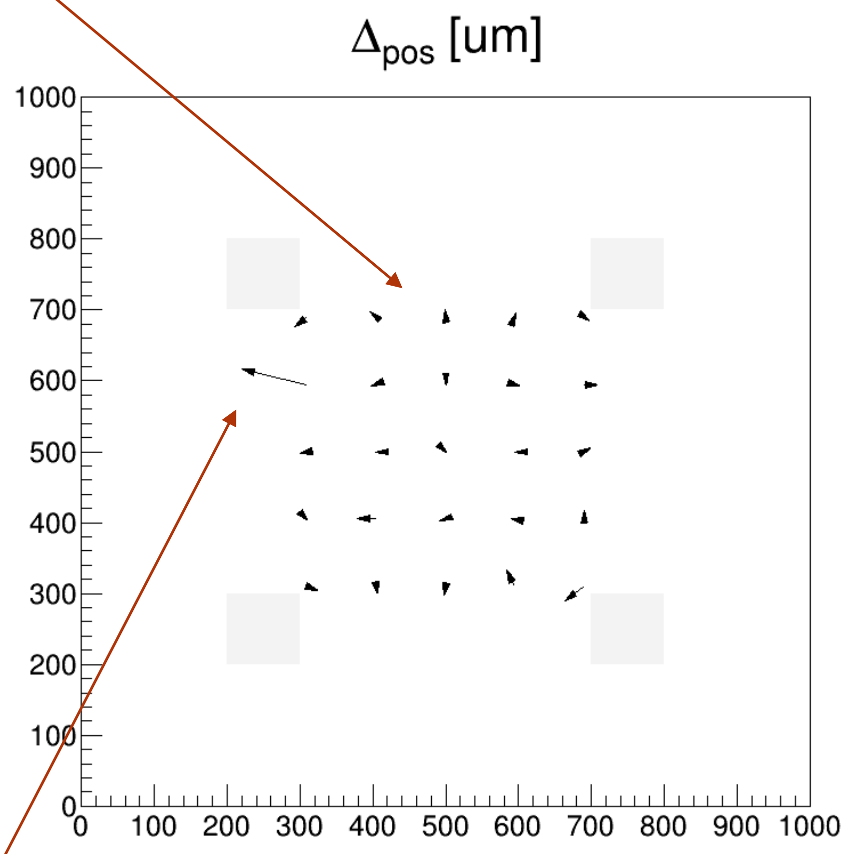
Reconstructed position resolution – small pads



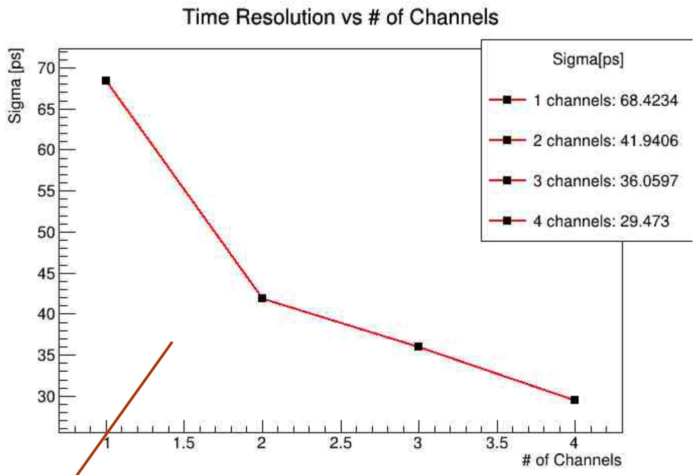
No characteristic 'pincushion' shape since reference is taken from the sensor itself



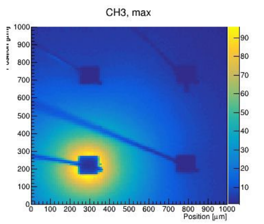




However at the edges the reconstruction can fail!

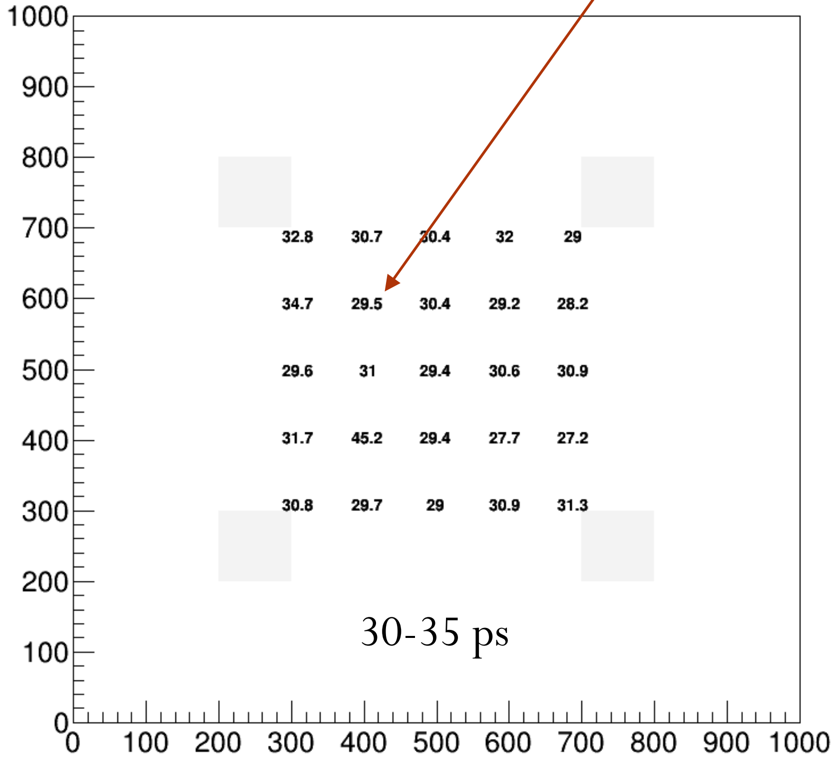


Jitter – small pads



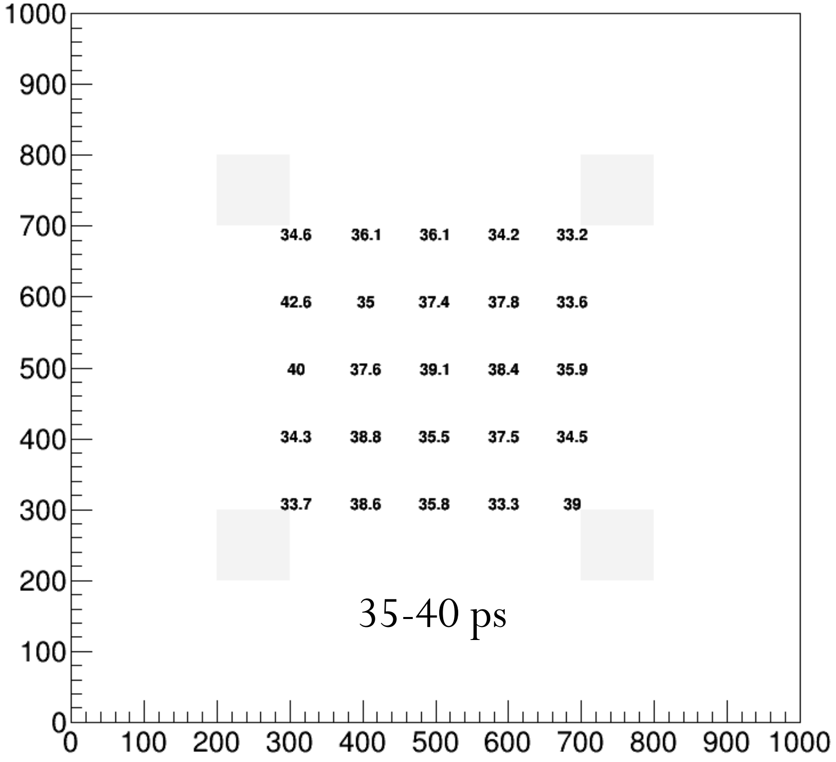
250V

σ_T [ps]



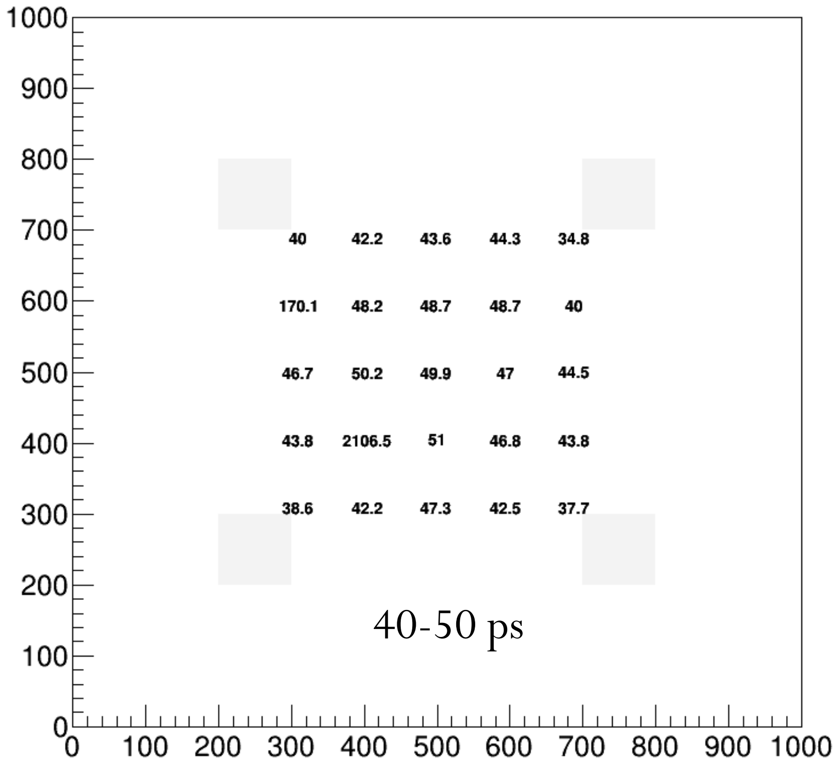
200V

σ_T [ps]



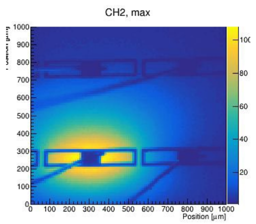
150V

σ_T [ps]

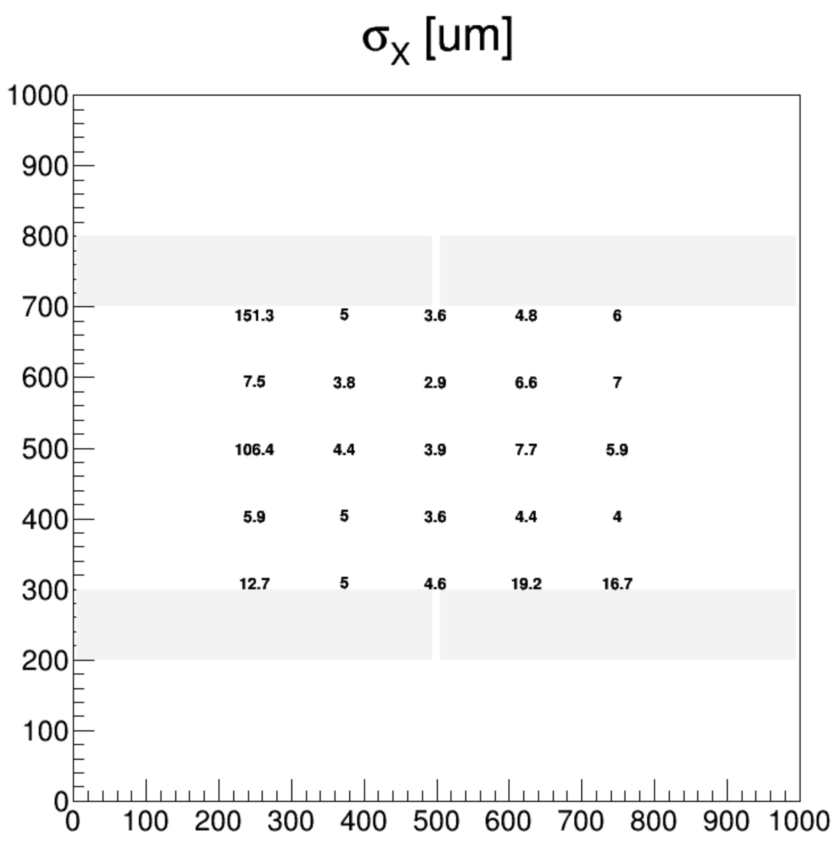


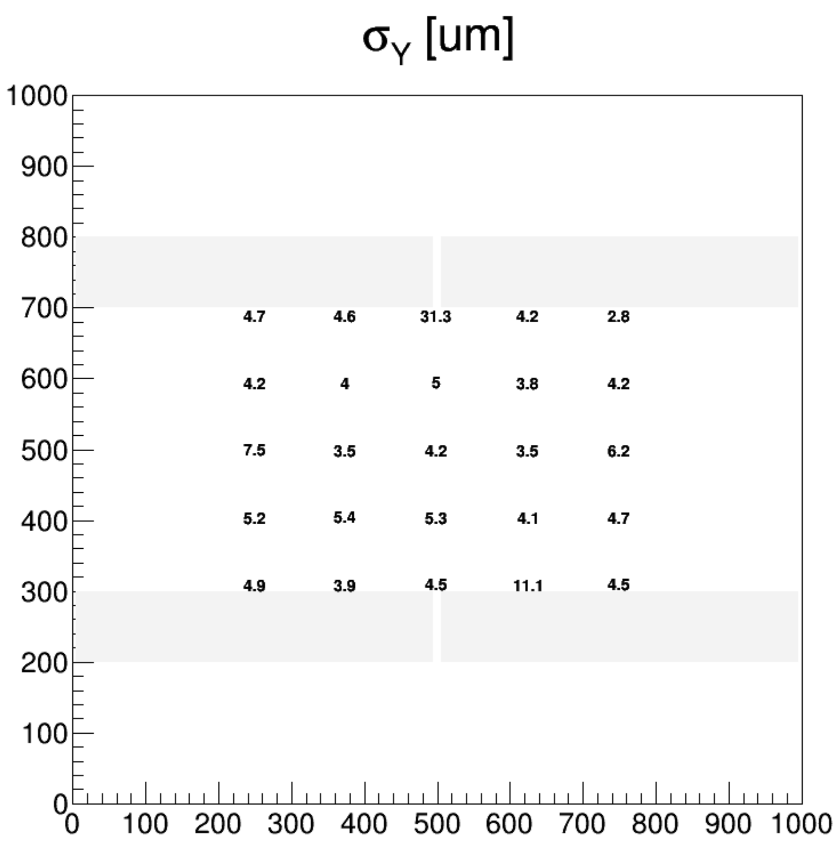
Jitter using the 4 channel combination is fairly constant in the region in between pads

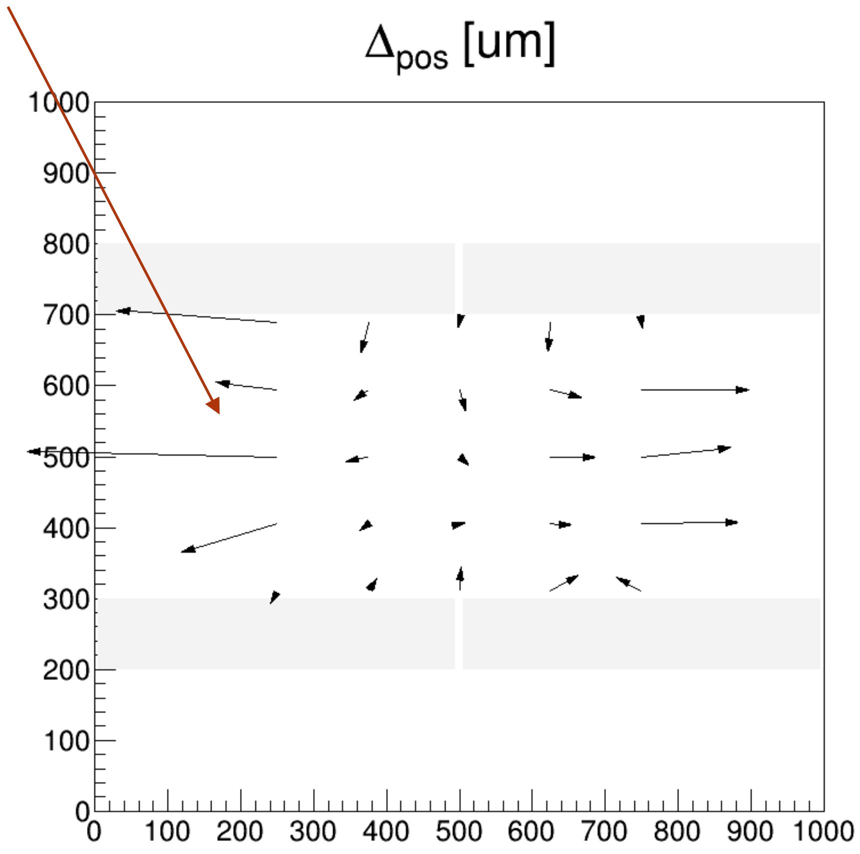
Reconstructed position resolution – microstrips



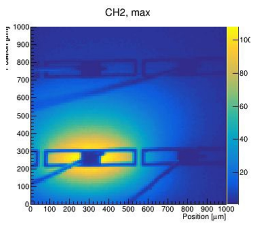
As expected better reconstruction in Y than in X, especially at the edges



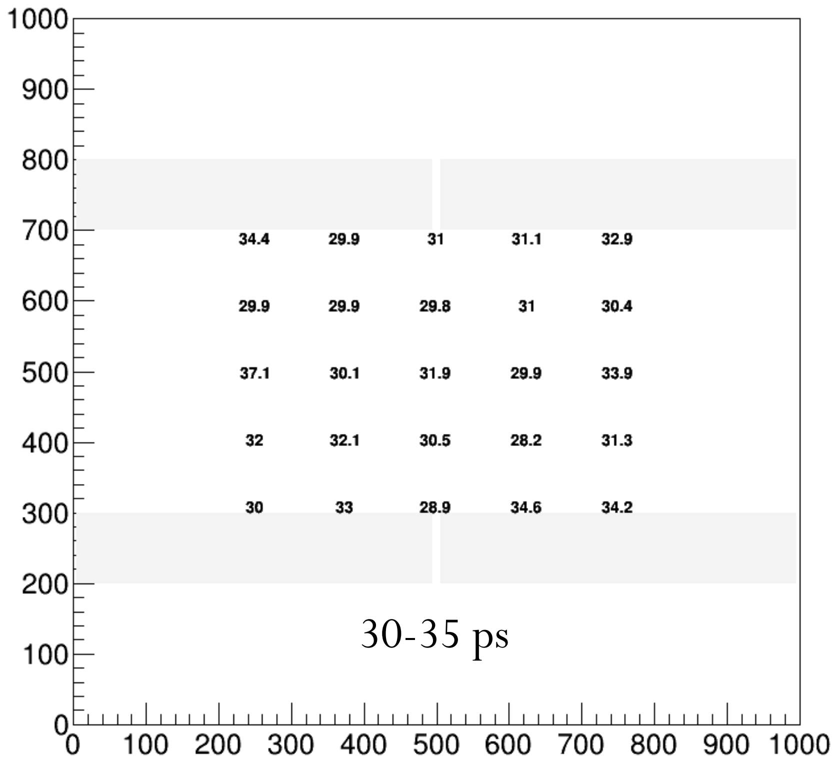




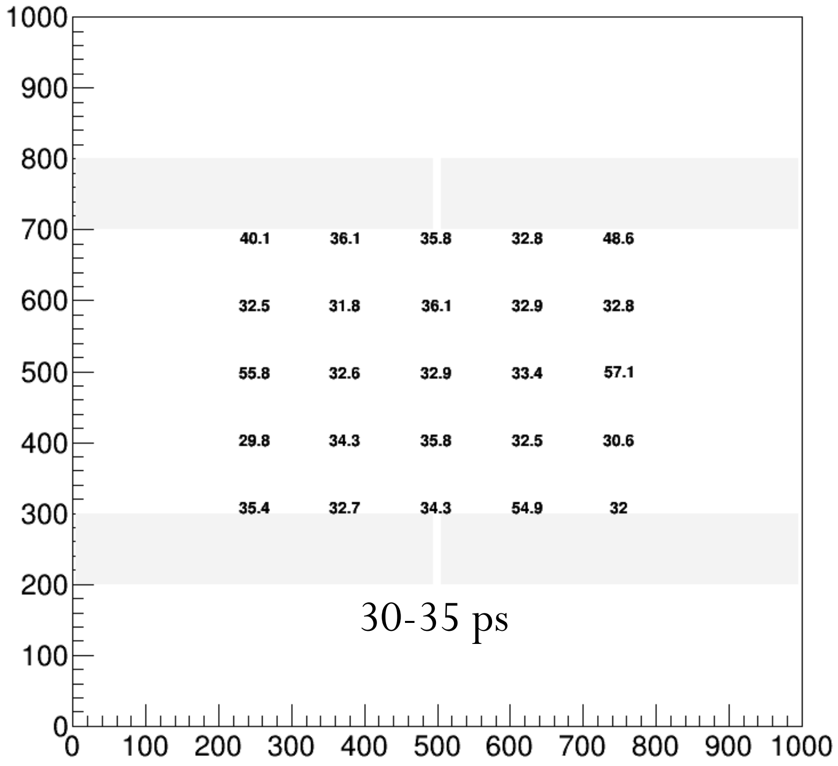
Jitter – microstrips



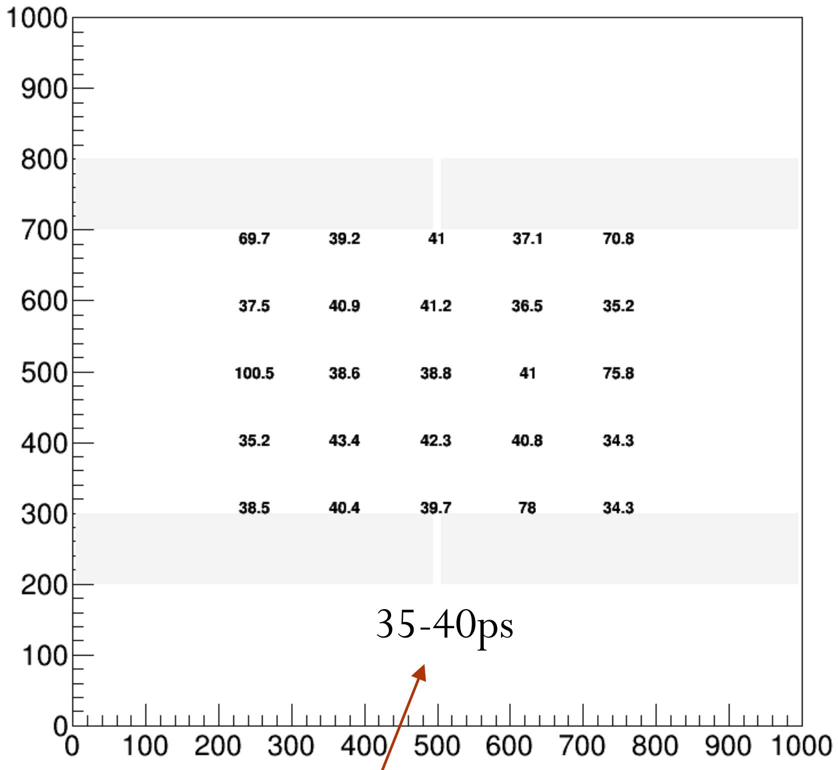
250V



200V



150V

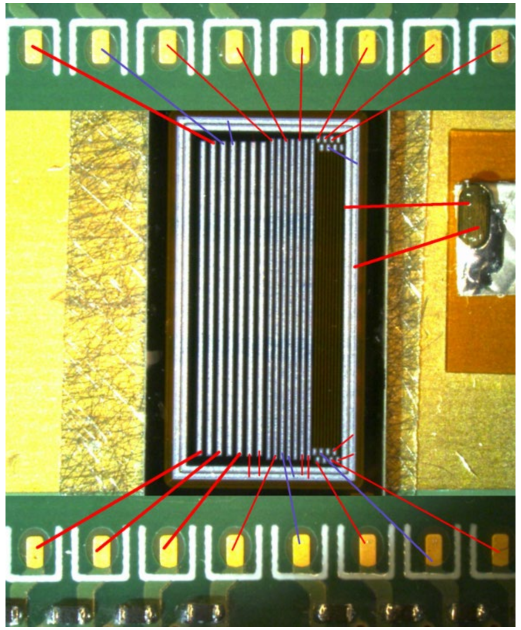


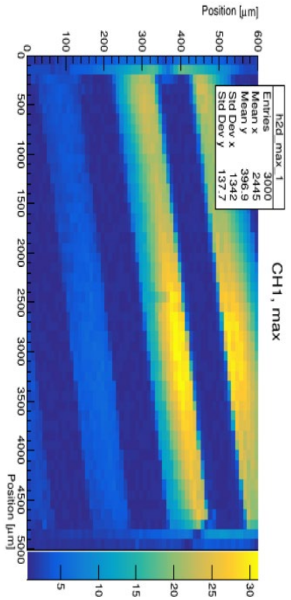
Better time resolution than with pads, related to higher S/N

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**
- **Charge sharing depends on many parameters**
  - N+ resistivity, strip geometry, strip length, sensor thickness
  - Behavior observed in prototypes and simulated with TCAD software

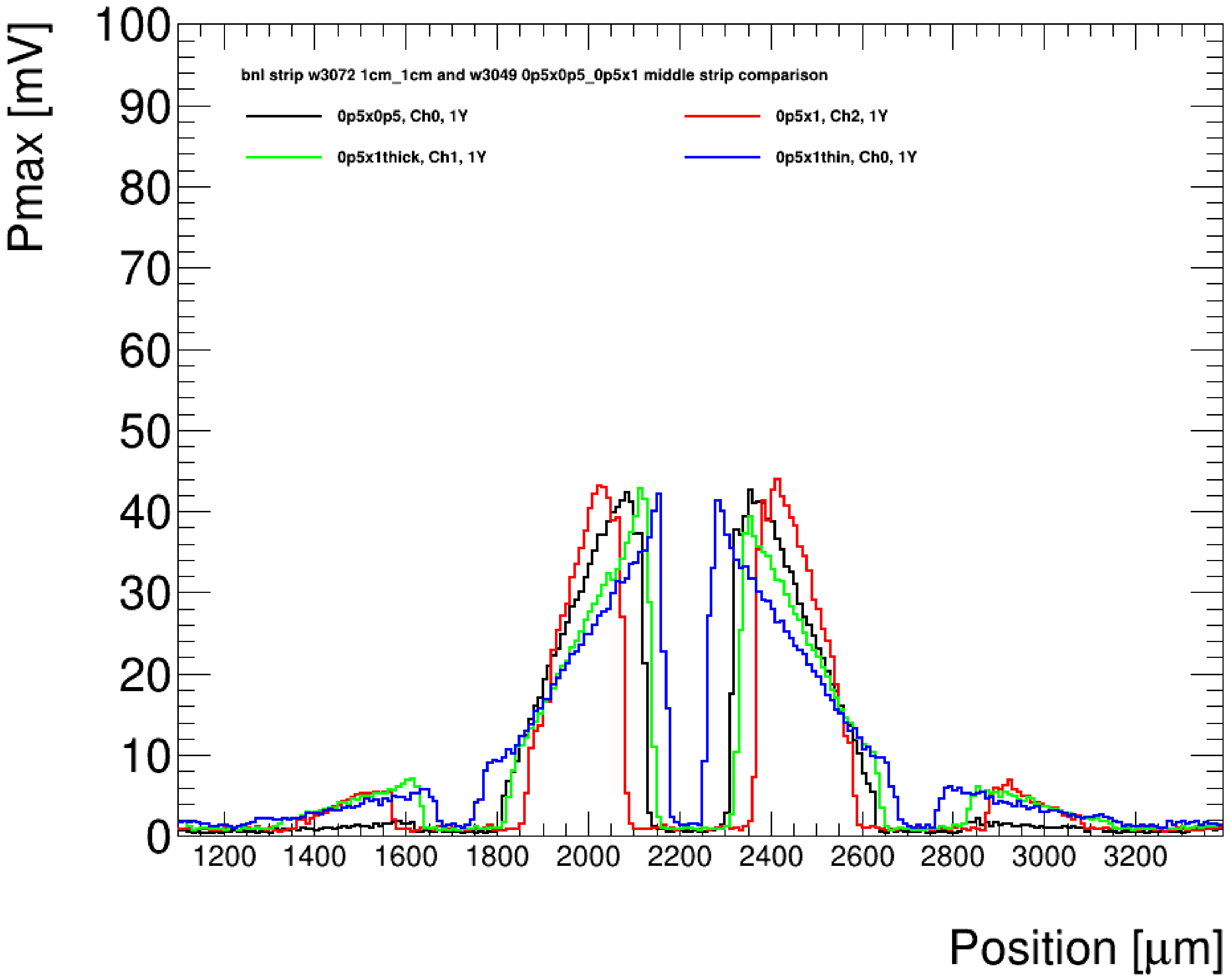
- Testing of further devices ongoing
  - Help in painting a complete picture
  - TCAD simulation advancing at the same pace
  - Prototype with good gain homogeneity and no issues with current and breakdown soon
- Great input for MC simulation and detector design of EPIC!
- **We're interested in testing some of the new sensors from HPK**





Backup

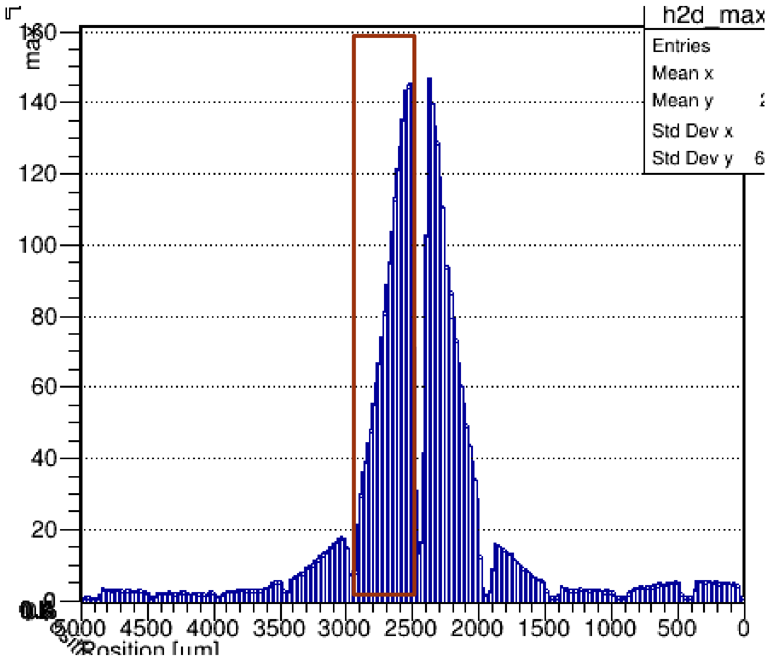
W3072 vs w3049



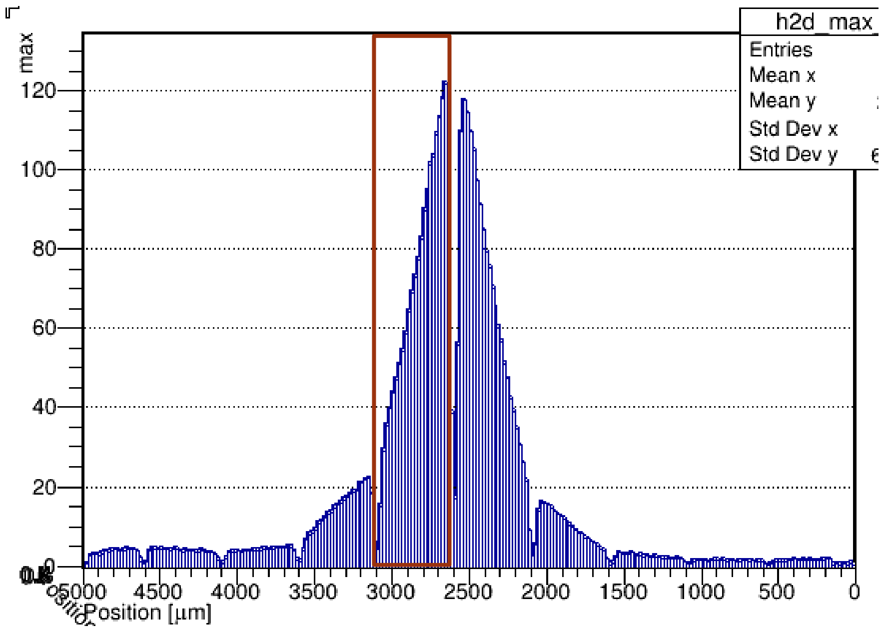
W3074 comparison

- 500um pitch, 50um width (Charge sharing after fist neighbor %)

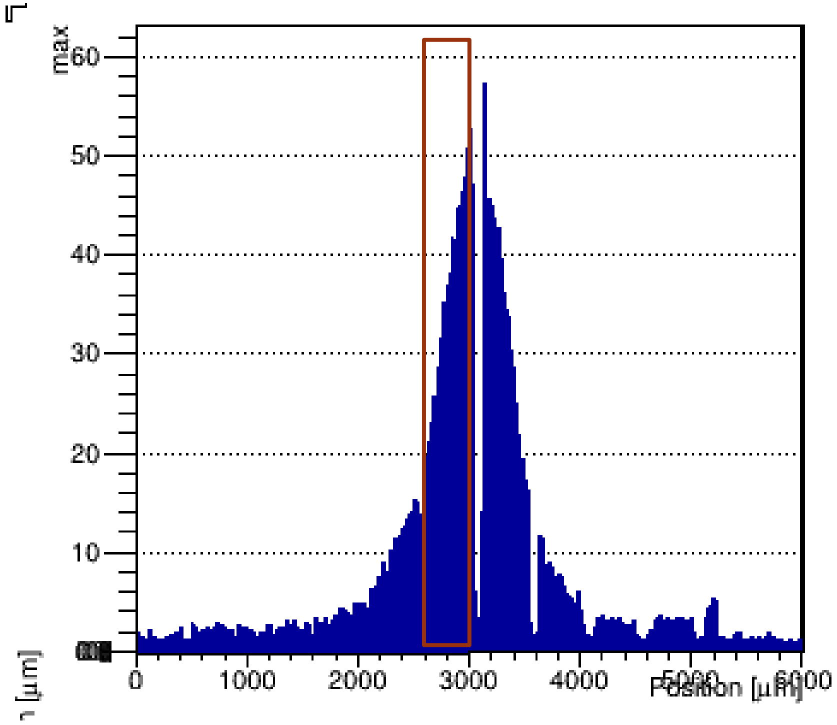
0.5 cm (13%)



1cm (18%)

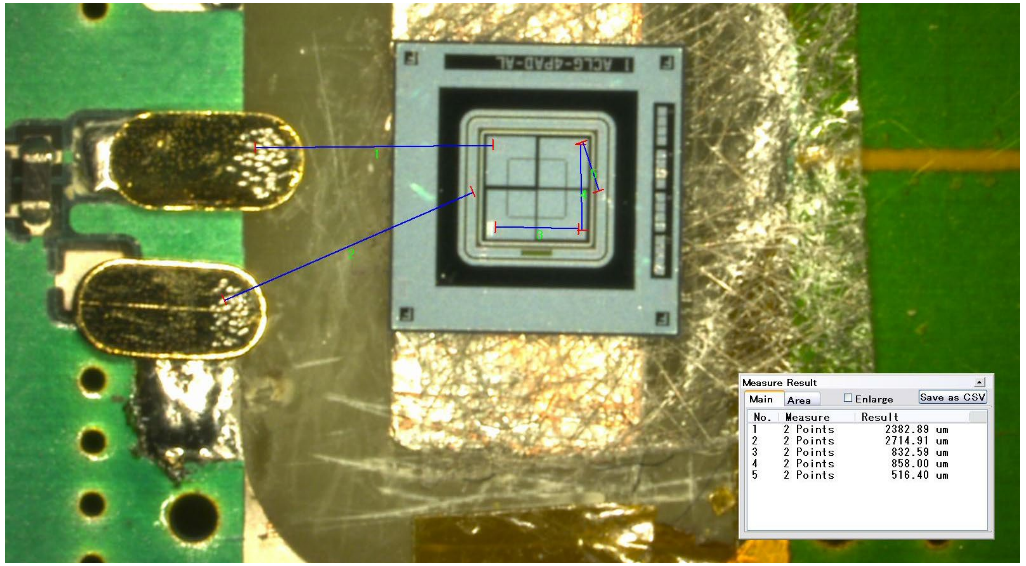


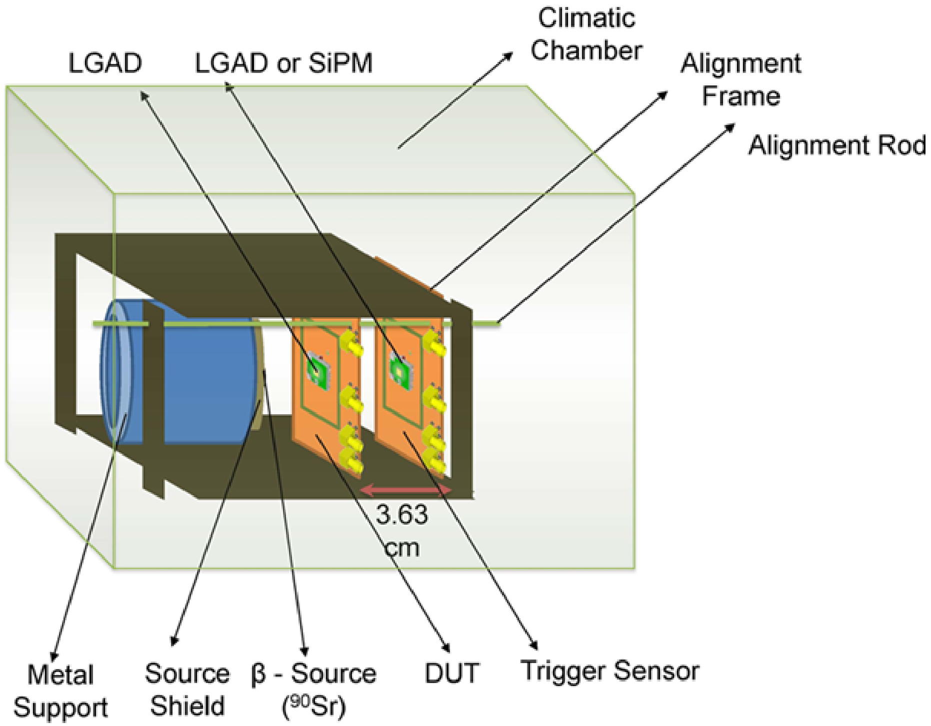
2.5cm (30%)



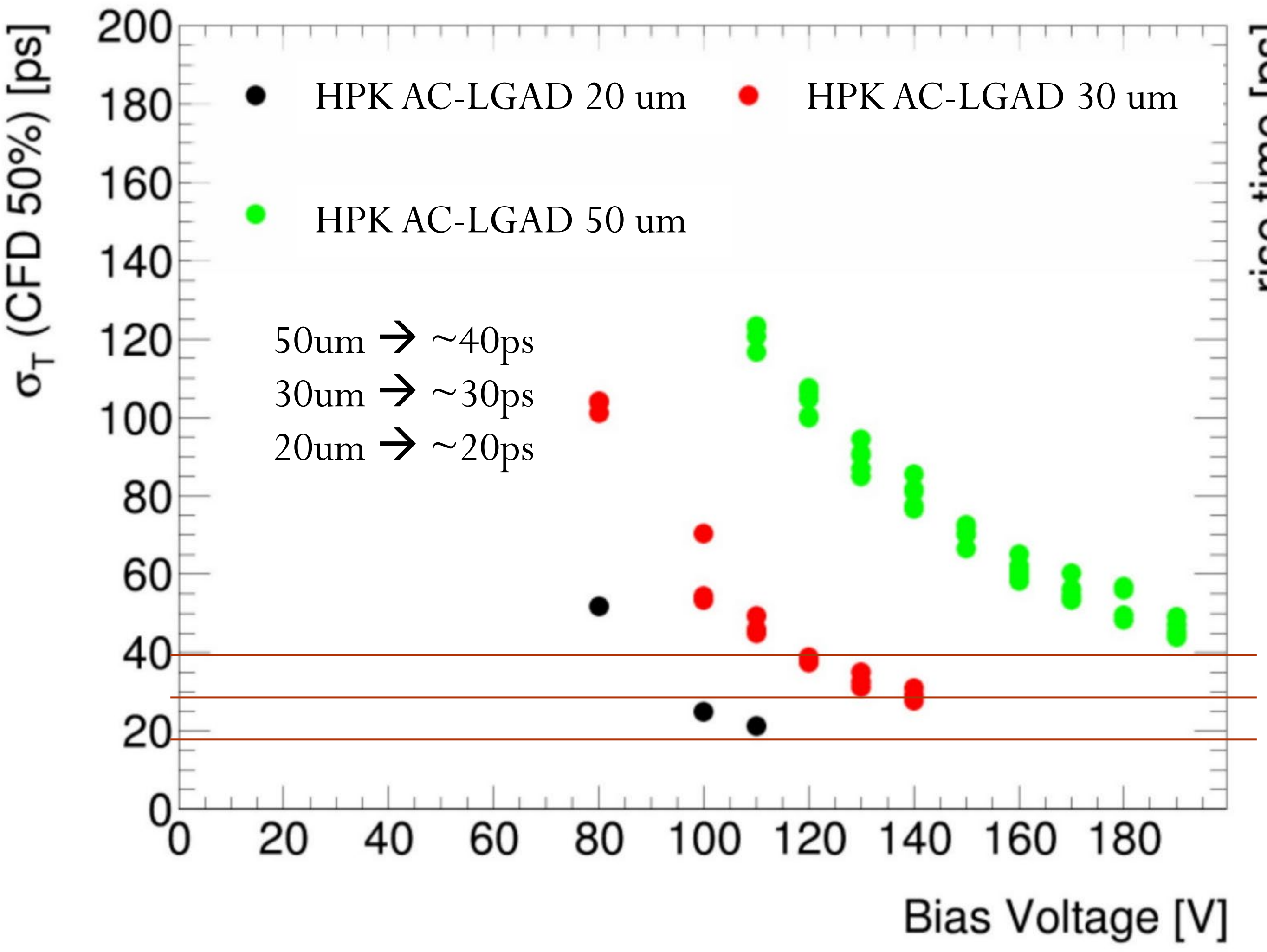
20/30/50um HPK device

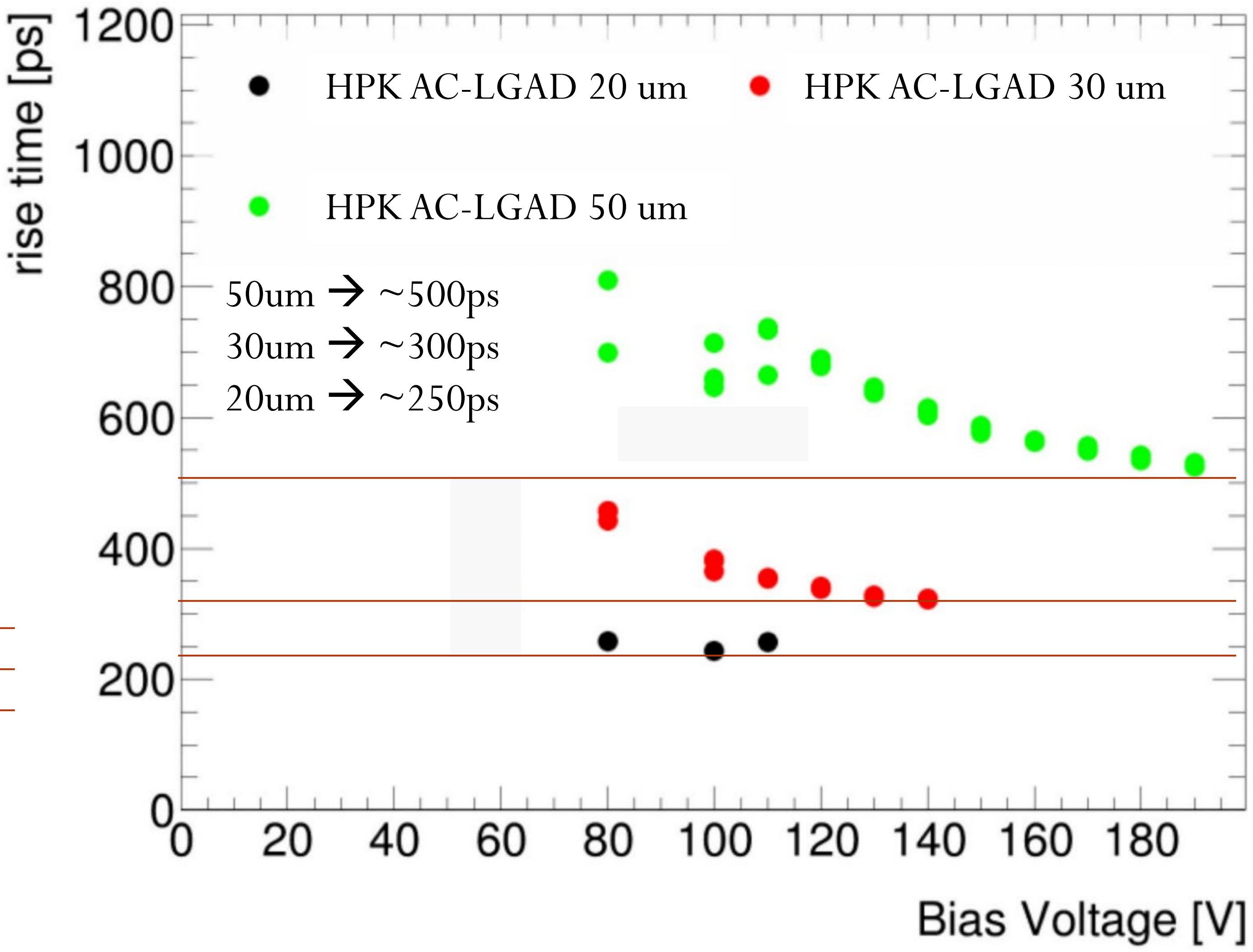
- HPK AC-LGAD production with 20/30/50 um of active thickness
  - AC-LGAD array 2x2
  - 500um pitch and ~500um pad size
- Tested with Sr90 source on UCSC 1ch boards
  - Results likely very similar to a DC-LGAD since the response under the metal pad is roughly constant
- Fast trigger LGAD to provide time 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

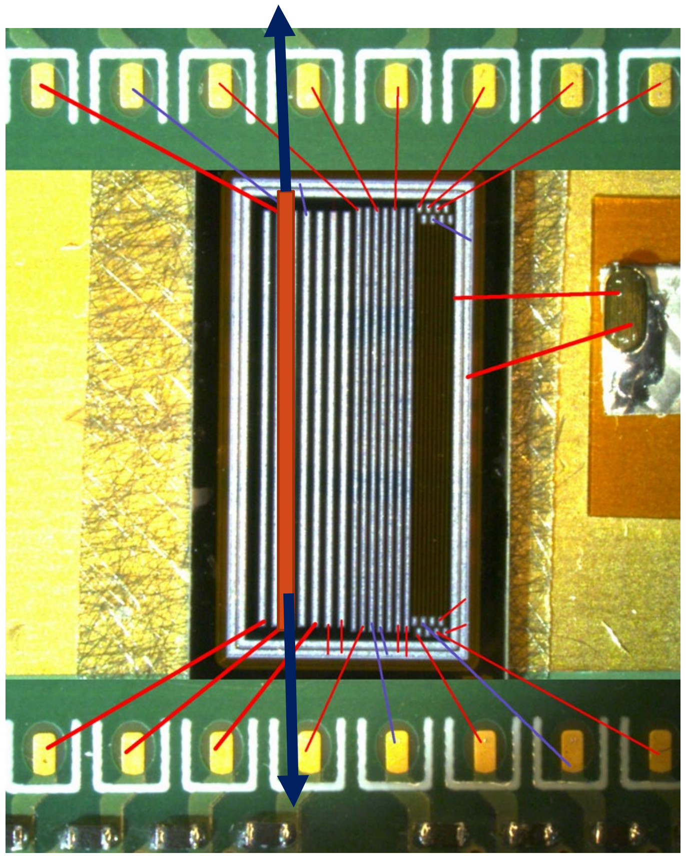


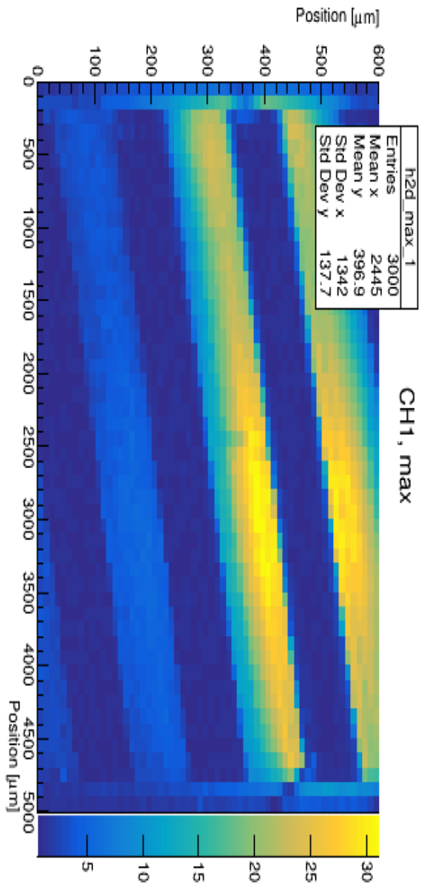


Data by: J. Ding

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

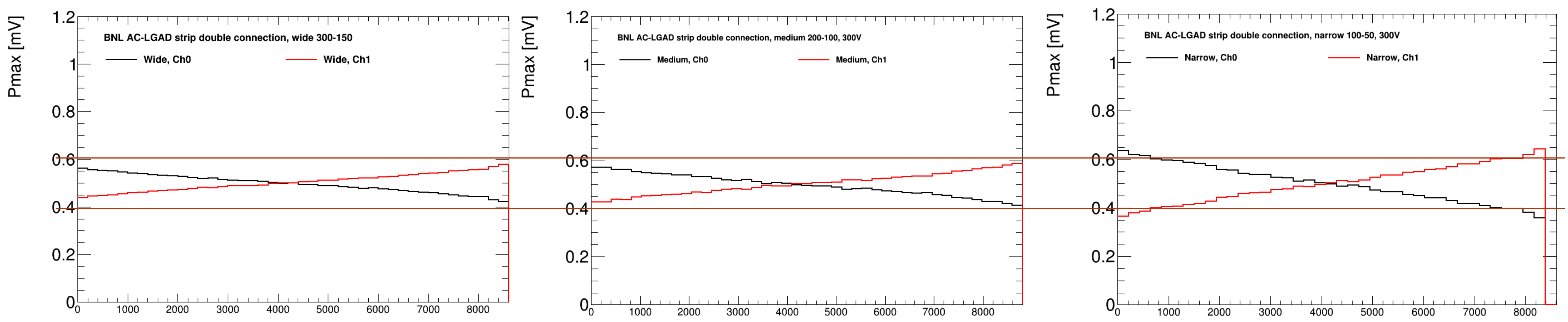
Strip metal resistance

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

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

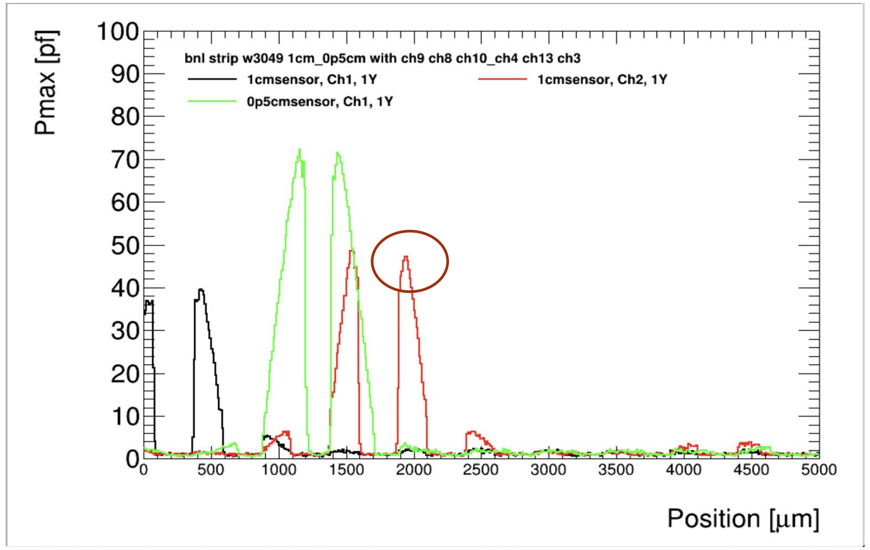
AC-LGAD studies – strip readout at both ends

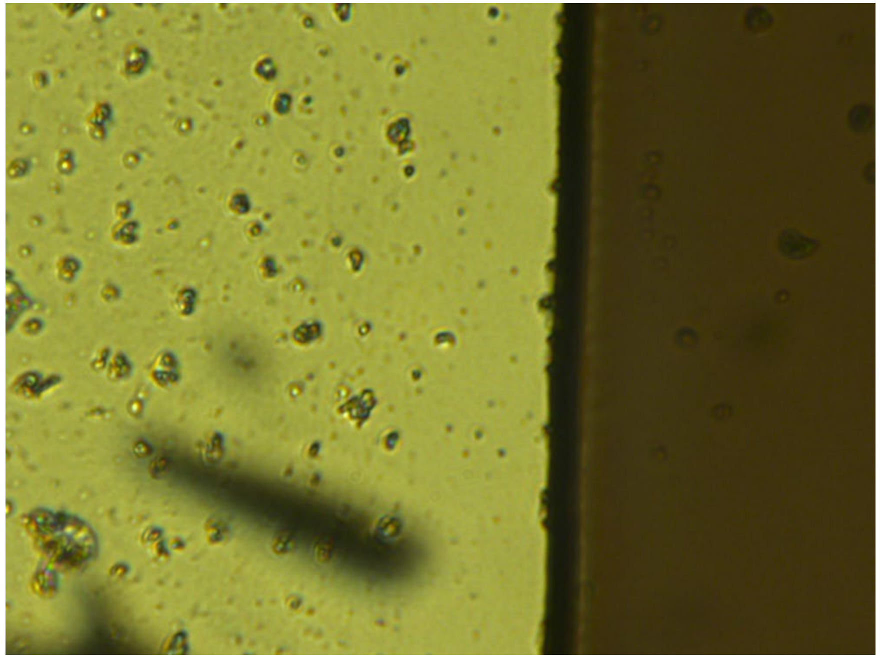
- Effect is similar in the three cases, more different for the 'narrow' strips
  - Fractions varying between 0.4 and 0.6
- Expected since the strip resistance is similar for 'wide' and 'medium'
- To increase the effect, it's necessary to increase the metal resistance on the strip



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

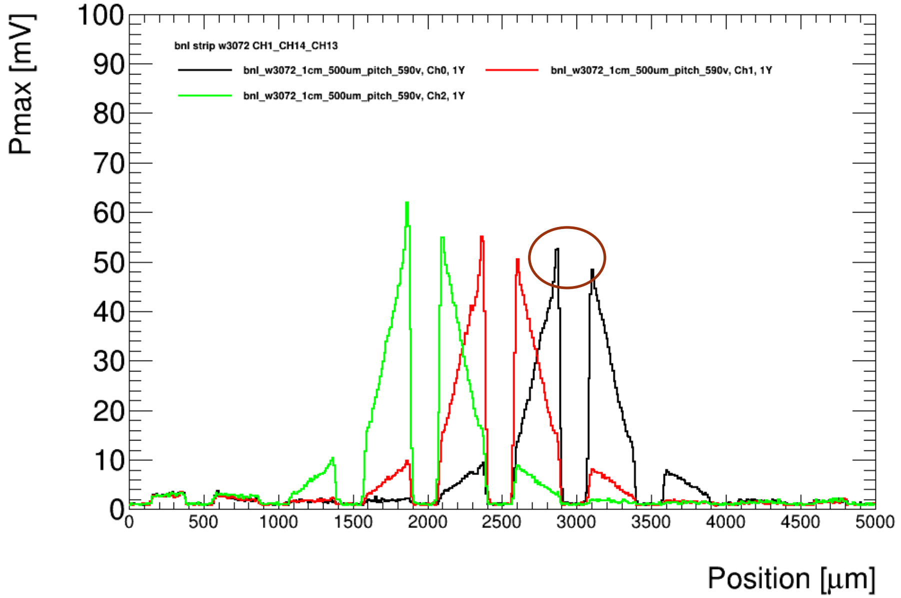
Different metal?

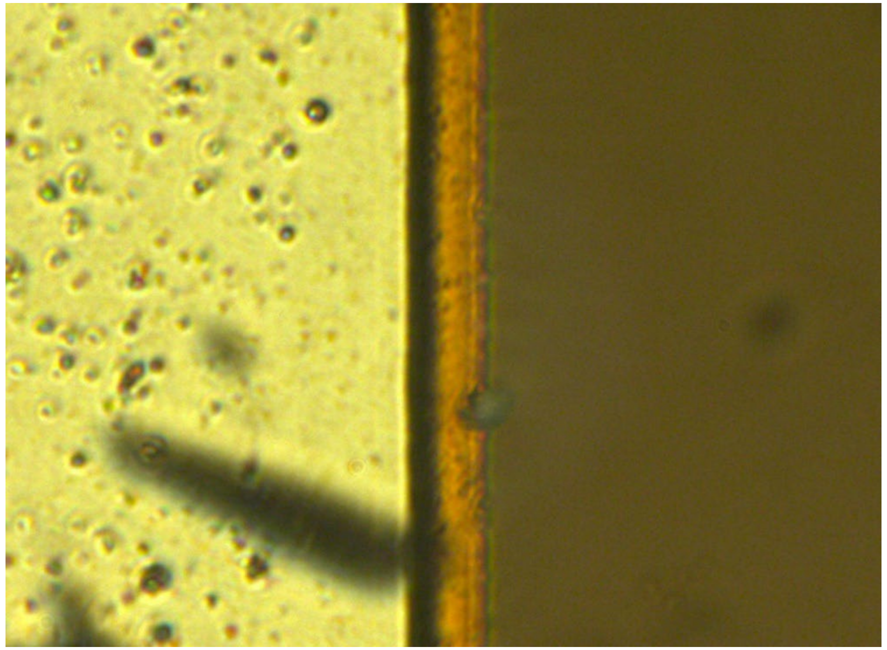




W3049

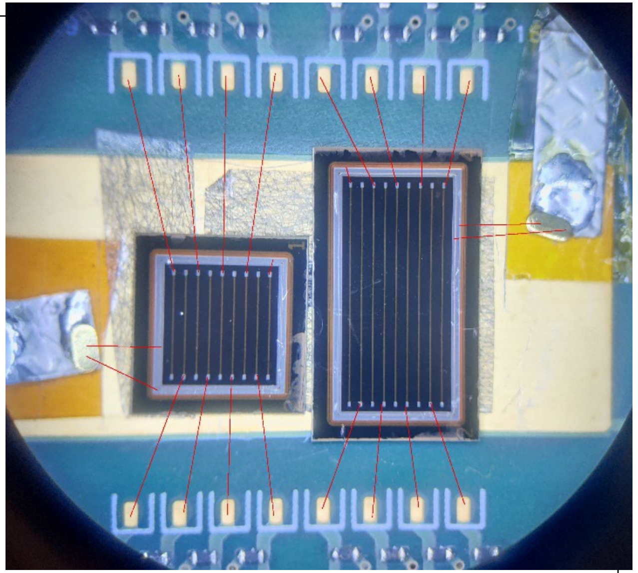
Sharper edges? Different metal?



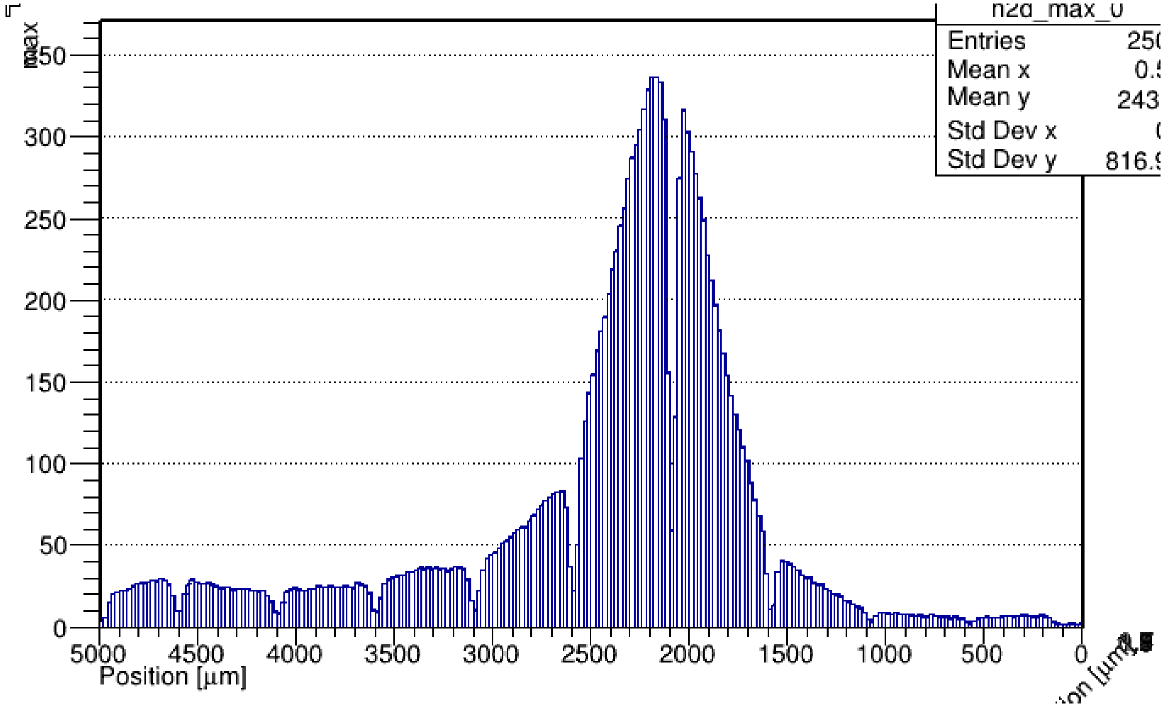


W3072

W3074 "narrow"

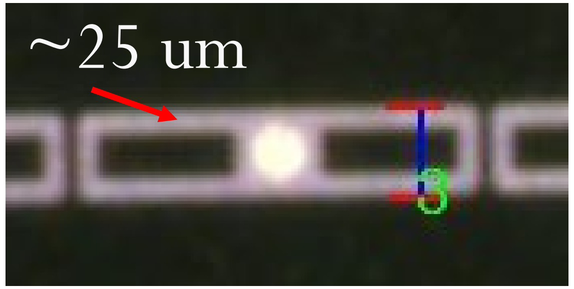


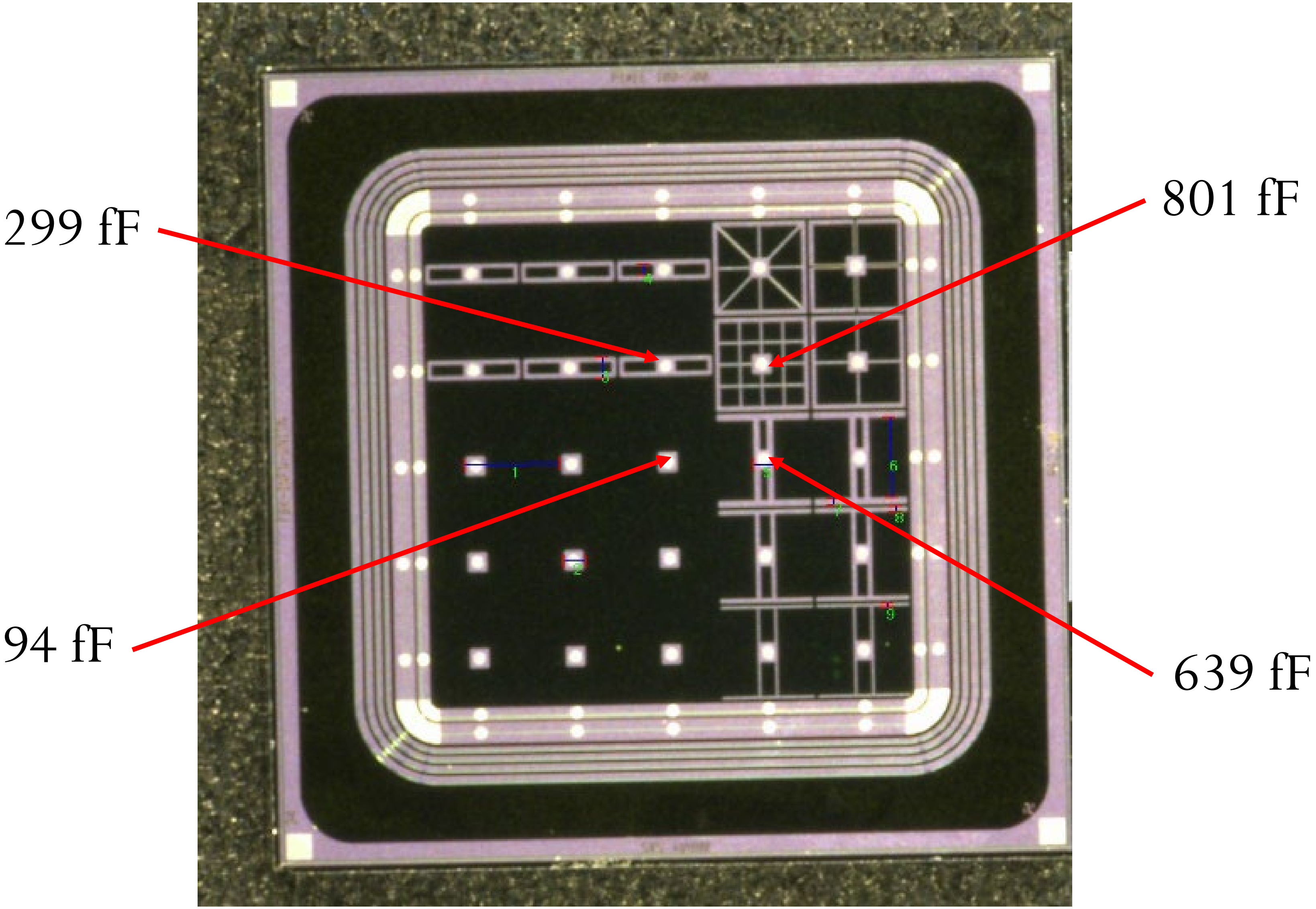
- 500um pitch, 20 um sensors
  - 1cm length, 50um width strips
  - 0.5cm length, 50um width strips
- Extreme gain in the 1cm? Biased at 110V as the other sensors
  - Signal up to 350mV, asymmetric response?



AC-LGAD AC-capacitances

- Measurement of the pad capacitance for each different type of pad
  - HV from the backside, N+ and guard ring grounded, capacimeter connected to top metal
  - The rest of the metal pads around it are floating
- Pad's capacitance scales will amount of metal coverage on top as expected
- **Opening in the metal does reduce the capacitance**
  - Micro-strips are ~100x500 um but the capacitance is not 5 times the one of 100x100 um pads
  - Capacitance is only ~3 times
  - Scales with the (2x) 175x50 um area of the opening
  - H-pad measured has thicker arms so the capacitance is significantly higher

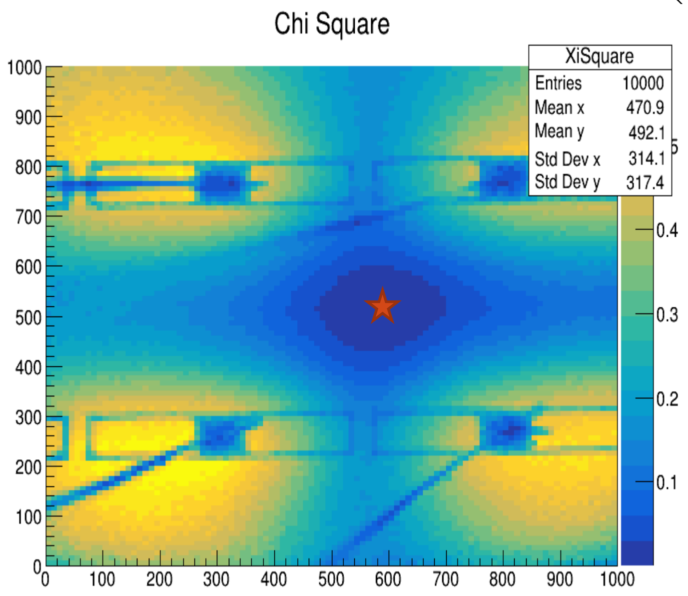


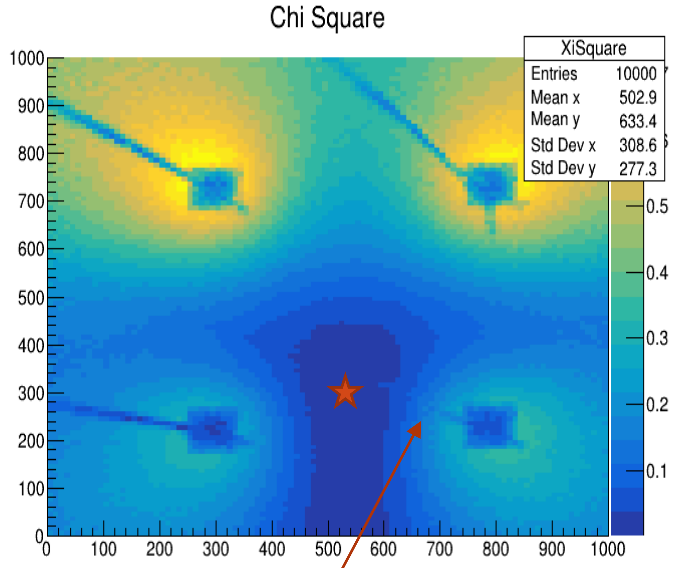


Position reconstruction technique

- Position reconstruction is made by generating a reference file on the detector itself
  - Fine scan of the area averaging waveforms in each position using the TCT laser (using 2GHz scope)
  - From this reference file a fraction map is calculated for each of the 4 channels
- Then several single events are taken for each of the test positions
  - The position of each events is calculated by doing a X^2 of the fractions in the event and the fraction maps from the average scan (using a 16ch CAEN digitizer based on DRS4)
  - The minimum X^2 is taken as the reconstructed position (for now limited to the fine scan binning of ~10um, so anything under 5um of precision is not fully accurate)
- **Reconstruction not based on master formula or charge imbalance** since it's not trivial to model these geometries

- Jitter is evaluated on the sigma of a Gaussian fit of the distribution of CFD 50% timestamps with the trigger signal
  - The timestamp is calculated using 4 channels weighted with the Pmax^2
  - Jitter seems to be higher than expected, might be because of the low bandwidth of the CAEN digitizer
  - Caveat: the time delay is not taken into account, to have a correct timestamp it needs to be considered. If the position resolution is high the effect should be small.





Note: some position are close to the wire bond so the reconstruction might fail