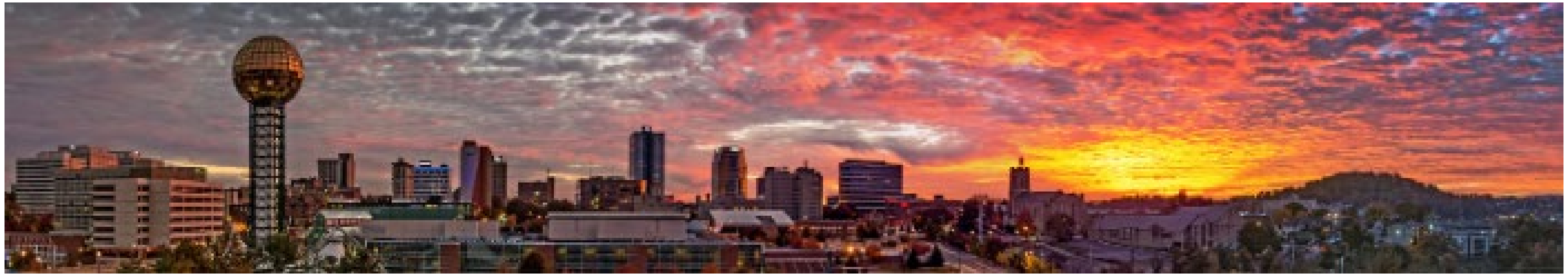

Performance of first full-size production of AC-LGADs for the ePIC detector

Dr. Simone M. Mazza (SCIPP, UC Santa Cruz)
On behalf of SCIPP and ePIC TOF

VERTEX 2025, Aug. 2025, University of Tennessee

SCIPP
SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS
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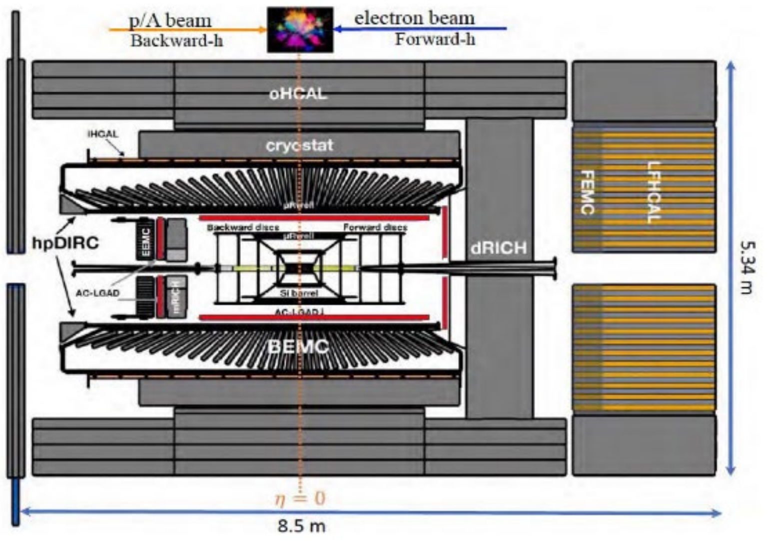
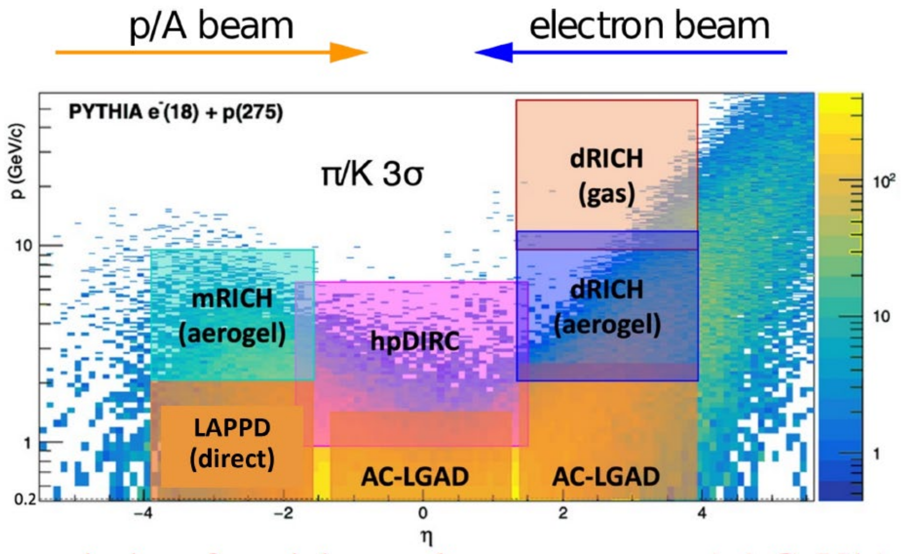
ePIC

The ePIC detector

- **4D tracking** is a necessity to reach ePIC's physics goals
- **Particle identification with time of flight (TOF)**
  - For e/π/K/p at low/intermediate momentum
  - Require good time resolution and meaningful flight distance
- **A TOF layer** is foreseen for both barrel and end-cap in EPIC
  - Barrel (BTOF) ith 1cm-long strip
  - End-cap (FTOF) with 500 x 500 um pixels
  - Off-momentum detector (OMD) with same design as FTOF
- For more details see Satoshi's talk tomorrow https://indico.phy.ornl.gov/event/677/contributions/2742/
- **TOF layers based on AC-LGAD technology**

Subsystem	Area (m^2)	dimension (mm^2)	channel count	timing σ_t (ps)	spatial σ_x (μm)	material budget (X/X_0)
Barrel TOF	12	0.5*10	2.4M	35	30 ($r \cdot \phi$)	3%
Forward TOF	1.1	0.5*0.5	3.2M	25	30 (x, y)	5%

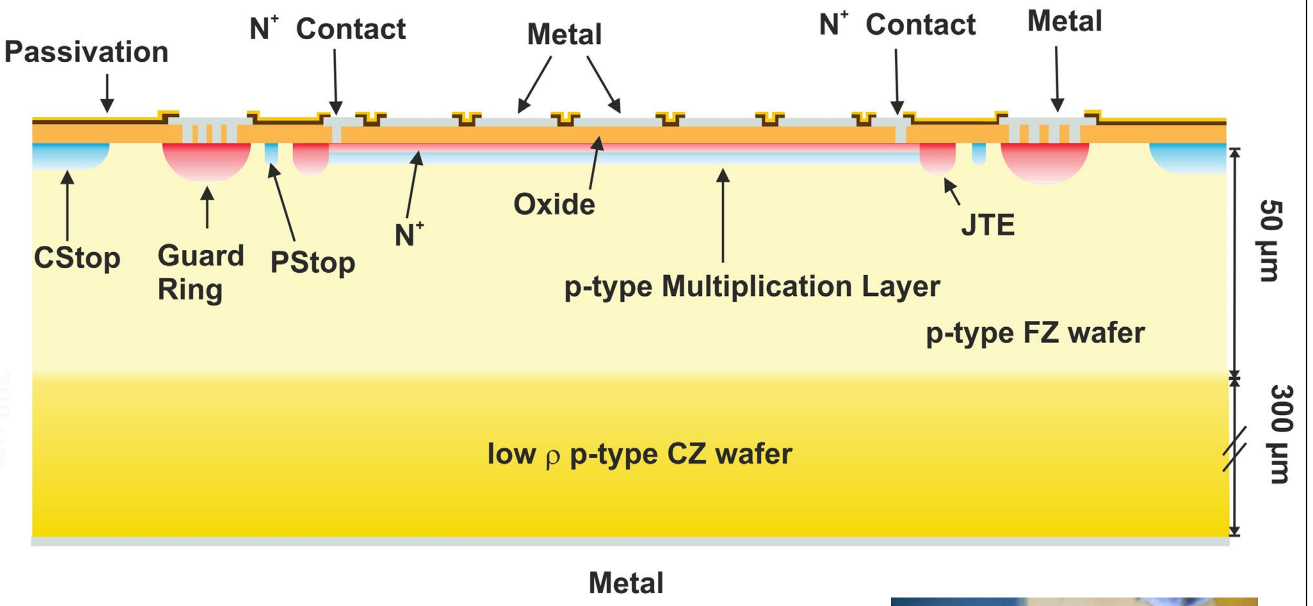


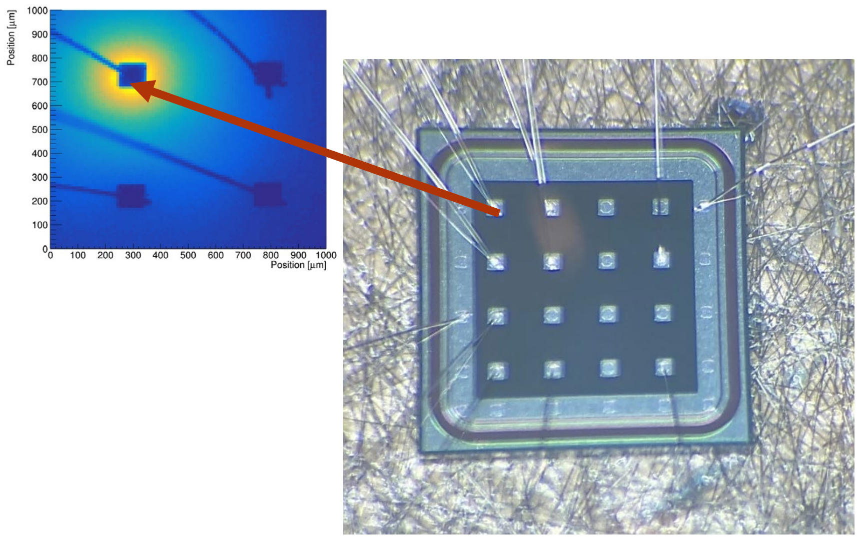


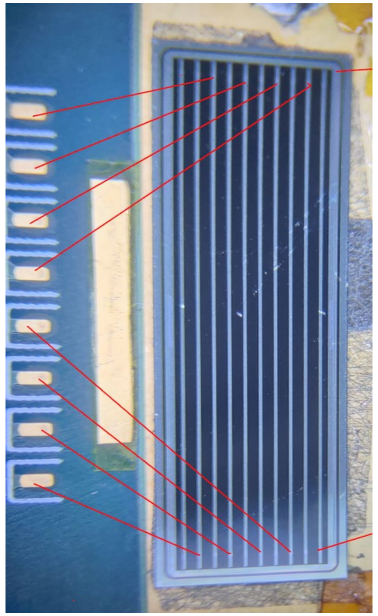
AC-LGADs

- 'Standard' LGADs has granularity limited to ~mm scale due to the high field on the surface
- Most advanced high-granularity prototype **AC-coupled LGAD**
  - Continuous multiplication layer coupled with resistive (low doping) N+ layer after the gain layer
  - Readout pads are AC-coupled with insulator (oxide) layer
  - Any surface metal geometry is possible
- **AC-LGAD has intrinsic charge sharing**
  - Gain increases the S/N and allows for smaller metal pads
  - Using information from multiple pixels/strips for hit reconstruction

- **Reduce channel density and power dissipation while maintaining good resolution**
  - Many parameter to optimize: oxide thickness, N+ resistivity…



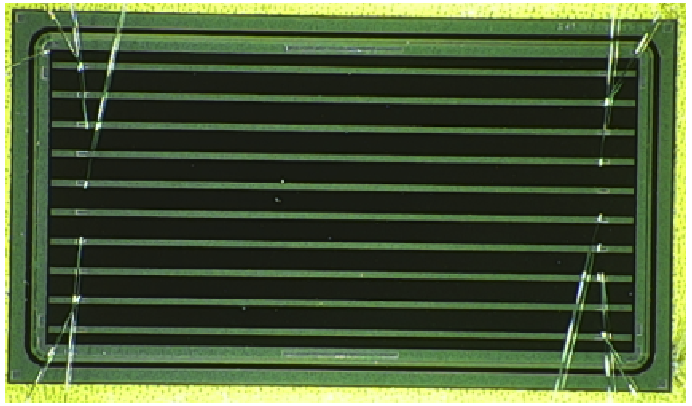


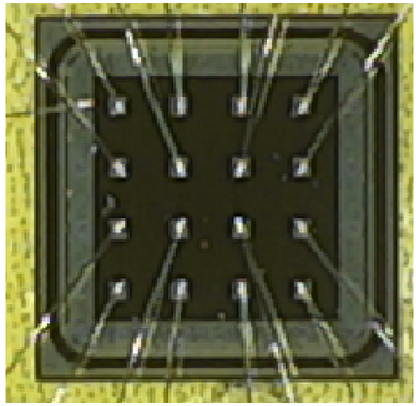


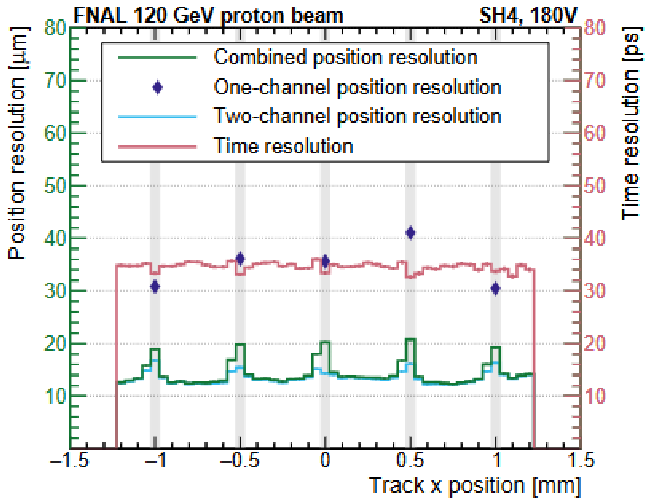
2023 HPK production

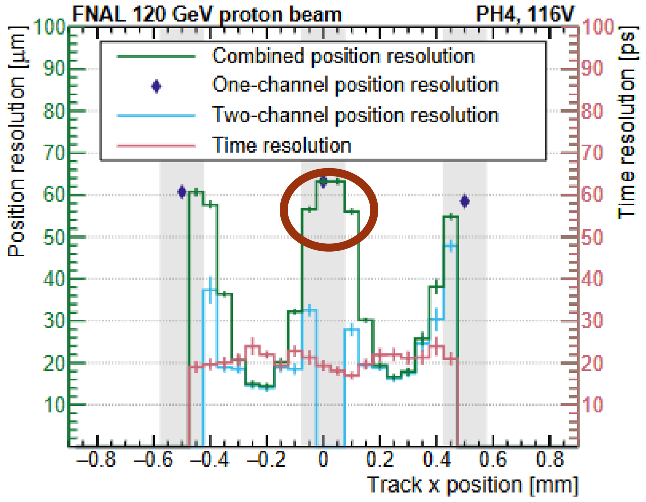
2023 HPK production

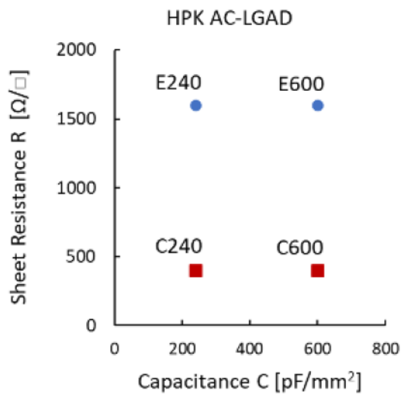
- Test beam and laboratory campaign to characterize HPK sample
  - Matrix of different pitch/size metal, different N+ resistivity and oxide thicknesses
- FNAL test beam results from HPK 2023 production, most ePIC requirements are met
  - Time resolution ~35ps for 1cm x 500um strips and ~20ps for 500um pitch pixels
  - **Pixel position resolution under metal sub-par**, 2024 production with different pixel geometry might solve it
- Laboratory studies done with TCT laser
  - Type E strips (more resistive) have better performance for strips
  - (Type C better for pixels)
  - 1cm strip length is the best compromise

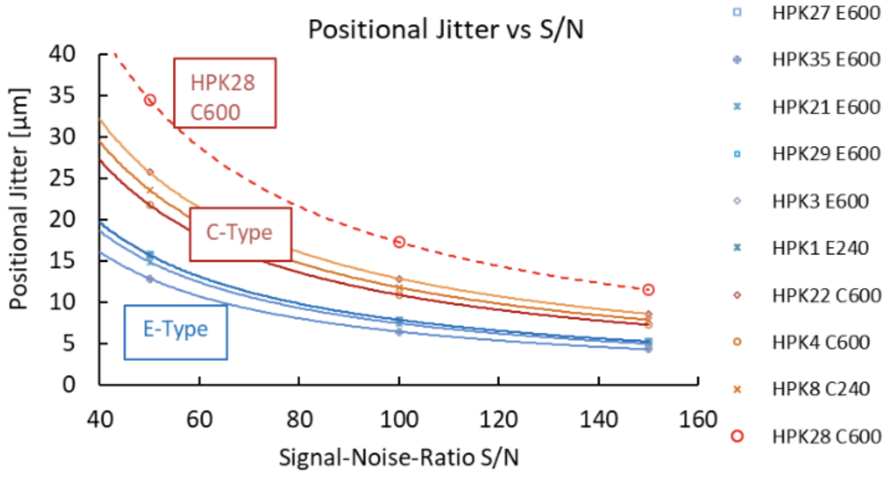












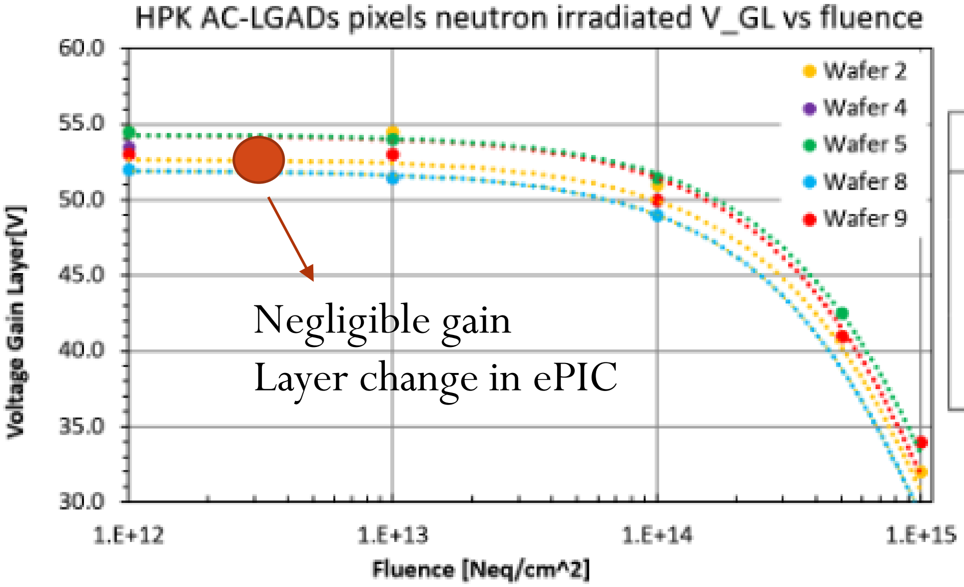
Dr. Simone M. Mazza - University of California Santa Cruz

References: https://arxiv.org/abs/2407.09928 https://doi.org/10.1016/j.nima.2024.169478

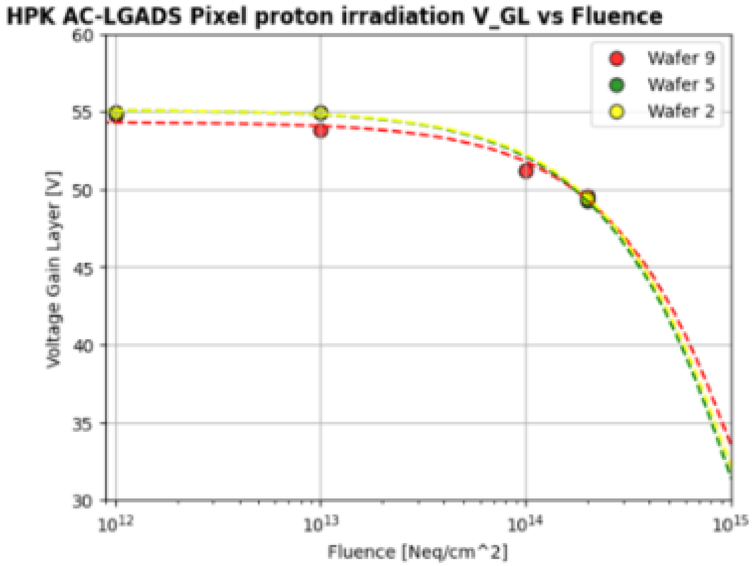
Irradiation effects on AC-LGADs

- Neutron (IJS) and proton (FNAL) irradiation on 2023 HPK production
  - Thanks to I. Mandic and S. Seidel for the irradiation campaign!
- Up to 1e13 Neq, no significant change in sensor IV properties and gain layer doping
  - Leakage current scales with bulk volume
  - Current and breakdown voltage increases with fluence (as expected)
- Gain layer doping proportional to Vgl (gain layer depletion voltage) or 'foot' (star in the plot)
  - Degradation parameter, 'c' factor, from fit on the distribution vs fluence
- Behavior across wafers is consistent
- Comparable results for protons and neutrons, degradation similar to "standard" DC-LGADs

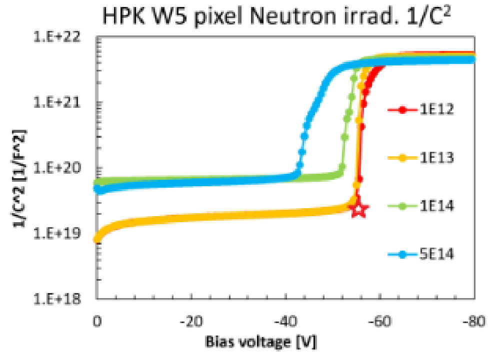
- See: https://arxiv.org/abs/2503.16658



Wafer	C factor $\left[\frac{cm^2}{Neq}\right]$
W2	5.38×10^{-16}
W4	3.69×10^{-16}
W5	4.93×10^{-16}
W8	5.81×10^{-16}
W9	4.54×10^{-16}



Wafer	C factor $\left[\frac{cm^2}{Neq}\right]$
W2	5.42×10^{-16}
W5	5.63×10^{-16}
W9	4.85×10^{-16}

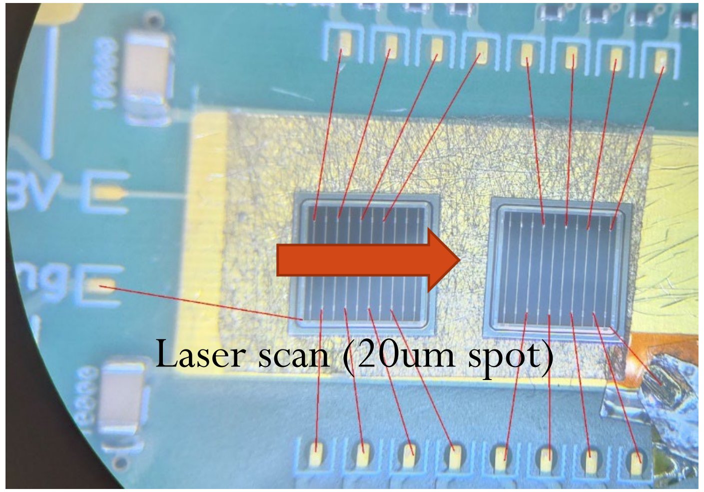


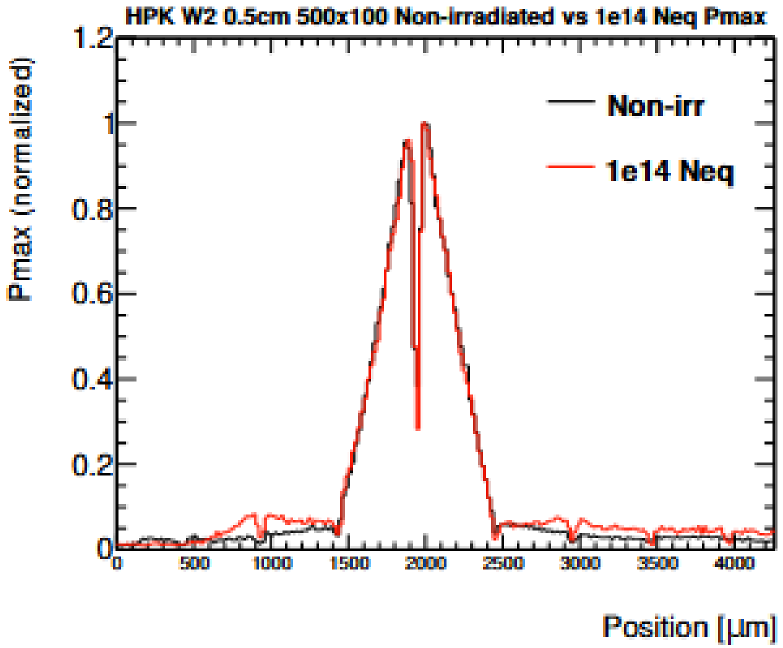
Student: J. Ding, M. Davis

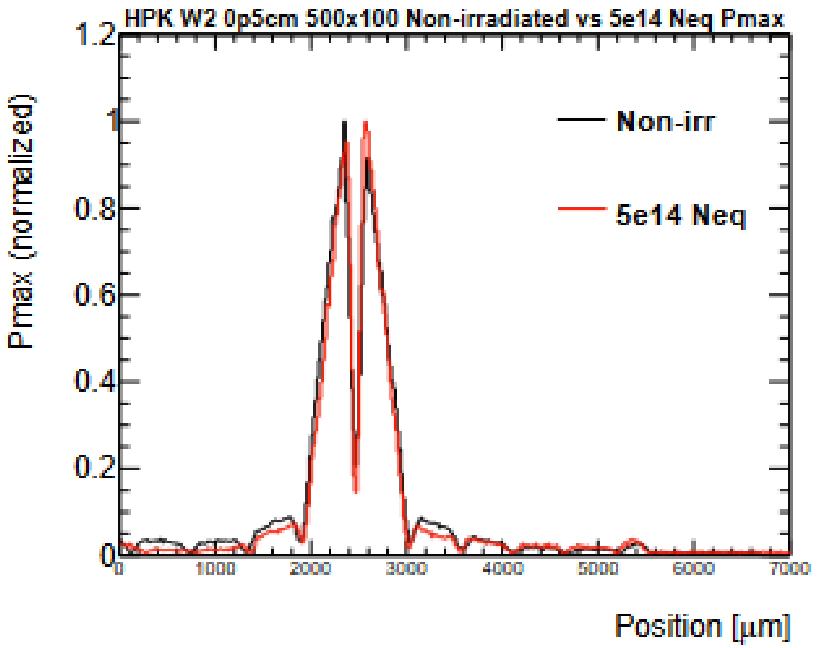
EURO-LABS EUROPEAN LABORATORIES FOR ACCELERATOR BASED SCIENCES

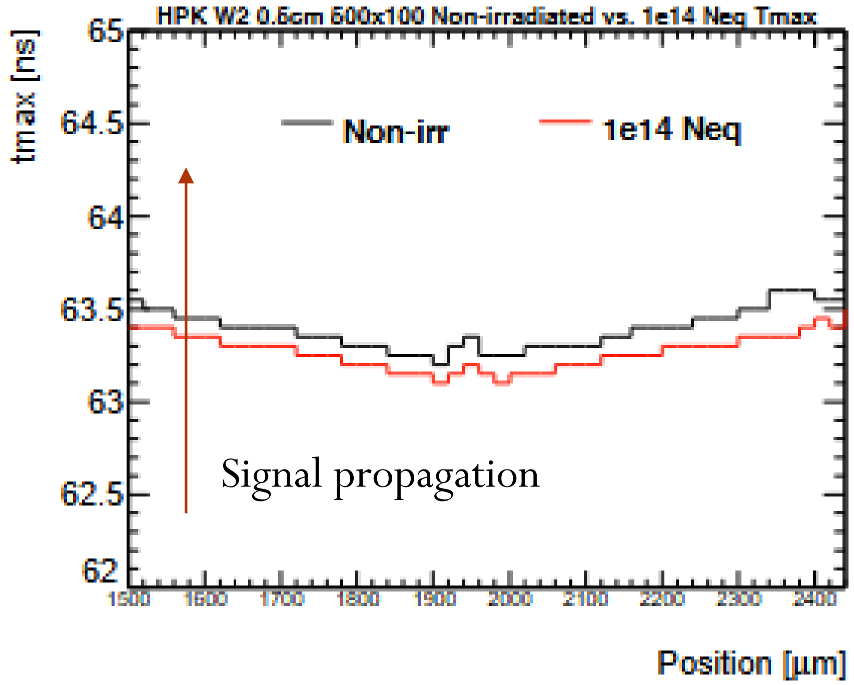
TCT laser studies - Neutrons

- Using laser TCT setup with cooling plate and FNAL 16ch board
- Direct AC-LGAD strips comparison non-irradiated and irradiated sensors
  - Two sensors types at two neutron fluence points 1e14Neq and 5e14Neq
  - Irradiated sensor was biased to higher voltages
- **At first order, the charge sharing distribution is unchanged**
- **Signal propagation in resistive N+ is the same**





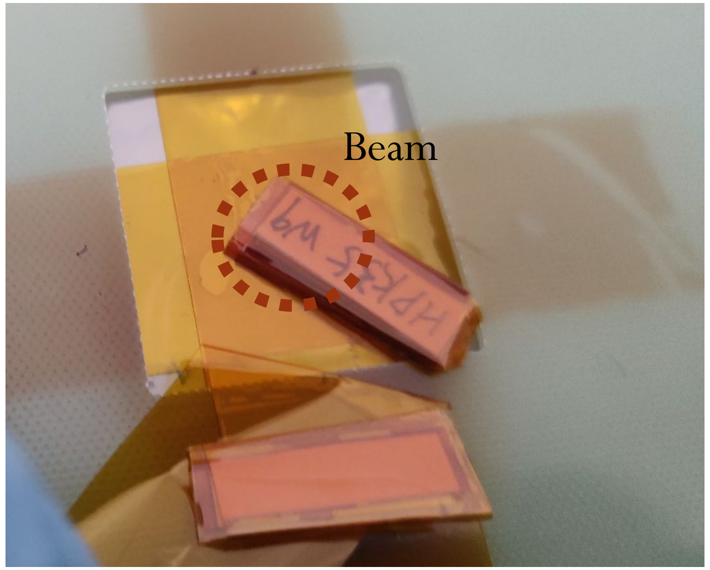


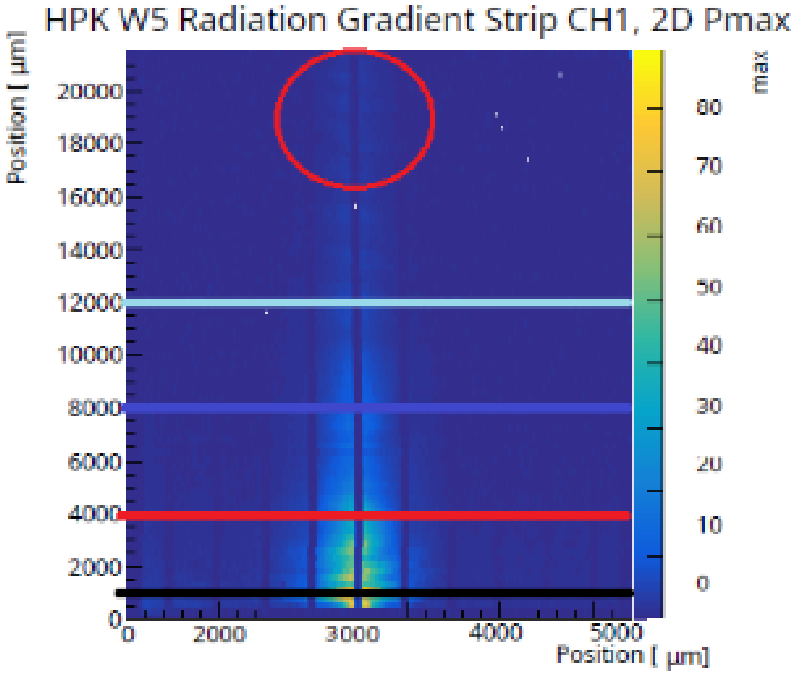


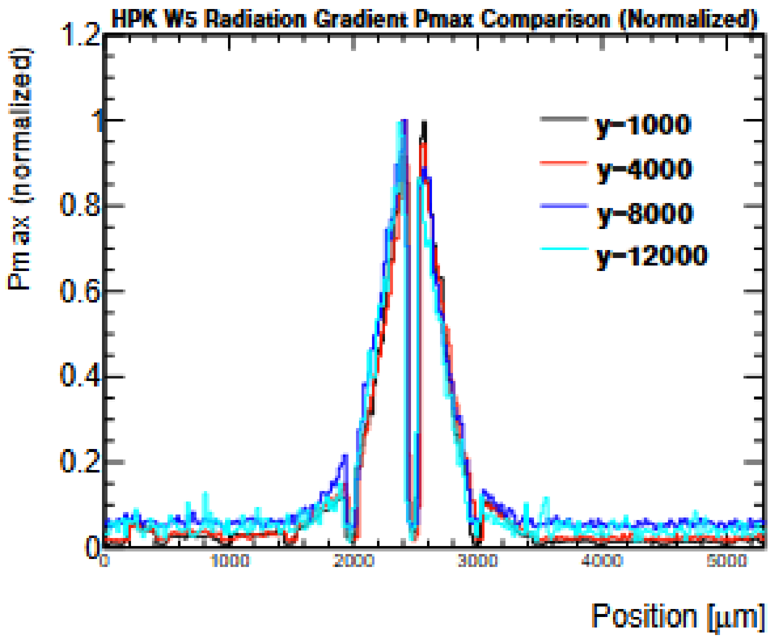
Student: G. Stage, A. Borgijin

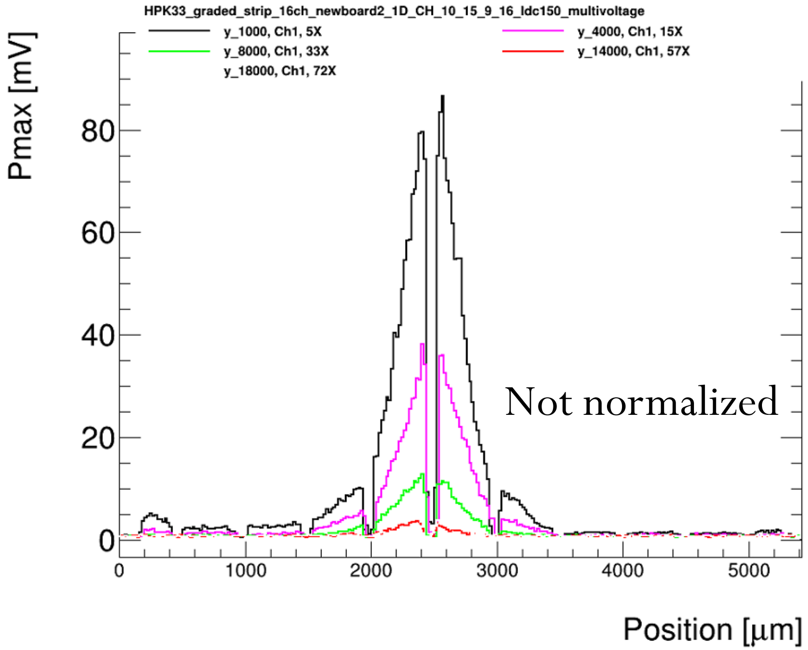
TCT laser studies - Protons

- Graded irradiation on an HPK 2cm strip sensor (500um pitch, 50um)
  - Fluence parallel to the strip each ~0.5cm: 4.4E+14Neq, 3.5E+14Neq, 1.8E+14Neq, 7.8E+13Neq
- Circle in image and plot indicates the beam position
- Effect of the irradiation clear in the gain layer signal degradation
  - However, the charge sharing profile doesn't change → good!









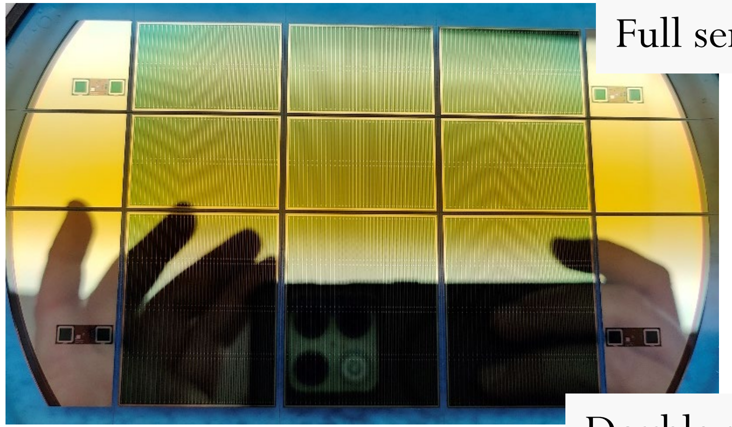
Student: G. Stage, A. Borgijin

2024 HPK production

Strip production

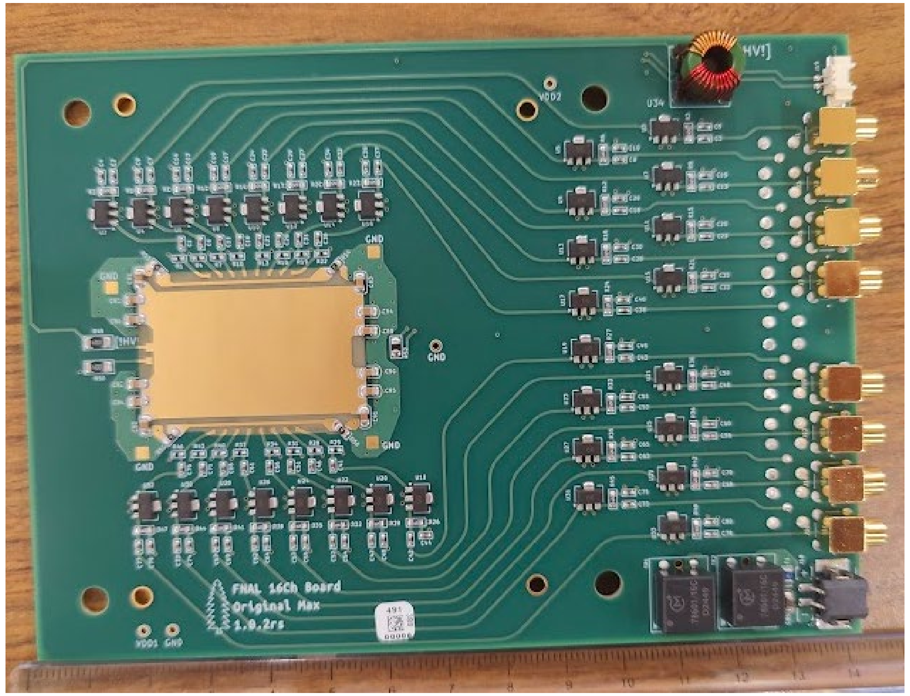
- ePIC full-size production of HPK strip AC-LGADs with devices up to 3.2x4.2 cm
  - Nominal size 3.2x2.2 cm with 1cm strip 'segments'
  - Strip width: 40-50um, strip pitch 500, 750, 1000 um
- 8 wafers in hand, four 50um thick and four 30um thick

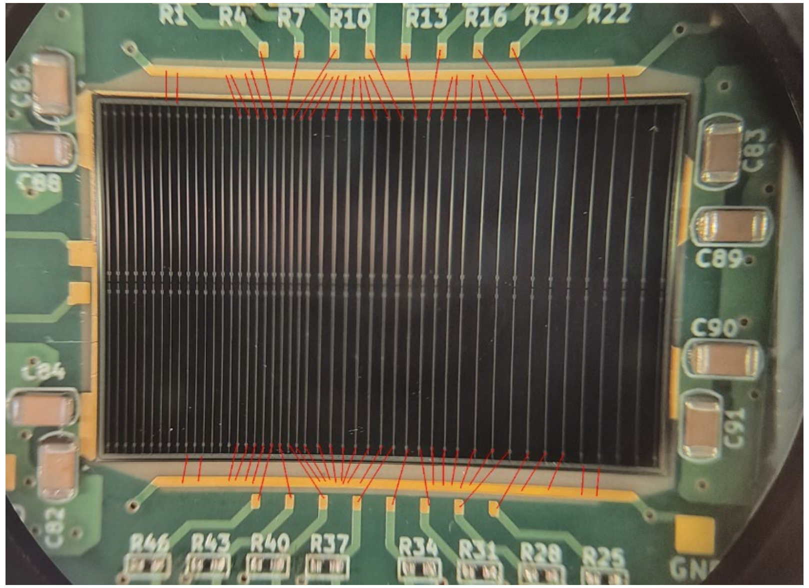
Half sensors

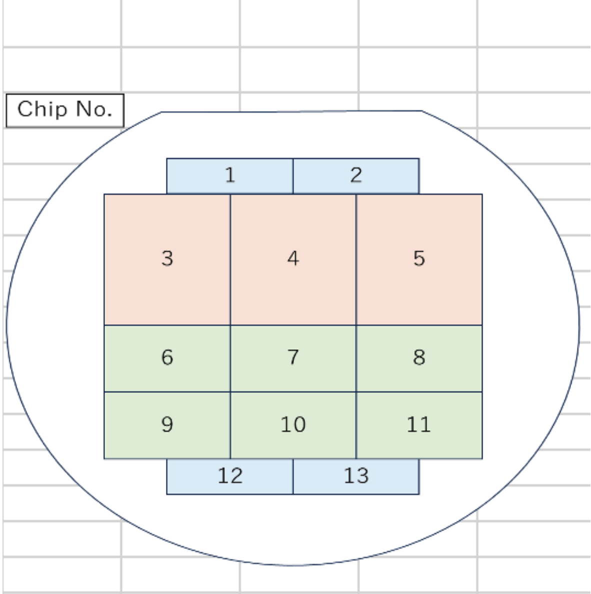


Full sensors

Double sensors

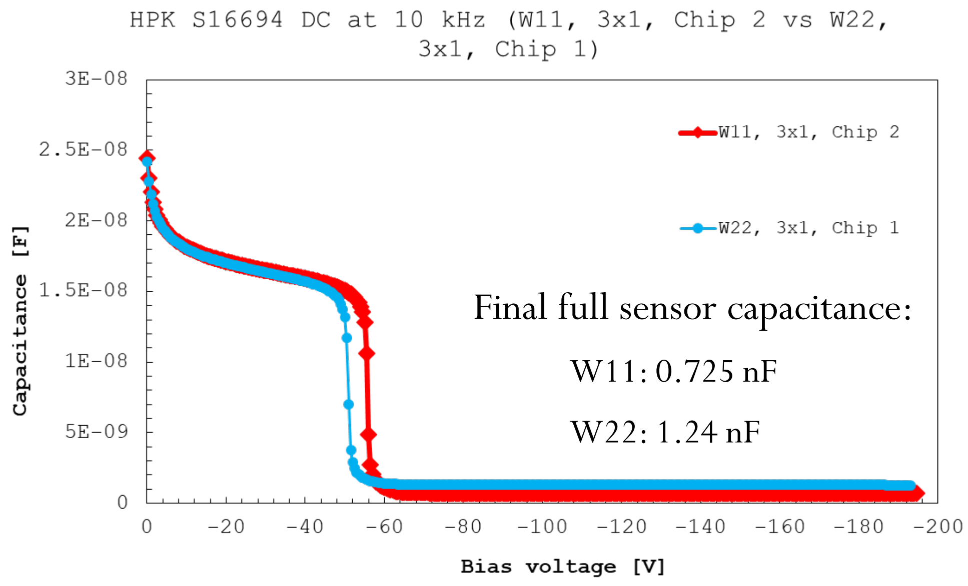


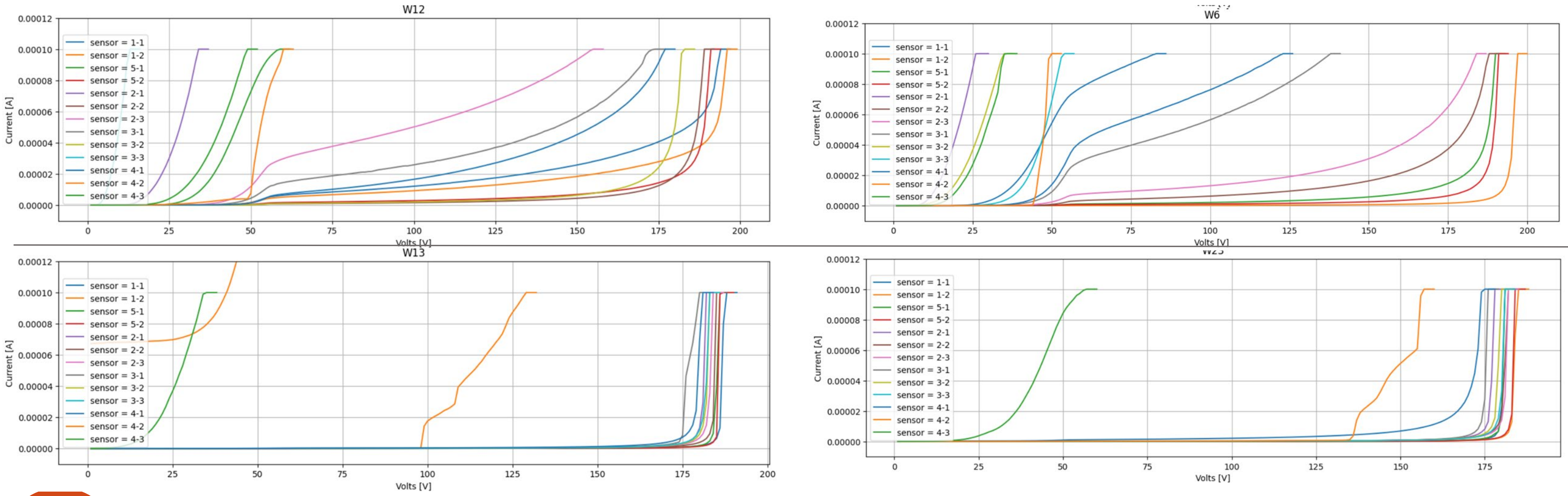




HPK strip production results – IV/CV

- Yield is not optimal, better for 30um wafer
  - HPK confirmed that 50um low yield was resolved in next production
- Capacitance of full detector scales with thickness
- Measurement of strip capacitance (input capacitance to the amplifier) is not trivial
  - Significantly changing with probing frequency
  - Should be around 10pF for strip → a challenge for the readout!





50um

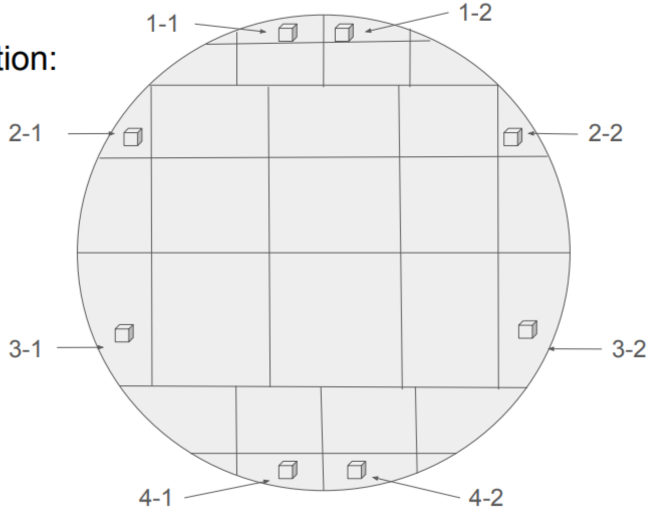
30um

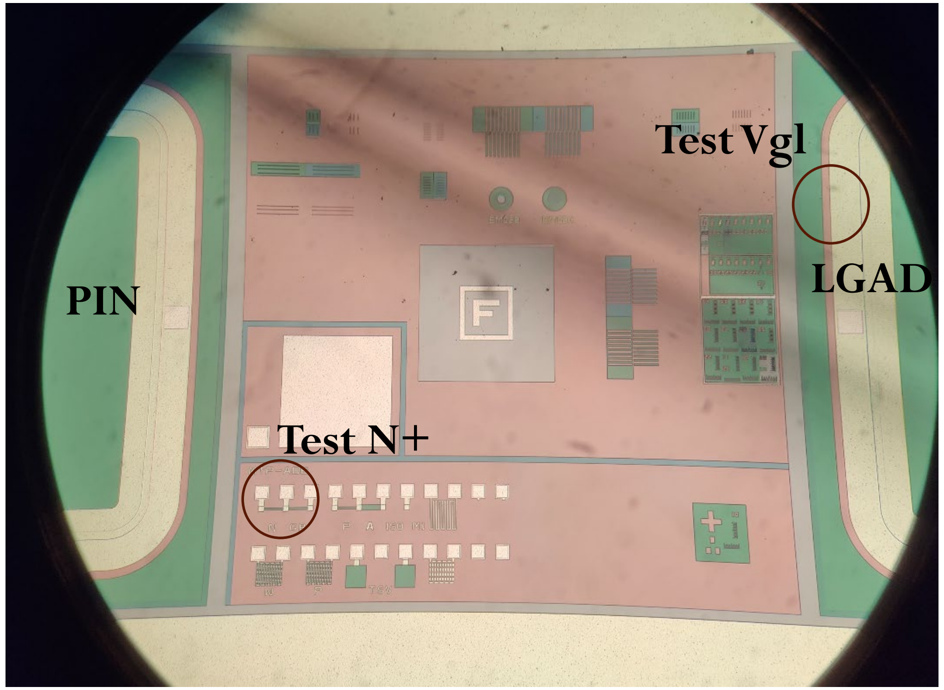
Student: G. Stage, A. Borgijin

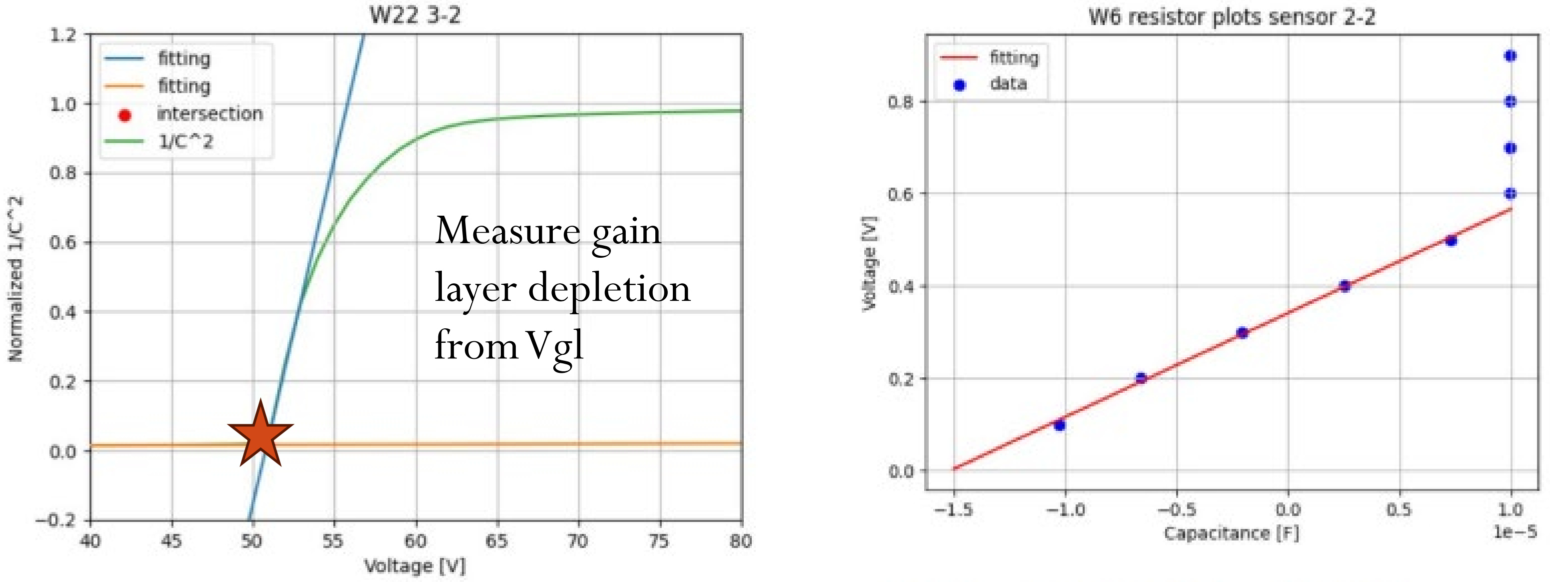
HPK production testing

- **Check gain and N+ homogeneity** across the wafer and between the wafers
  - Wafer edge is usually the most sensible
- Using test structures at the edge of the wafer to test gain and N+ resistivity
  - Measure Vgl of the LGAD test structure
  - Measure current vs voltage for N+ test
- Gain layer variation across wafer <1%
- Resistivity variation across wafer <10%

Orientation:





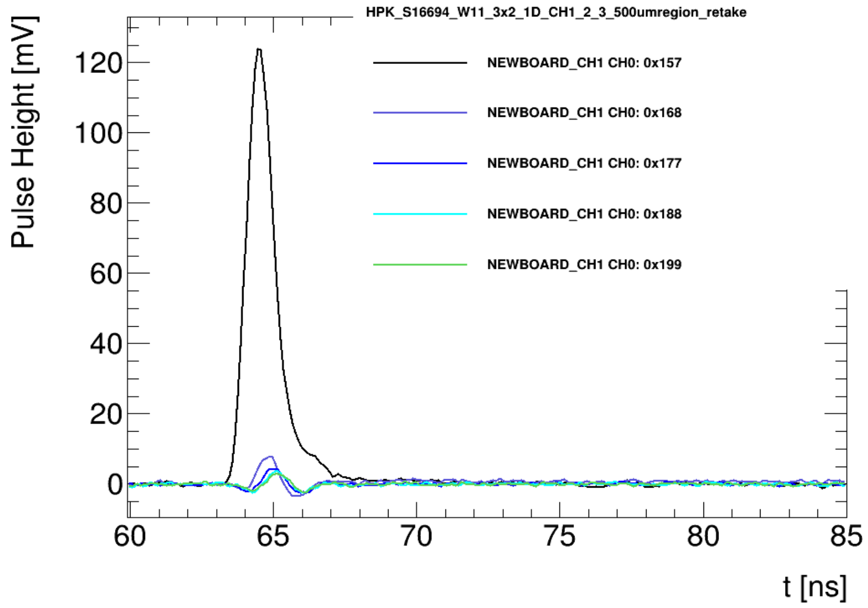


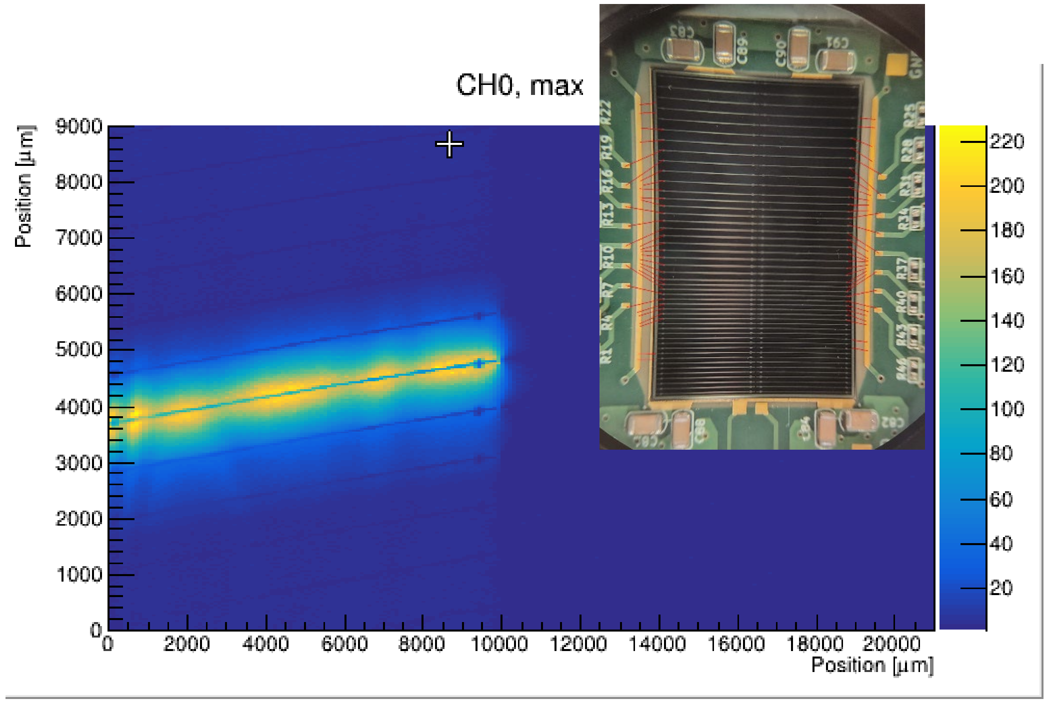
V(I) = 22504*I + 0.341

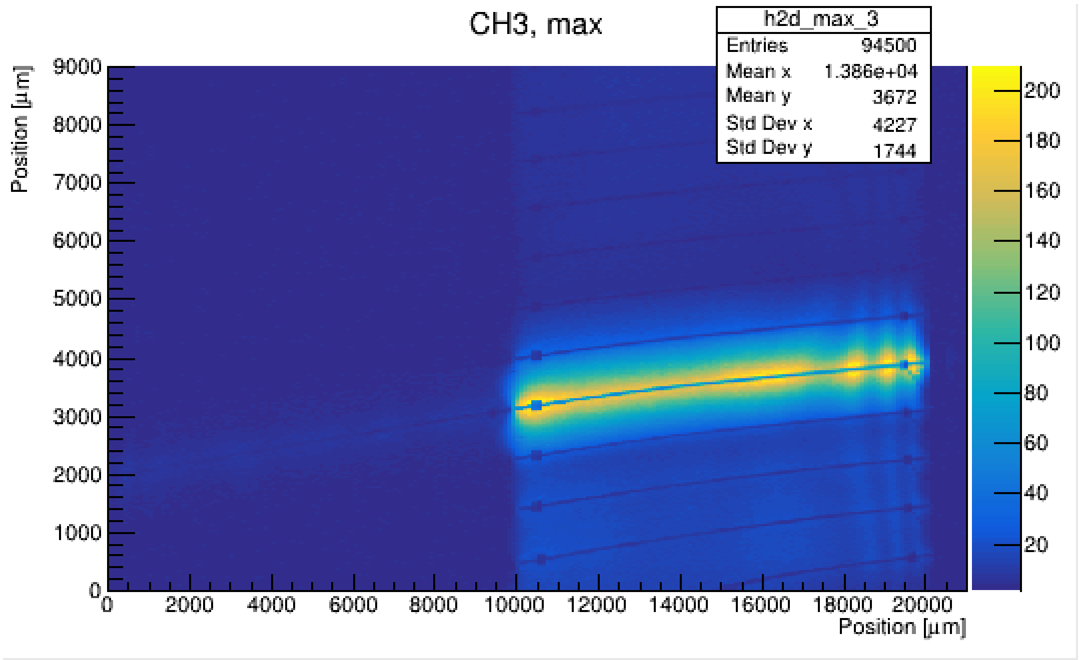
Student: M. Davis, S. Beringer

HPK production results - TCT

- Full size sensors tested on a large board with laser TCT
  - Both 50um and 30um thicknesses, show similar performance
- Sensor works well, some gain variation across strip but it's unclear if due to laser reflections, will verify at test beam
- Pulse as expected with rise-time 600-700 ps for 50um and 400ps for 30um
- Time of arrival variation delay ~2ps/um (250ps for 500um) perpendicular to the strip and ~0.01ps/um (<100ps for 1cm) parallel to the strip (metal propagation)



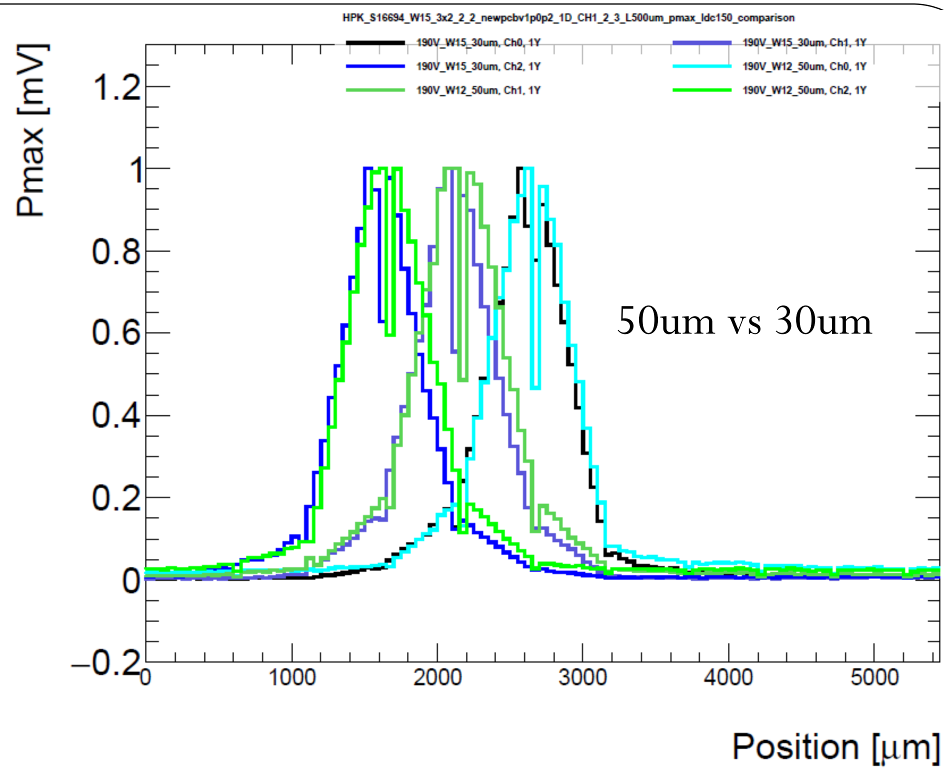


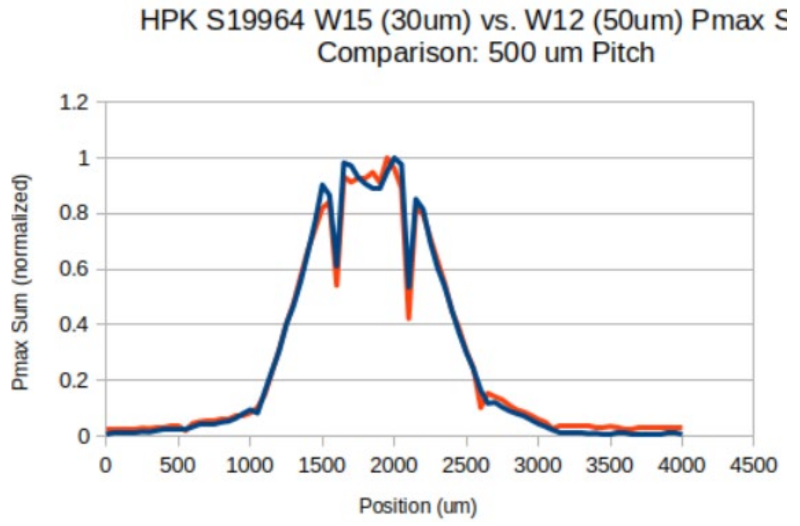


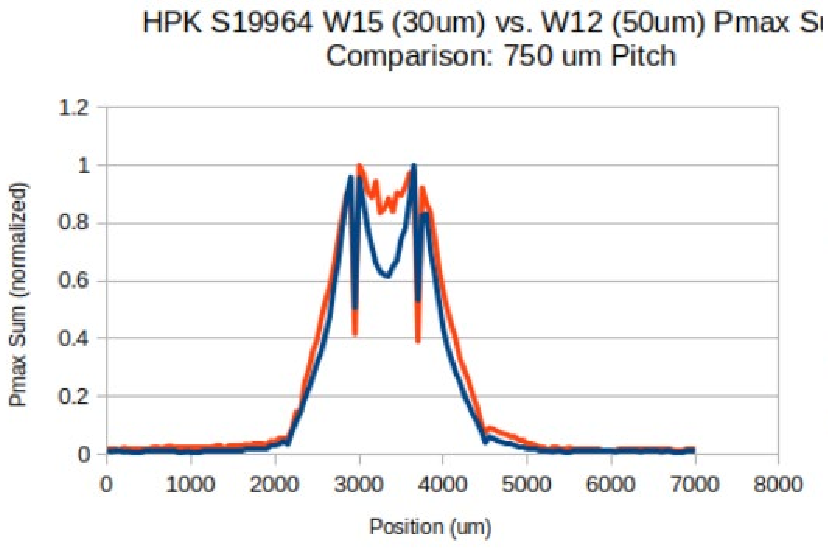
Student: G. Stage, A. Borgijin

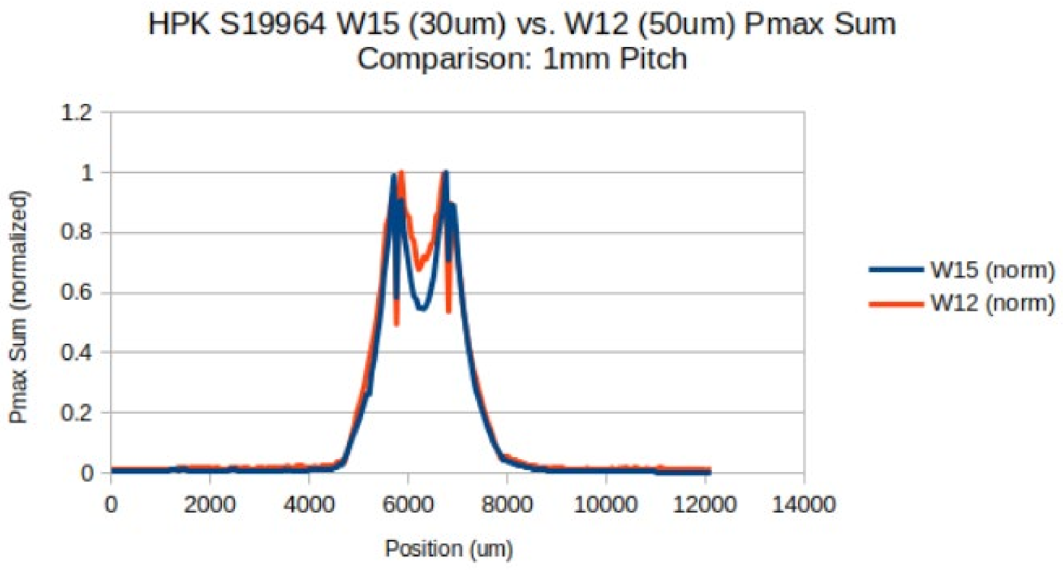
HPK production results - TCT

- Signal for all pitches is similar near the strip
- Similar signal profile for 50um and 30um pitch at 500um pitch
- Thinner sensors show higher S/N loss between strips
  - S/N loss small for 500um
  - S/N loss up to ~30% for 750um
  - S/N loss up to ~40% for 1000um





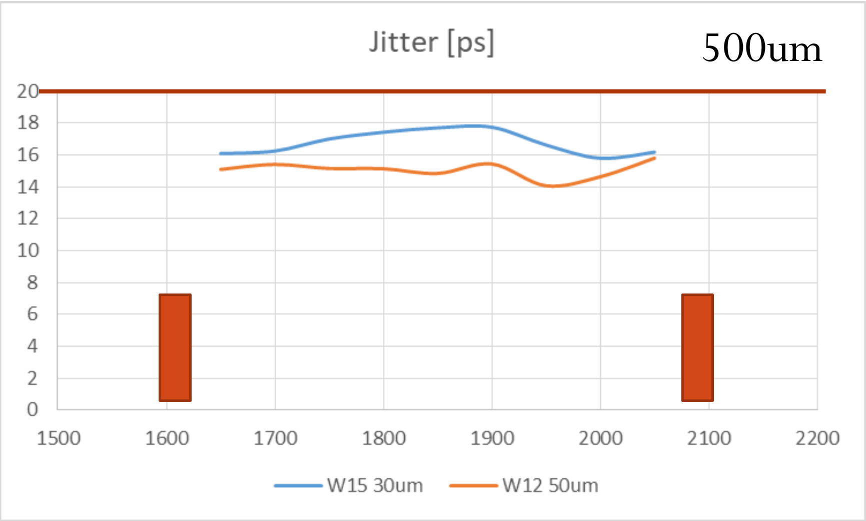


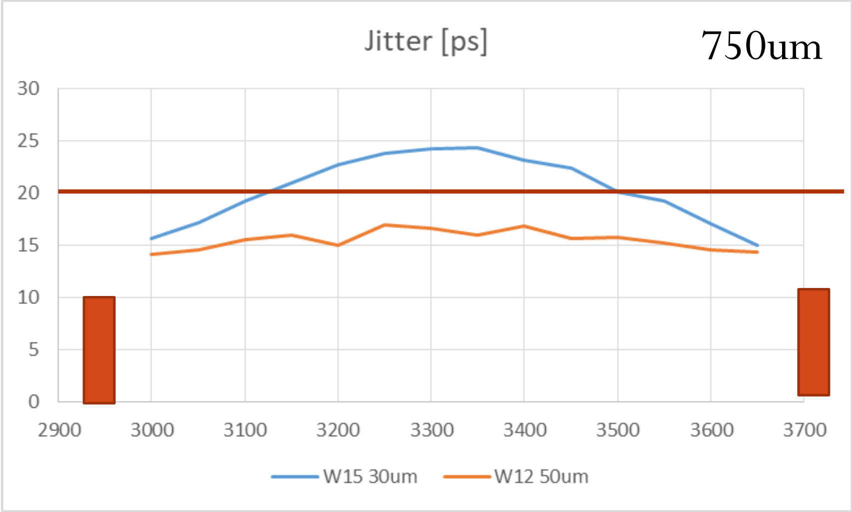


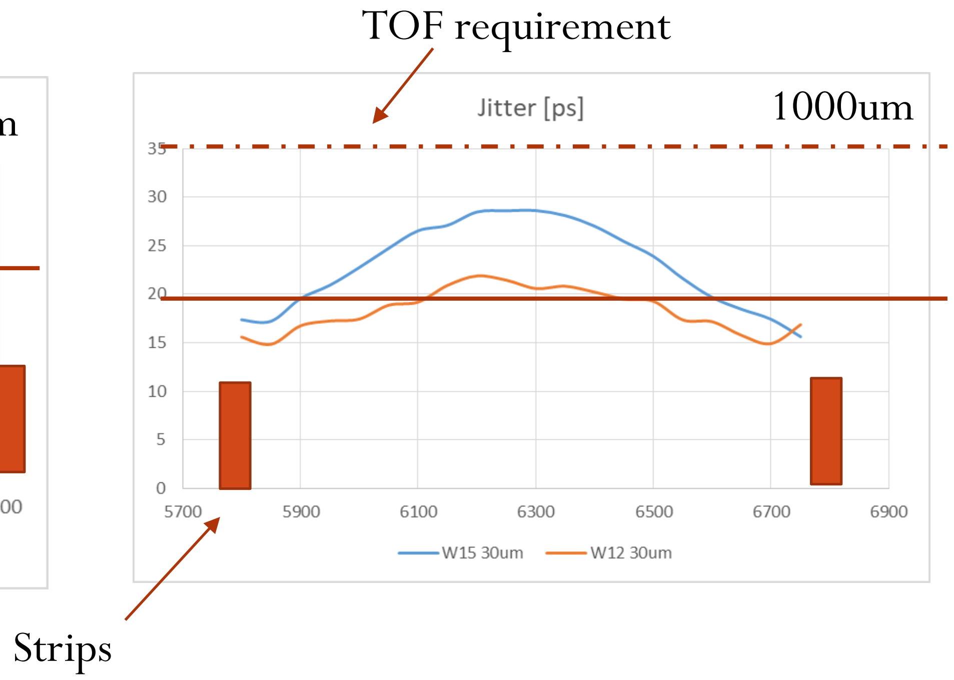
Student: G. Stage, A. Borgijin

HPK production results - TCT

- Measuring the Jitter as $\sigma_{\mathrm{T}} = Rise_T/(\frac{S}{N})$
- Only measured in-between strips
- Assuming 60mV signal under strip for 50um sensor (input from Jlab testbeam), adjusted for thickness for 30um
  - 500ps rise for 50um and 300ps rise for 30um



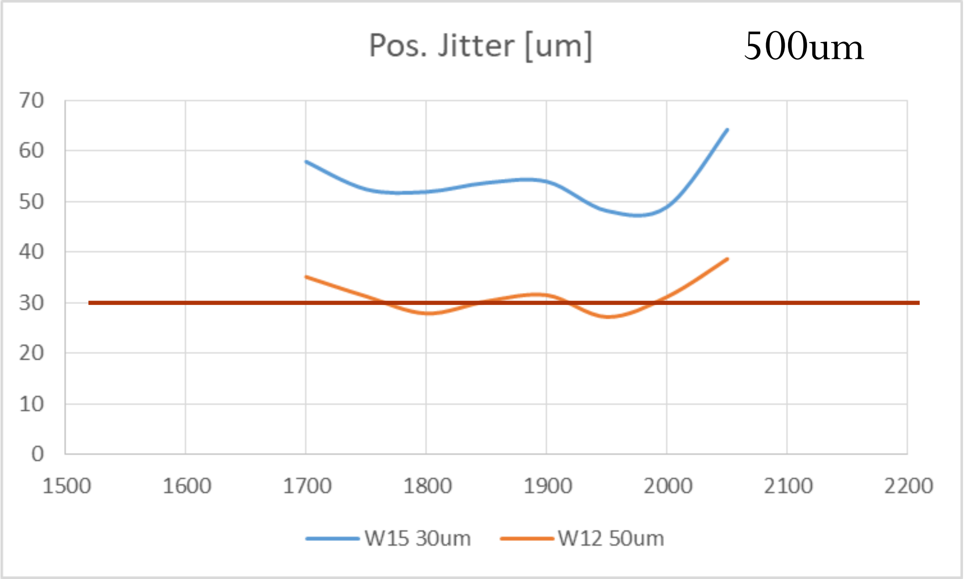


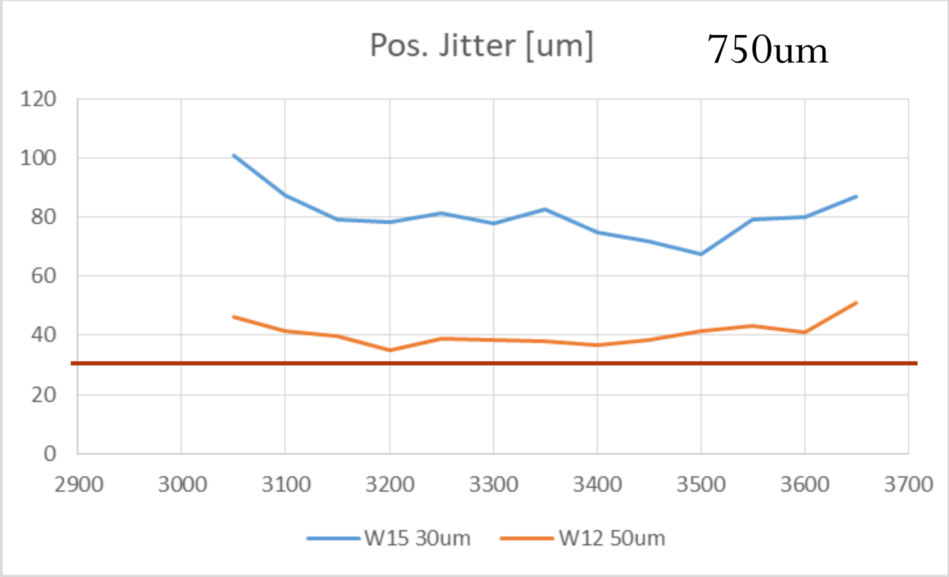


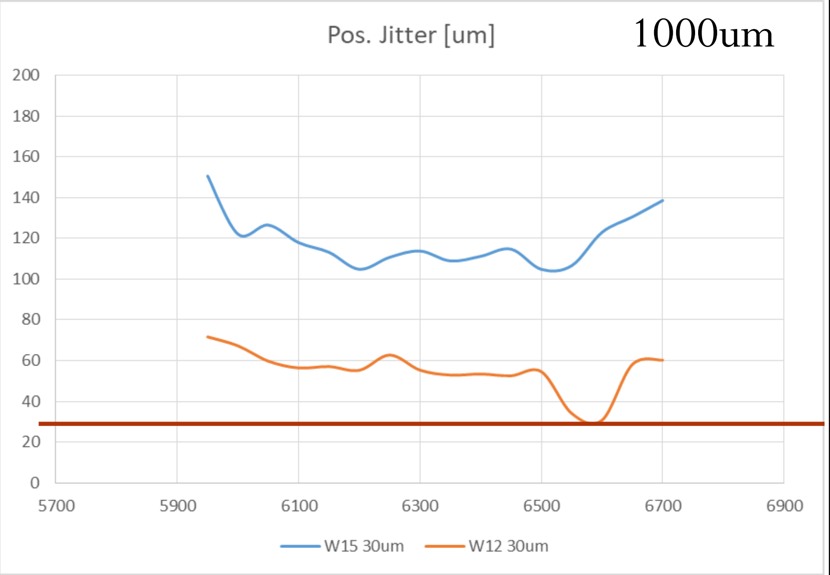
Student: G. Stage, A. Borgijin

HPK production results - TCT

- Measuring the position resolution as position Jitter
- $\sigma_J(pos) = \sqrt{2}\left(\frac{dPos}{dFrac}\right) * \frac{1}{S/N}$
- Assuming 60mV signal under strip for 50um sensor (input from Jlab testbeam)







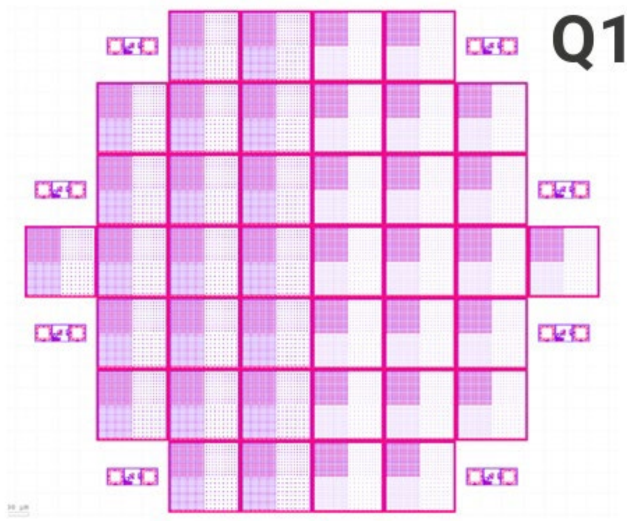
Method explained in https://doi.org/10.1016/j.nima.2024.169478

Student: G. Stage, A. Borgijin

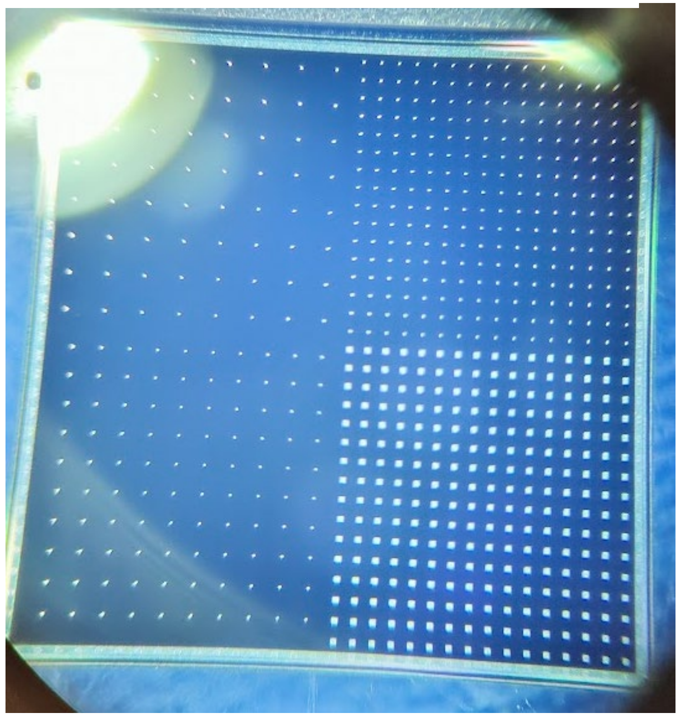
Pixel production

- ePIC full-size production of pixel AC-LGADs from HPK with devices up to 1.6x1.6 cm
  - Pixel pitch and width: 50,100,150um, pitch 500, 750, 1000 um
- 4 wafers in hand, two 30um thick and two 20um thick
- All devices tested with IV
  - Yield >80% for all wafers
- CV and pixel capacitance still to be measured

Detector type	Thickness	Pitch-width 1 “Legacy”	Pitch-width 2	Pitch-width 3	Pitch-width 4
W3 pixBIG	20um	500-150	500-100	750-100	1000-100
W3 pixSmol	20um	500-150	500-50	750-50	1000-50
W7 pixBIG	30um	500-150	500-100	750-100	1000-100
W7 pixSmol	30um	500-150	500-50	750-50	1000-50



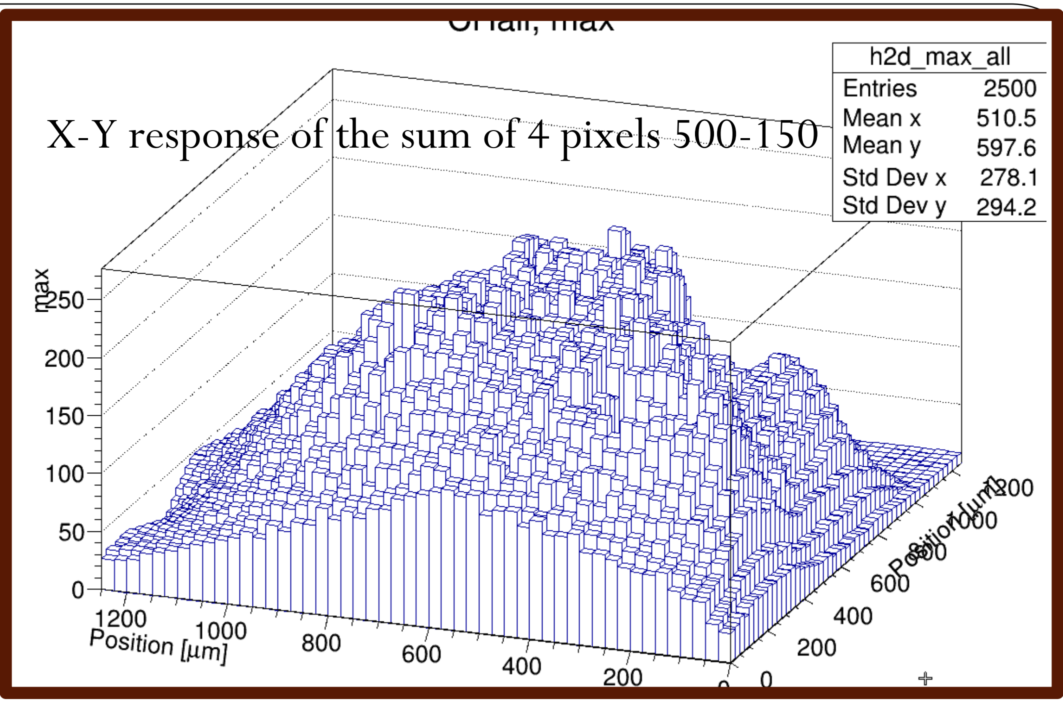
HPK Sensor production for pixel ongoing, first trials with EICROC1 when available (Q4 2025)



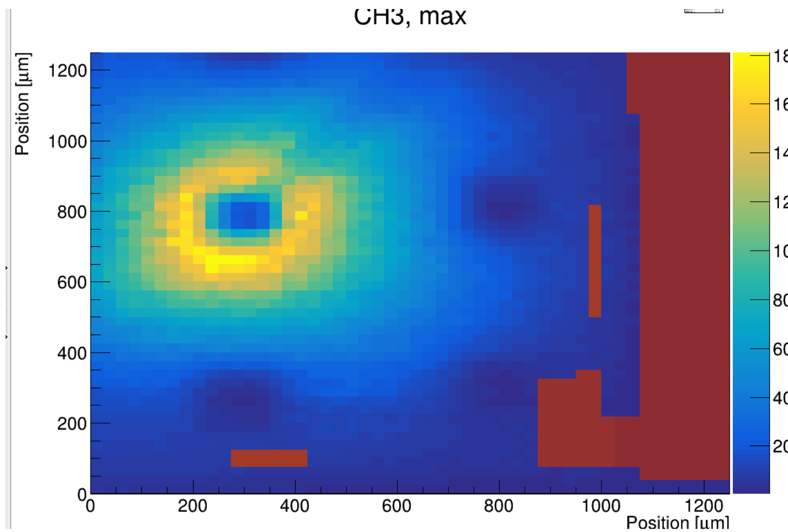
Students: N. Lynch, A. Drumm, Y. Spinos, O. Khandelwal

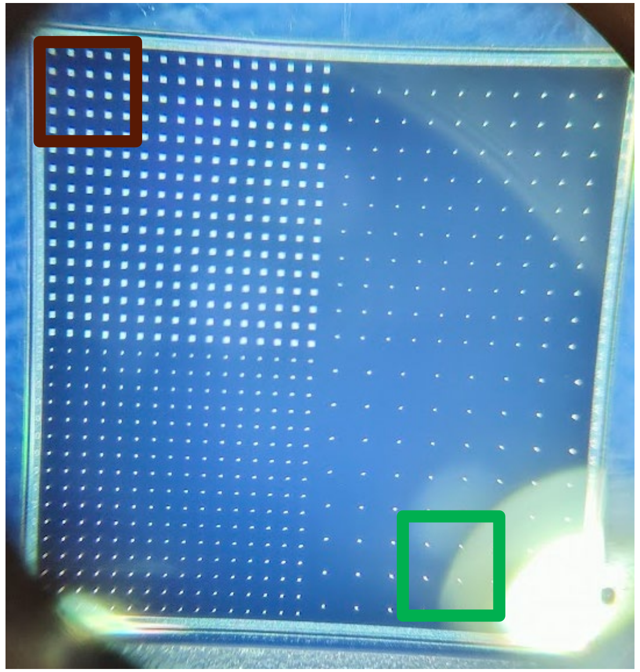
Pixel results - TCT

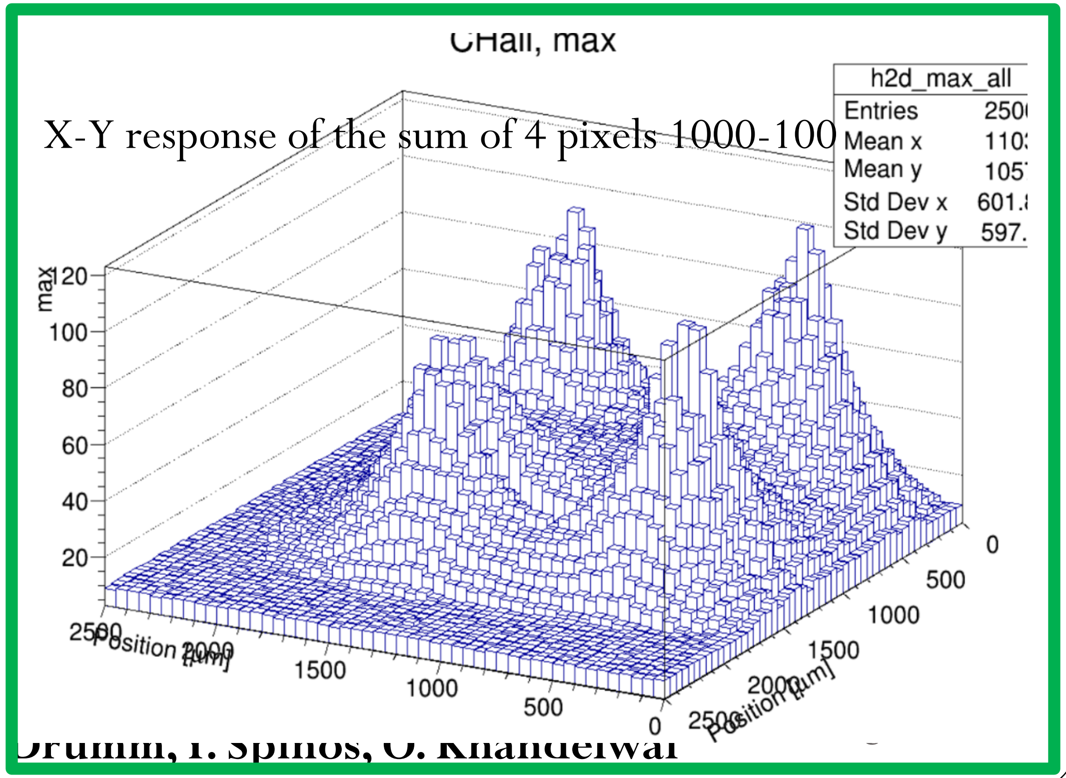
- Full size sensors tested on a large board with laser TCT
- Sensor: W7 (30um) – big pixels
- 500-150 ("legacy") vs 1000-100
- Large loss of S/N if distance is increased and pixel size is decreased
- **Rise time ~300ps for both thicknesses**
- **Signal propagation is similar for all geometries**



X-Y response of a single pixel 500-150



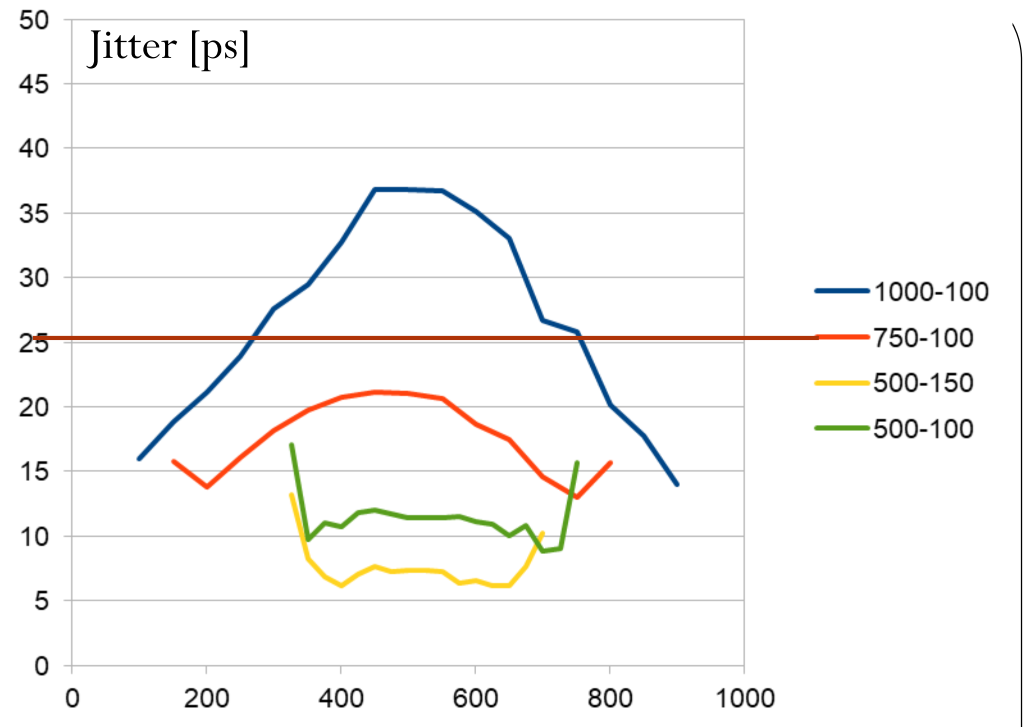


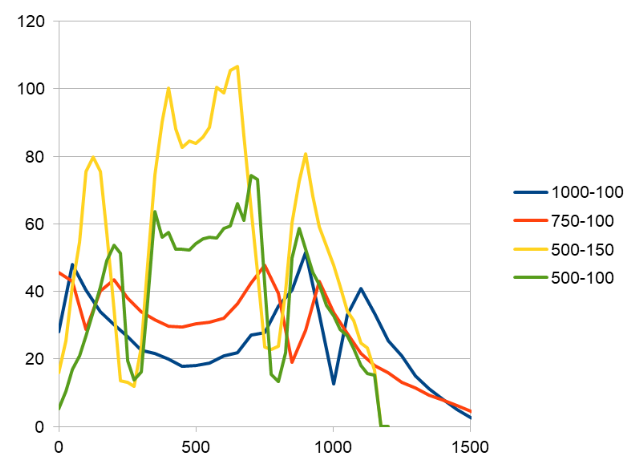


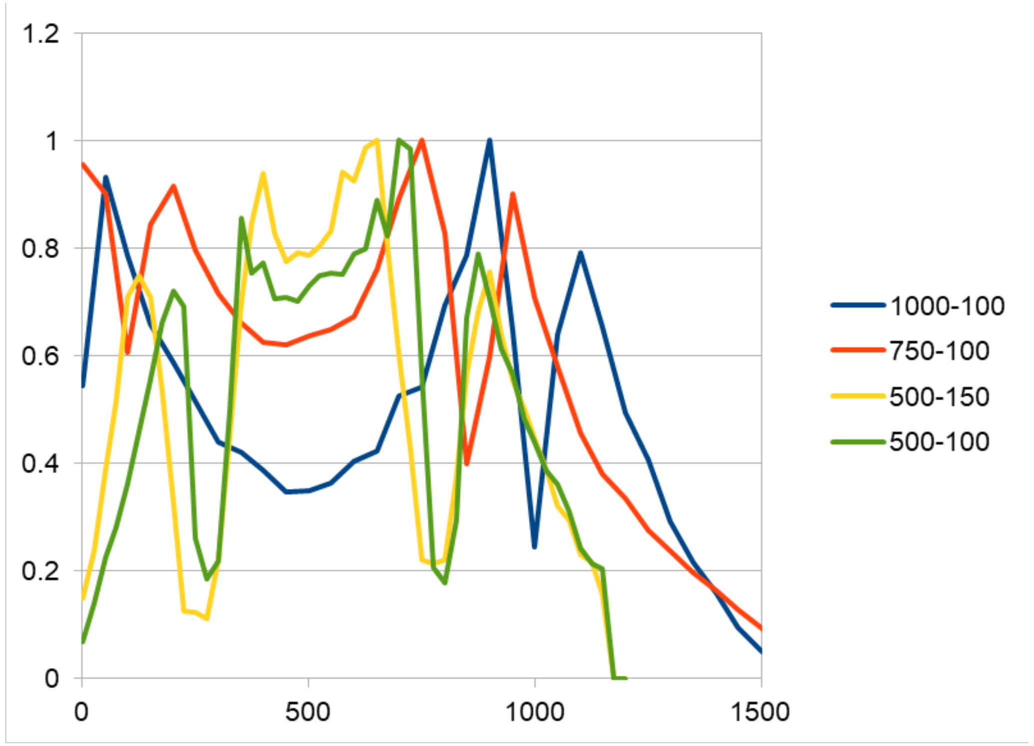
Students: N. Lynch, A. Drumm, T. Spinos, U. Khandelwal

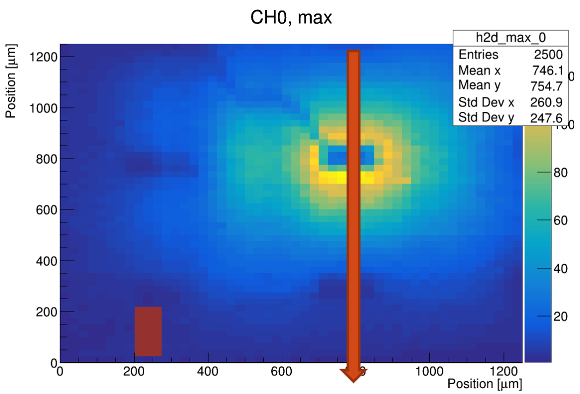
HPK pixel production results - TCT

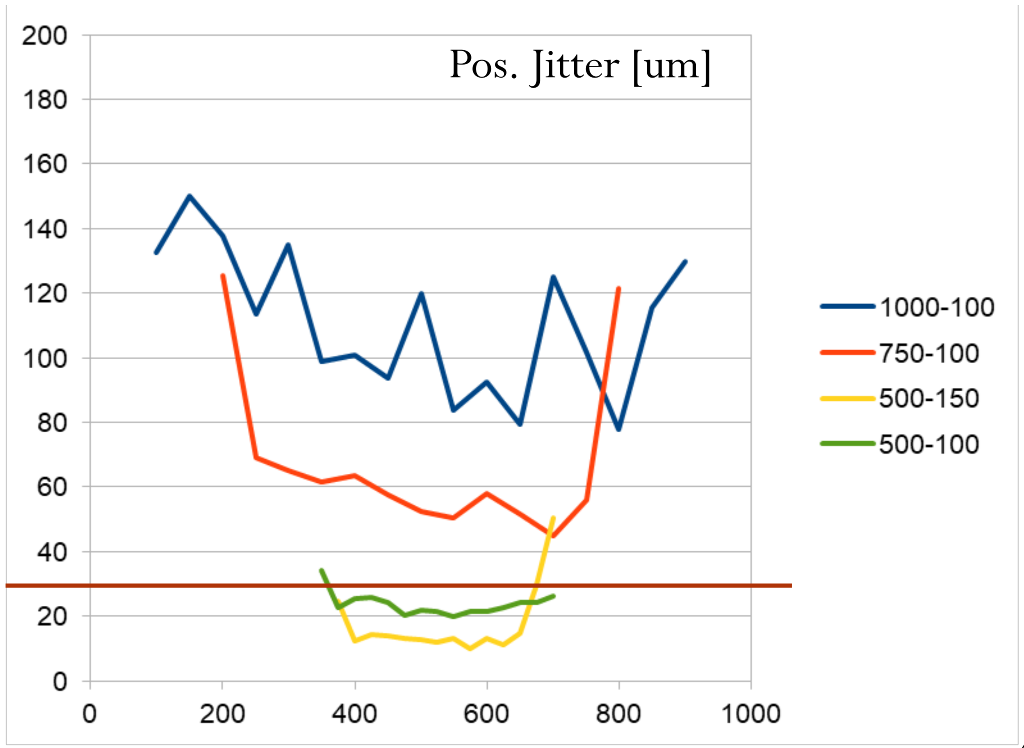
- W7 (30um) large pixels: S/N loss between pixels
- Measuring the Jitter and position Jitter as before in-between pixels
- Assuming 100mV signal near pixel for 500-150um configuration
- Performance of smaller (100um) pixels for 500um pitch is similar to “legacy” geometry, but up to 60% S/N loss for larger pitch









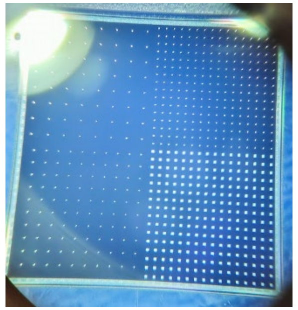


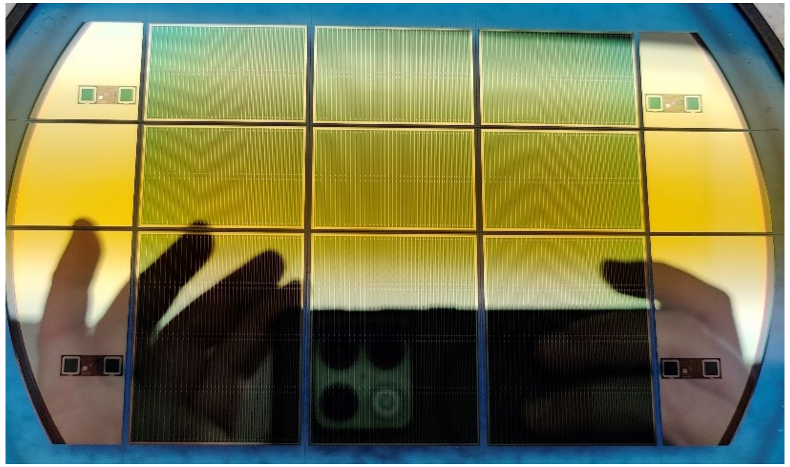
W7 (30um) pixSmol | W7 (30um) pixBIG | W3 (20um) pixSmol | W3 (20um) pixBIG

All signals normalized to have 100mV of signal near 500-150um geometry

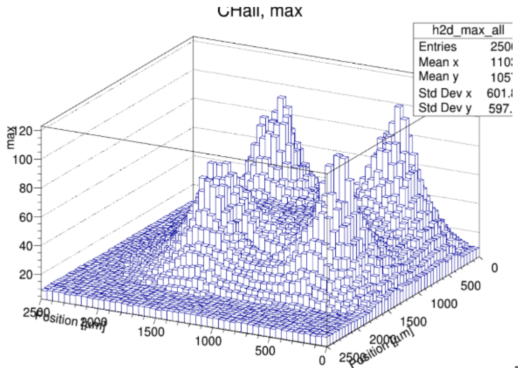
Conclusions

- Sensors for the ePIC TOF layers are reaching maturity
  - Tested effect of radiation damage on AC-LGADs, no unforeseen effect observed (especially for low radiation level at ePIC)
  - Received first large-scale AC-LGAD production from HPK, first results are good → <u>**still a lot to test!**</u>
- Test beam just completed at Jlab for first few full size strip detectors
  - Expect results for CPAD
- Another test beam planned this year at DESY and Tohoku University for full-size sensor testing and readout electronic testing
  - Can only do so much with laser in the lab…





- An additional HPK production is ongoing, will receive devices soon
- Another FBK production is ongoing→ allow for another vendor characterization




SCIPP
SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS
UC SANTA CRUZ
Thanks for the attention

Many thanks to the SCIPP group students and technicians!
In particular to students:
J. Ding, G. Stage, A. Borjigin, C. Altafulla, M. Davis, S. Beringer
N. Lynch, A. Drumm, Y. Spinos, O. Khandelwal

Thanks to HPK for fabricating sensors for this study

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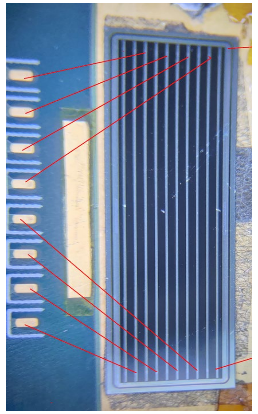
This work was supported by eRD112 funds from EIC and PED program

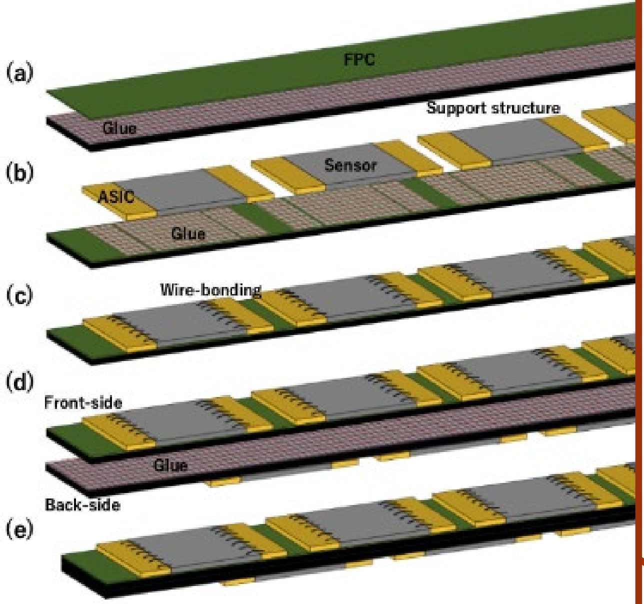
Thanks to IJS (G. Kramberger, I. Mandic) and UNM (S. Seidel) for providing sensor irradiation at Lubjiana and FNAL ITA

This project has received funding from the European Union's Horizon Europe Research and Innovation program under Grant Agreement No 101057511 (EURO-LABS).

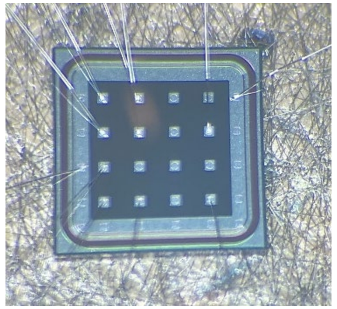
Backup

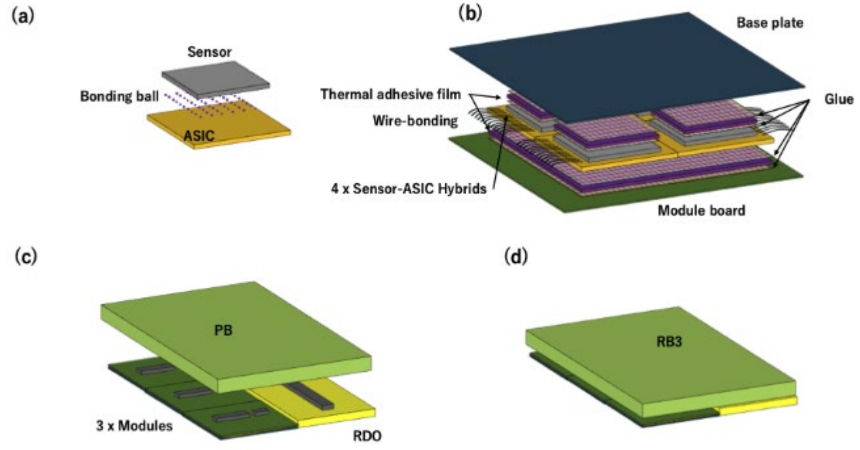
TOF layout in ePIC



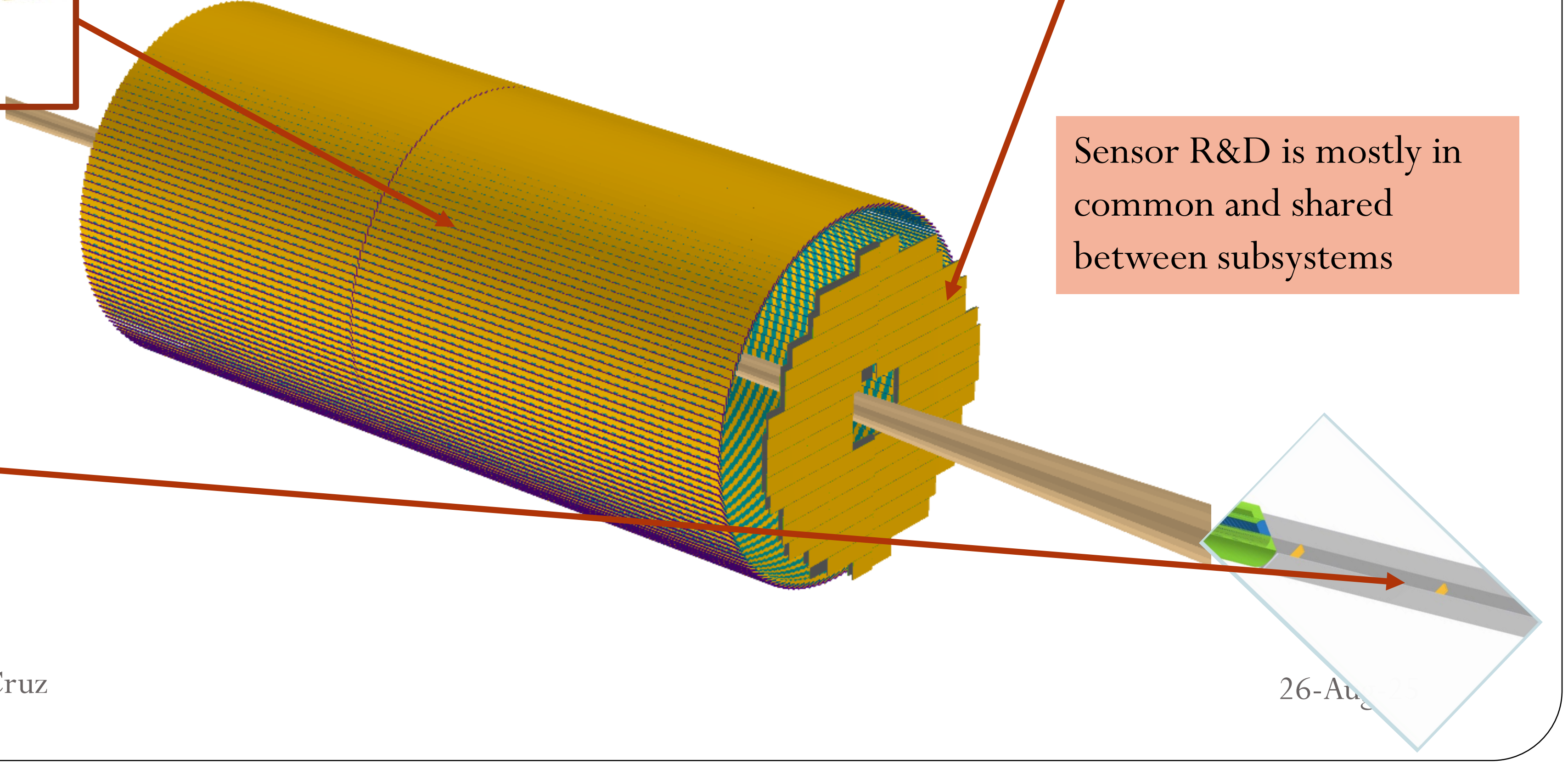


Sensors: strips
Readout: FCFD

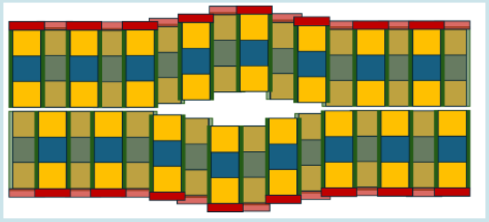




Sensors: pixels
Readout: EICROC



Sensor R&D is mostly in common and shared between subsystems

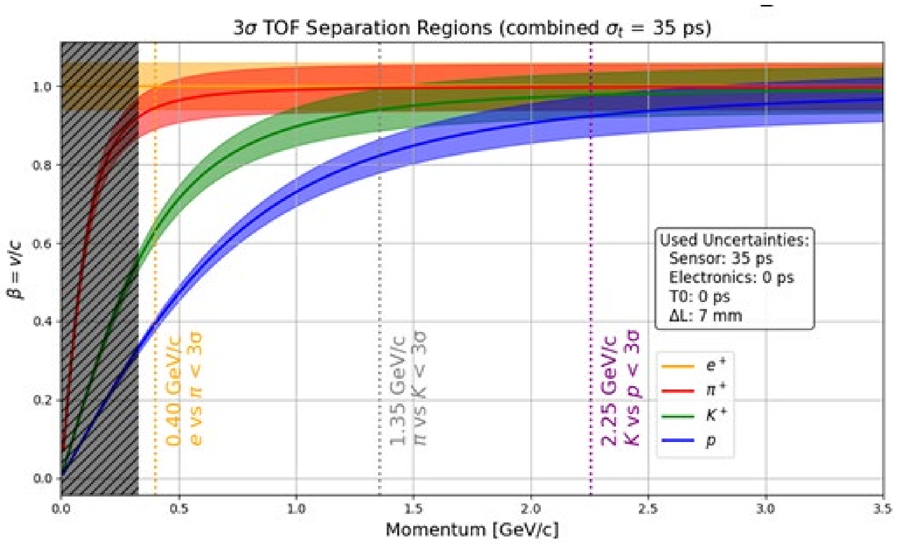


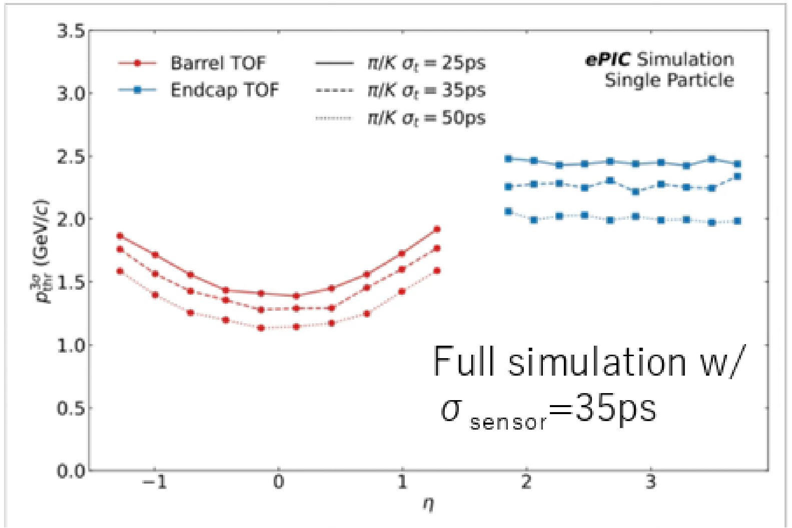
Sensors: pixels
Readout: EICROC

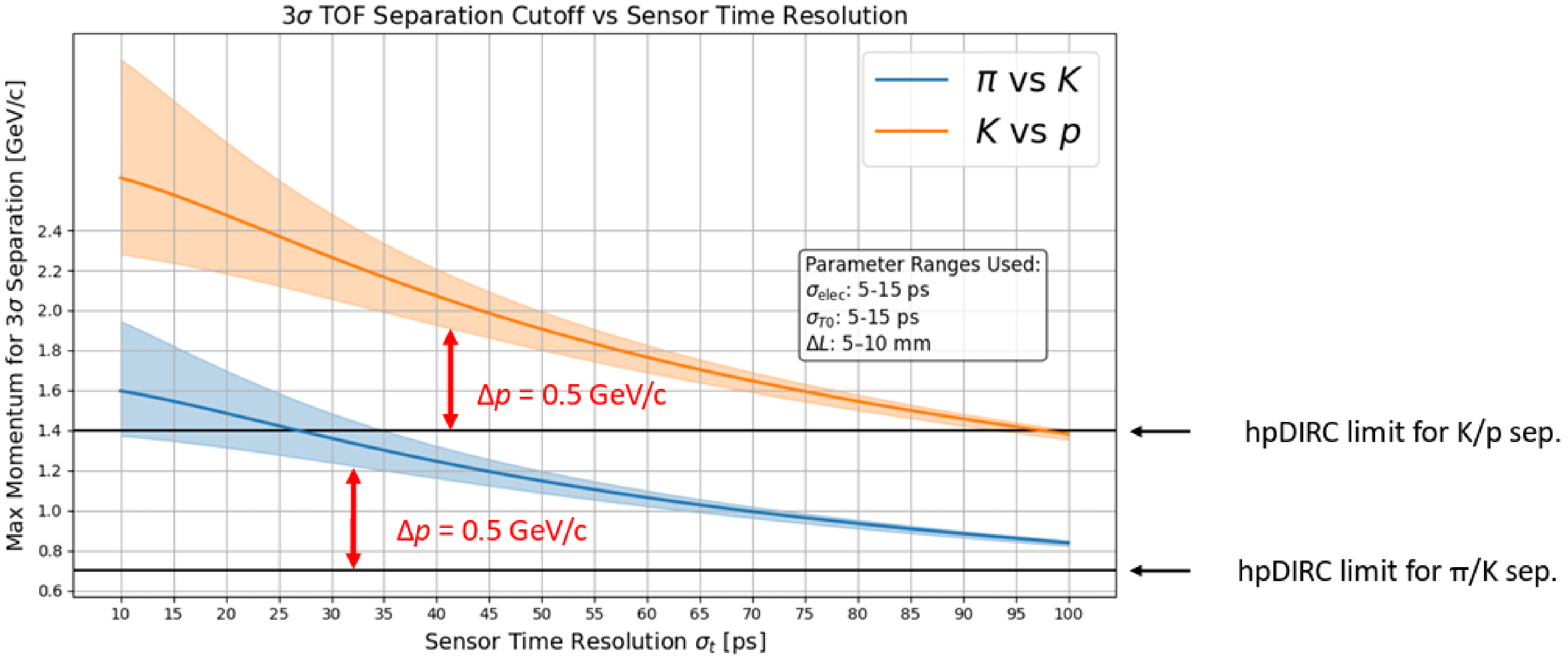
Off-Momentum Detectors (OMD)

Why TOF?

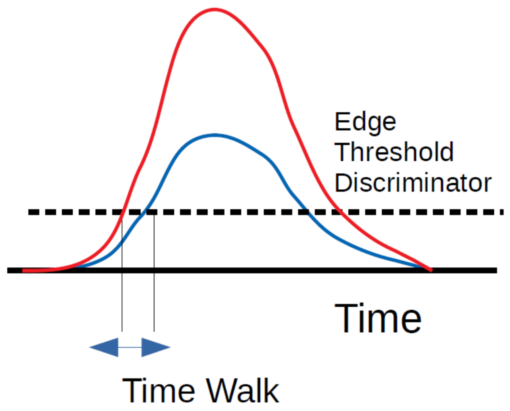
- Heavy flavor (HF) measurement is the most important subject at EIC
  - Identification of HF hadrons decay products with TOF PID
- BOTF default performance: 35ps
  - e/PI separation up to 0.4 GeV
  - Pi/K separation up to 1.35 GeV
  - K/P separation up to 2.25 GeV
- Improves the hpDIRC particle ID by over 0.5 GeV
- Better time resolution increases the range of separation
  - Study in progress to understand exact requirements

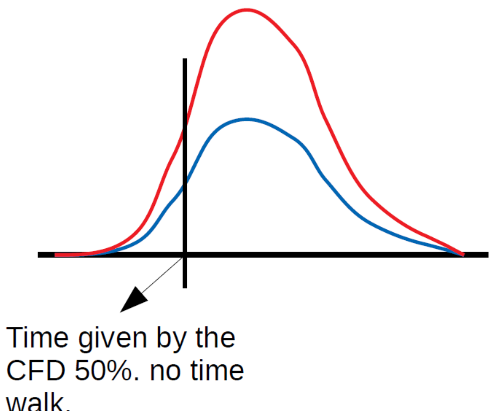


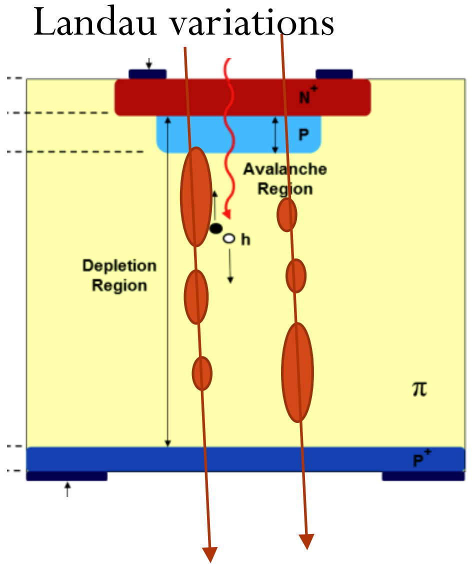


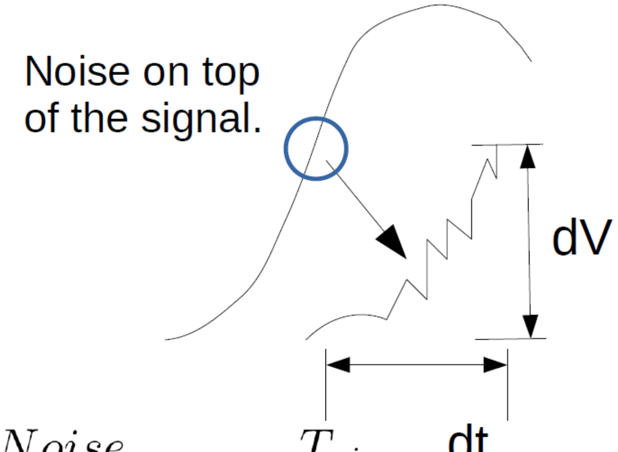


Time resolution









$$\sigma_{Jitter} = \frac{Noise}{dV/dt[CFD\%]} \approx \frac{T_{rise}}{SNR}$$

Sensor time resolution main terms

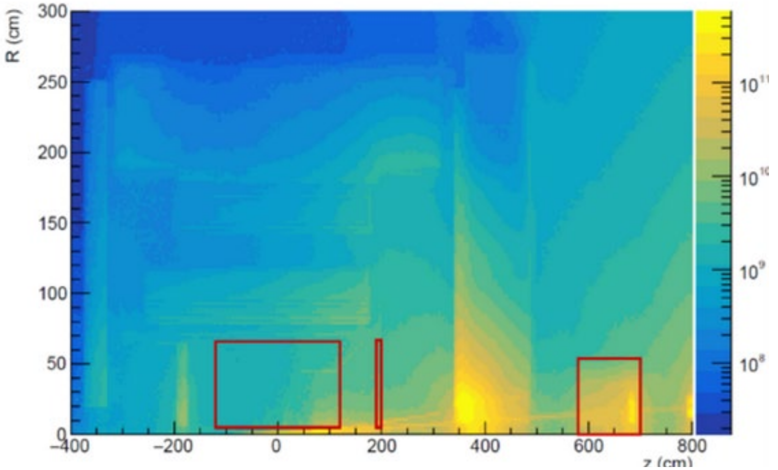
$$\sigma^2_{timing} = \sigma^2_{time\,walk} + \sigma^2_{Landau\,noise} + \sigma^2_{Jitter} + \sigma^2_{TDC}$$

- **Time walk**:
  - Minimized by correcting the time of arrival using pulse width or pulse height (e.g., use 50% of the pulse as ToF)
- **Jitter**: from electronics
  - Proportional to $^1/_{\frac{dV}{dt}}$
  - Reduced by increasing S/N ratio with gain
- **TDC term**: from digitization clock (electronics)
- **Landau term**: proportional to silicon sensor thickness
  - Reduced for thinner sensors
  - Dominant term at high gain

- **Bottom line: thin detectors with high S/N**

Radiation levels at ePIC

- Radiation hardness of LGADs has been studied and optimized extensively for the HL-LHC timing end cap upgrades in ATLAS and CMS
  - Relatively large-pad, conventional (DC-coupled) LGADs
- At the EIC radiation levels will be much lower than at the LHC (< 5e12 cm^{-2} over their lifetime)
  - AC-LGADs with resistive n^+ layer, which may be susceptible to radiation damage by changes in the n^{++}/n^+ electrode and the coupling dielectric
- HPK (and BNL) strip and pixel sensors were irradiated with reactor neutrons at JSI/Ljubljana and at FNAL ITA
- Total fluences between 1e12 and 1e15 Neq – some much higher than envisioned at the EIC over the full time of life
- Thanks to G. Kranberger and I. Mandic for the JSI irradiation
  - Funded by EUROLABS
- Thanks to S. Seidel and J. SI (UNM) for the proton irradiation



RAW fluence			
System	Average	Min	Max
Barrel	5.4×10^{10}	3.4×10^{10}	5.9×10^{11}
End-cap	1.3×10^{11}	5.1×10^{10}	1.6×10^{12}
B0 trackers	3.9×10^{11}	3.3×10^{10}	1.8×10^{12}
NEQ fluence			
System	Average	Min	Max
Barrel	3.6×10^{10}	1.1×10^{10}	1.3×10^{12}
End-cap	1.2×10^{11}	3.2×10^{10}	8.4×10^{11}
B0 trackers	4.5×10^{11}	2.7×10^{10}	4.2×10^{12}

Table 8.2: RAW and NEQ fluence per system for the lifetime of the ePIC experiment, assuming 10 years of data taking at 50% time.

Pixels

Fluence	V(GL)					
	W2	W4	W5	W8	W9	W11
Thickness	**50 µm**	50 µm	**50 µm**	50 µm	**20 µm**	20 µm
Capacitance	**240**	240	**600**	600	**600**	600
N+ resistivity	**2**	0.5	**2**	0.5	**2**	0.5
1.00E+12	54.5	52	54.5	52	53	
1.00E+13	54.5	51.5	54	51.5	53	
1.00E+14	51	50	51.5	49	50	
5.00E+14	41		42.5		41	38.5
1.00E+15	32				34	31

Strips W2

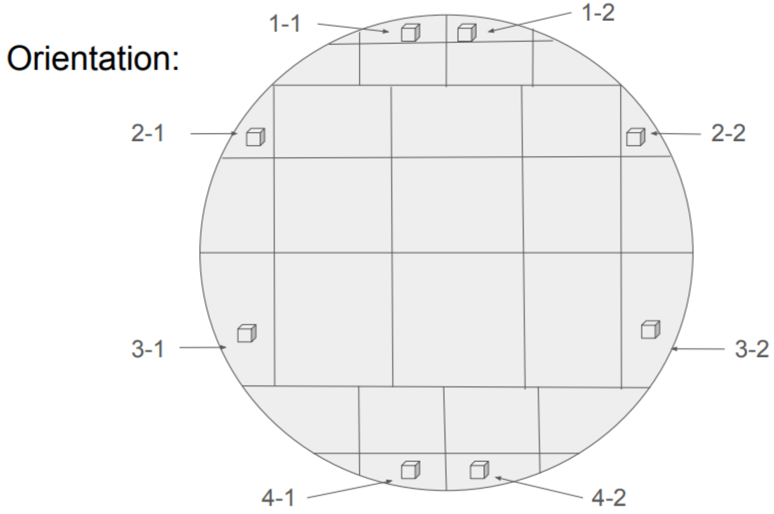
Fluence	0.5 cm	1 cm	2 cm
1.00E+14	52	52	
5.00E+14	44		48
1.00E+15		38	42

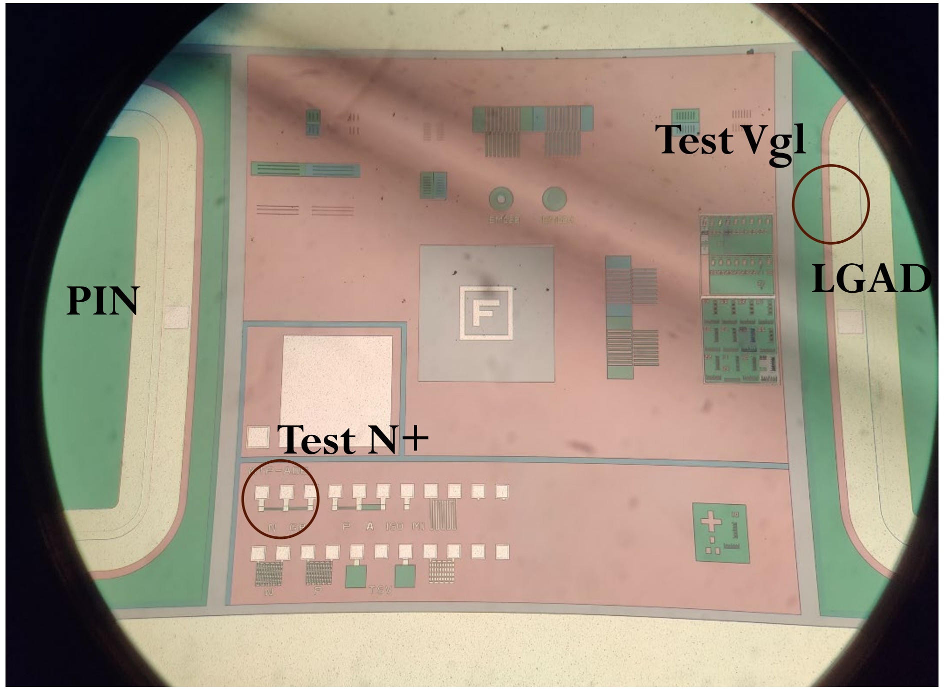
Strips W5

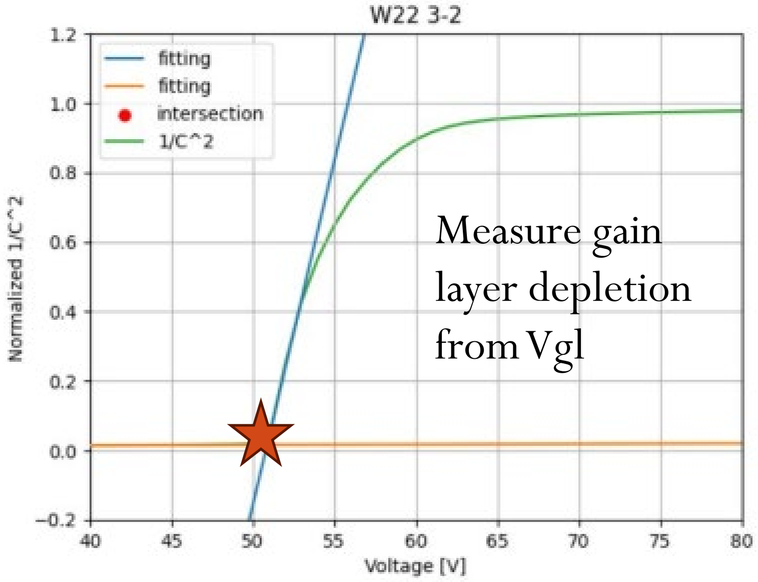
Fluence	0.5 cm	1 cm	2 cm
1.00E+12	54	54	
1.00E+13	42		54
1.00E+14		52	53

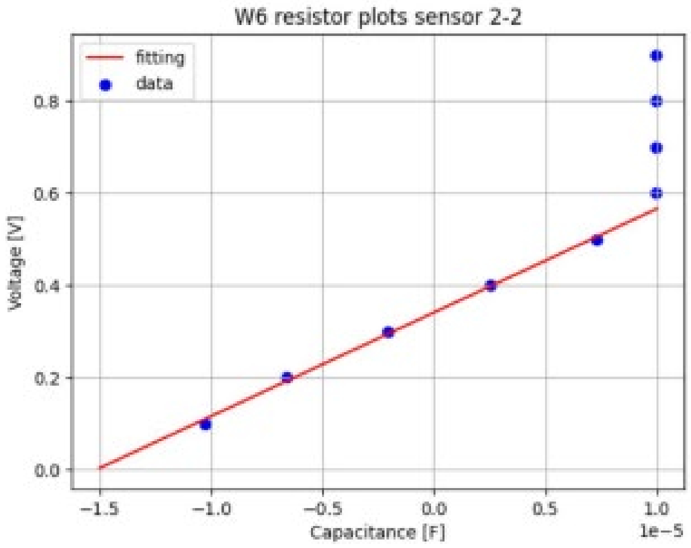
HPK production testing

- **Check gain and N+ homogeneity** across the wafer and between the wafers
  - Wafer edge is usually the most sensible
- Using test structures at the edge of the wafer to test gain and N+ resistivity
  - Measure Vgl of the LGAD test structure
  - Measure current vs voltage for N+ test







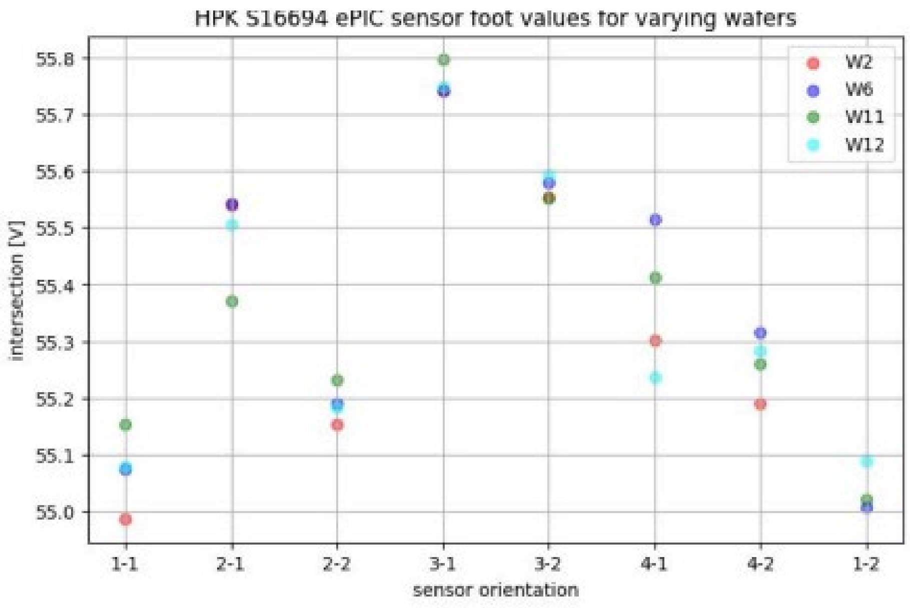


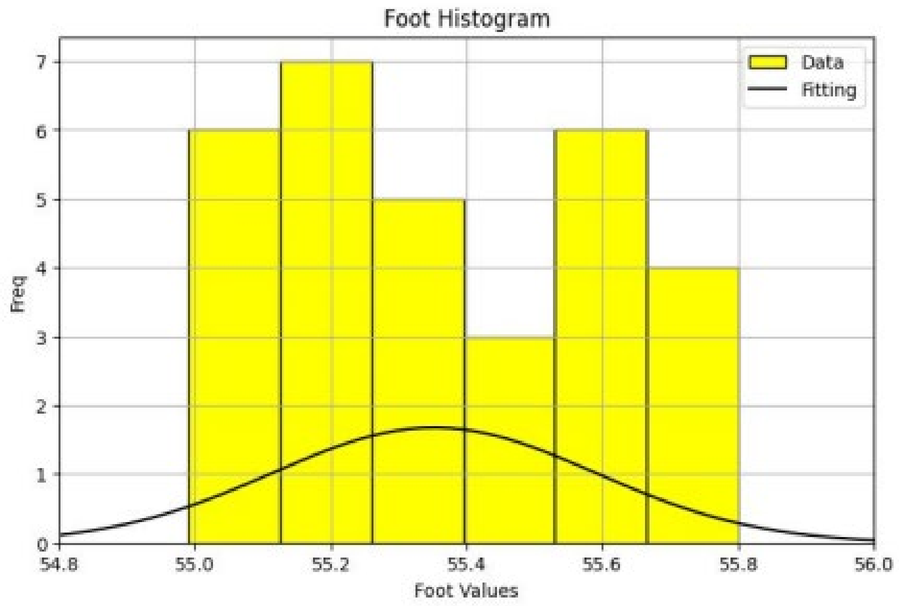
$V(I) = 22504*I + 0.341$

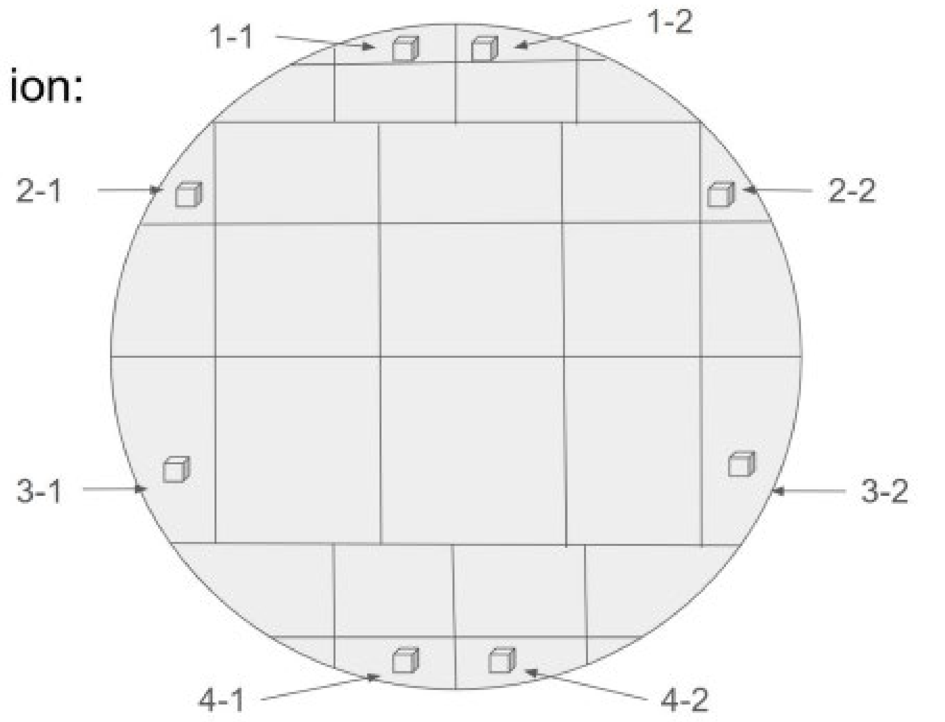
Student: M. Davis, S. Beringer

Gain layer test

- 50um wafer
- 0.4% variation
- Minor change across wafer that is consistent on all wafer
- Slight mis-alignment of implanter beam and wafer?
- Similar variation for 30um wafer



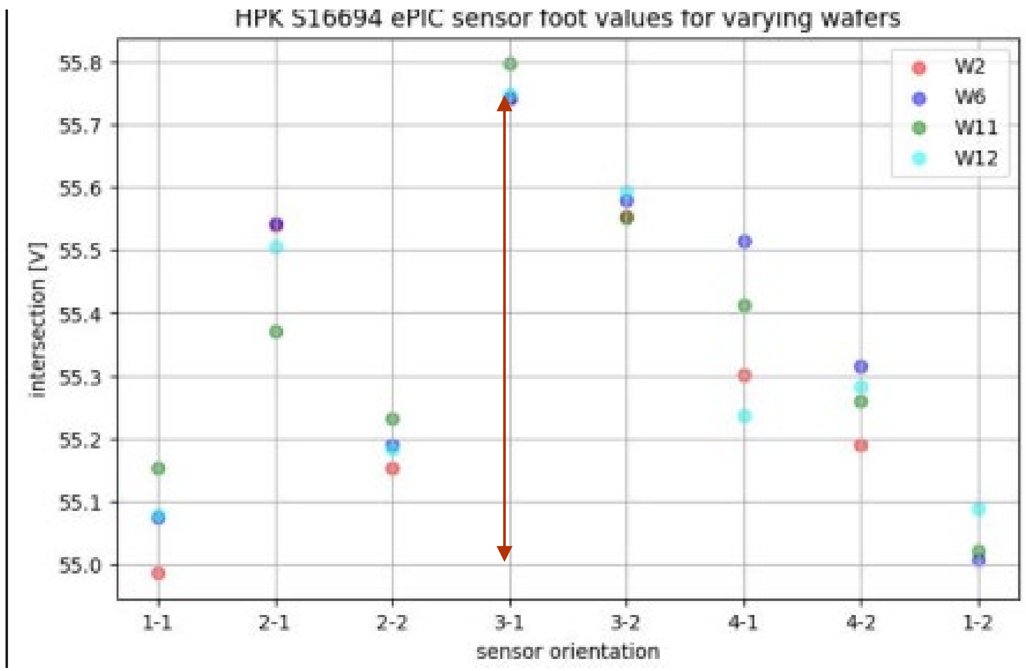




Mean = 55.26
Sigma = 0.23

Student: M. Davis, S. Beringer

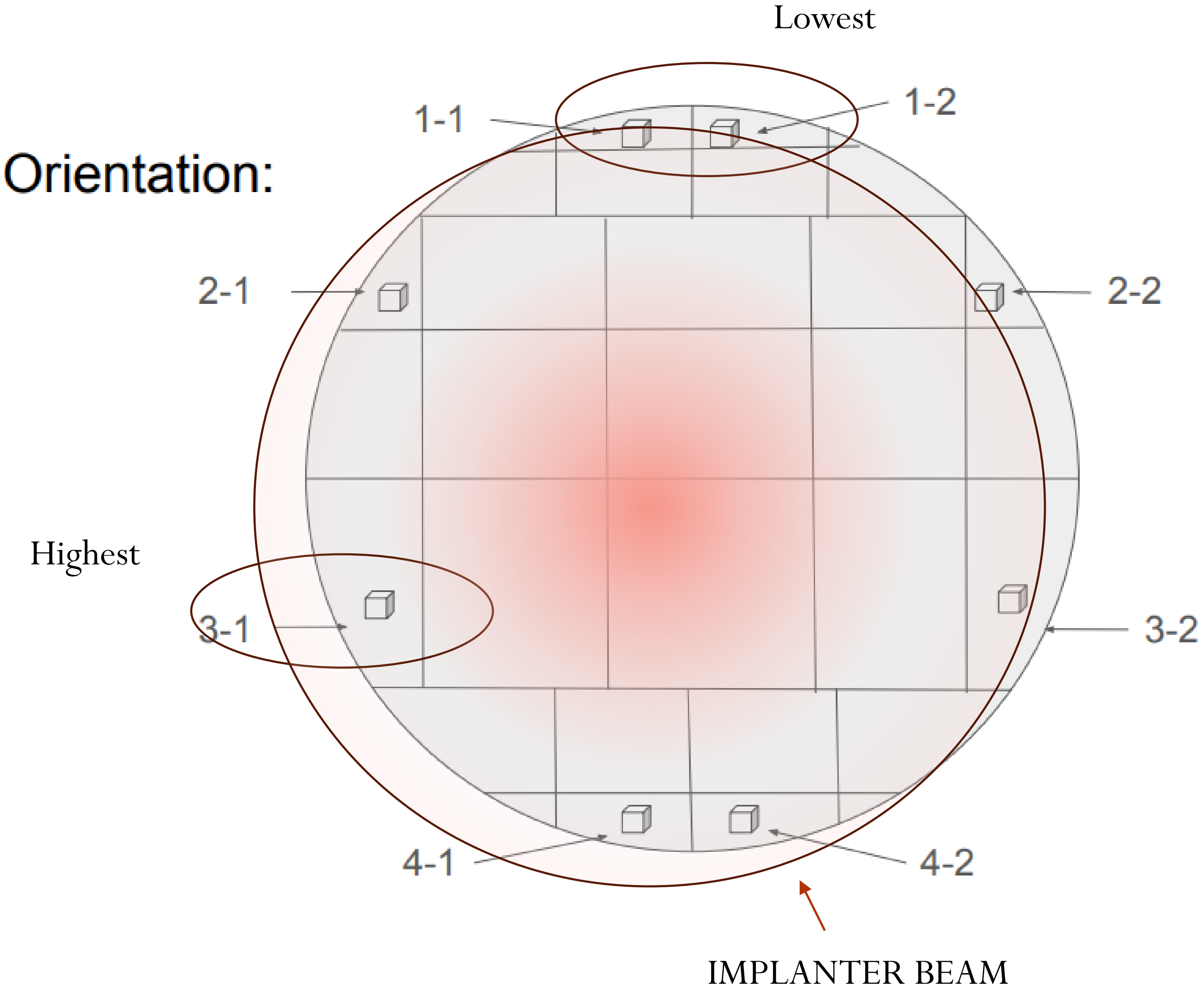
Gain test



Max variation ~1%

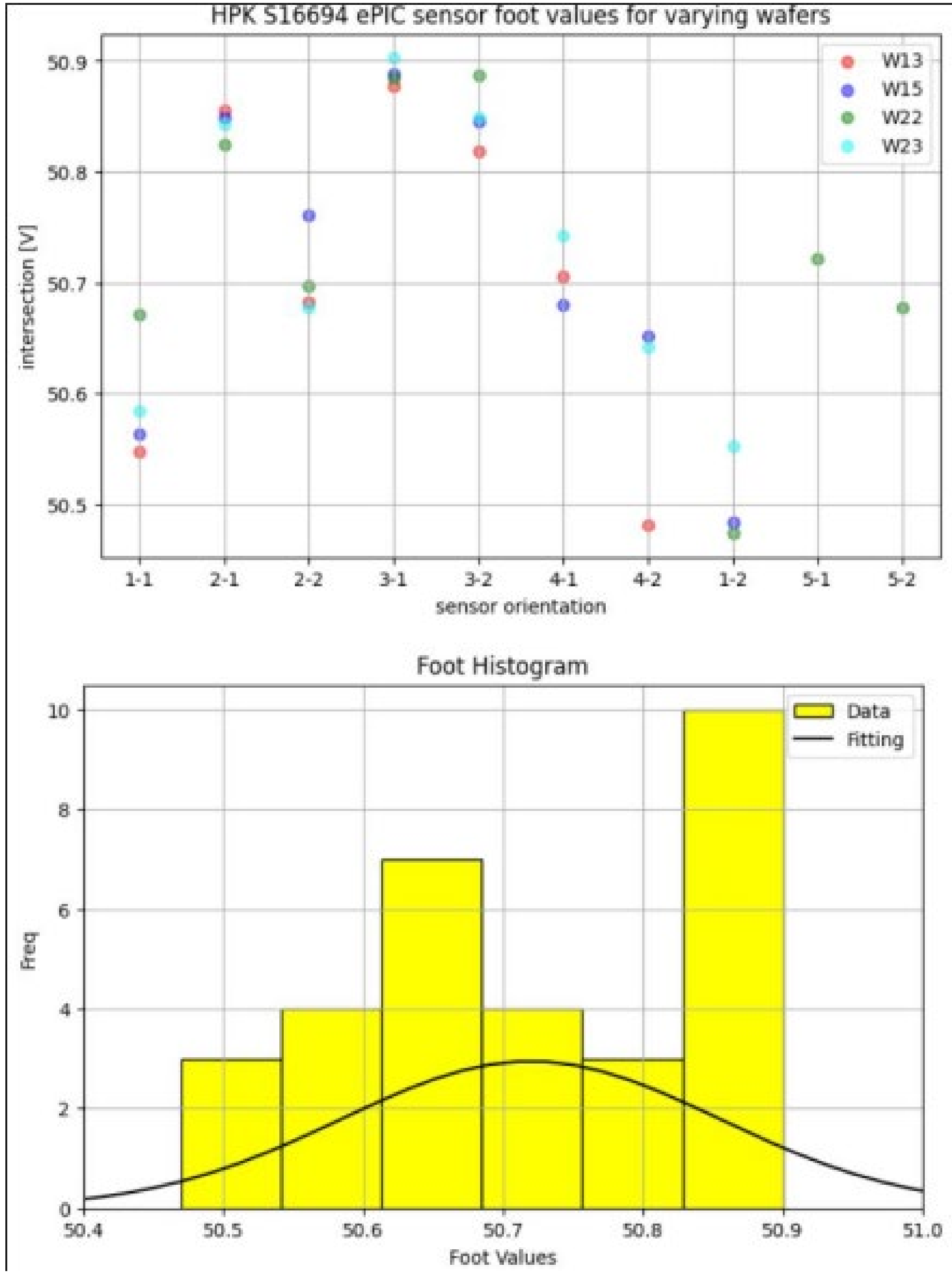
Very likely not an issue across the sensor

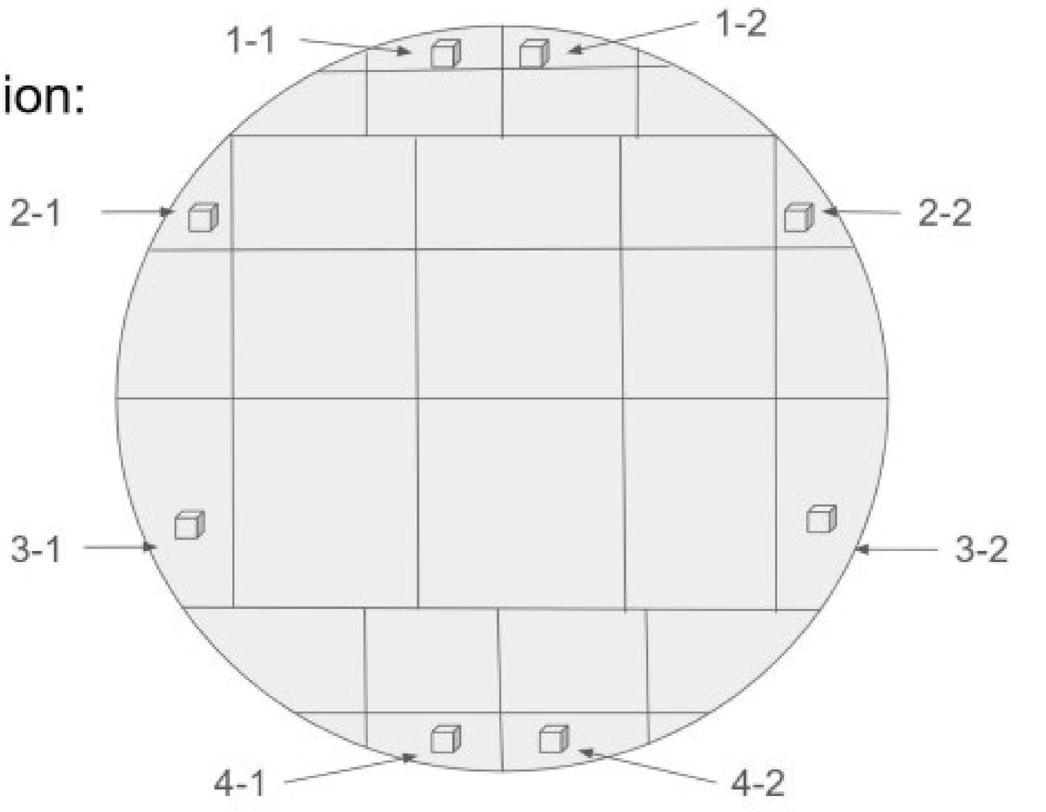
Might be valuable input to HPK



Gain test

- 30um wafers
- 0.2% variation
- Similar consistent inhomogeneity across wafers

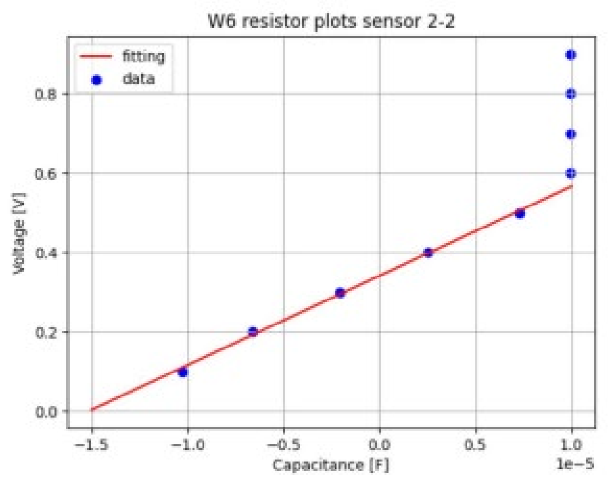




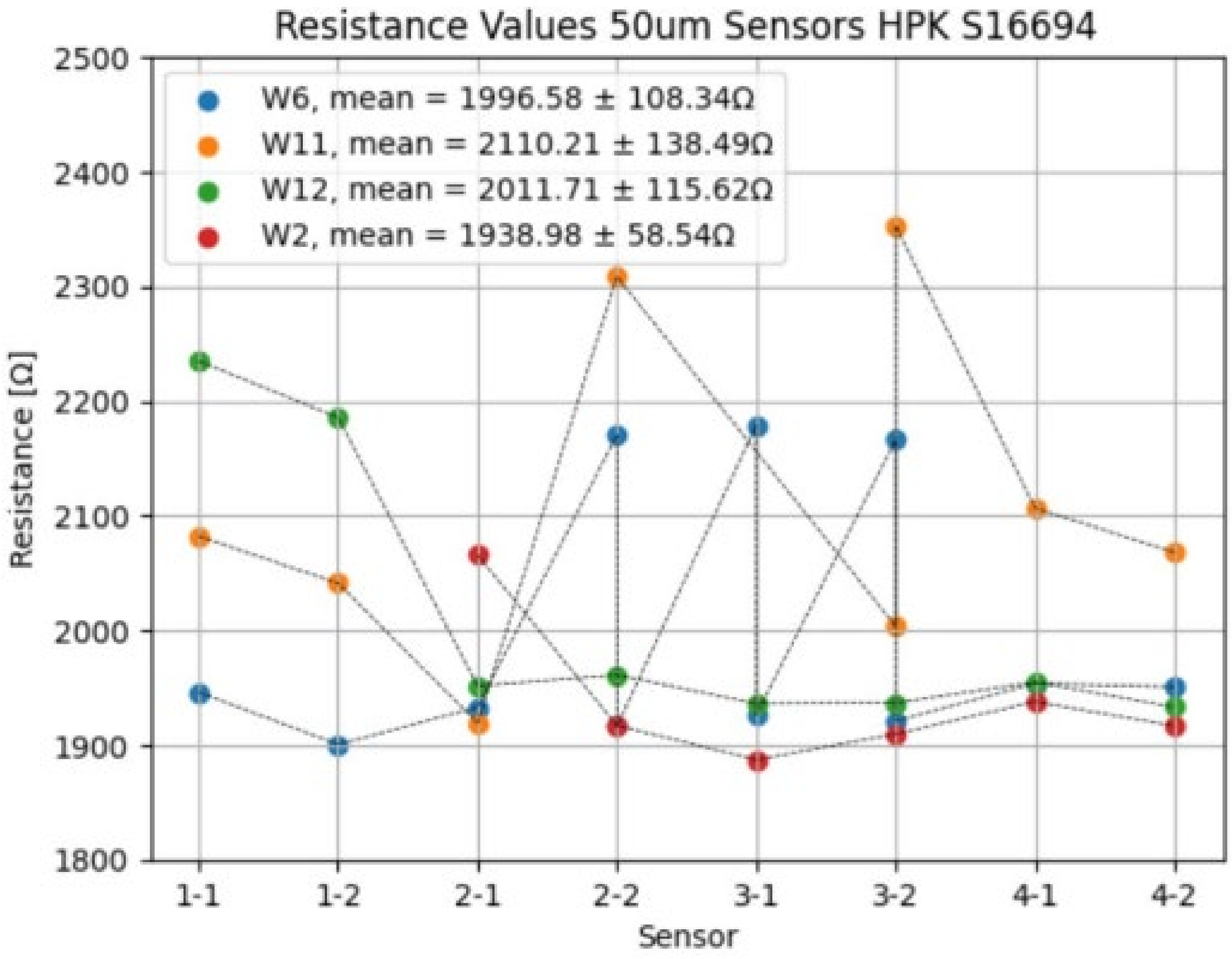
Mean = 50.72
Sigma = 0.13

N+ resistivity test

- Measuring resistivity for all 50um wafers
- Linear fit on the IV in the connection, 10 squares in the line so divide by 10
  - Results in line with HPK specs (~2kOhm)
- Variation on the wafer and across wafers is more prominent than with gain layer
  - Max variation ~10-20%
- Similar variation for 30um wafers



V(I) = 22504*I + 0.341 → R = 2250 Ω

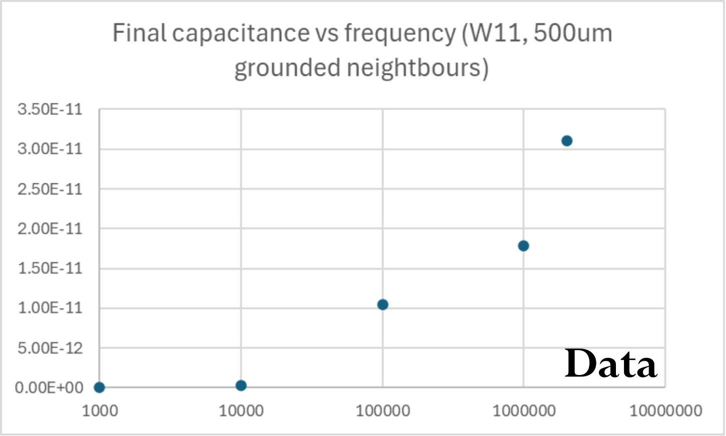


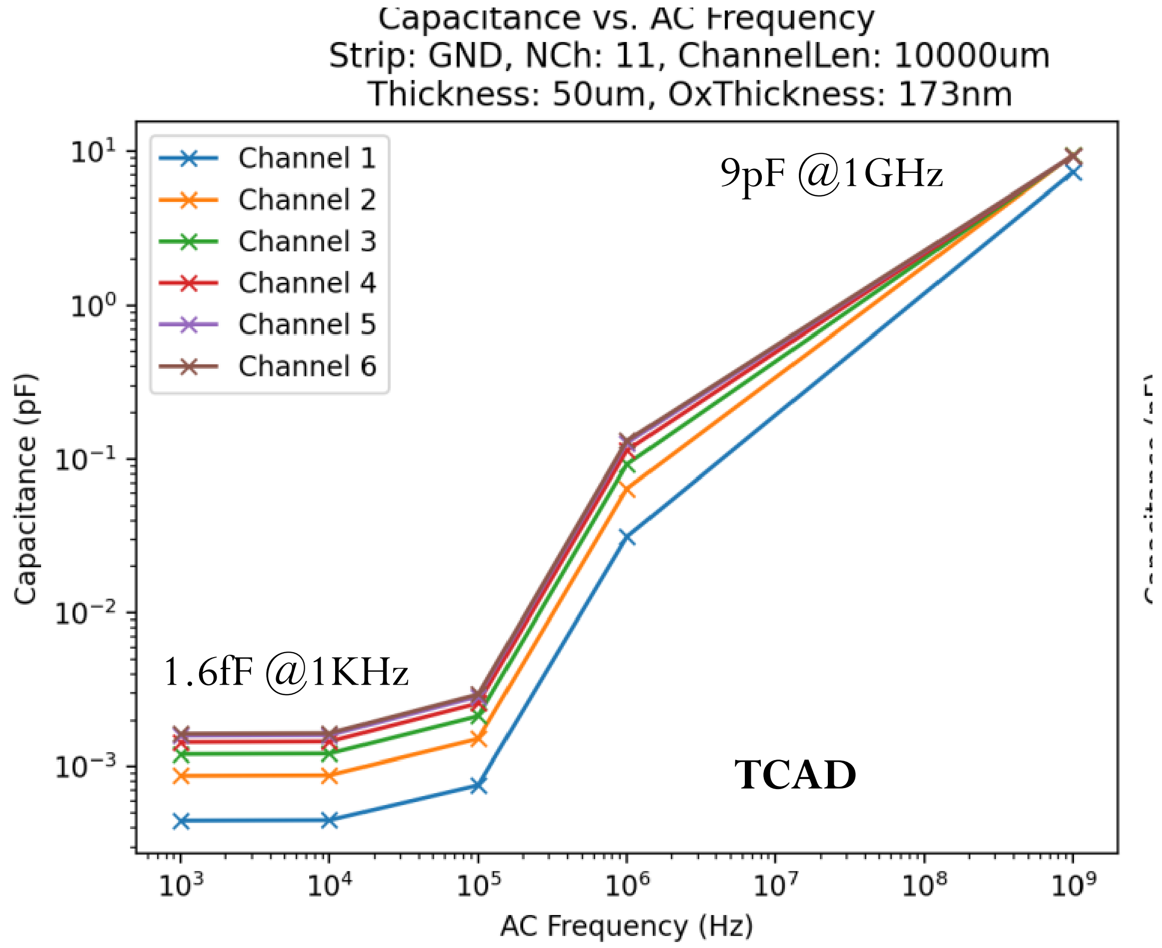
Student: M. Davis, S. Beringer

Strip AC capacitance

- Strip AC capacitance measured from N+ to metal, grounding neighboring strips
  - Large change from 0.05pF to 30pF (max is 2MHz)
- Simulated the strip capacitance using TCAD Sentaurus
  - Using probing frequency but there's no assumption on the circuit (CpRp etc)
  - Can test up to 1Ghz
- Value changes a lot with frequency, in general much smaller (factor ~10) values than data
- Theoretic max capacitance assuming 50um thickness, 500um width and 1cm length is around 10pF
  - Final value at 1GHz for TCAD might be realistic
- → "real" value should be around 10pF,
  - That's FCFD target as well

- 11 Channel Device
- Substrate Thickness: 50 um
- Channel Pitch: 500 um
- Channel Metal Width: 50 um
- Channel Length: 1 cm
- Oxide Thickness: 172.66 nm (600 pF/mm2)
- Single Backside (Anode) electrode
- Dual collection (Cathode) electrodes on the sides
- CVSweep Frequencies: 1e3, 1e4, 1e5, 1e6, 1e9 Hz
- Middle Channel: 50 Ohm terminated
- Other Channels: GND or Floating
- **Mixed Mode** Simulation for AC Sweep

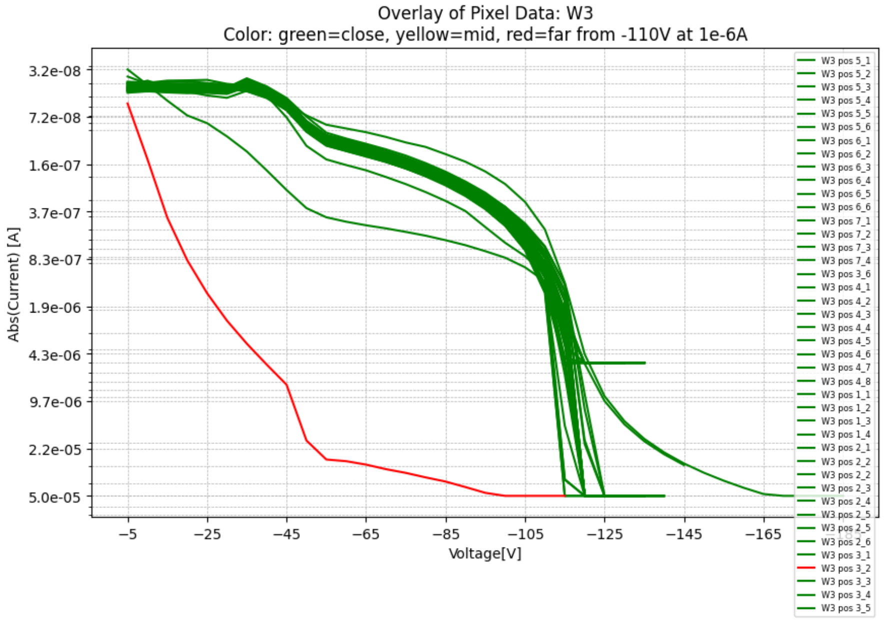


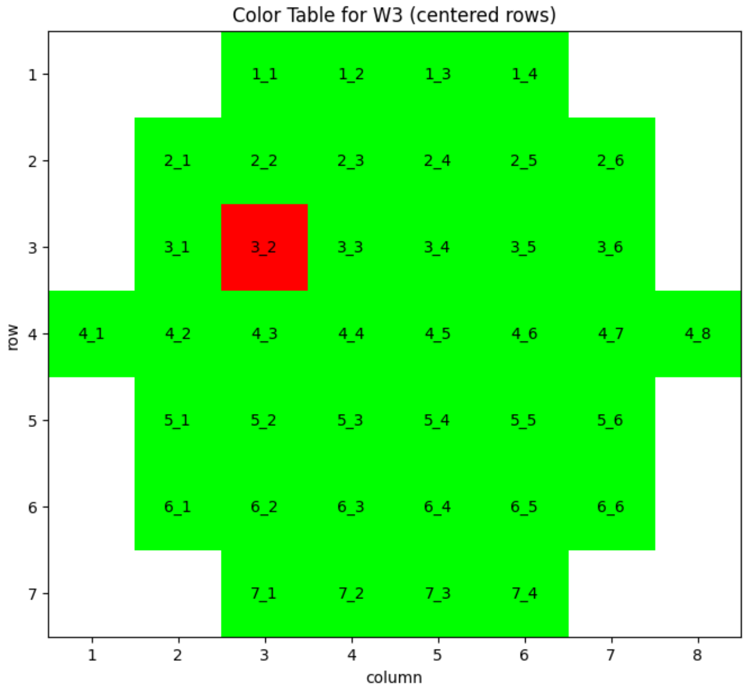


Credits: T. Shin

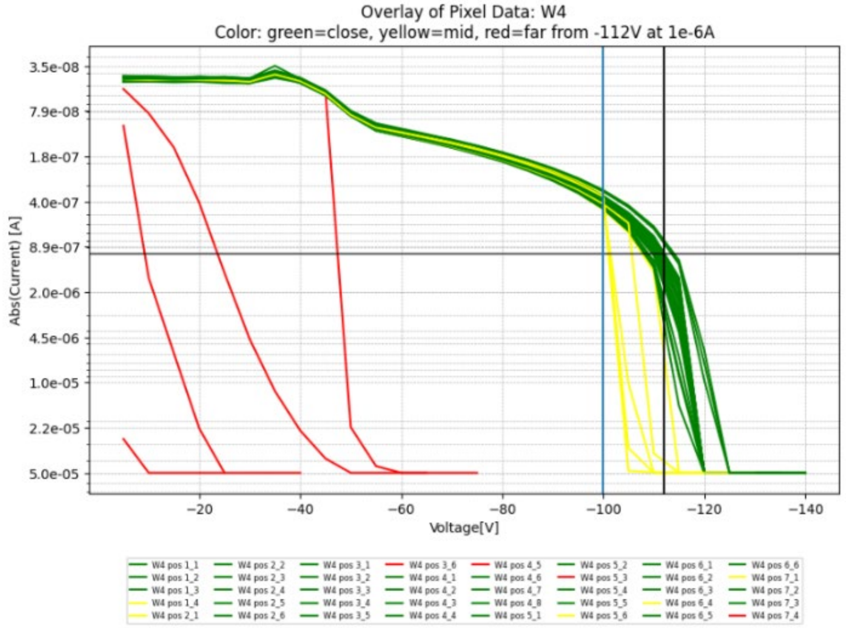
Pixel sensors – 20um wafers

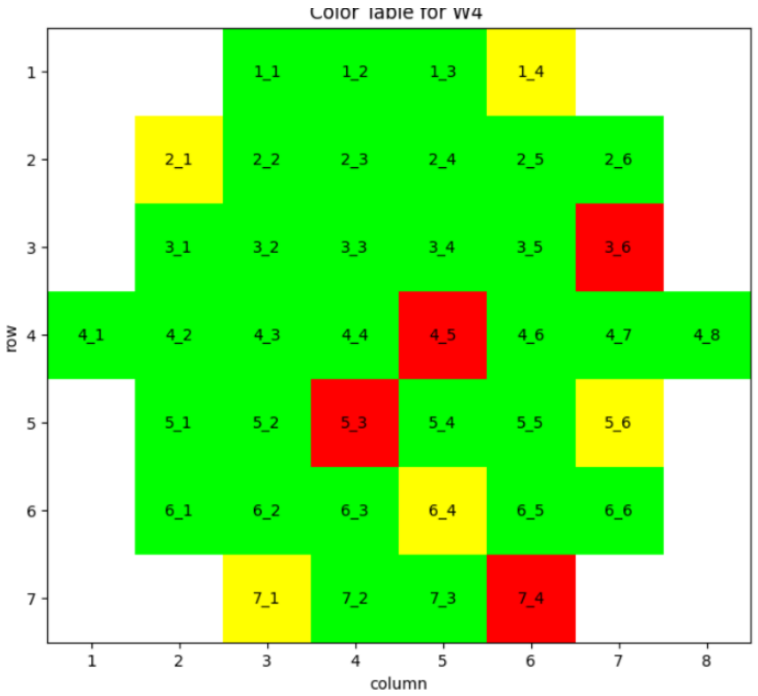
- W3 - 20um thick





- W4 - 20um thick

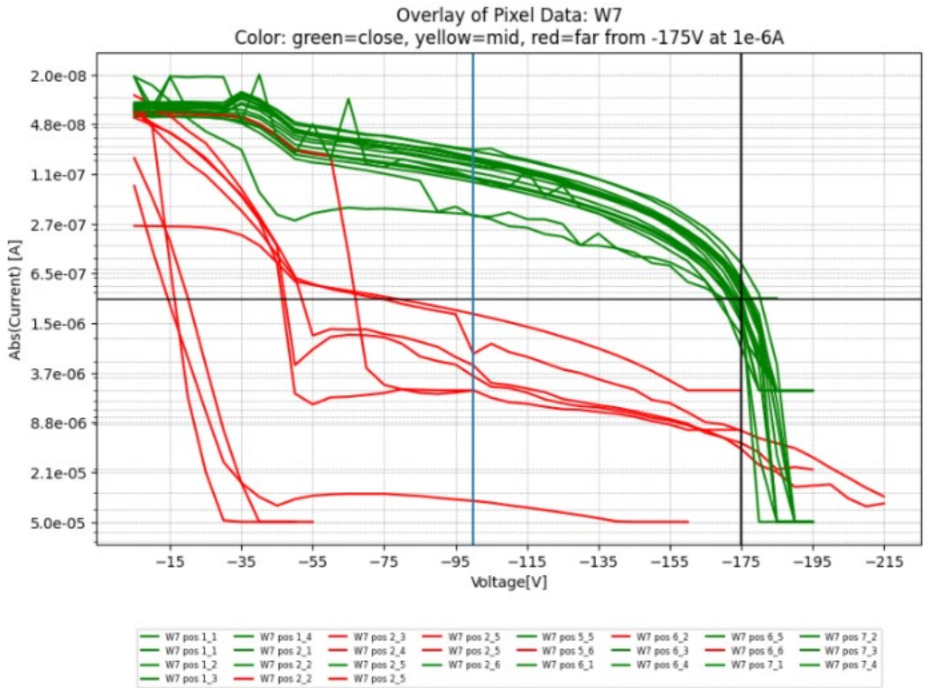


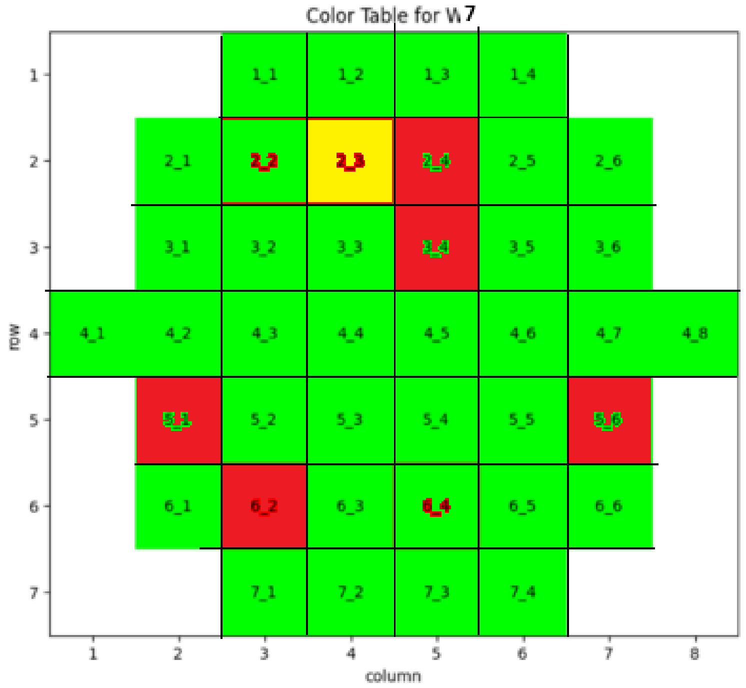


- More data here (almost complete)
  - https://docs.google.com/spreadsheets/d/1J7IuZuRaYmpDjLfzsFhHAh88glab9uHFaDUo3HoOE1o/edit?usp=sharing

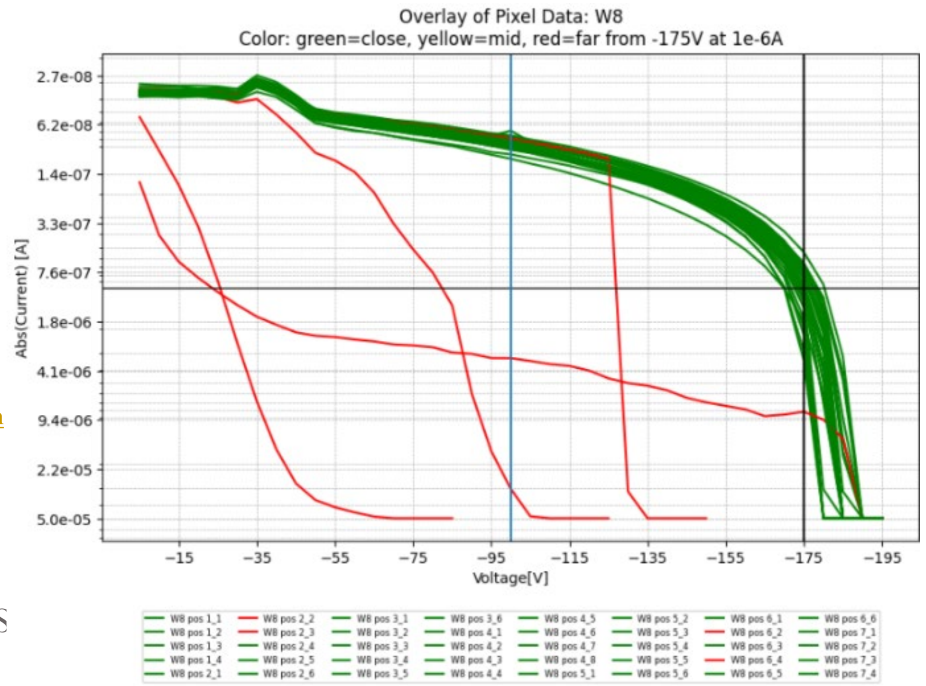
Pixel sensors – 30um wafers

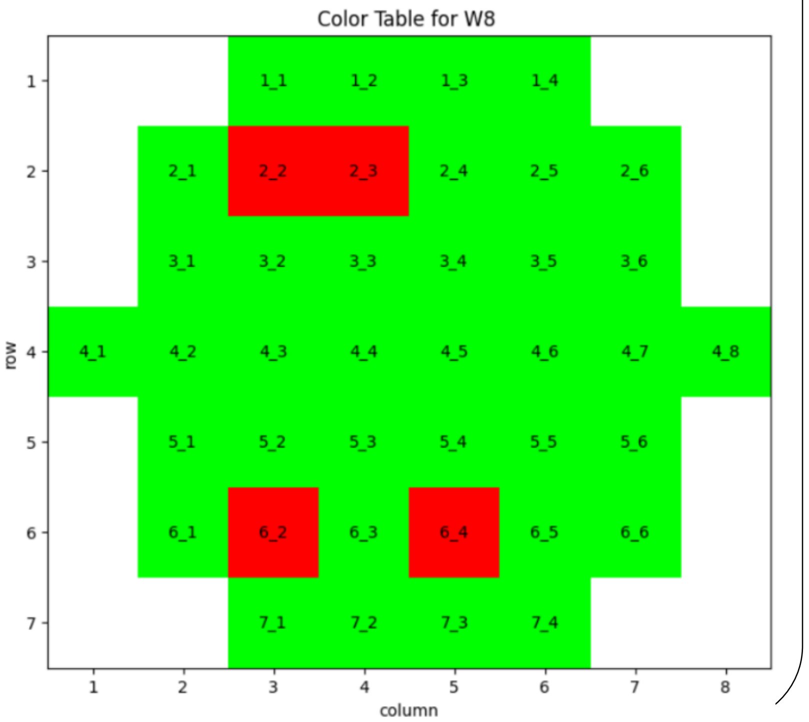
- W7 - 30um thick





- W8 - 30um thick

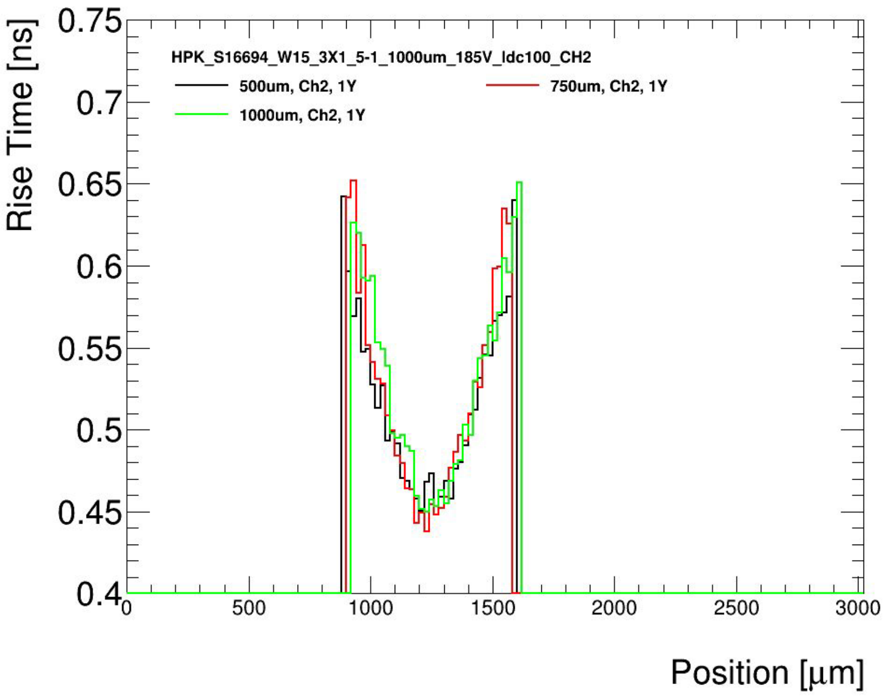


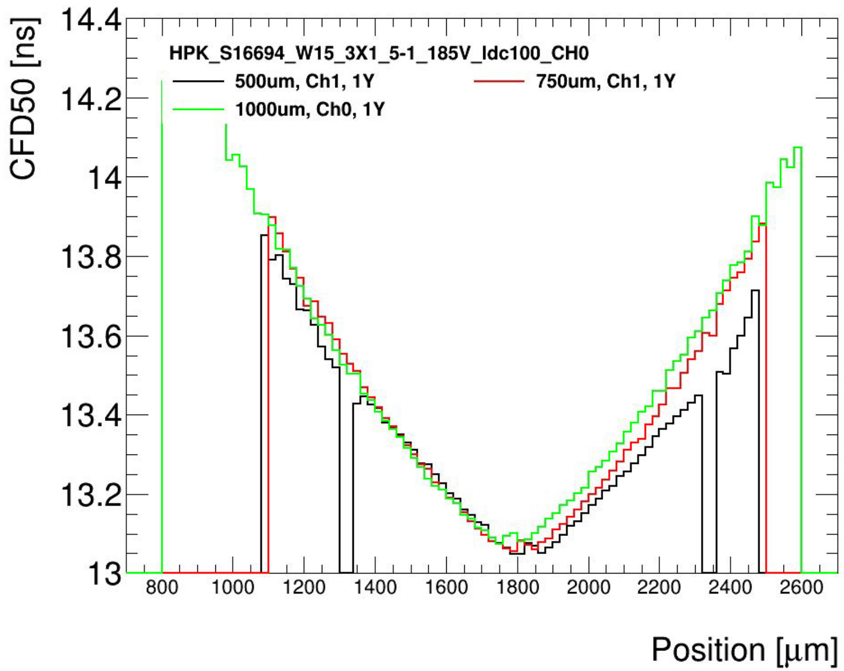


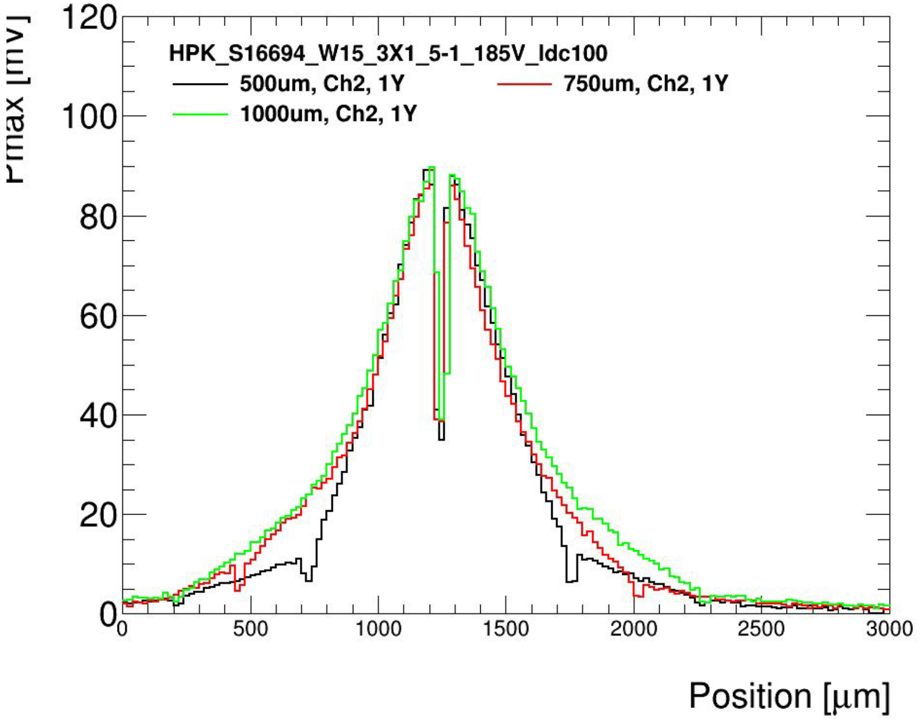
- More data here (almost complete)
  - https://docs.google.com/spreadsheets/d/1J7IuZuRaYmpDjLfzsFhHAh88glab9uHFaDUo3HoOE1o/edit?usp=sharing

HPK production results - TCT

- Signal for 1000um, 750um and 500um pitch is similar near the strip
- Signal propagation and rise time is the same for all pitches



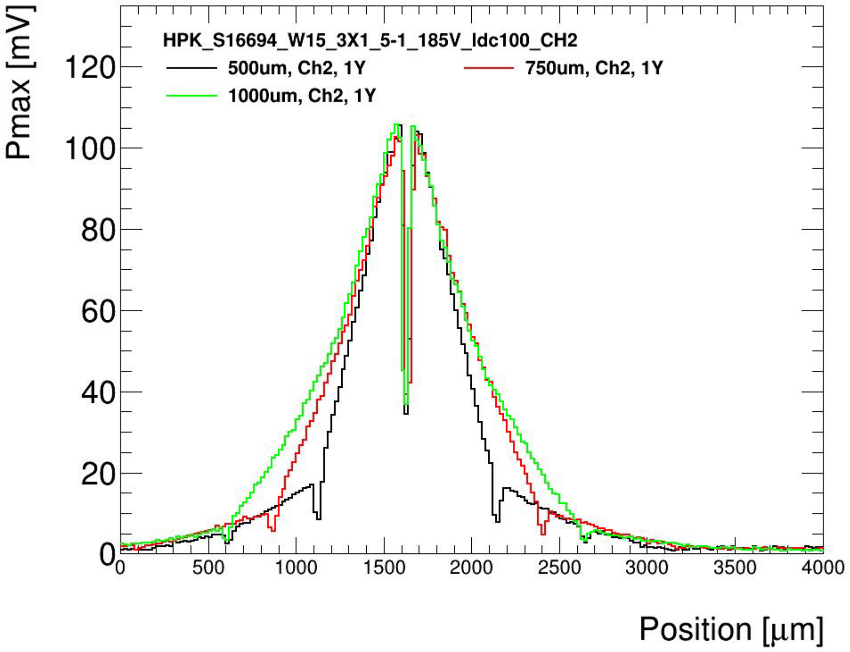


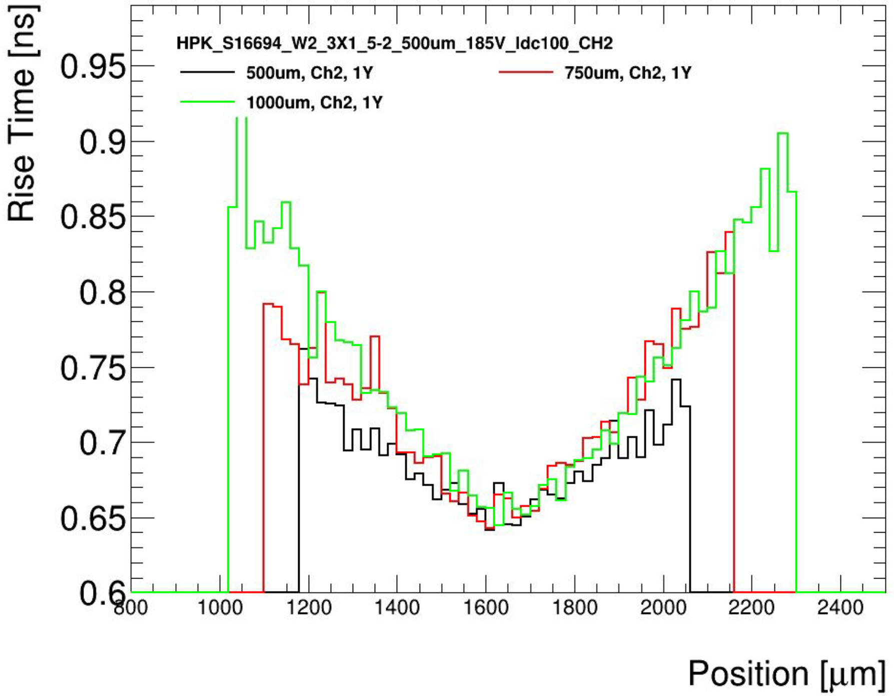


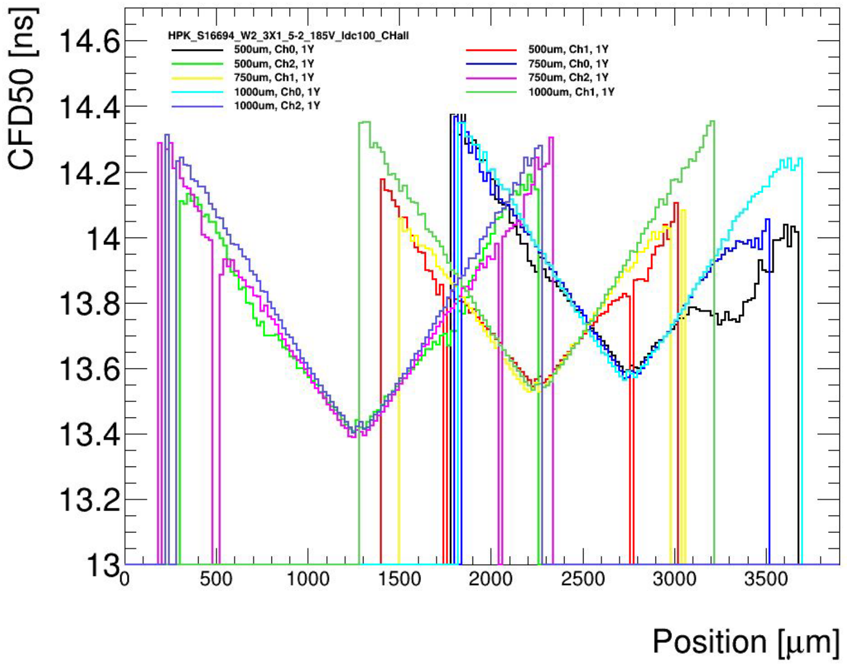
Student: M. Davis

HPK production results - TCT

- Signal for 1000um, 750um and 500um pitch is similar near the strip



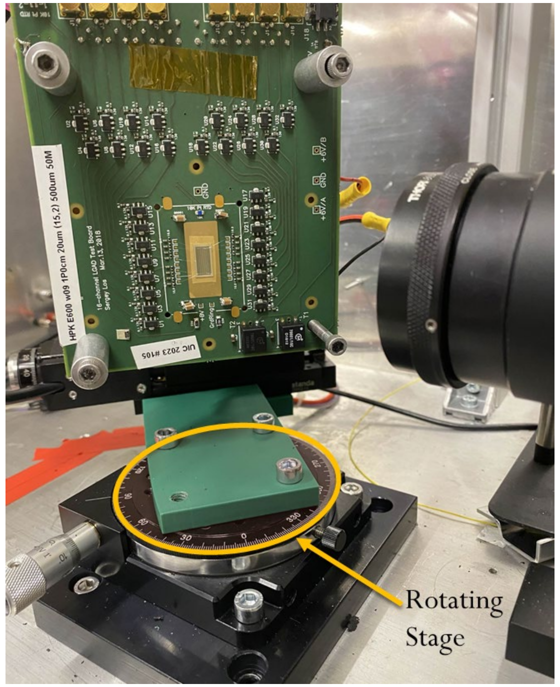


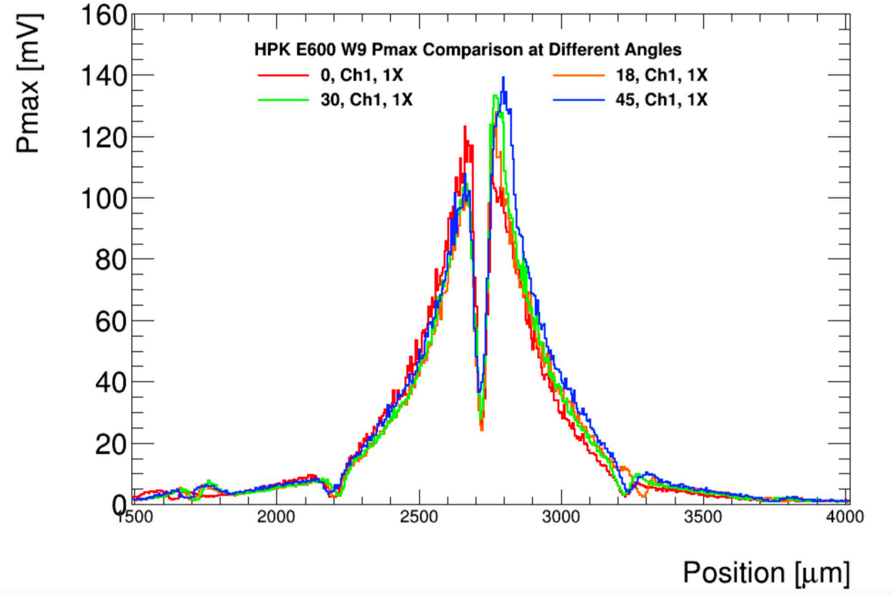


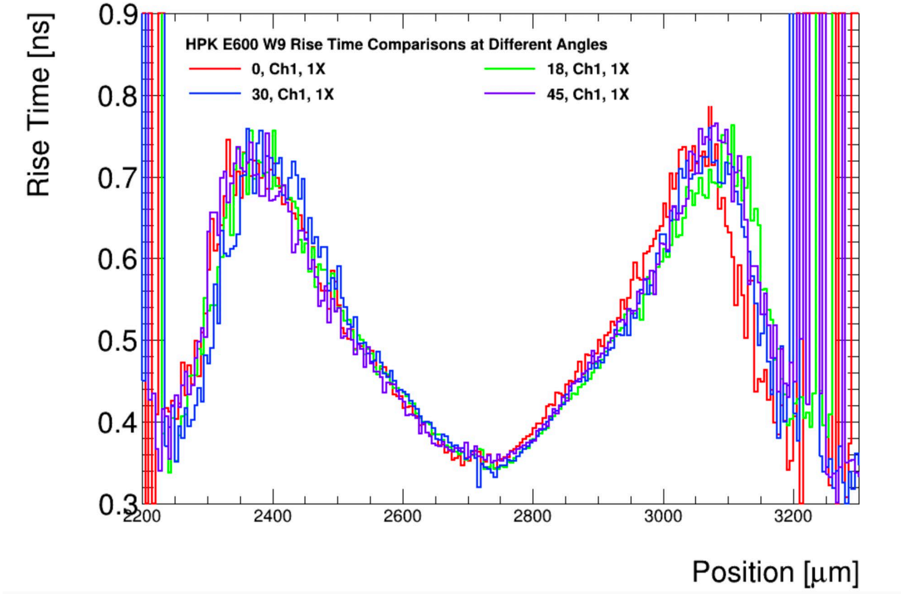
Student: M. Davis

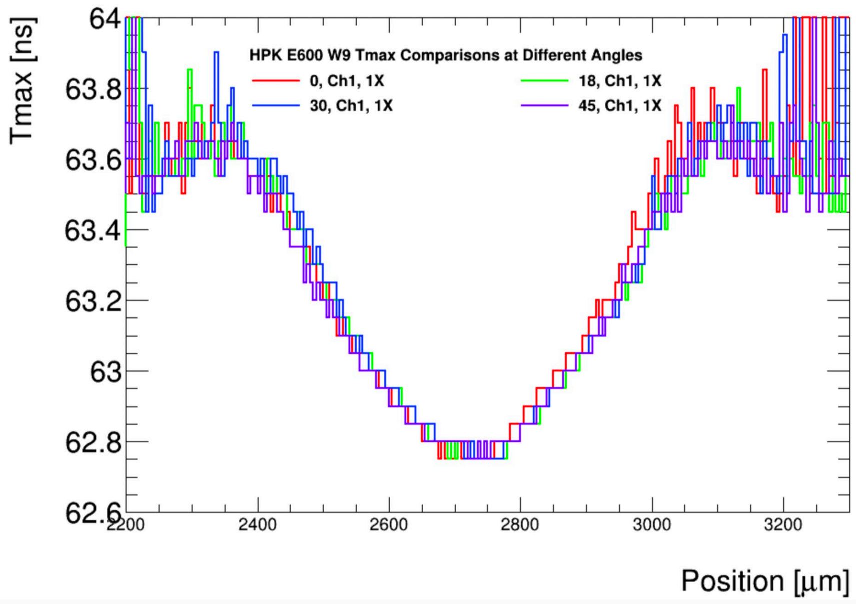
Angled charge injection

- Strip modules in ePIC barrel-TOF are layered with a 18-degree tilt angle in the design baseline, forward disk region also get tracks with large incident angle (up to 30-degree)
  - Laboratory characterization and beam tests so far have been conducted at normal incidence
  - Added a angular stage to our TCT laser setup to study the effects of angle of incidence
- Tested a strip AC-LGAD with the new setup (Pixel next)
  - **At larger angles, signal profile in neighboring strips also shows shift with rotational angle, but effect is small and can be corrected if angle is known**
  - Laser light is shone under strips
- Differences in time-of-arrival and rise time are minimal for the angles measured





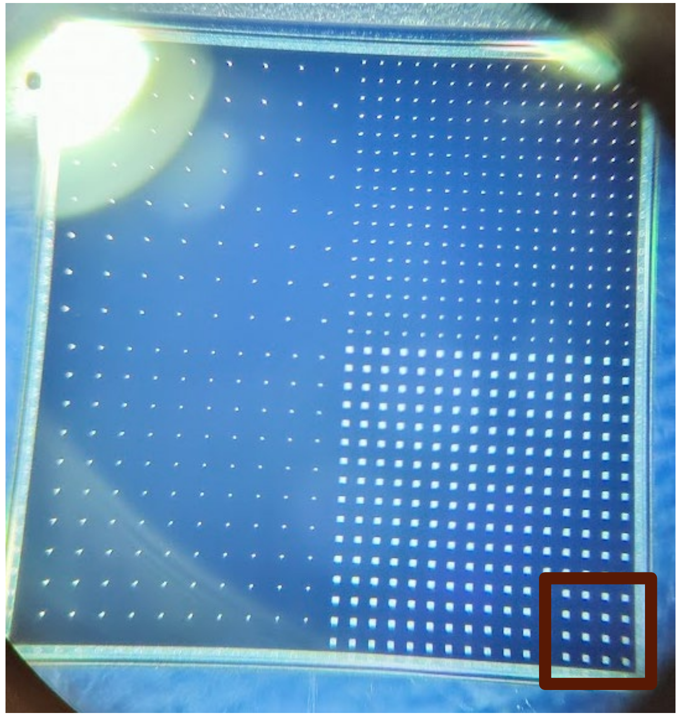


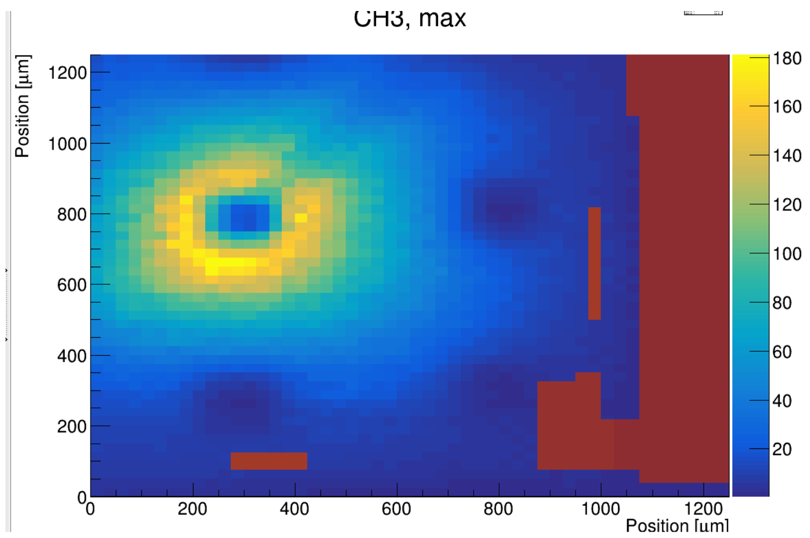


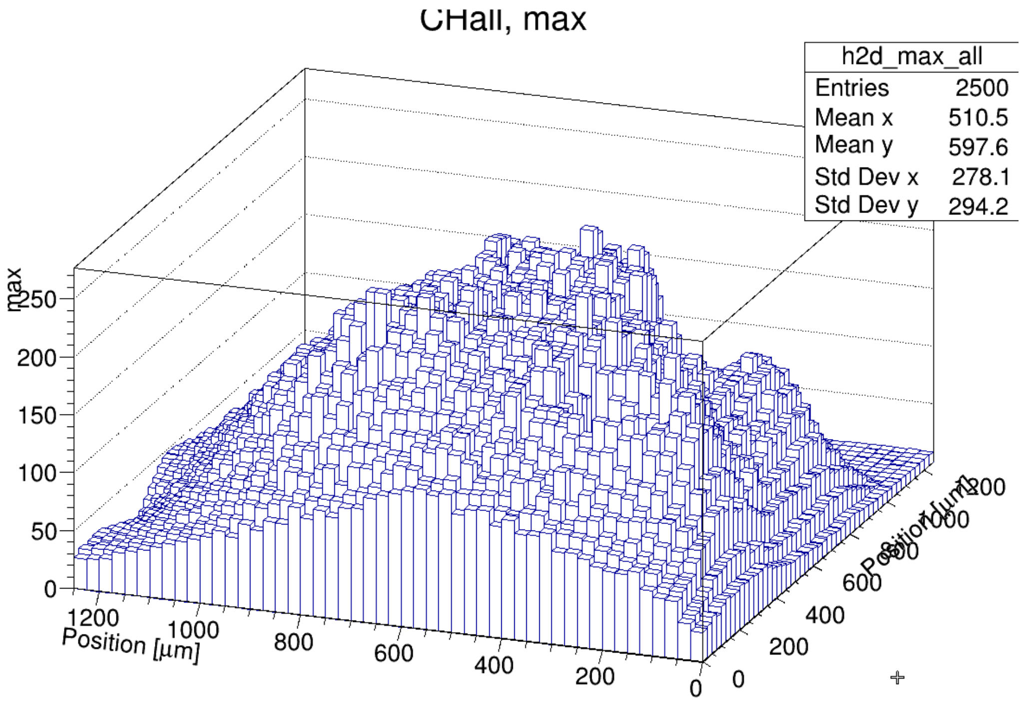
Student: J. Ding

Pixel results - TCT

- Full size sensors tested on a large board with laser TCT
- Sensor: W7 (30um) – pix BIG – 500/150um
- Large signal (~250mV) no S/N loss in the center
- Always same laser power (ldc 100) and same Voltage (185V)
- Focused around the 150um pads, might be sub-optimal for other corners



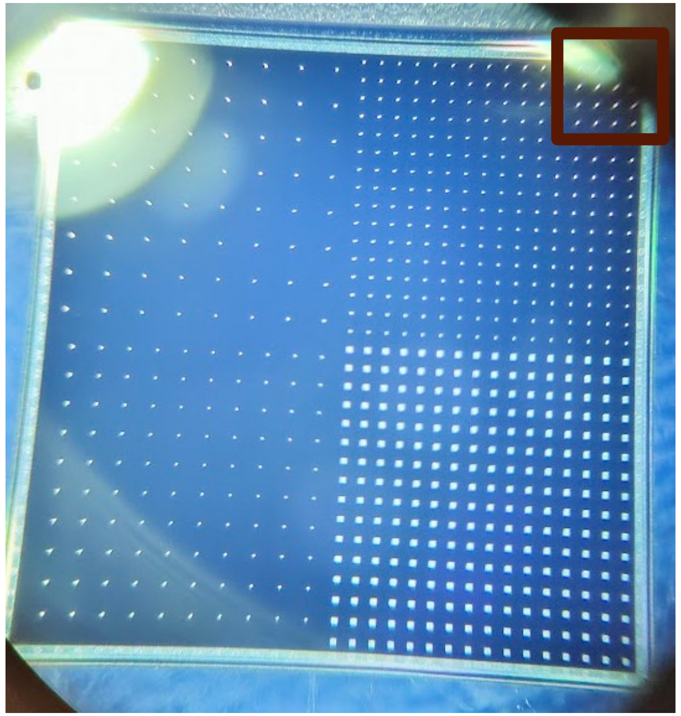


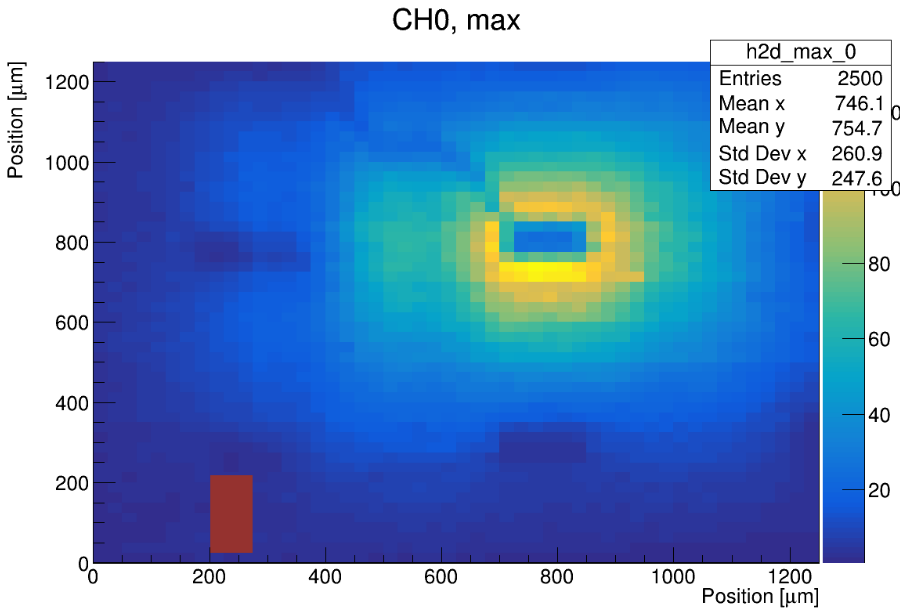


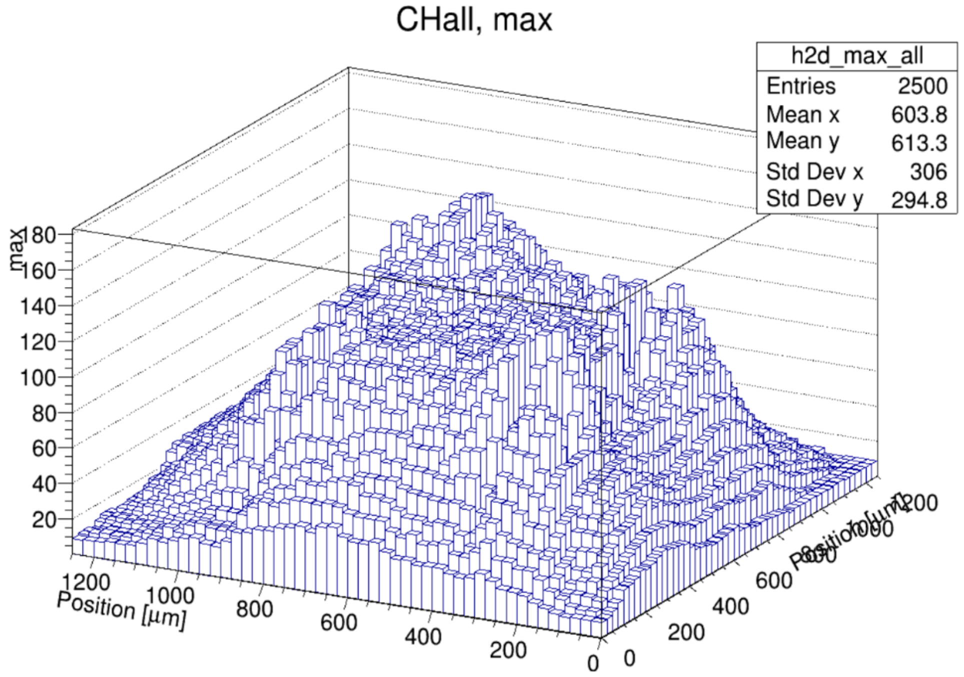
Students: N. Lynch, A. Drumm, Y. Spinos, O. Khandelwal

Pixel results - TCT

- Full size sensors tested on a large board with laser TCT
- Sensor: W7 (30um) – pix BIG – 500/100um
- Smaller signal (~160mV) no S/N loss in the center



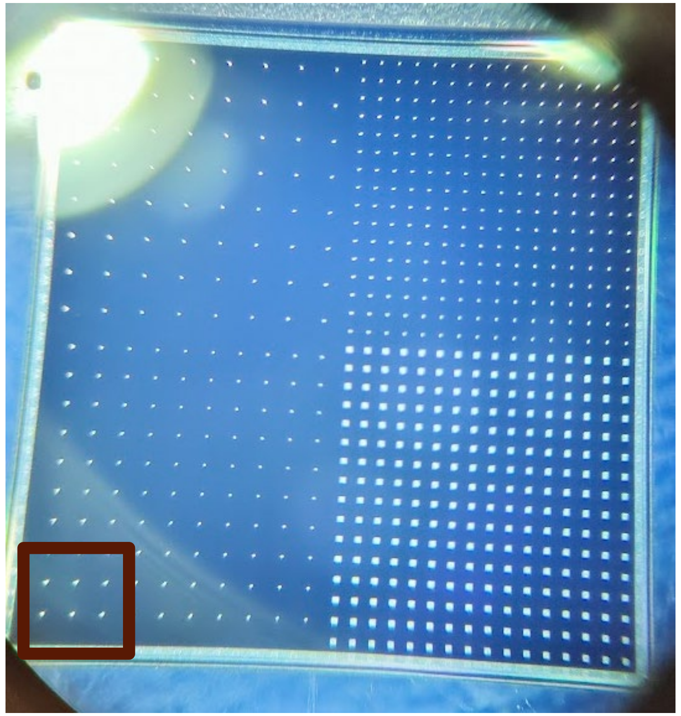


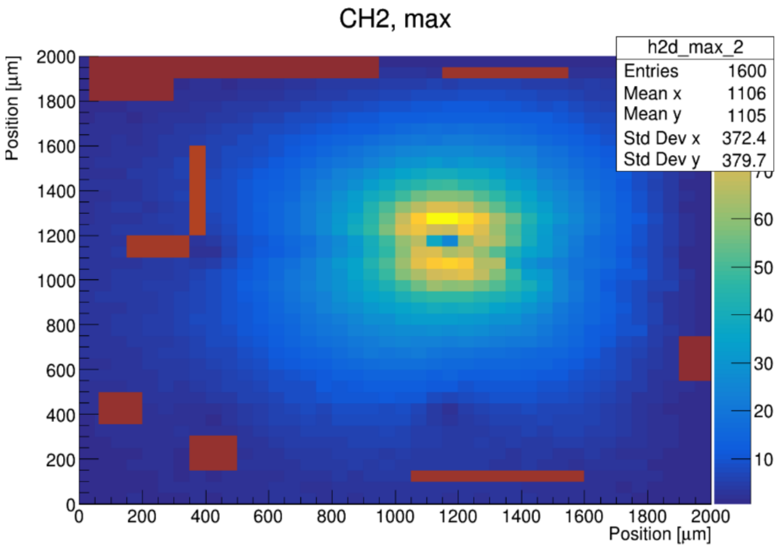


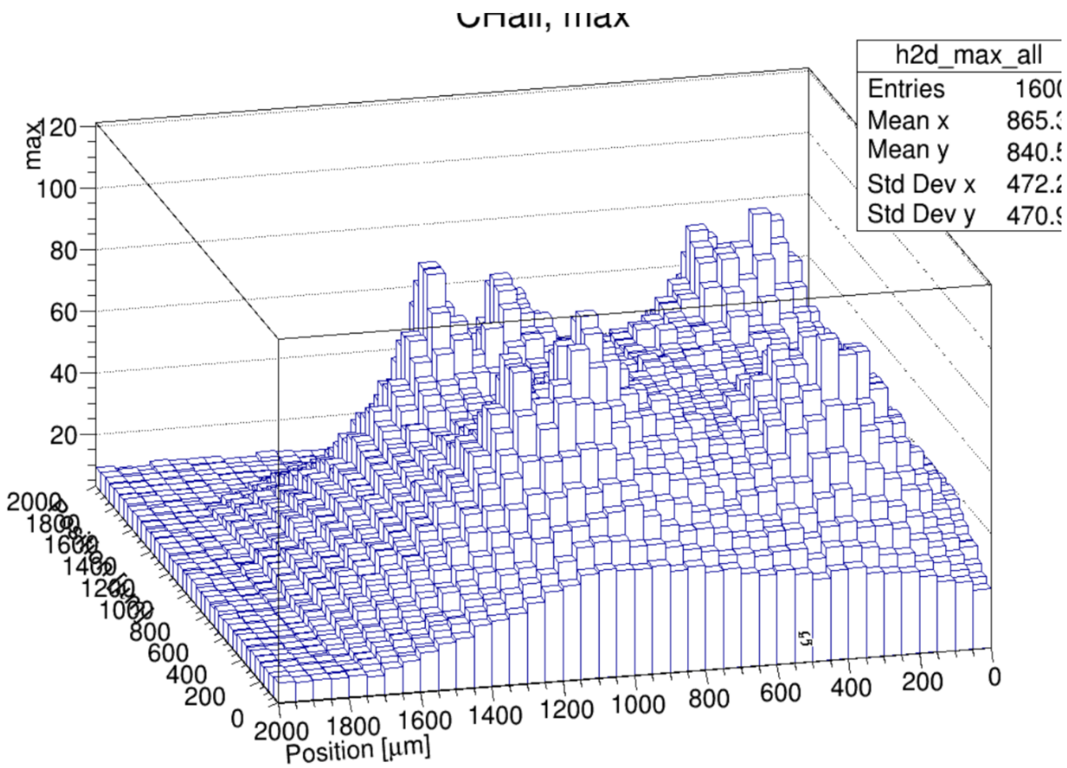
Students: N. Lynch, A. Drumm, Y. Spinos, O. Khandelwal

Pixel results - TCT

- Full size sensors tested on a large board with laser TCT
- Sensor: W7 (30um) – pix BIG – 750/100um
- Smaller signal (~80mV) with S/N loss in the center



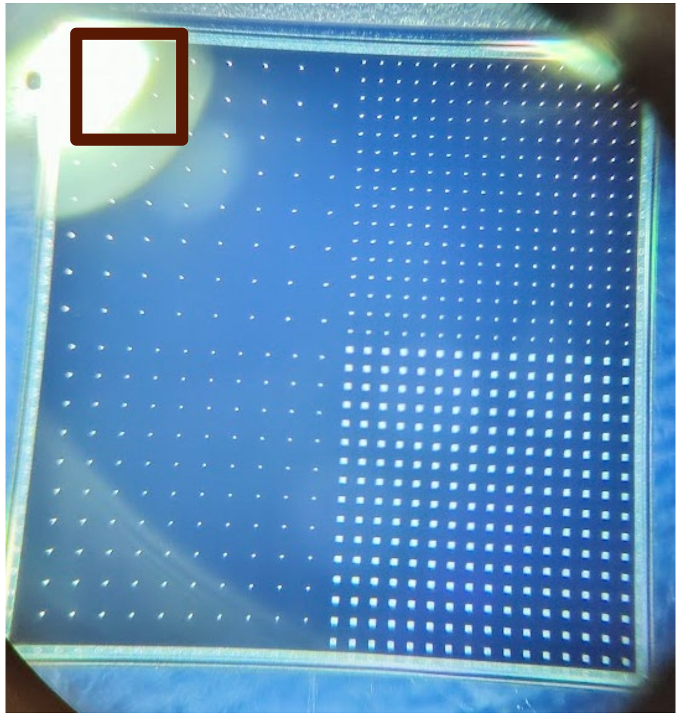


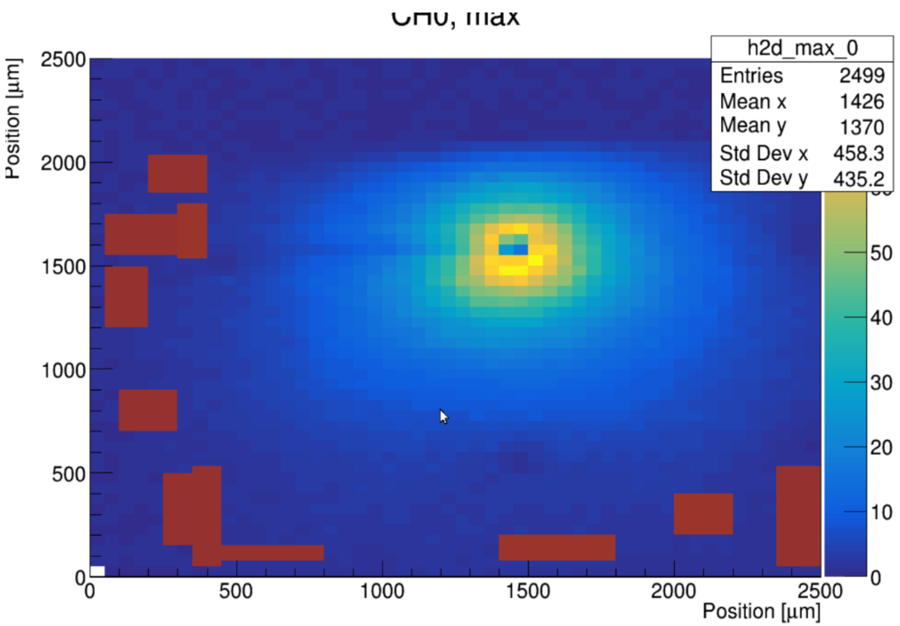


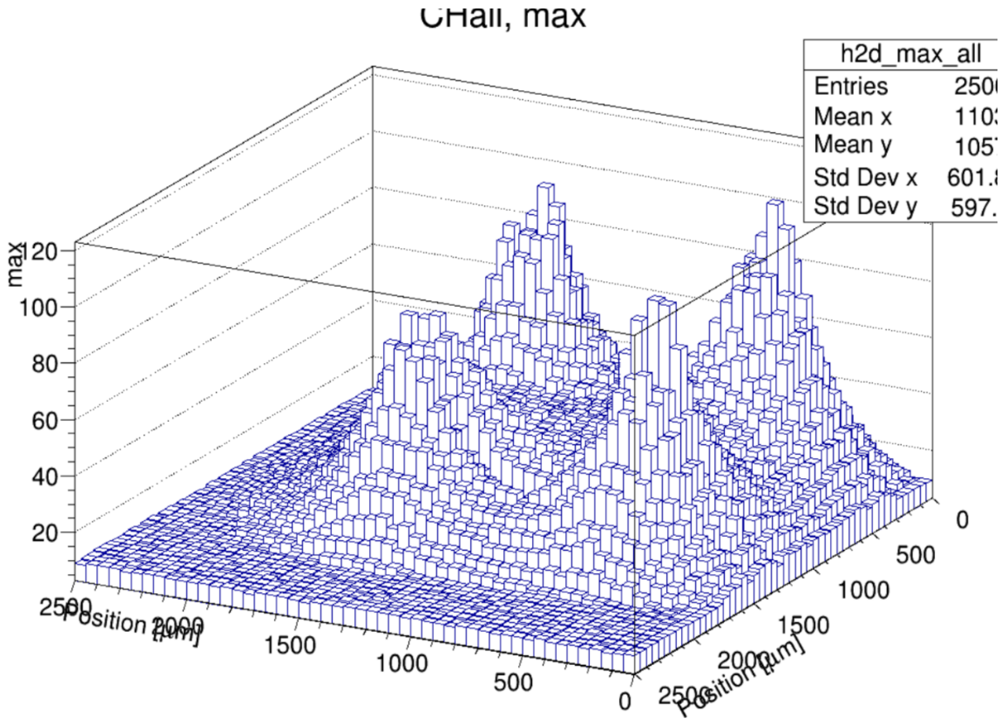
Students: N. Lynch, A. Drumm, Y. Spinos, O. Khandelwal

Pixel results - TCT

- Full size sensors tested on a large board with laser TCT
- Sensor: W7 (30um) – pix BIG – 1000/100um
- Smaller signal (~100mV) large S/N loss in the center
- Tested with smaller (50um) pads as well: the effect is more pronounced



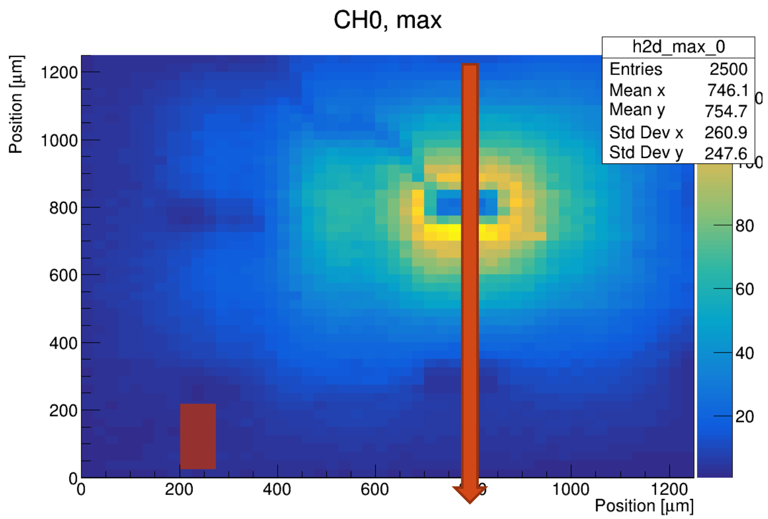


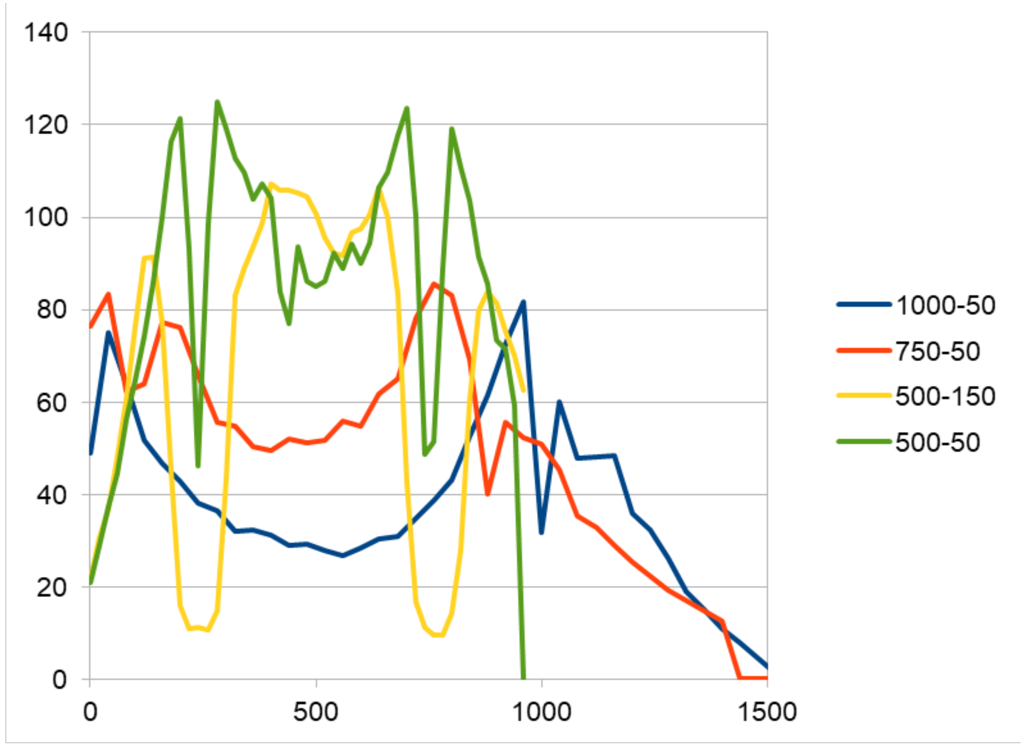


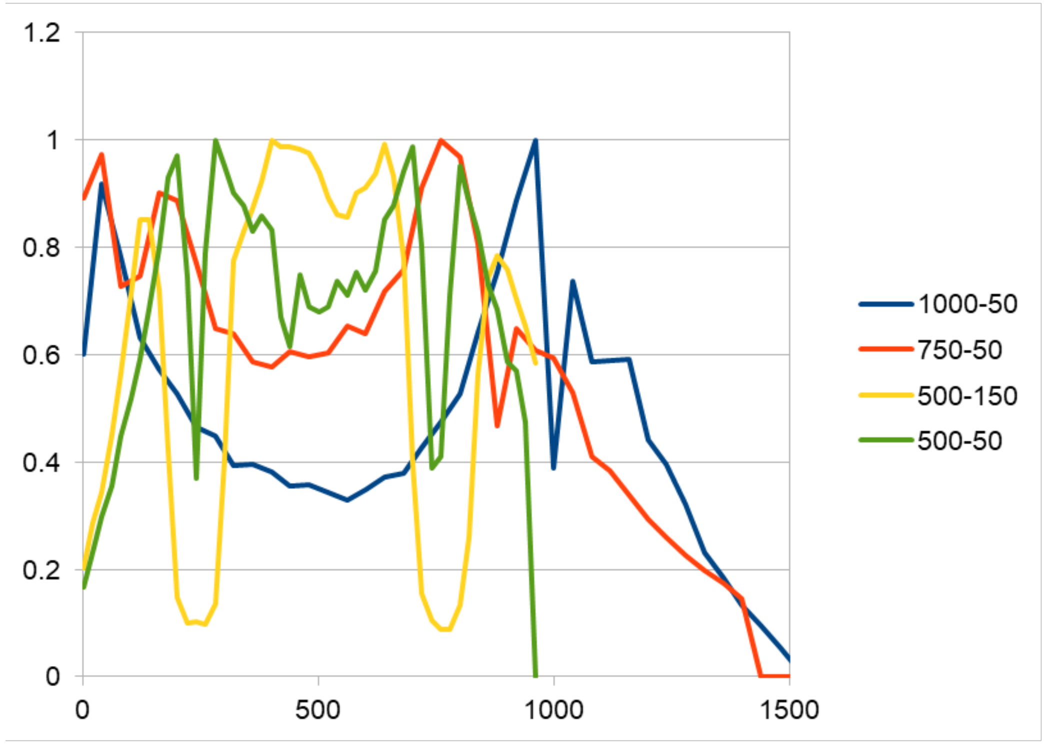
Students: N. Lynch, A. Drumm, Y. Spinos, O. Khandelwal

HPK pixel production results - TCT

- W7 (30um) small pixels
- Comparing S/N loss for the different configurations
- Absolute signal and normalized

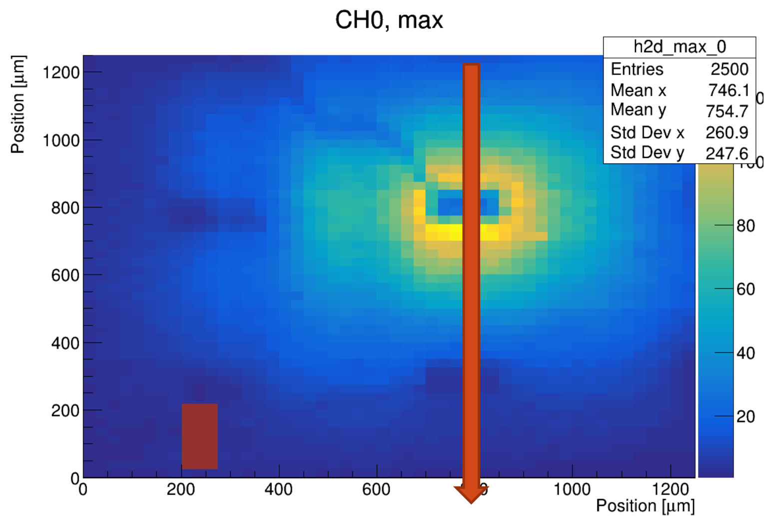


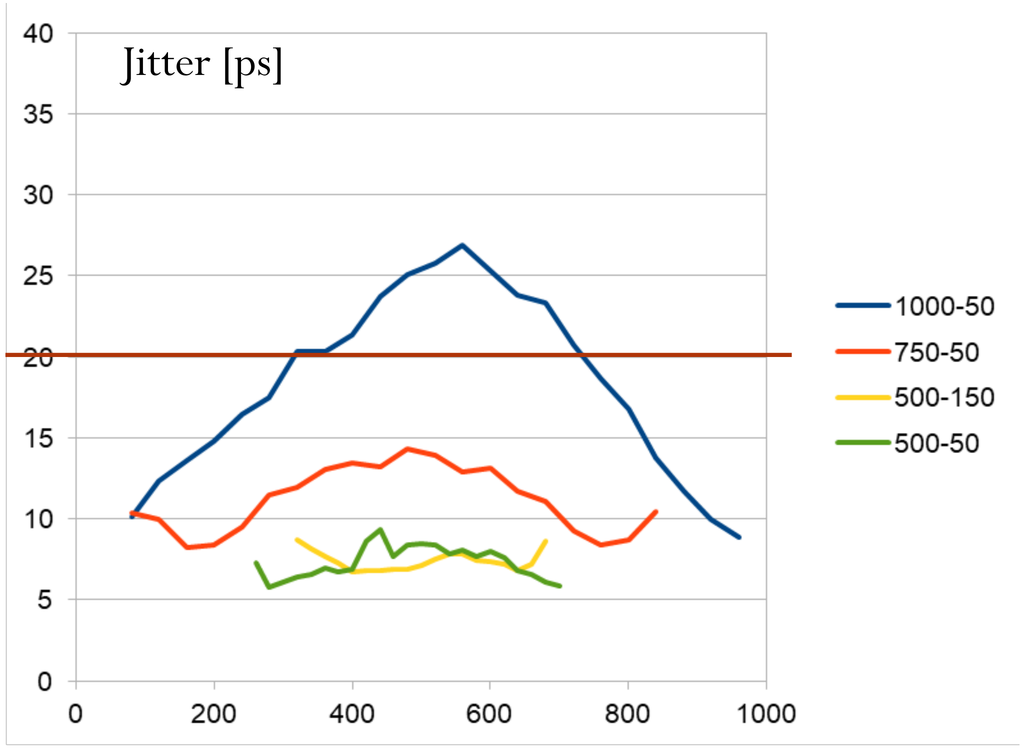


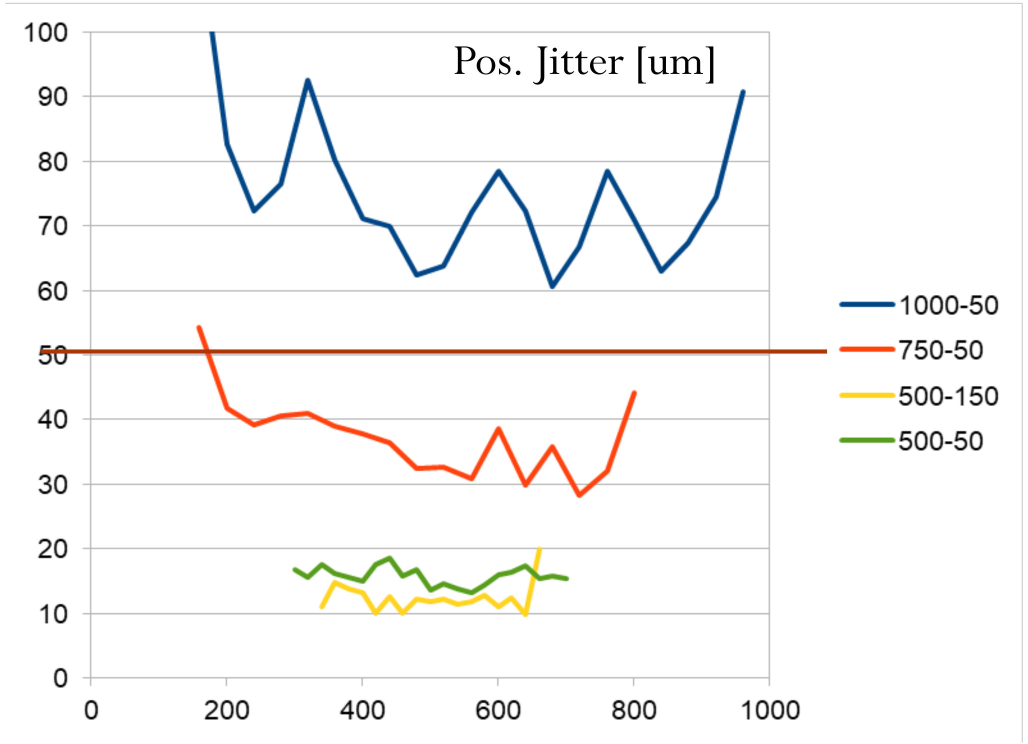


HPK pixel production results - TCT

- W7 (30um) small pixels
- Measuring the Jitter and position Jitter as before
  - Only measured in-between pixels
- Assuming 100mV signal near pixel for 500-150um configuration

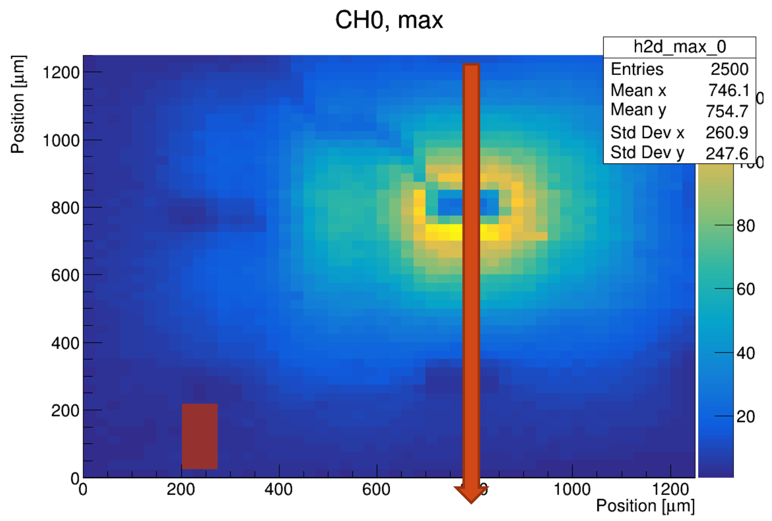


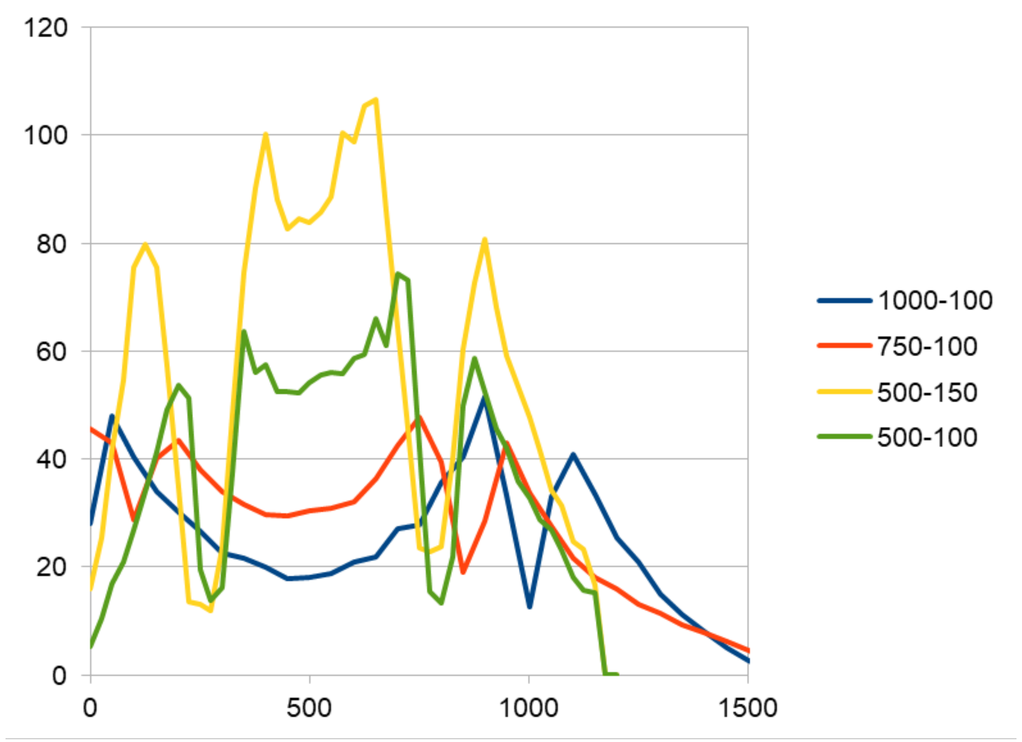


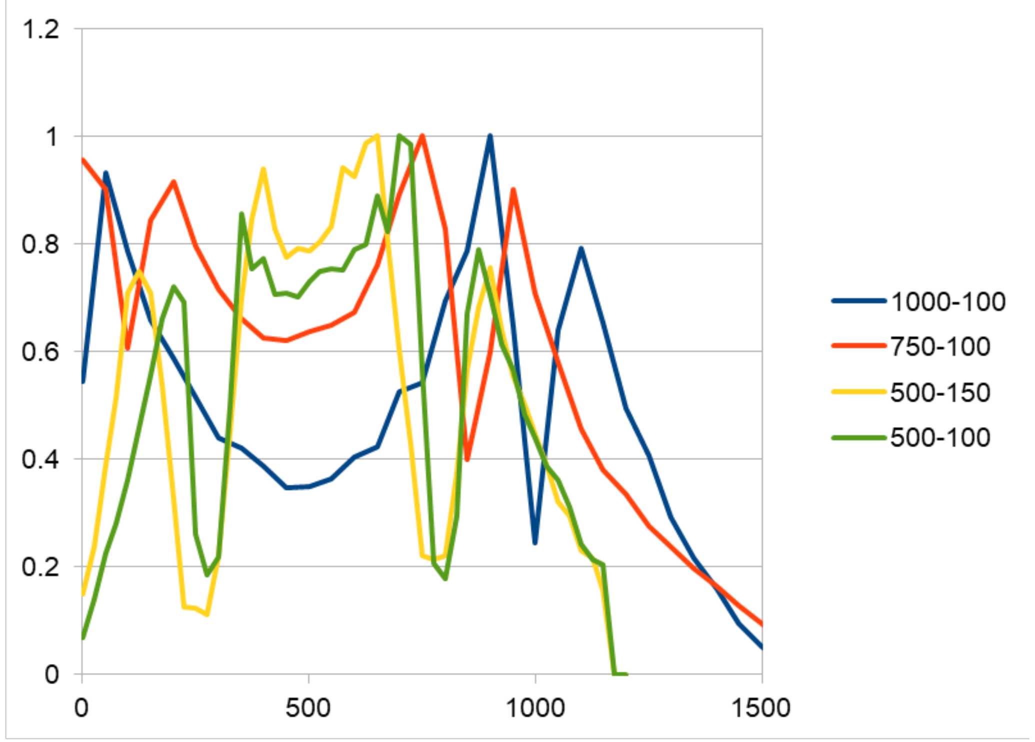


HPK pixel production results - TCT

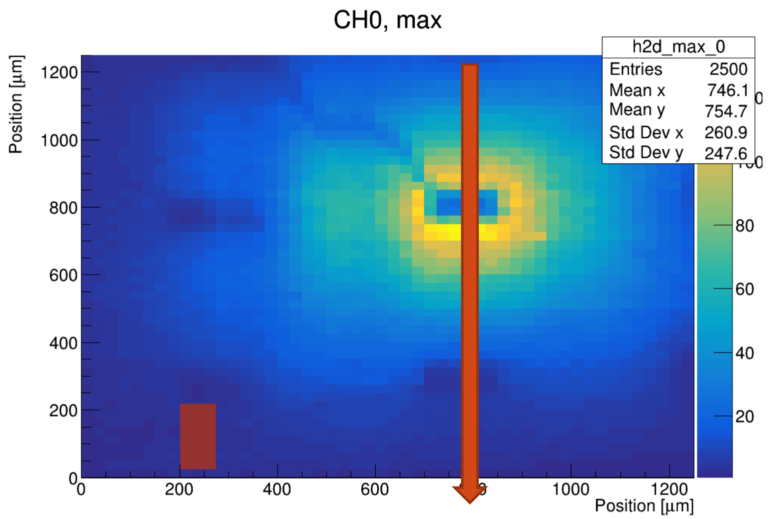
- W7 (30um) large pixels
- Comparing S/N loss for the different configurations
- Absolute signal and normalized



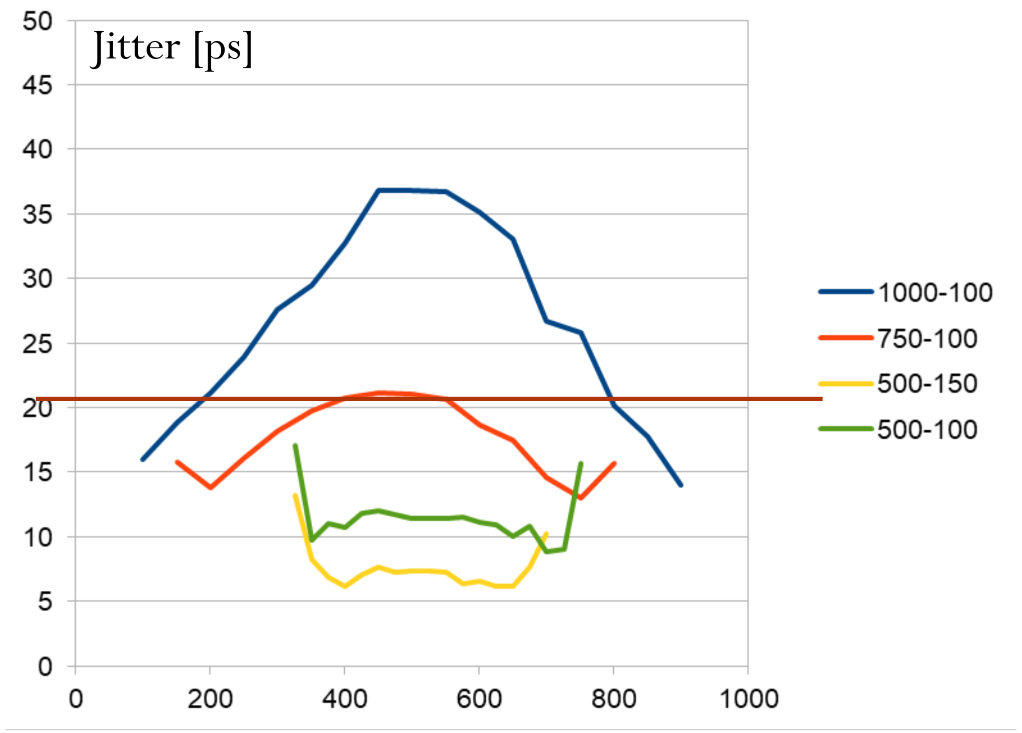


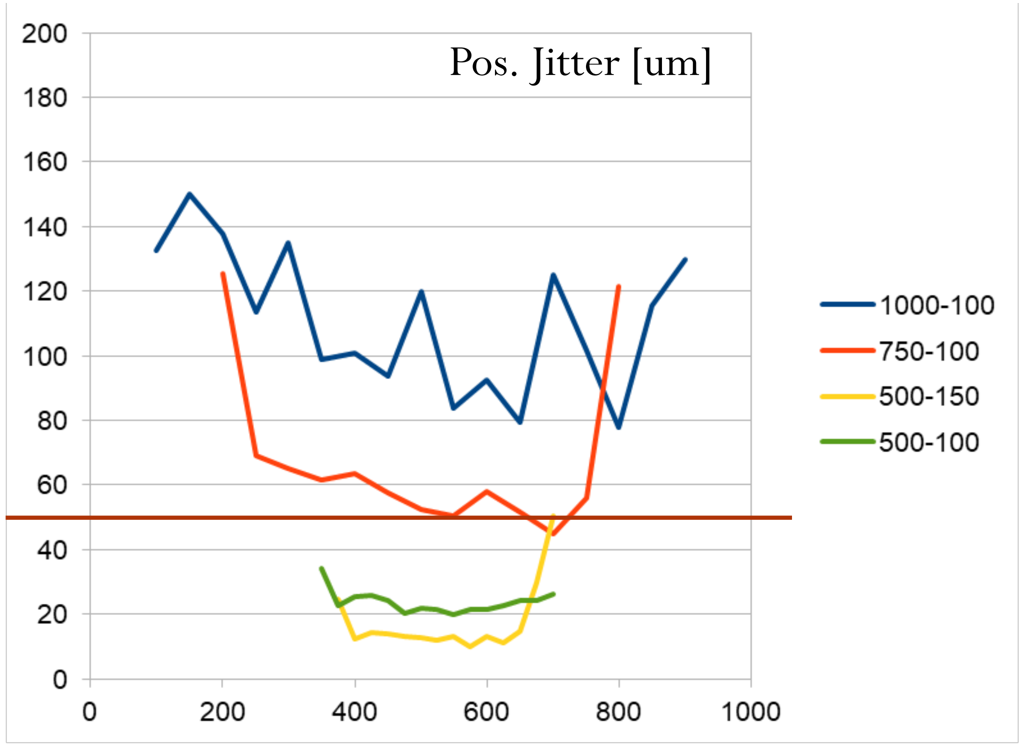


HPK pixel production results - TCT

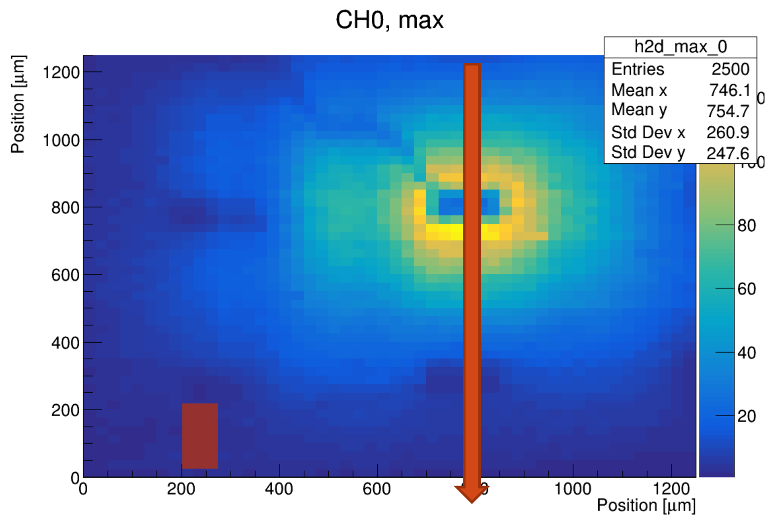


- W7 (30um) large pixels
- Measuring the Jitter and position Jitter as before
  - Only measured in-between pixels
- Assuming 100mV signal near pixel for 500-150um configuration

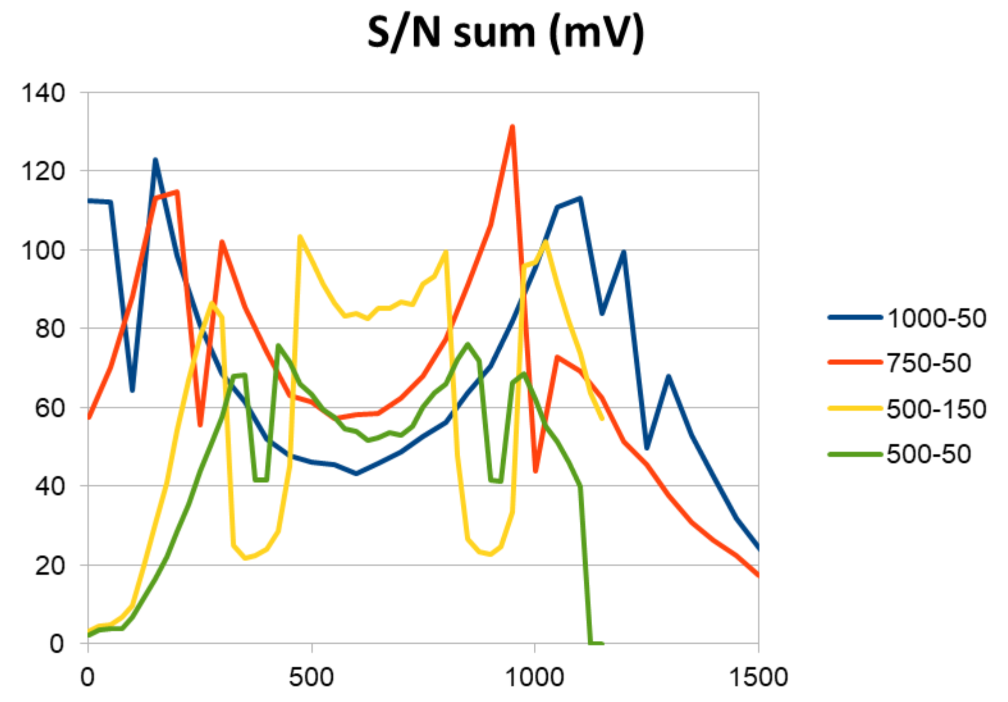


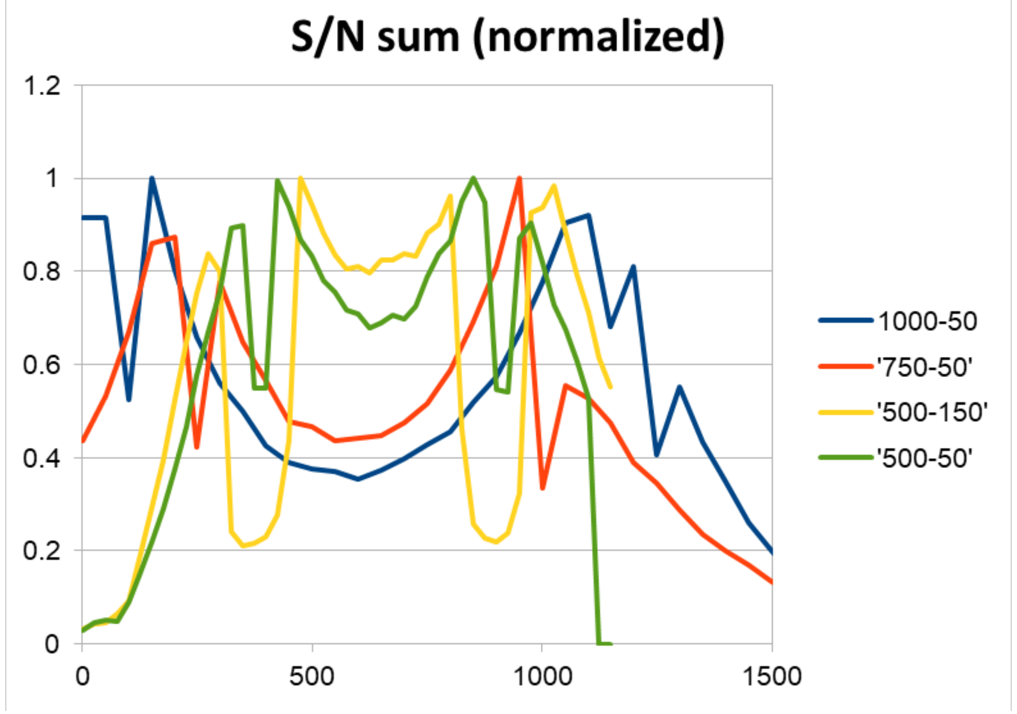


HPK pixel production results - TCT

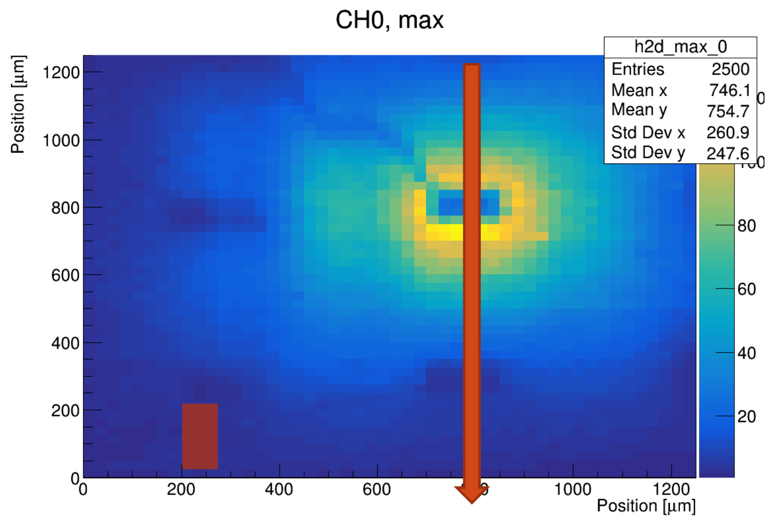


- W3 (20um) small pixels
- Comparing S/N loss for the different configurations
- Absolute signal and normalized

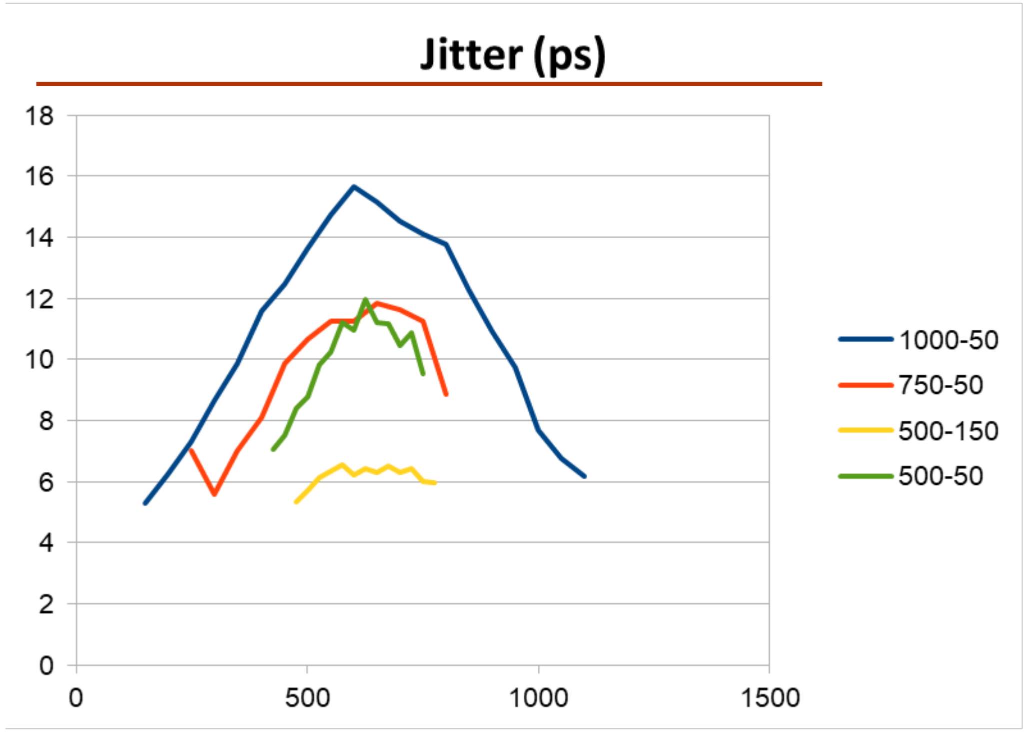


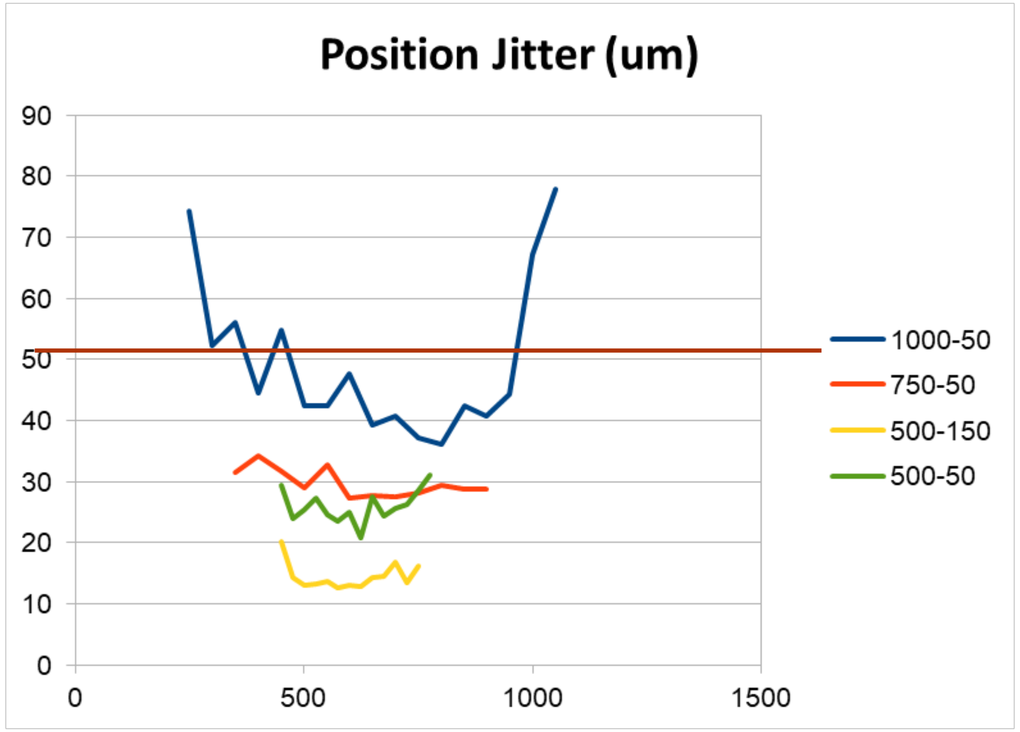


HPK pixel production results - TCT



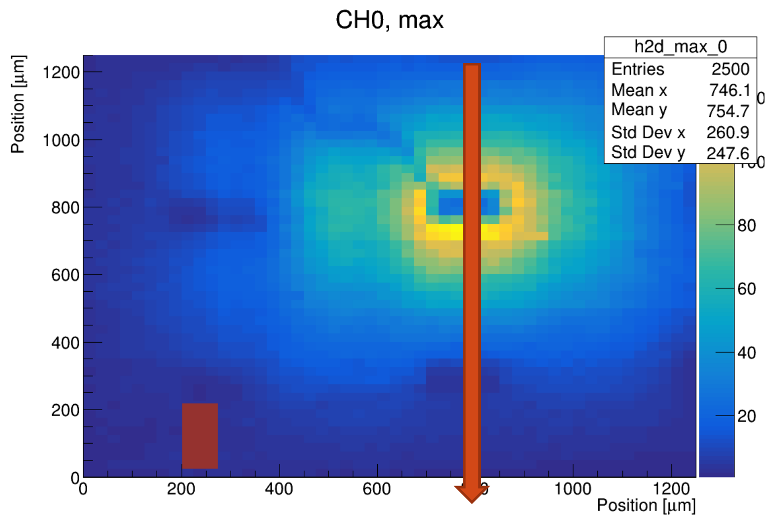
- W3 (20um) small pixels
- Measuring the Jitter and position Jitter as before
  - Only measured in-between pixels
- Assuming 100mV signal near pixel for 500-150um configuration

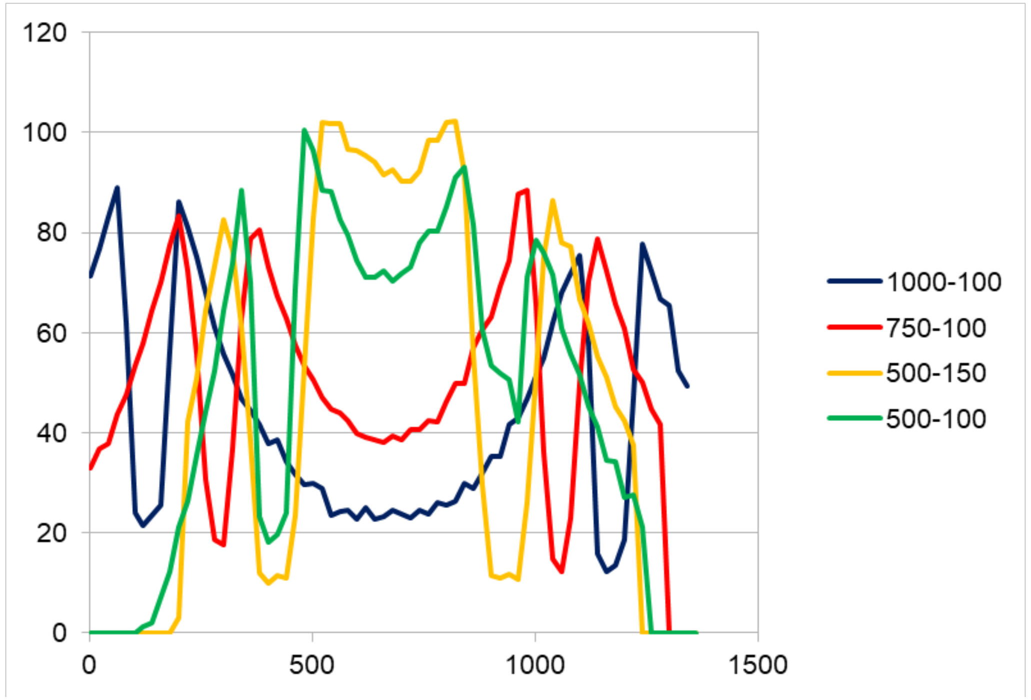


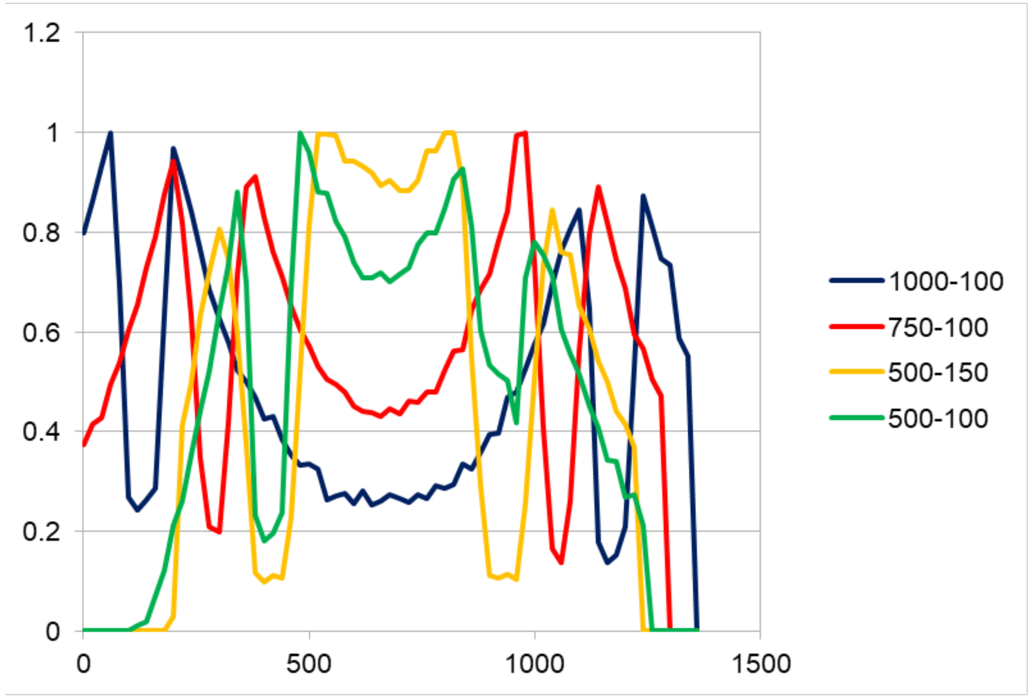


HPK pixel production results - TCT

- W3 (20um) big pixels
- Comparing S/N loss for the different configurations
- Absolute signal and normalized







HPK pixel production results - TCT

- W3 (20um) big pixels
- Measuring the Jitter and position Jitter as before
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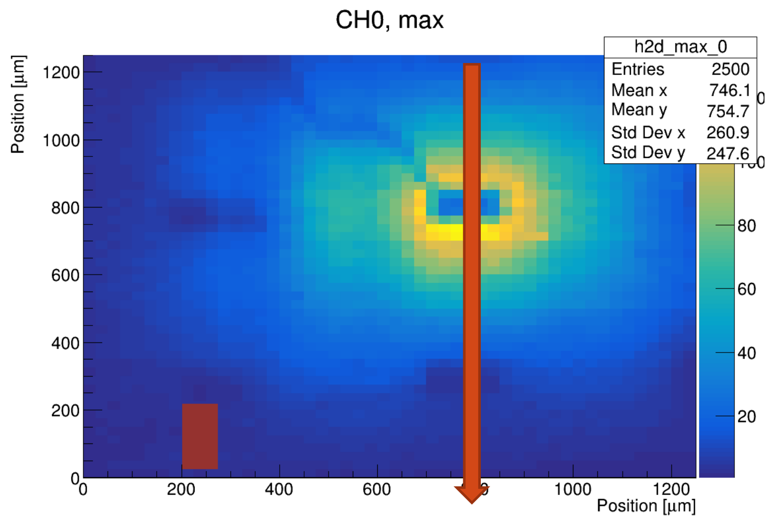
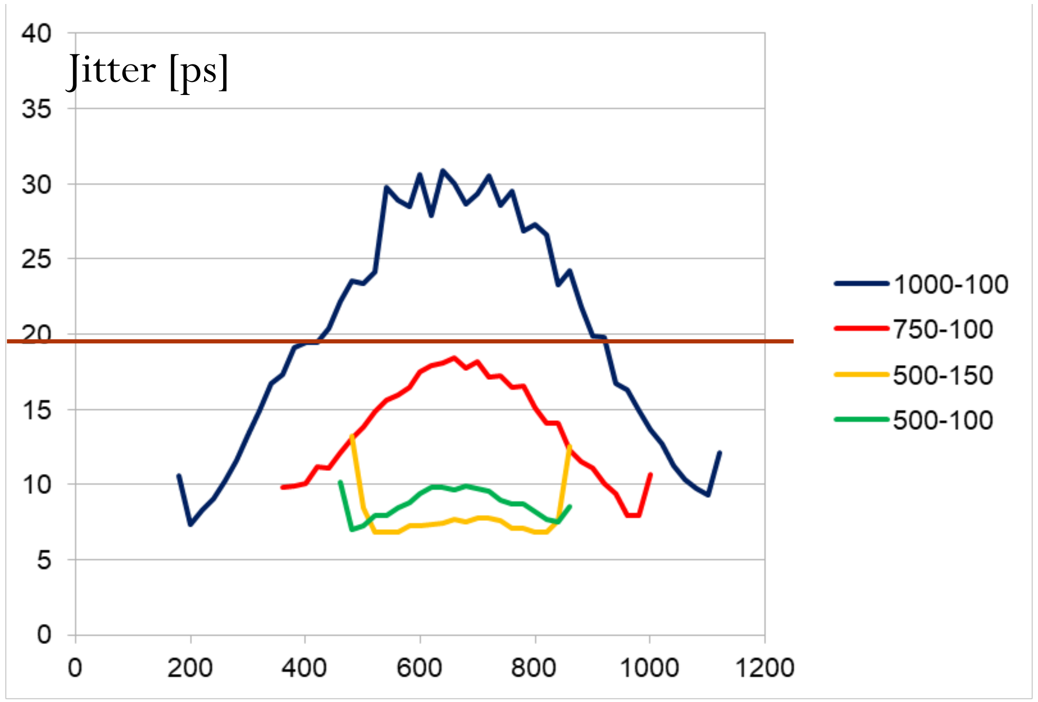
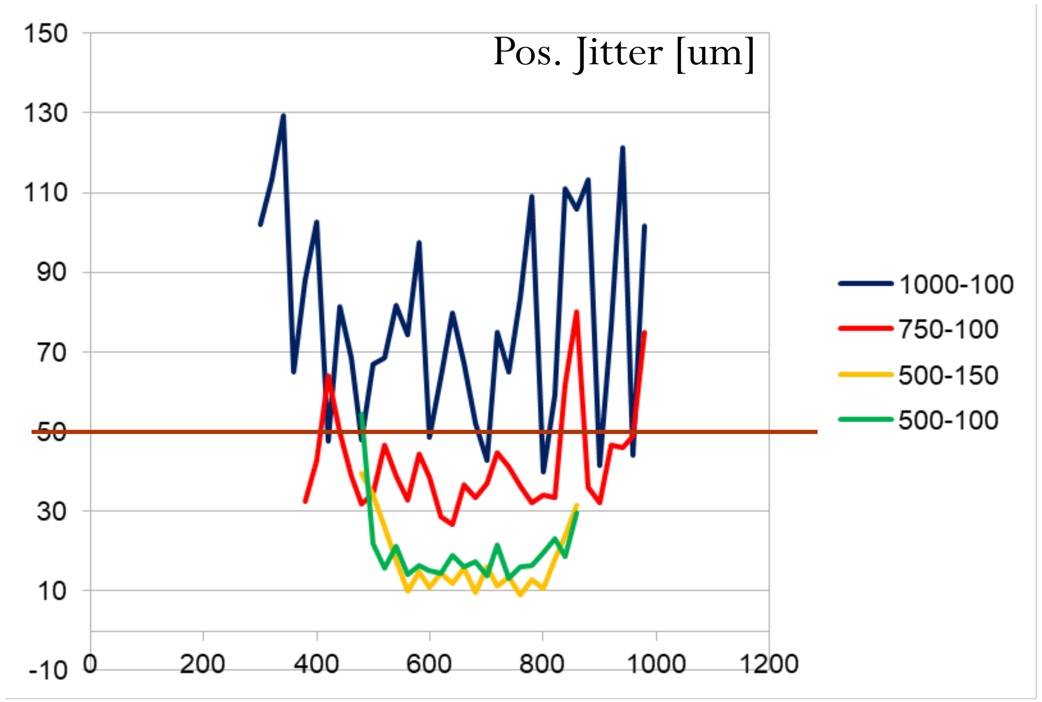
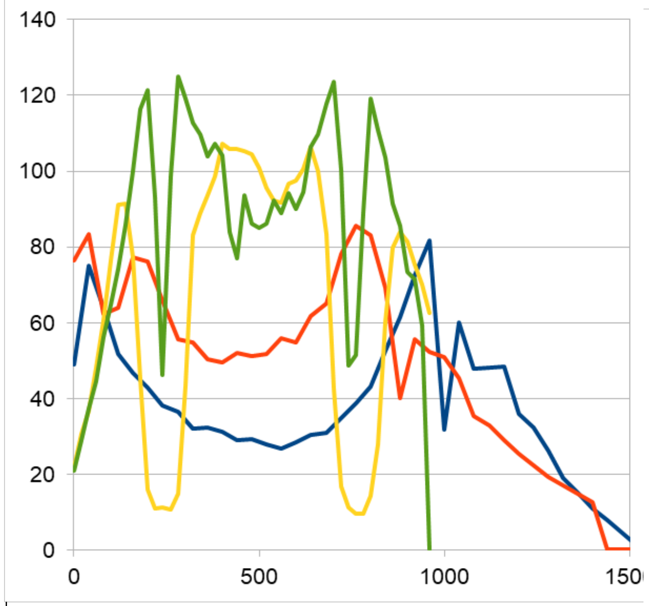
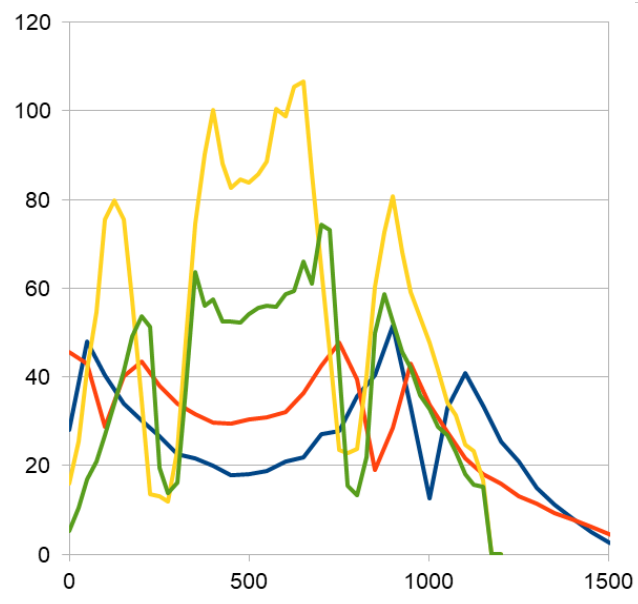


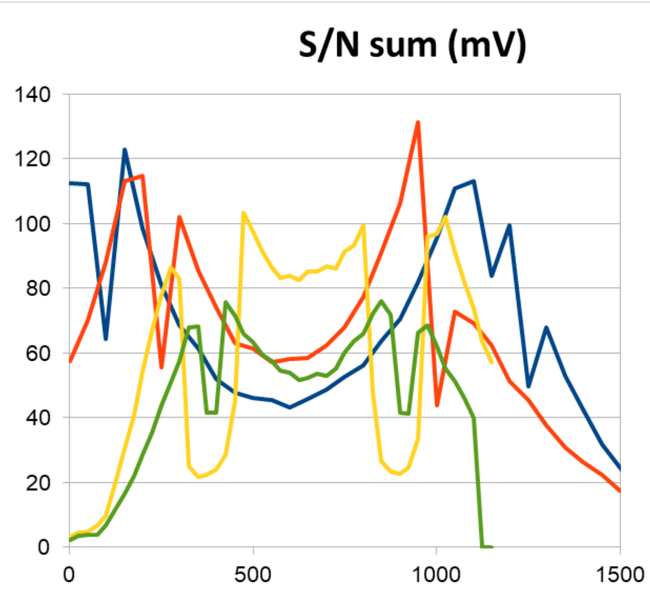


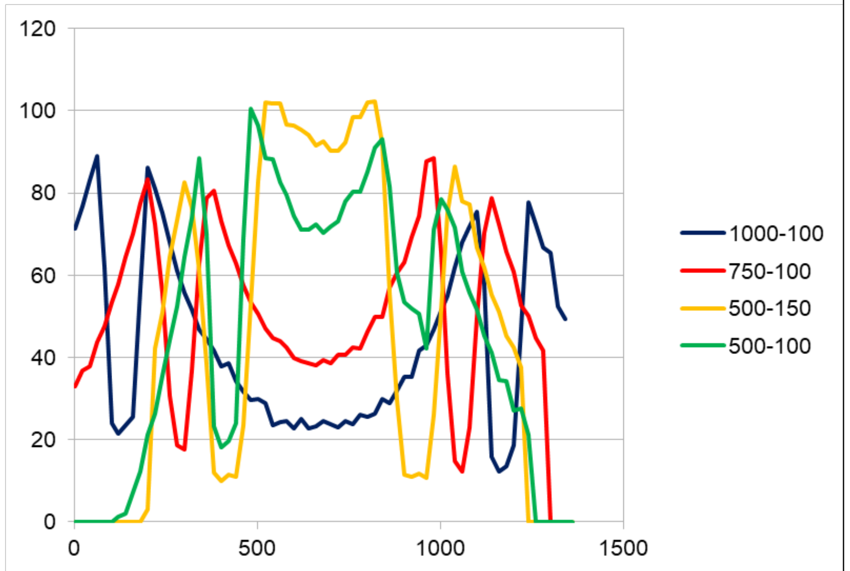


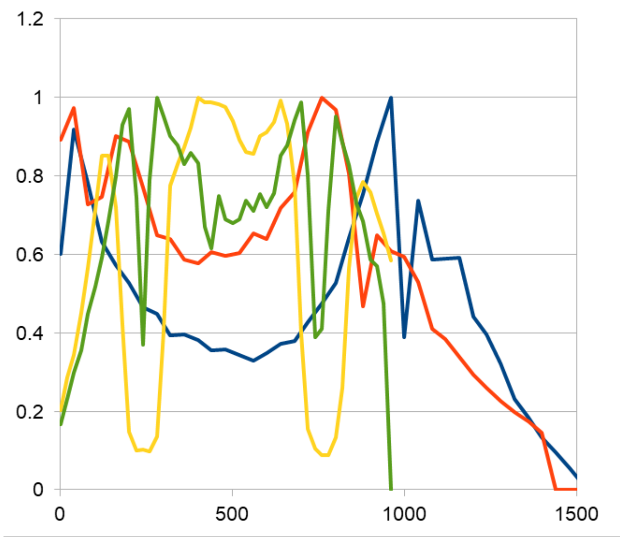
W7 (30um) pixSmol | W7 (30um) pixBIG | W3 (20um) pixSmol | W3 (20um) pixBIG

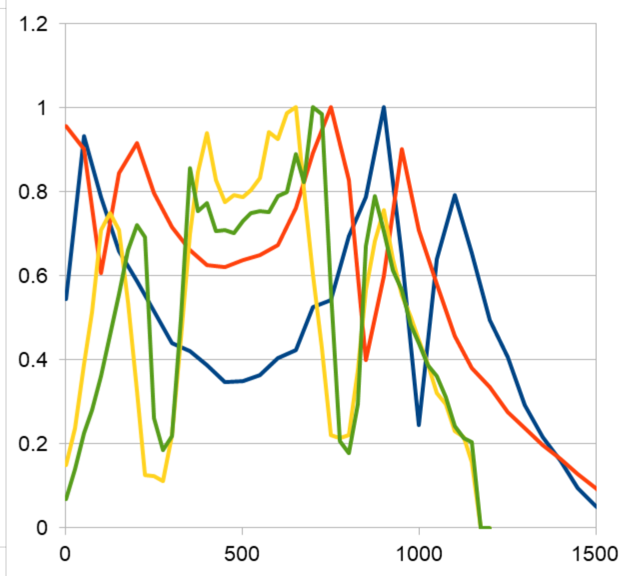


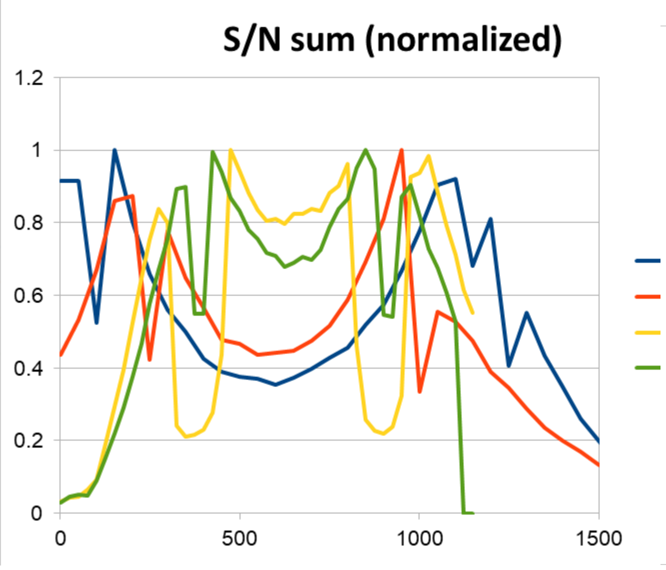


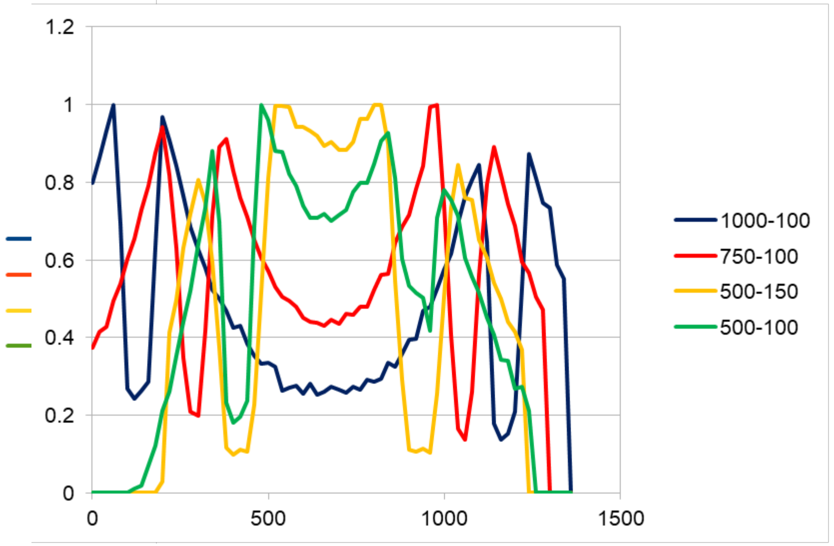




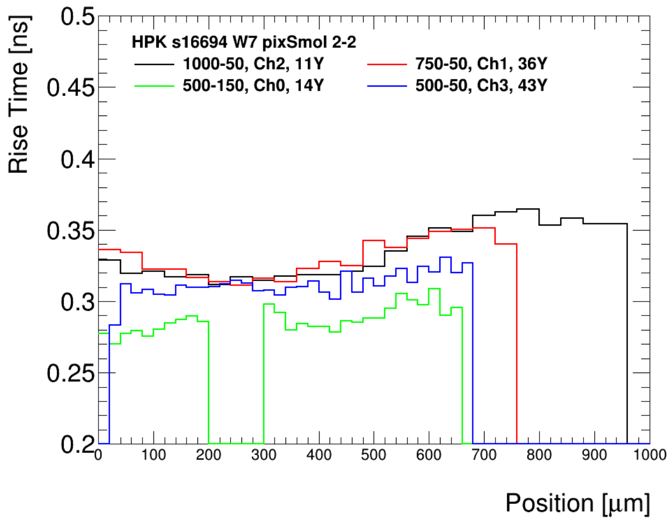


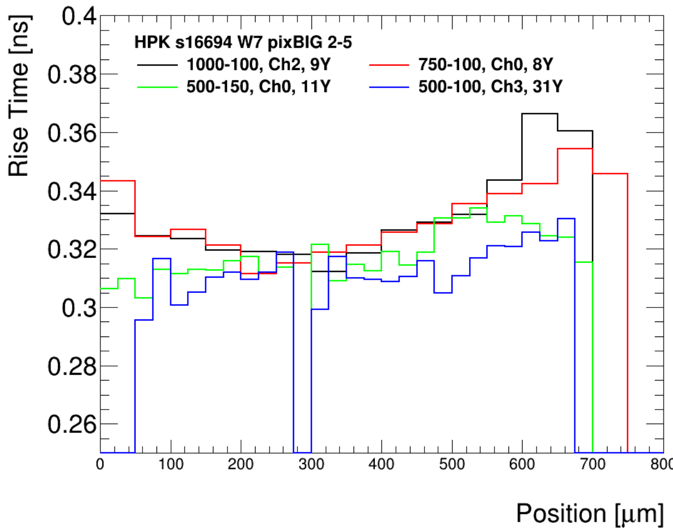


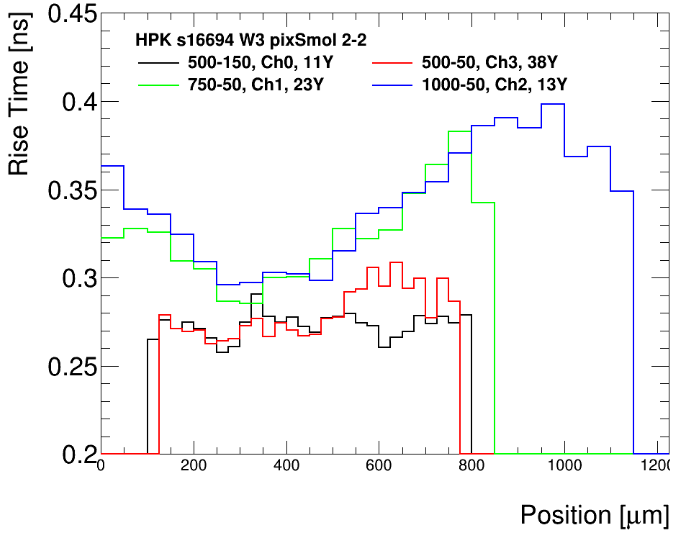


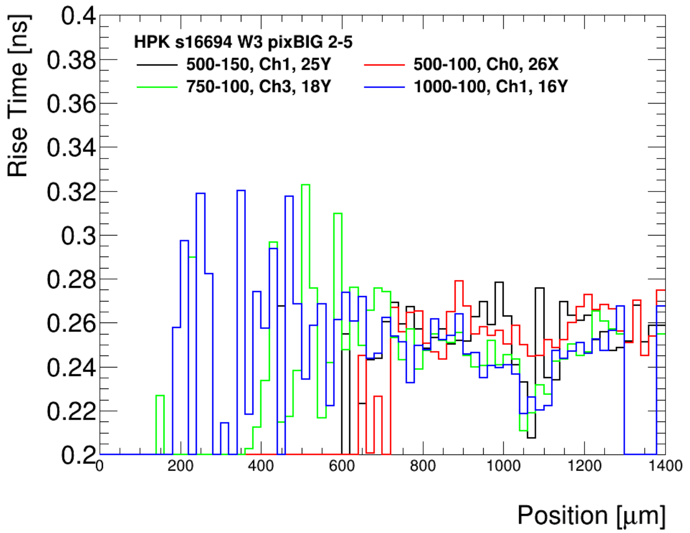


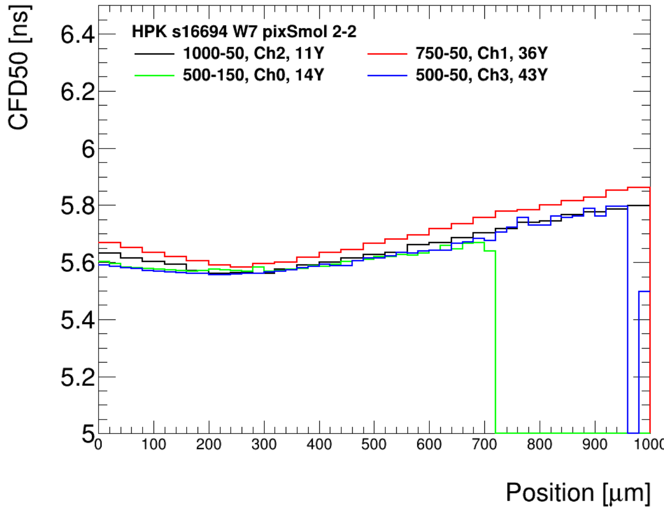
W7 (30um) pixSmol | W7 (30um) pixBIG | W3 (20um) pixSmol | W3 (20um) pixBIG

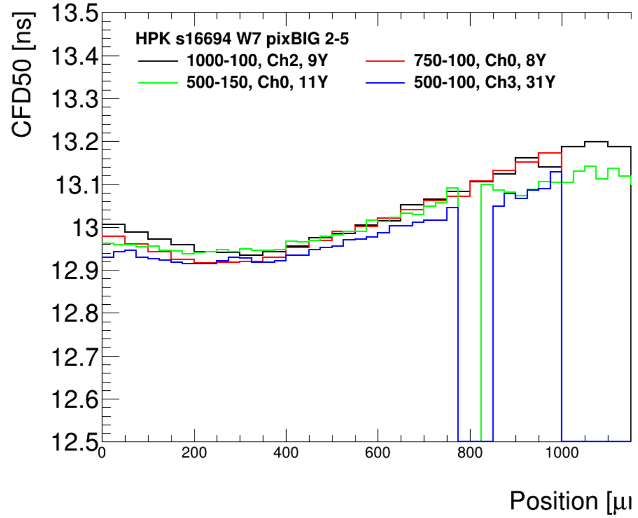


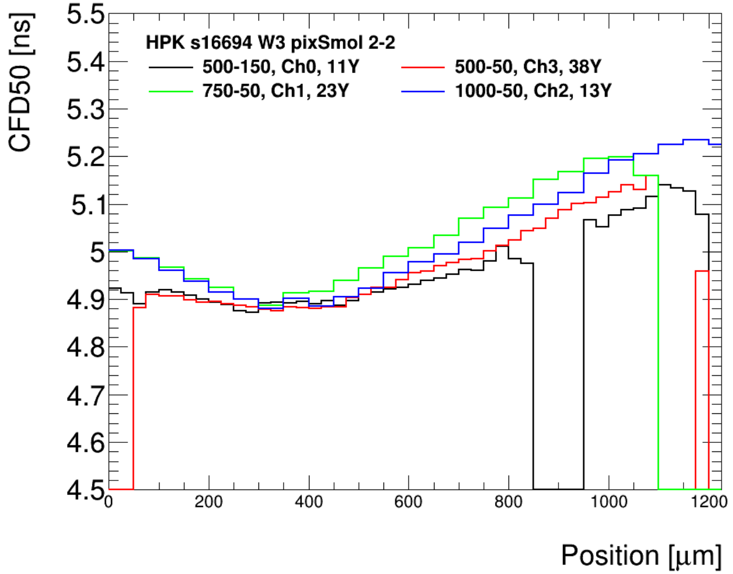


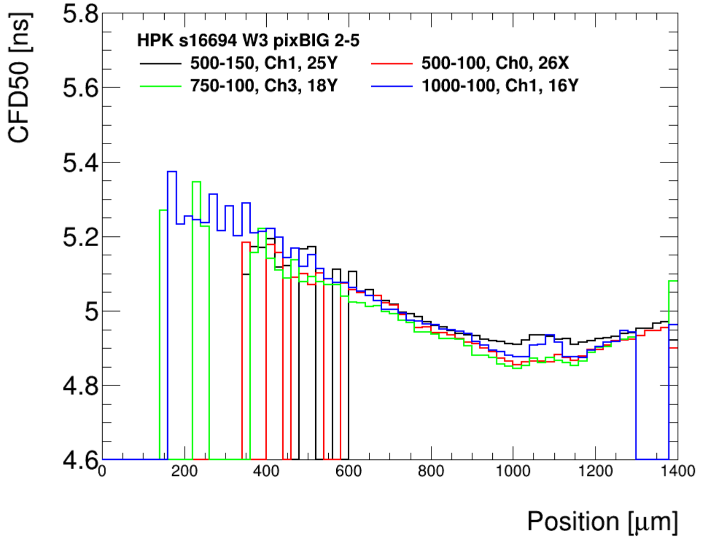












W7 (30um) pixSmol   W7 (30um) pixBIG   W3 (20um) pixSmol   W3 (20um) pixBIG