Sensors QA/QC for TOF

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On behalf of SCIPP and ePIC TOF

ePIC collaboration meeting, Glasgow 2026

Sensor QA/QC

- Sensors should be tested before assembly
  - HPK will provide IV (current over voltage) measurement for all devices on wafer (before dicing)
  - HPK will also provide CV (?)
  - Dicing process can affect the sensors, furthermore, there might be a miscommunication in sensor identification
  - Need a total or partial re-test at institutes
- At pre-assembly level: test every sensor and homogeneity
  - To verify wafer level testing
  - To test parameters homogeneity
- At production level: quick verification of work and spot performance verification

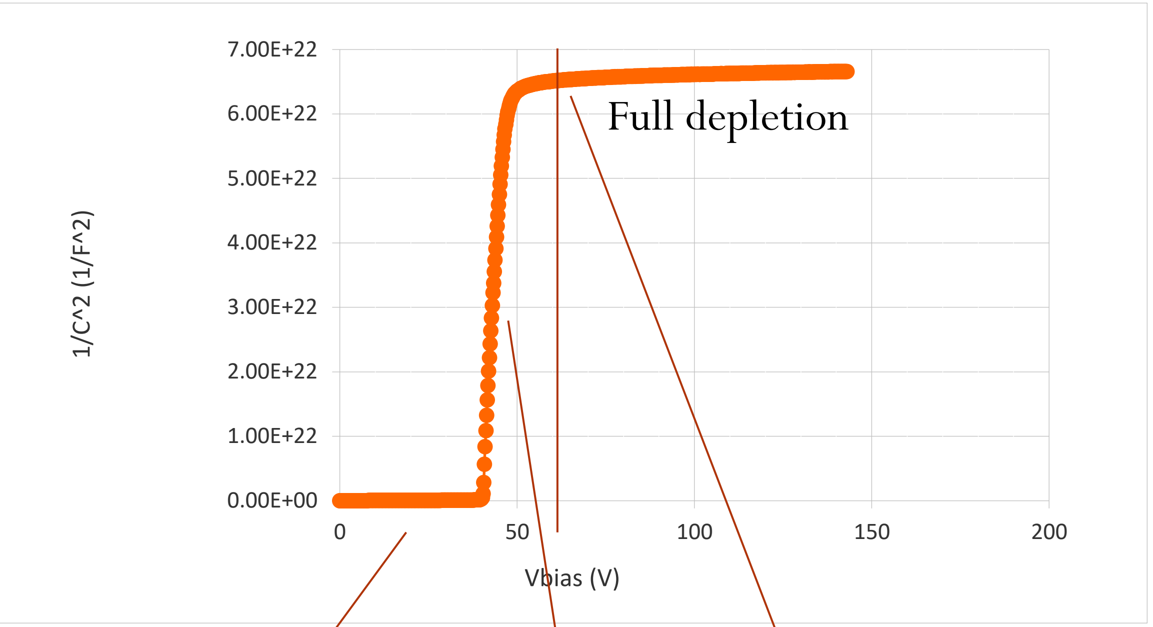
Sensor testing

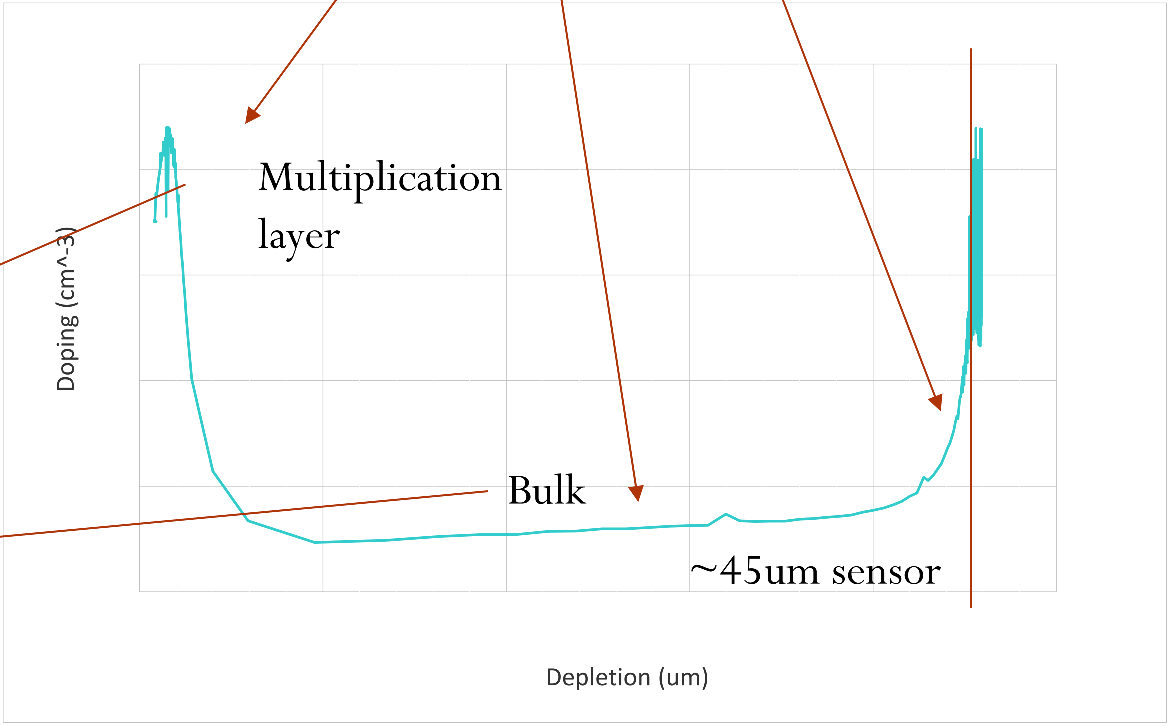
- Probe station, manual with 2 needles is enough [time needed]
  - Mount sensor [5 minutes]
  - Current over voltage, verify breakdown and operating voltage [1 minute]
  - Capacitance over voltage, verify gain homogeneity [10 minutes]
  - N+ resistance homogeneity, on test structure (few per wafer), [5+1 minute]
  - Oxide capacitance measurement?
- Automatic probe station with jig for multiple sensors can reduce time significantly

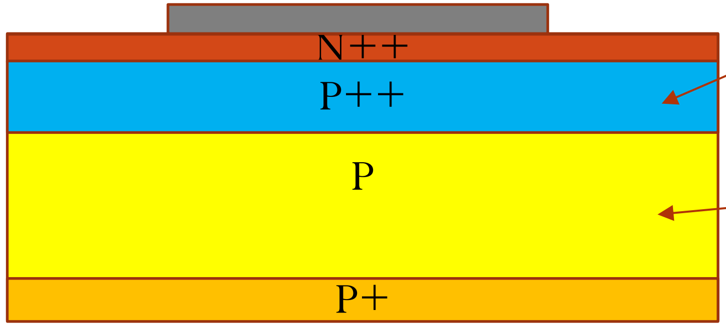
- Laser TCT or source [time needed]
  - Mount sensor [2-3 hours (wire bonding)]
  - Charge collection [2-3 hours]
- Speed up the process: probe card with some active readout coupled with a source
  - Can be developed if we want to bulk test the charge collection of devices

CV and gain layer

- Capacitance over voltage (CV)
  - Study doping concentration profile and full depletion of the sensor
  - Doping profile can be extracted from the $1/C^2$ derivative
- Study of the "foot" for LGADs on $1/C^2$
  - $1/C^2$ is flat until depletion of multiplication layer because of the high doping concentration
  - Proportional to gain layer active concentration
- Bulk doping concentration proportional to the derivative of $1/C^2$ before depletion







Requirements

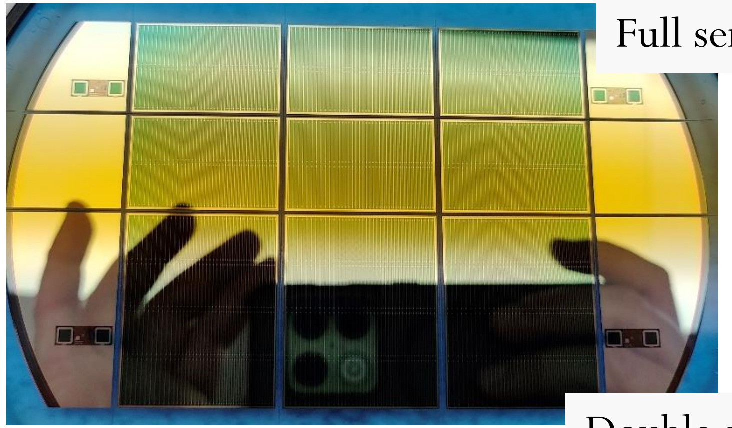
- Lessons learned from the previous productions
  - What parameters to check (breakdown, gain layer depletion, N+ resistivity)
  - Spot systematic issues (50um low yield)
  - Spot assembly issues (post-bonding leakage current)
  - Establish bookkeeping and database

- What requirements do we want
  - Gain homogeneity requirements
  - Breakdown homogeneity
  - Operating voltage variation to maintain time resolution
  - Yield (what does HPK offer in contract?)

HPK s16694 production – 2024/2025

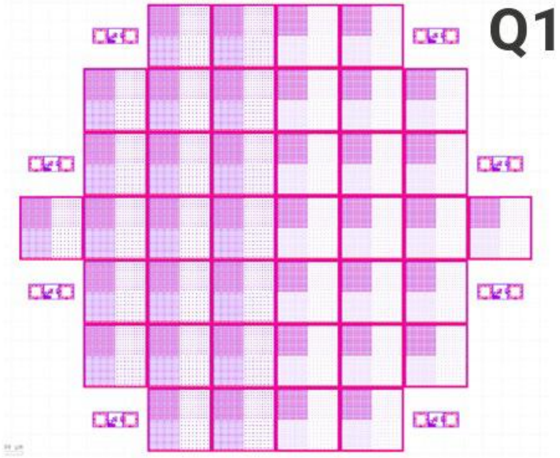
- ePIC full-size production of HPK strip and pixel AC-LGADs
  - Multi-pitch and multi-electrode size
- 8 strip wafers, 50um and 30um thick
- 4 pixel wafers, 30um and 20um thick
- Fully tested electrically and sample tested with laser and test beams
  - Measured parameters variation

Half sensors

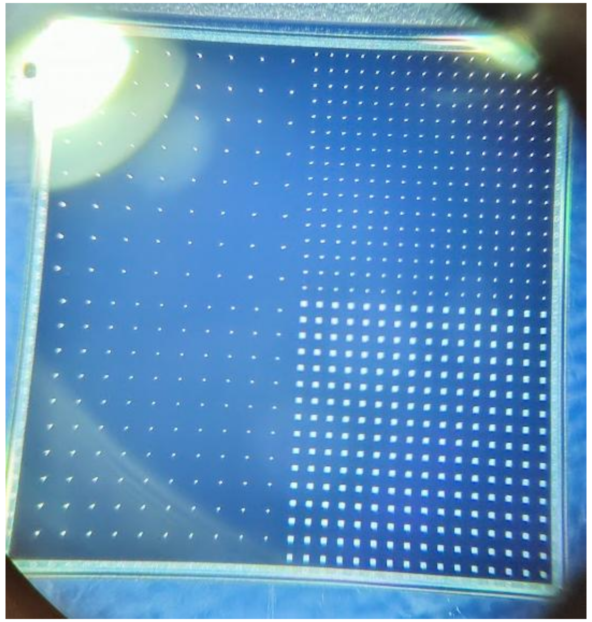


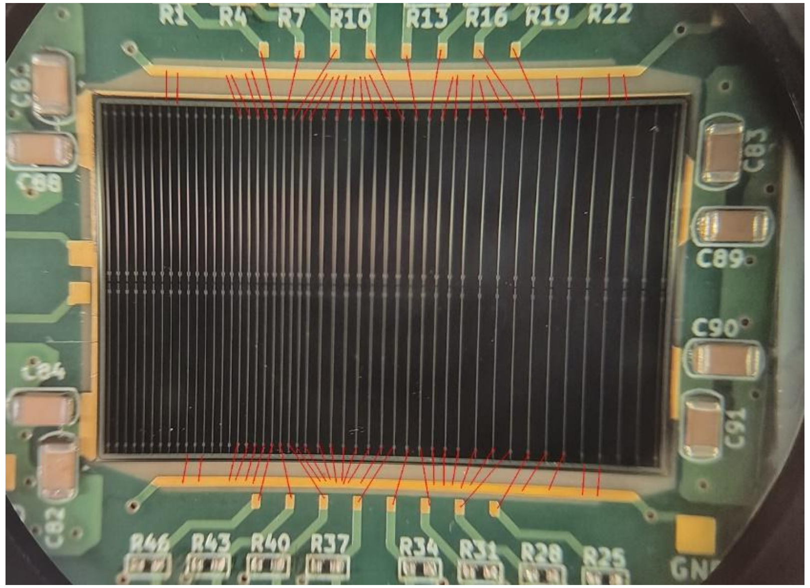
Full sensors

Double sensors



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





Need to migrate this to ePIC database!

AC-LGAD sensor inventory

File Edit View Insert Format Data Tools Extensions Help

A1 | Batch number

Table1

Batch number	Vendor	Received	Wafer	W (L,C)	Pixel/strips	Geometry	Thickness	Current location	Last update	I @ 100V	BV	OK/NG	Tests done	Notes
HPK s16694	HPK	October 2024	11	1-1	strips	half size multipitch	50 um	UCSC	March 2025	-	40	NG	IV	
HPK s16694	HPK	October 2024	11	1-2	strips	half size multipitch	50 um	FNAL	March 2025	7.54.E-06	190	OK	IV	
HPK s16694	HPK	October 2024	11	2-1	strips	full size multipitch	50 um	UCSC	March 2025	-	55	NG	IV	
HPK s16694	HPK	October 2024	11	2-2	strips	full size multipitch	50 um	UCSC	March 2025	8.57.E-06	190	OK	IV, Laser TCT	Broke during dismount
HPK s16694	HPK	October 2024	11	2-3	strips	full size multipitch	50 um	BNL	March 2025	-	35	NG	IV	
HPK s16694	HPK	October 2024	11	3-1	strips	full size multipitch	50 um	UCSC	March 2025	-	50	NG	IV	
HPK s16694	HPK	October 2024	11	3-2	strips	full size multipitch	50 um	FNAL	March 2025	2.54.E-05	185	High curr...	IV, Laser TCT	on board v1.1
HPK s16694	HPK	October 2024	11	3-3	strips	full size multipitch	50 um	UCSC	March 2025	-	50	NG	IV	
HPK s16694	HPK	October 2024	11	4-1	strips	double size multipitch	50 um	BNL	March 2025	-	55	NG	IV	
HPK s16694	HPK	October 2024	11	4-2	strips	double size multipitch	50 um	UCSC	March 2025	1.91.E-05	185	OK	IV	
HPK s16694	HPK	October 2024	11	4-3	strips	double size multipitch	50 um	BNL	March 2025	6.68.E-05	115	NG	IV	
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HPK s16694	HPK	October 2024	2	1-2	strips	half size multipitch	50 um	UCSC	March 2025	-1.20E-06	190	OK	IV	
HPK s16694	HPK	October 2024	2	2-1	strips	full size multipitch	50 um	Hawaii	March 2025	-	35	NG	IV	
HPK s16694	HPK	October 2024	2	2-2	strips	full size multipitch	50 um	UCSC	March 2025	-	40	NG	IV	
HPK s16694	HPK	October 2024	2	2-3	strips	full size multipitch	50 um	Hawaii	March 2025	-	45	NG	IV	
HPK s16694	HPK	October 2024	2	3-1	strips	full size multipitch	50 um	UCSC	March 2025	-4.91E-05	155	High curr...	IV	
HPK s16694	HPK	October 2024	2	3-2	strips	full size multipitch	50 um	UCSC	March 2025	-	50	NG	IV	
HPK s16694	HPK	October 2024	2	3-3	strips	full size multipitch	50 um	UCSC	March 2025	-	20	NG	IV	
HPK s16694	HPK	October 2024	2	4-1	strips	double size multipitch	50 um	Hawaii	March 2025	-	40	NG	IV	
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HPK s16694	HPK	October 2024	2	4-3	strips	double size multipitch	50 um	Hawaii	March 2025	-	40	NG	IV	
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HPK s16694	HPK	October 2024	2	5-2	strips	half size multipitch	50 um	UCSC	March 2025	-2.53E-07	185	OK	IV	on v1.2 board, JLAB TB
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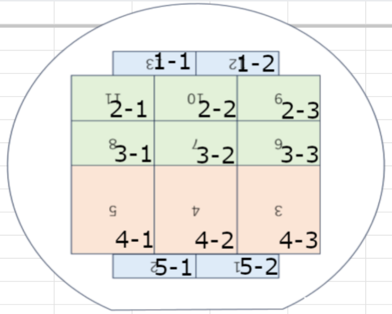
HPK s16694	HPK	October 2024	6	1-2	strips	half size multipitch	50 um	UCSC	March 2025	-3.10E-07	190	OK	IV	
HPK s16694	HPK	October 2024	6	2-1	strips	full size multipitch	50 um	UCSC	March 2025		25	NG	IV	
HPK s16694	HPK	October 2024	6	2-2	strips	full size multipitch	50 um	UCSC	March 2025	-6.30E-06	185	OK	IV	
HPK s16694	HPK	October 2024	6	2-3	strips	full size multipitch	50 um	UCSC	March 2025	-1.30E-05	180	High curr...	IV	
HPK s16694	HPK	October 2024	6	3-1	strips	full size multipitch	50 um	UCSC	March 2025	-5.60E-05	130	NG	IV	
HPK s16694	HPK	October 2024	6	3-2	strips	full size multipitch	50 um	UCSC	March 2025		35	NG	IV	
HPK s16694	HPK	October 2024	6	3-3	strips	full size multipitch	50 um	UCSC	March 2025		50	NG	IV	
HPK s16694	HPK	October 2024	6	4-1	strips	double size multipitch	50 um	UCSC	March 2025	-7.60E-05	120	NG	IV	
HPK s16694	HPK	October 2024	6	4-2	strips	double size multipitch	50 um	UCSC	March 2025		50	NG	IV	
HPK s16694	HPK	October 2024	6	4-3	strips	double size multipitch	50 um	UCSC	March 2025		35	NG	IV	
HPK s16694	HPK	October 2024	6	5-1	strips	half size multipitch	50 um	Hawaii	March 2025	-2.10E-06	190	OK	IV	
HPK s16694	HPK	October 2024	6	5-2	strips	half size multipitch	50 um	FNAL	March 2025	-1.10E-06	190	OK	IV	
HPK s16694	HPK	October 2024	12	1-1	strips	half size multipitch	50 um	UCSC	March 2025	-1.20E-05	190	OK	IV	
HPK s16694	HPK	October 2024	12	1-2	strips	half size multipitch	50 um	UCSC	March 2025	-9.30E-06	190	OK	IV	
HPK s16694	HPK	October 2024	12	2-1	strips	full size multipitch	50 um	UCSC	March 2025		30	NG	IV	
HPK s16694	HPK	October 2024	12	2-2	strips	full size multipitch	50 um	LBNL	March 2025	-1.60E-06	190	OK	IV	on v1.2 board, JLAB TB

Wafer position

NG		OK
NG	OK	NG
NG	High current	NG
NG	OK	NG
OK		OK



OK		OK
NG	NG	NG
High current	NG	NG
NG	NG	NG
OK		OK

NG		OK
NG	OK	High current
NG	NG	NG
NG	NG	NG
OK		OK

Add IV data for every device!

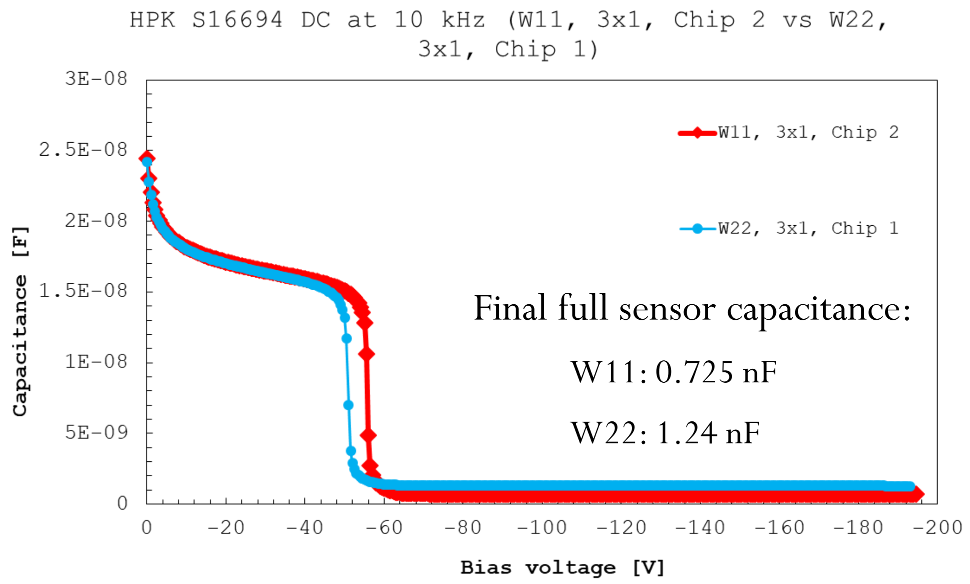
OK		OK
NG	OK	High current
High current	OK	NG
High current	NG	NG

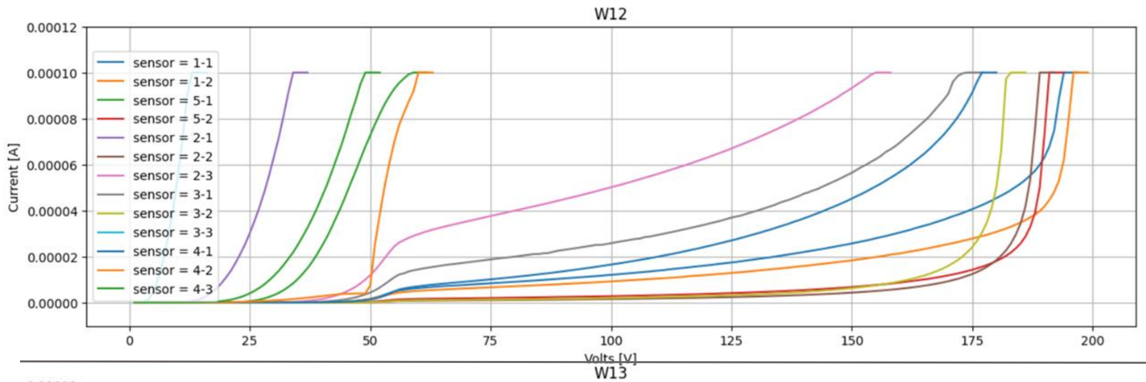
HPK S16694 strips 50 um | HPK S16694 strips 30um | HPK S16694 pixel 30um | HPK S16694 pixel 20um | JSI neutron 2024 | FNAL protons 2024 | Requests for sensors | JLAB TB | HP

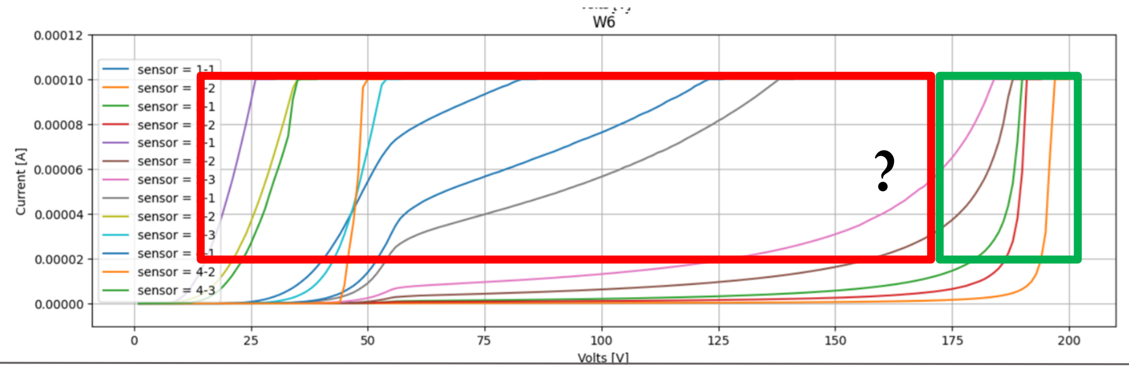
Database: https://docs.google.com/spreadsheets/d/1J7IuZuRaYmpDjLfzsFhHAh88glab9uHFaDUo3HoOE1o/edit?usp=sharing

HPK strip production results – IV/CV

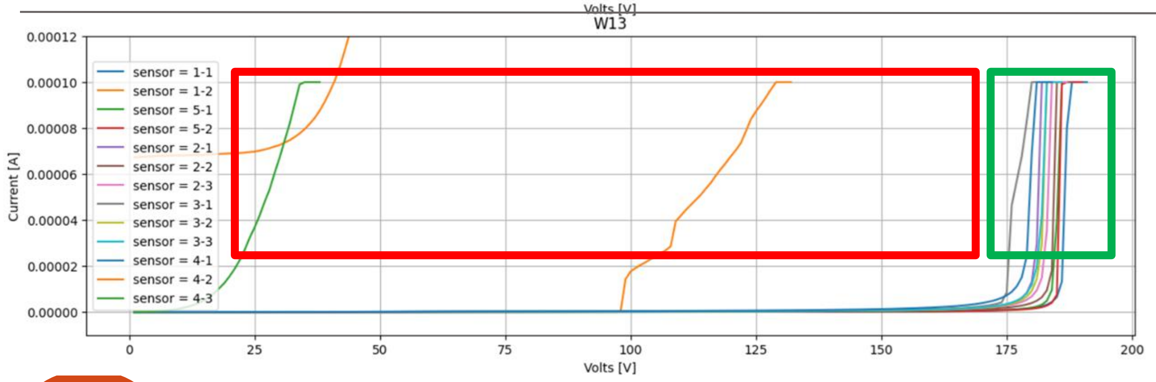
- Yield is not optimal for 50um, better for 30um wafer
- Capacitance of full detector scales with thickness
- IV requirement could be $V_{bd} > 170V$ (e.g., $I > 10uA$)
- Sensor with high current can be 2nd choice

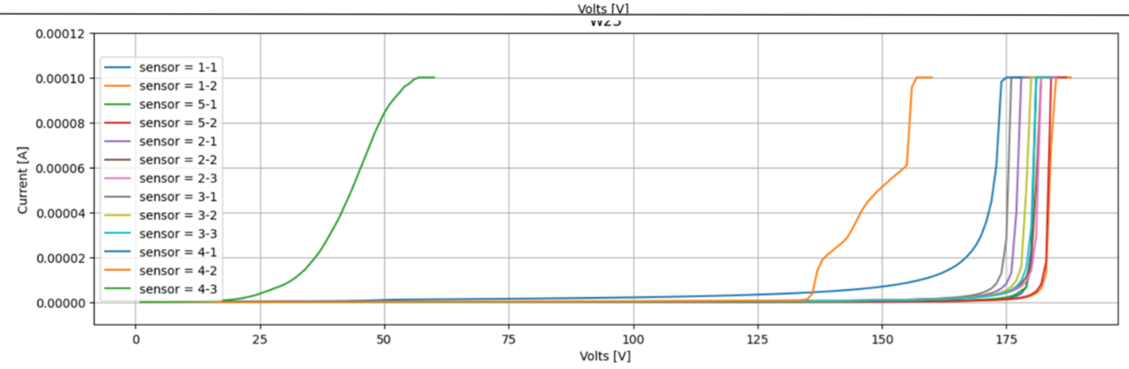






50um





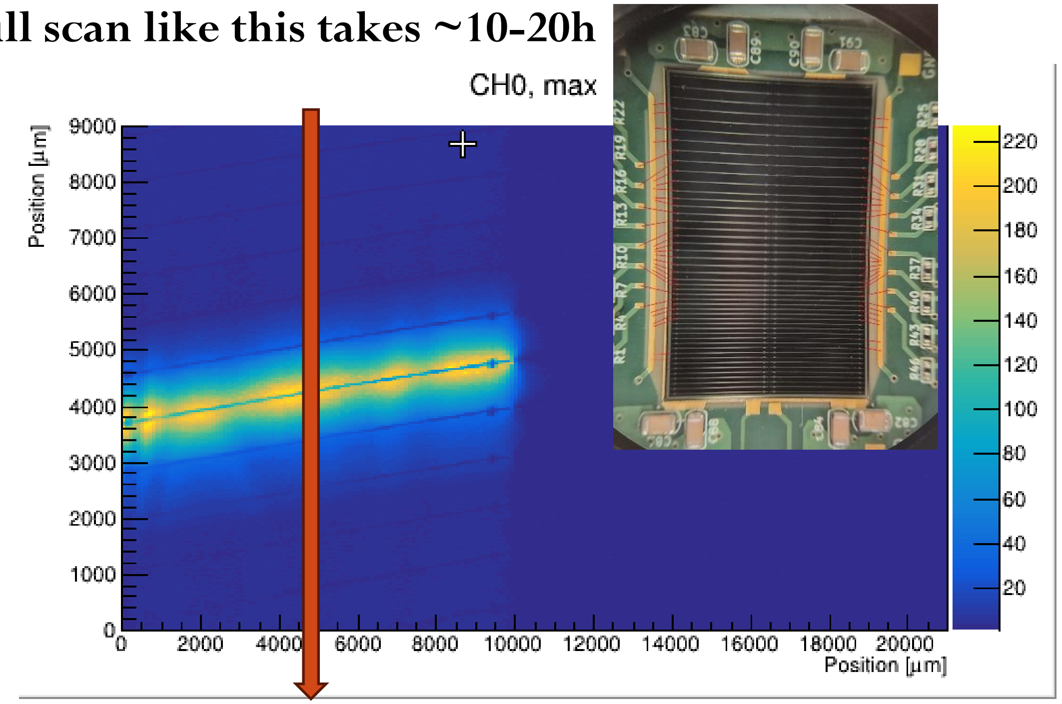
30um

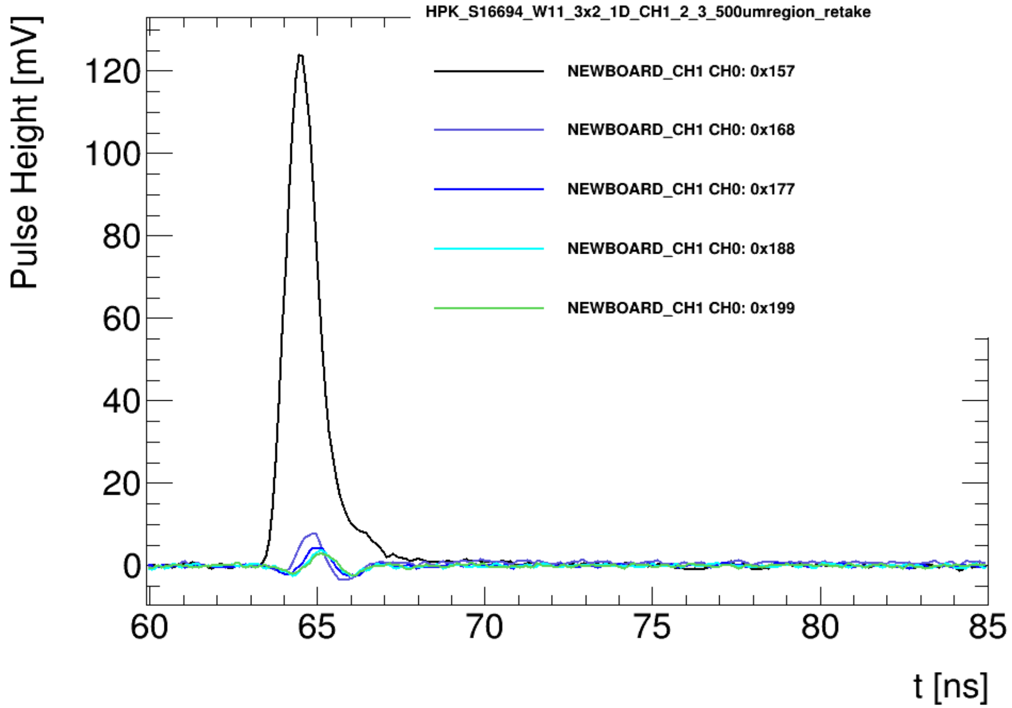
Student: G. Stage, A. Borgijin

HPK production results - TCT

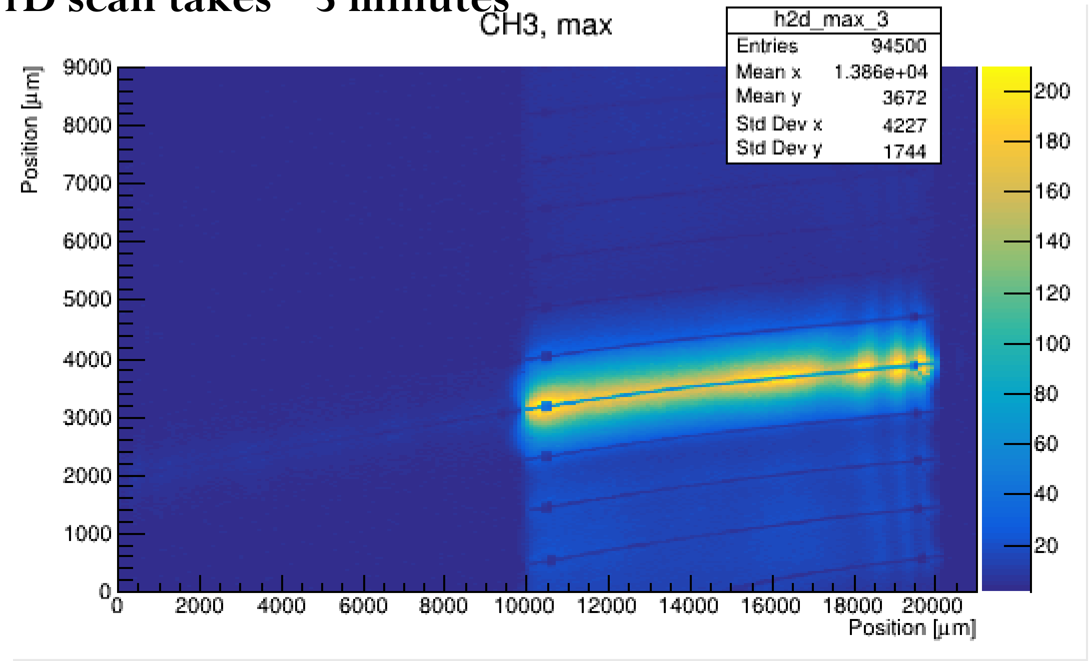
- Full size sensors tested on a large board with laser TCT
- Sensor works well, some gain variation across strip but it's unclear if due to laser reflections
- **Rise-time** 600-700 ps for 50um and 400ps for 30um
- **Time of arrival delay** ~2ps/um (250ps for 500um) perpendicular to the strip and ~0.01ps/um (<100ps for 1cm) parallel to the strip (metal propagation)

A full scan like this takes ~10-20h





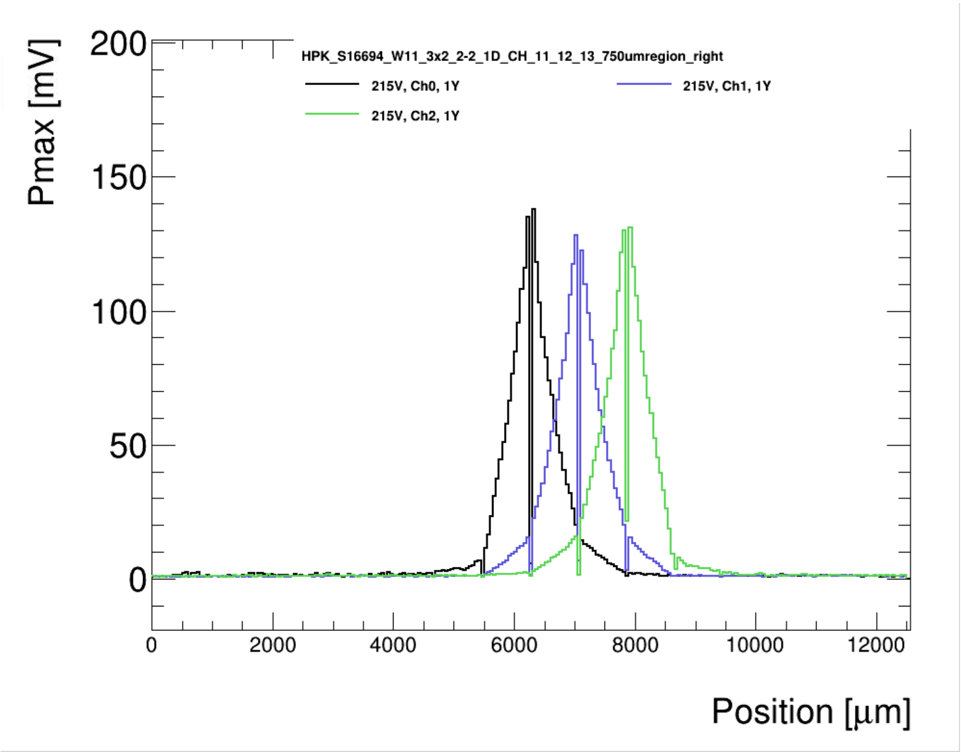
A 1D scan takes ~5 minutes

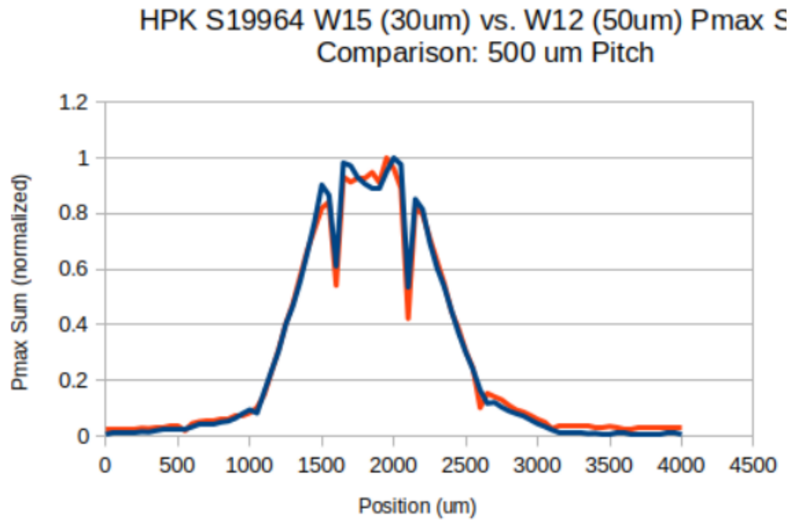


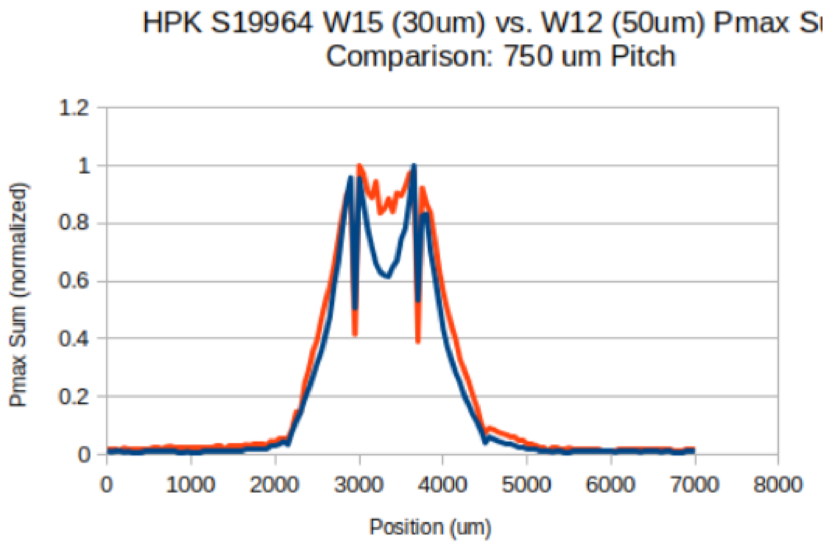
Student: G. Stage, A. Borgijin

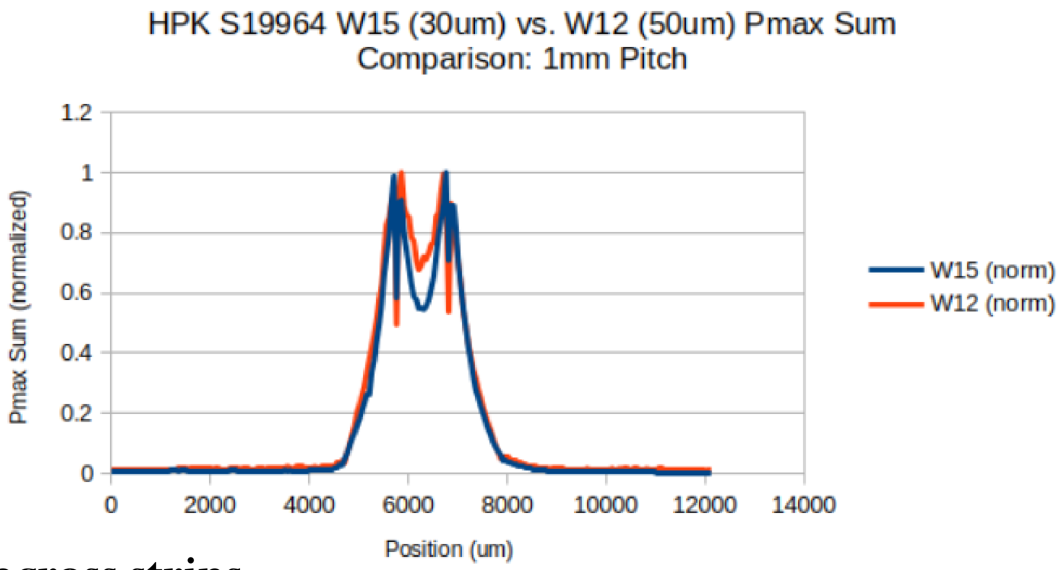
HPK production results - TCT

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







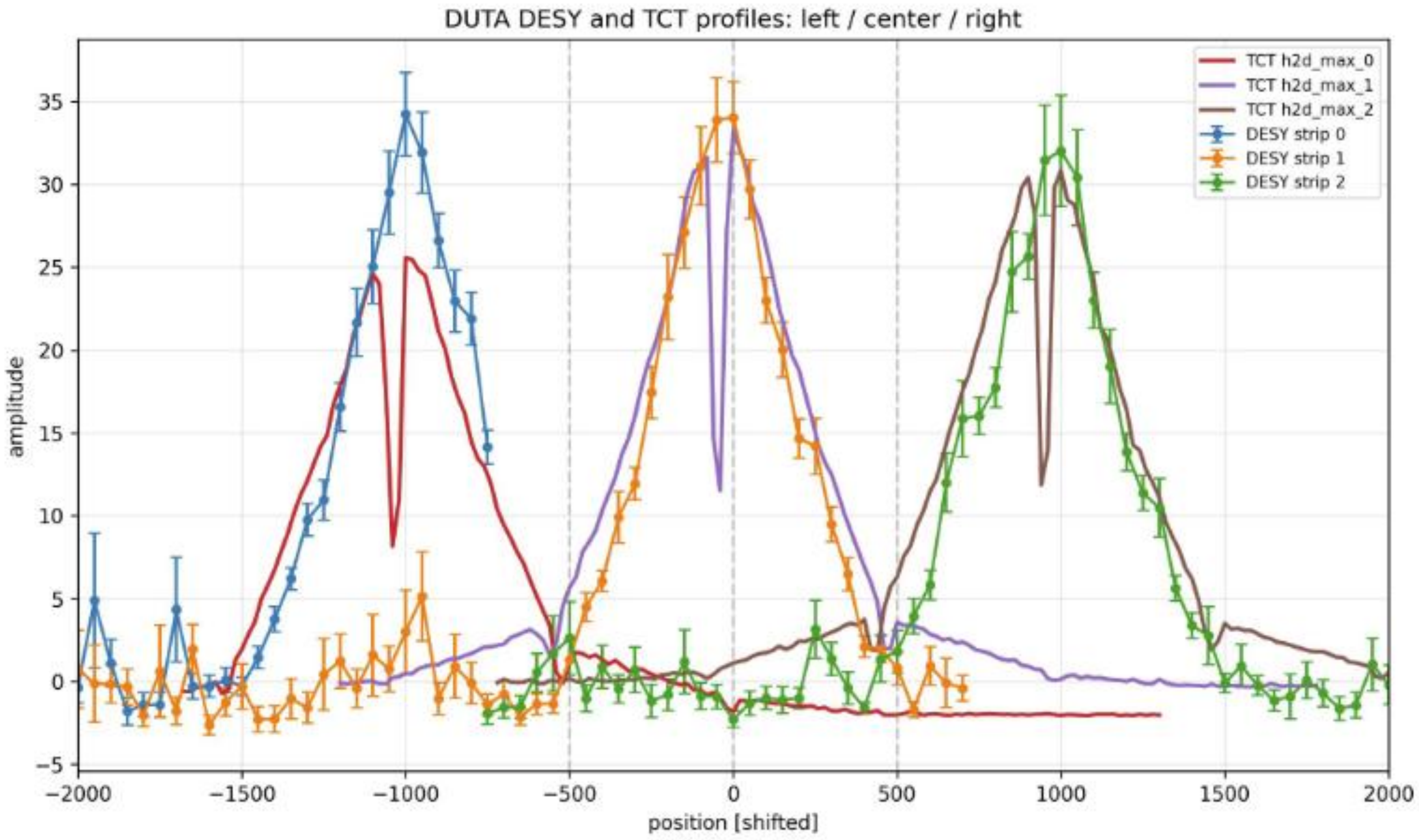


Produce samples of this plot to measure S/N variation across strips

Student: G. Stage, A. Borgijin

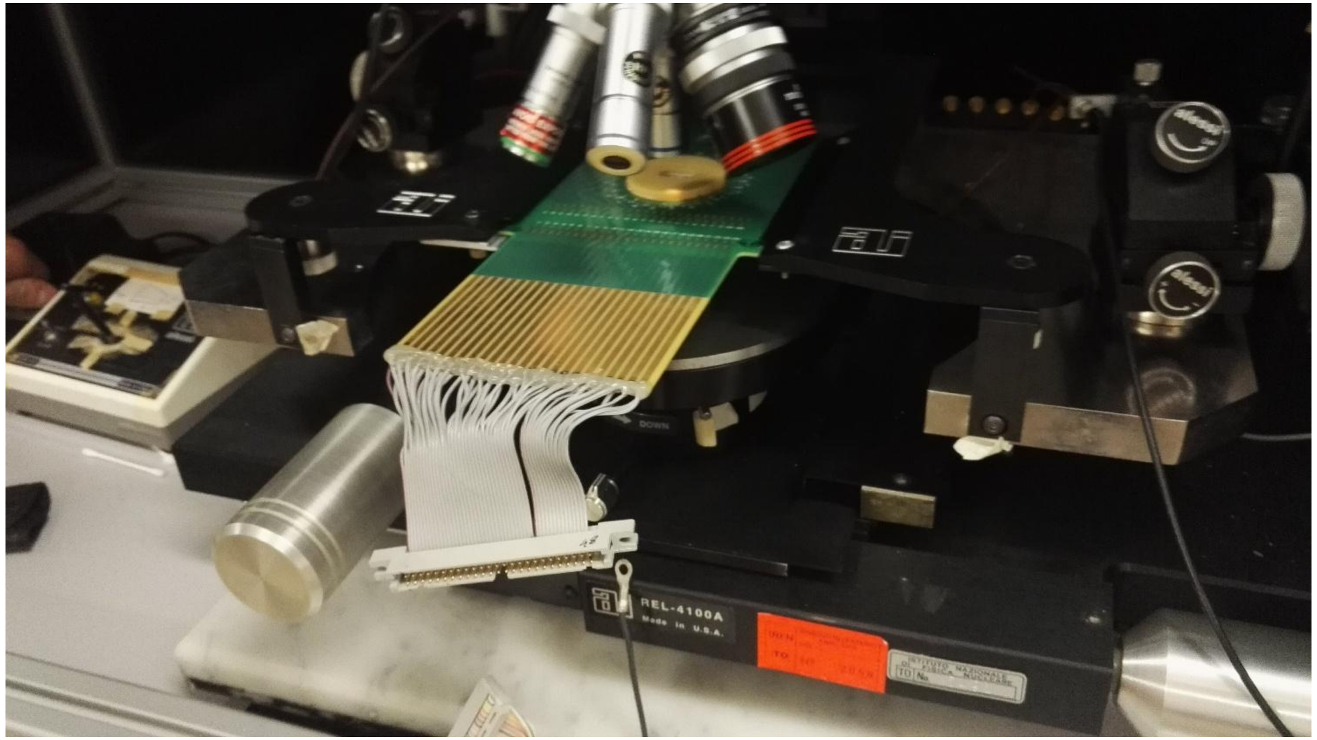
Laser TCT and testbeam comparison

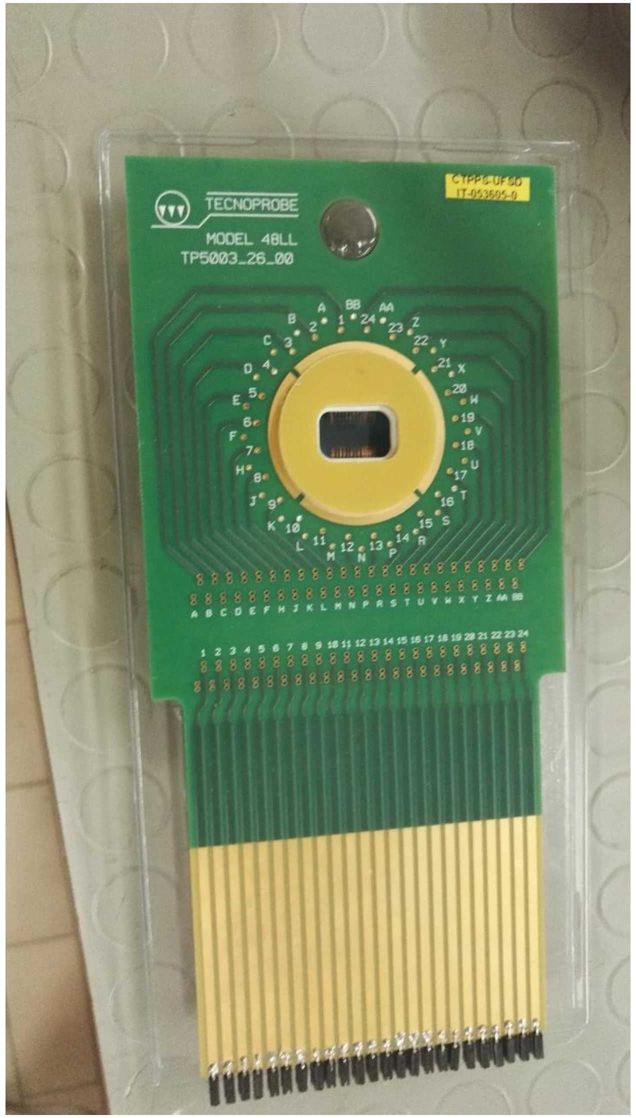
- Pretty good agreement!



Charge collection with probecard?

- Might be possible to setup, useful?

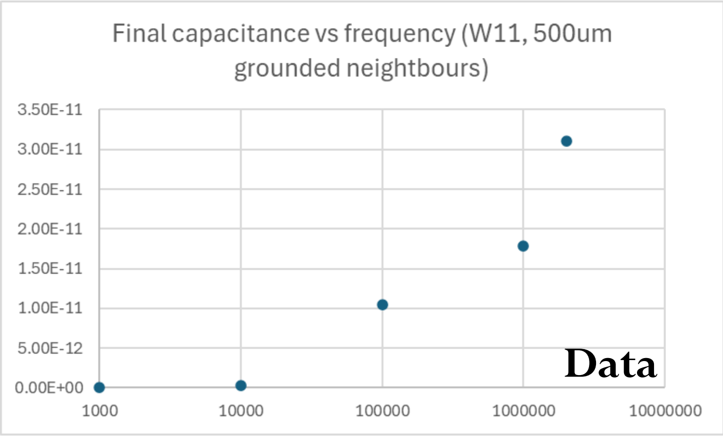


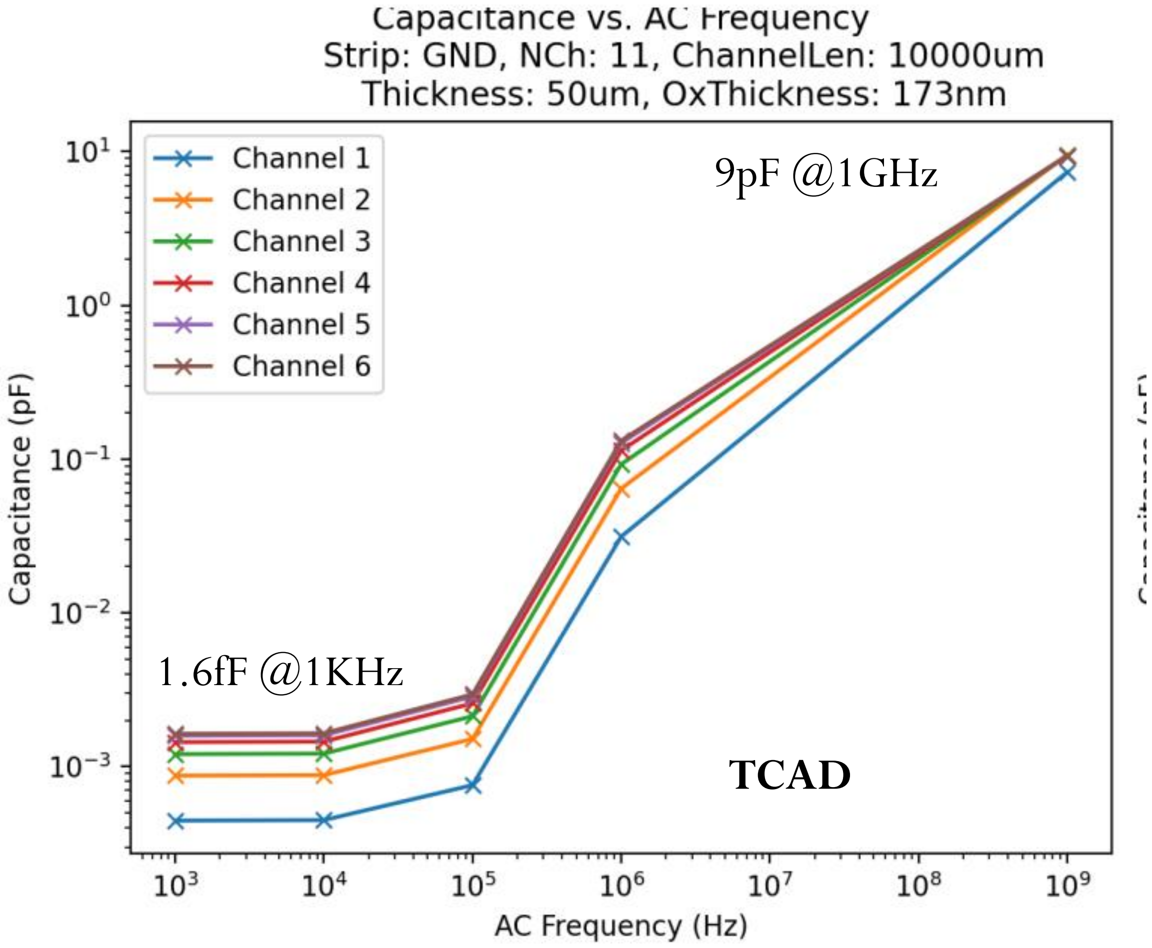


Strip AC capacitance

- 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

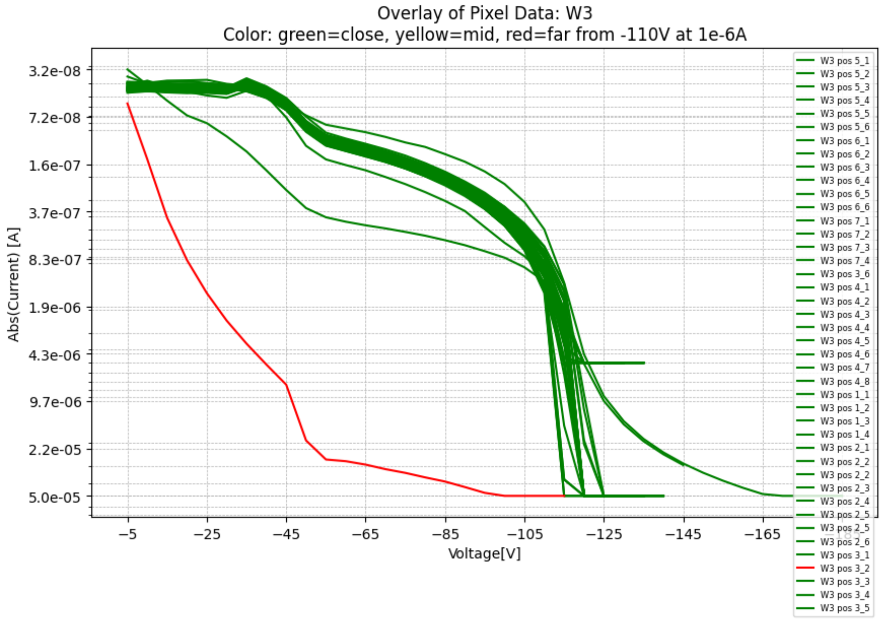


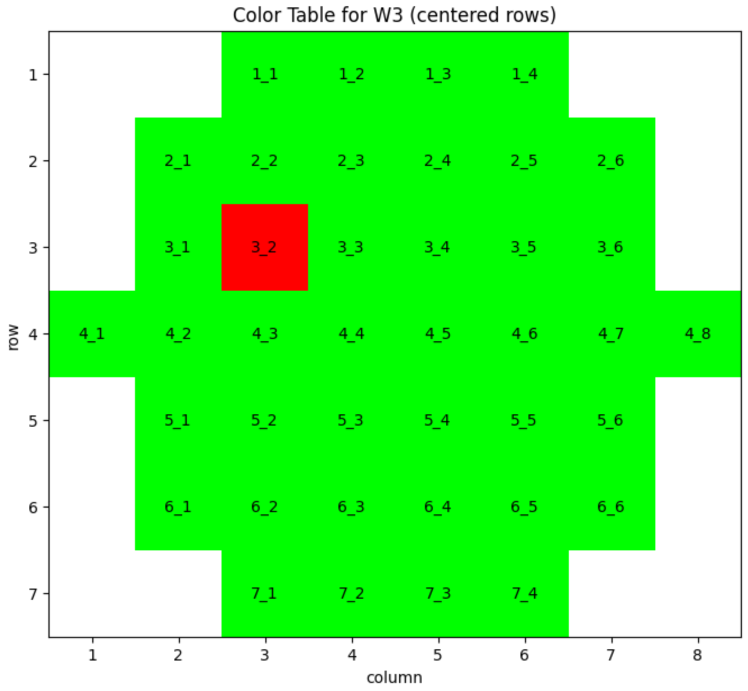


Credits: T. Shin

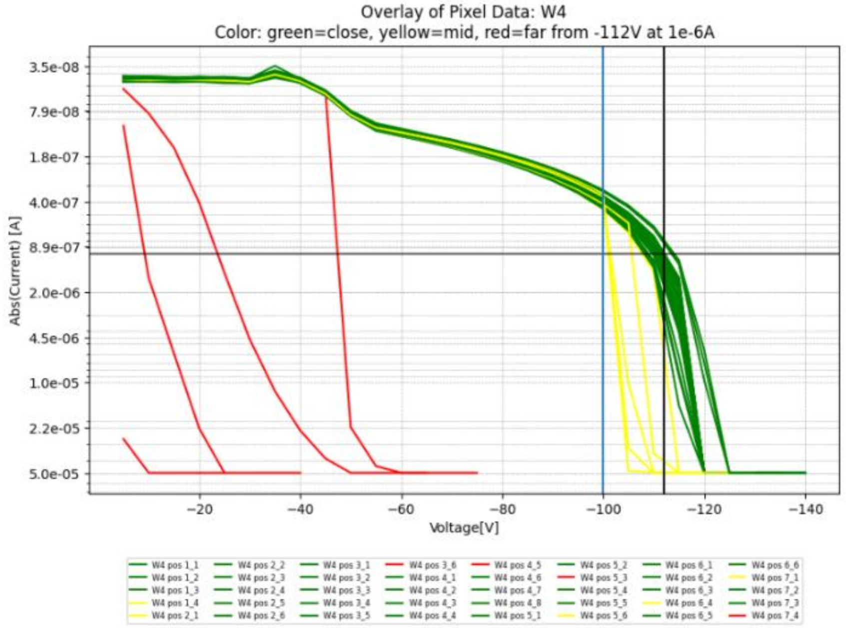
Pixel sensors – 20um wafers

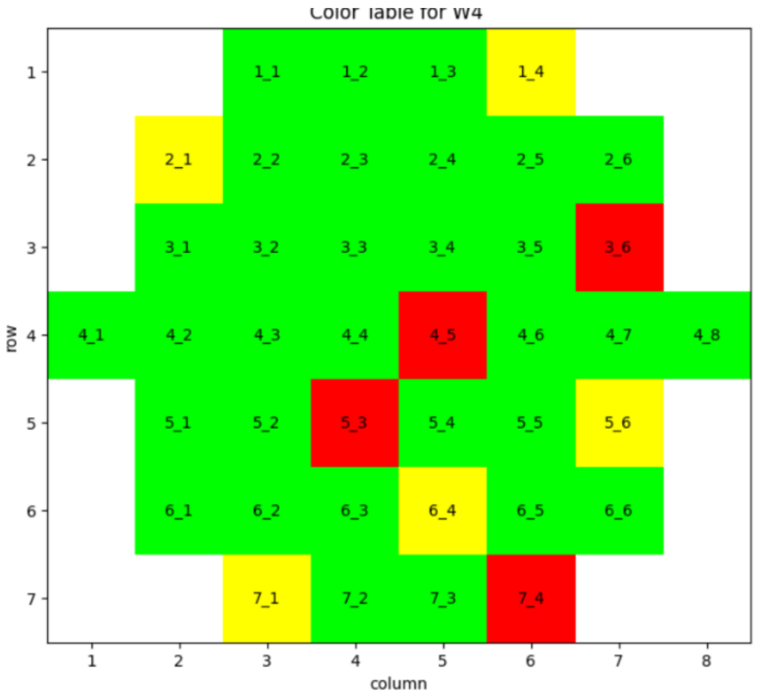
- W3 - 20um thick





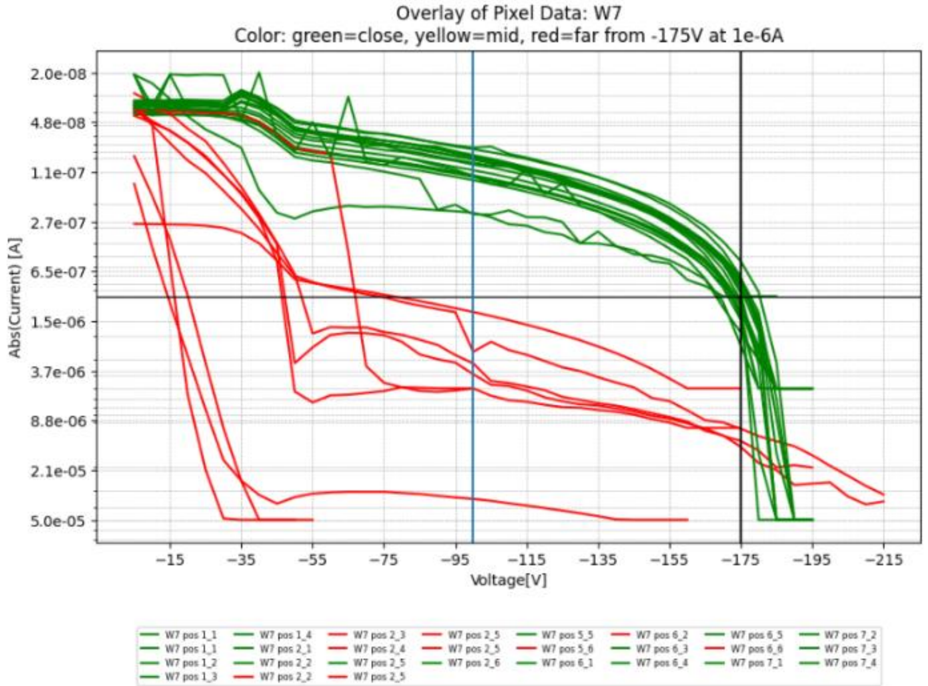
- W4 - 20um thick

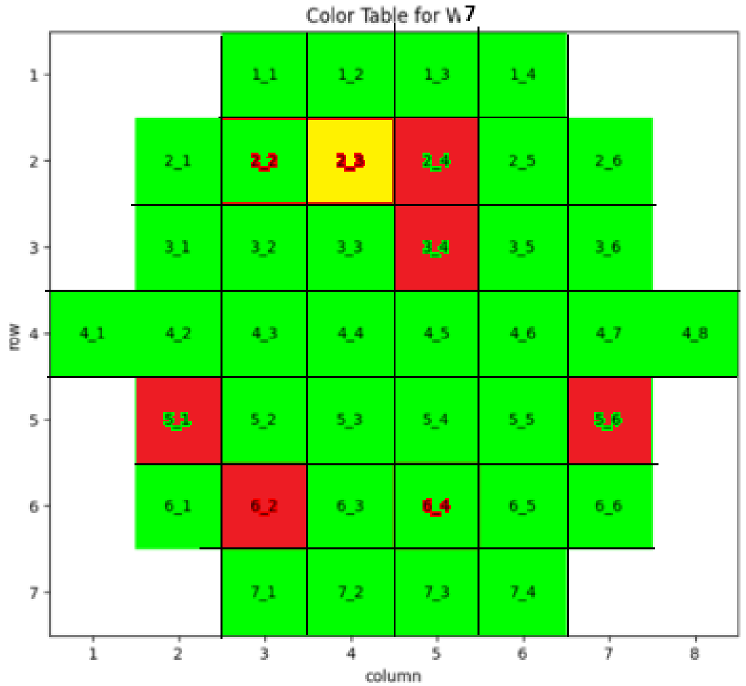




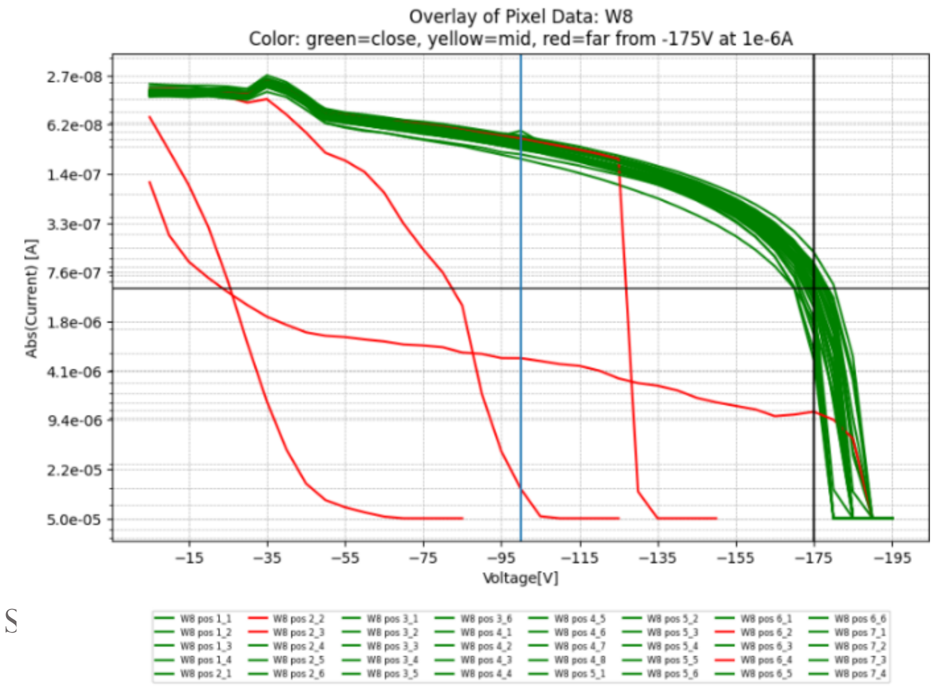
Pixel sensors – 30um wafers

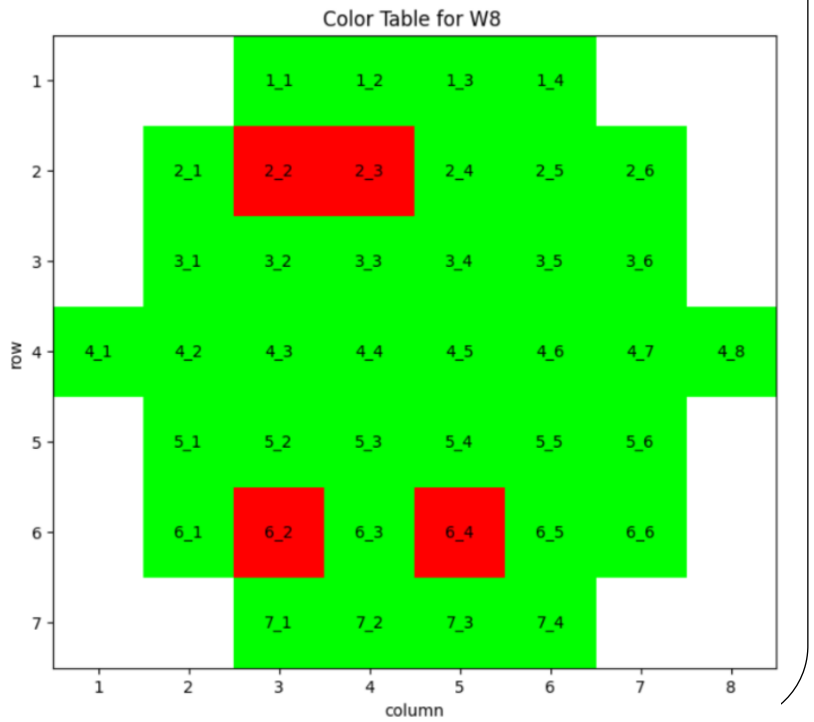
- W7 - 30um thick





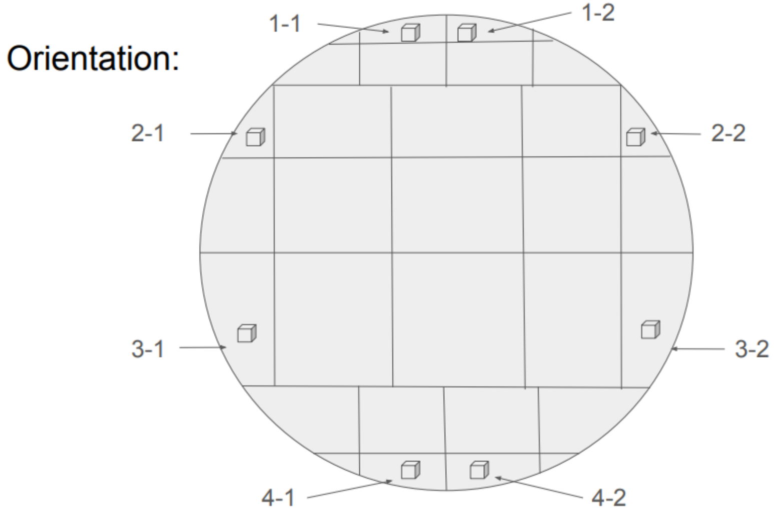
- W8 - 30um thick

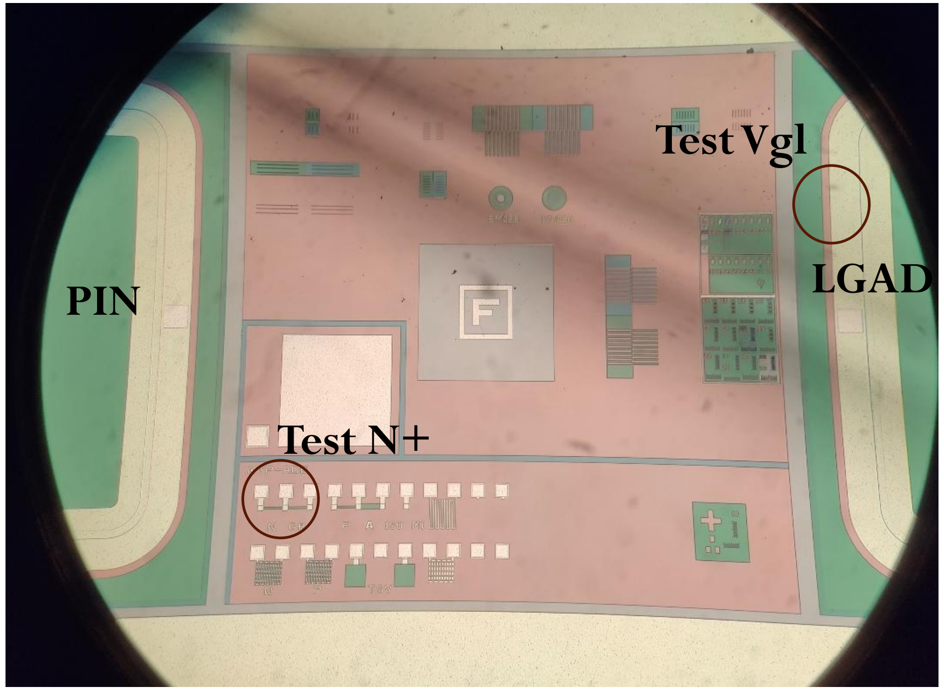


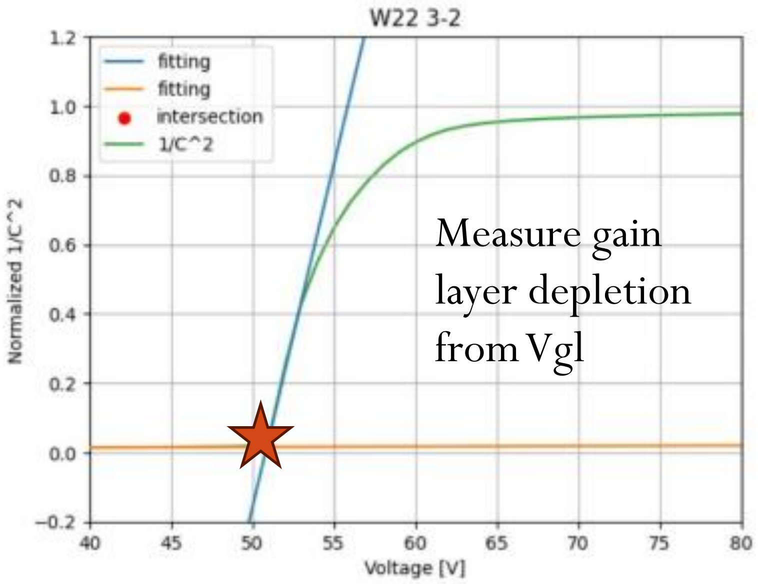


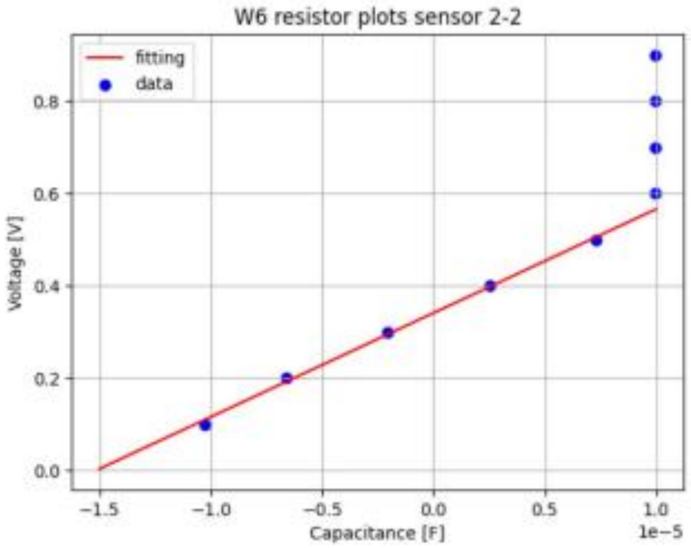
HPK production testing

- **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







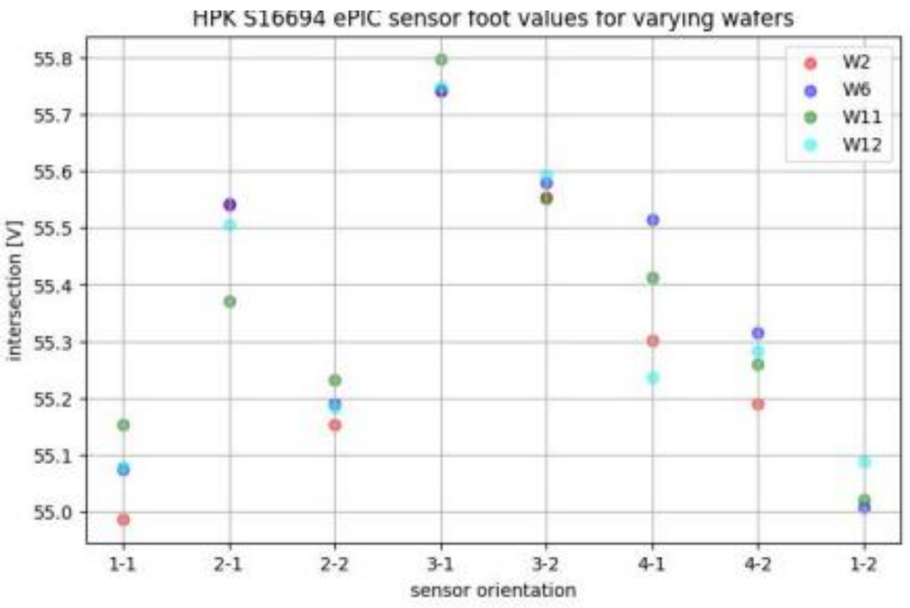


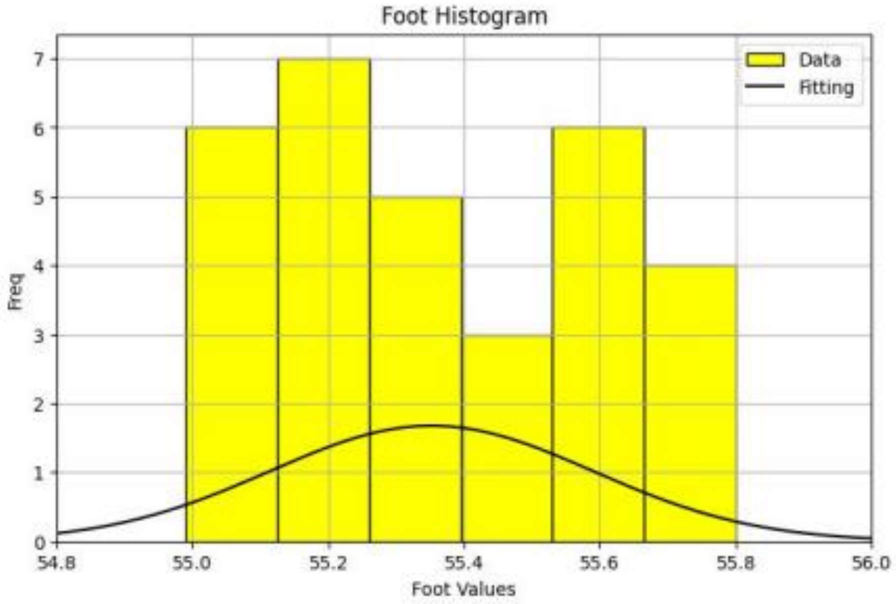
$V(I) = 22504*I + 0.341$

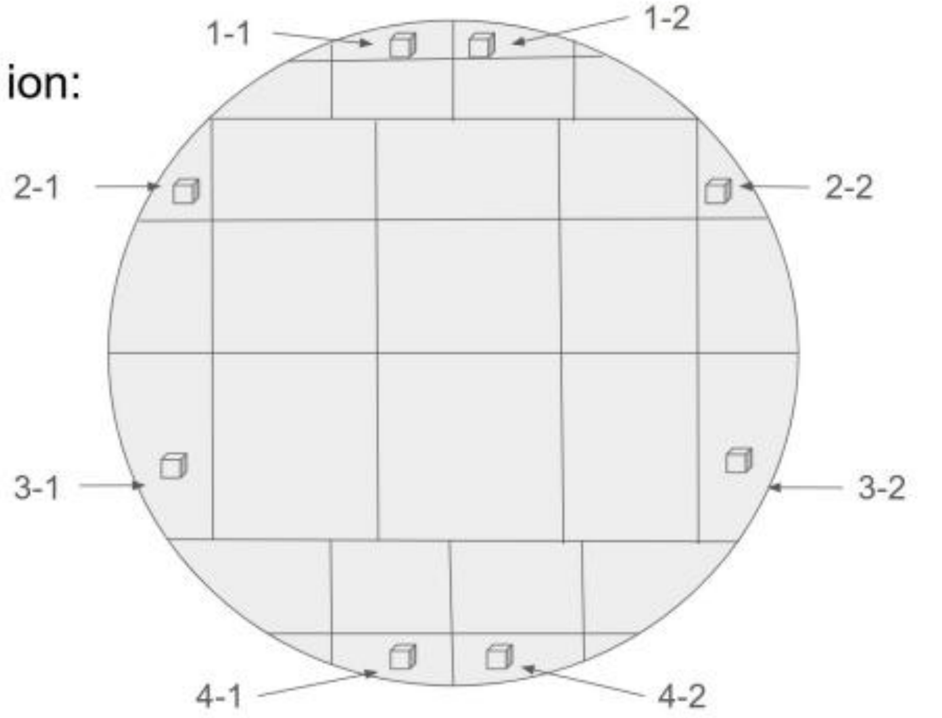
Student: M. Davis, S. Beringer

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?



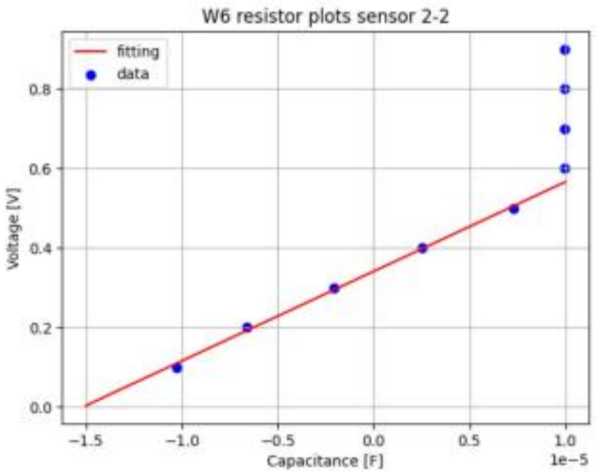




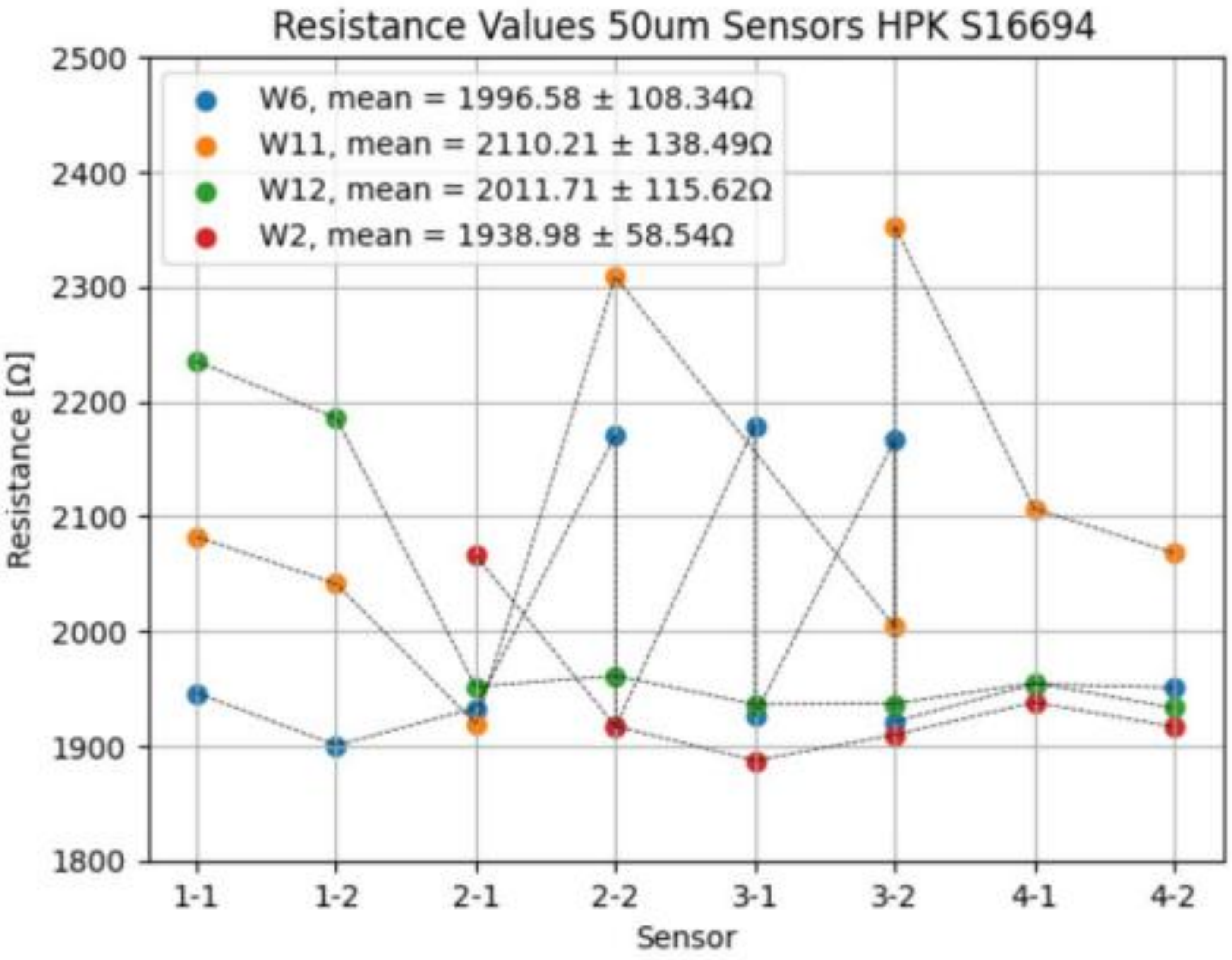
Mean = 55.26
Sigma = 0.23

N+ resistivity test

- Measuring resistivity for all 50um wafers
  - (30um wafers still in progress)
- 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%

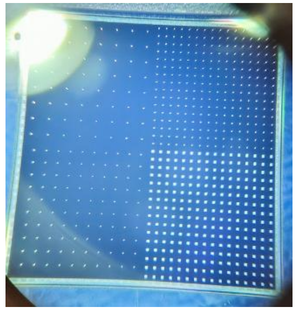


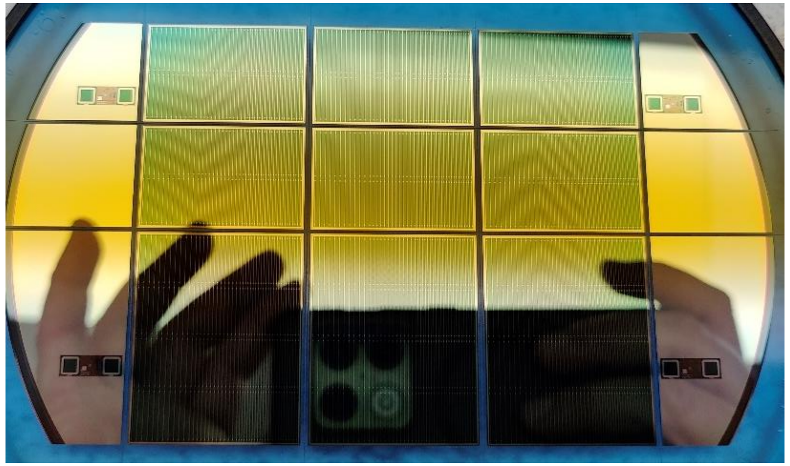
V(I) = 22504*I + 0.341 → R = 2250 Ω

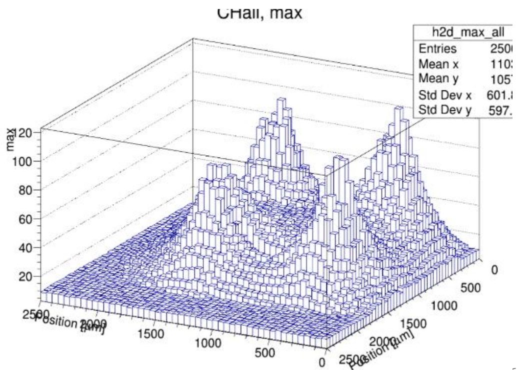


Conclusions

- Need to finalize the QA/QC procedure at pre-assembly and assembly level
- Pre-assembly
  - Test everything with IV, some with CV a selection with laser and testbeam
  - Test test structures
- Assembly
  - Test everything with IV, a selection with CV
  - Sample charge collection with probecard?



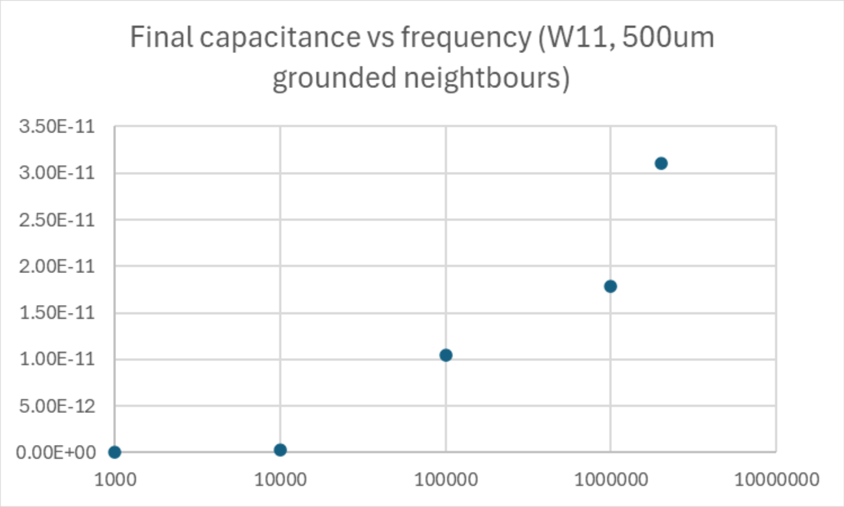


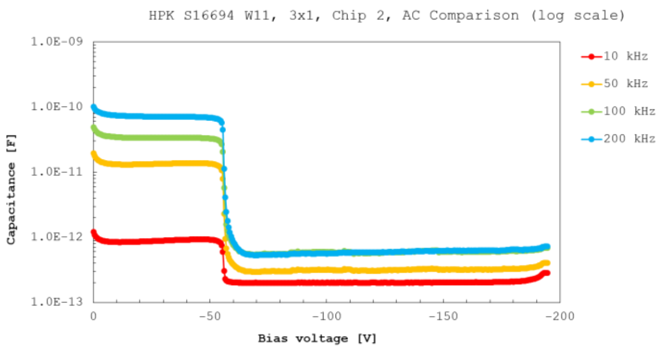


Backup

Strip capacitance

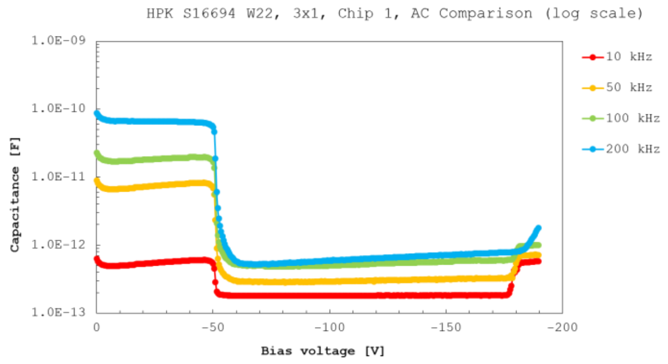
- Capacitance of AC strips with backside measurements, test on strip grounding neighbors
- Final capacitance measured the order of few pF for both wafers → remeasured
- As always it's tricky to pinpoint a number as result vary wildly with frequency
  - Value goes to 10-100 pF for higher frequencies
- Will measure also new wafers to double check





OLD

Frequency (kHz)	Final Strip Capacitance (pF)
10	0.28
50	0.41
100	0.69
200	0.72



Frequency (kHz)	Final Strip Capacitance (pF)
10	0.58
50	0.72
100	0.99
200	3.09

W11		Freq=1000Hz	Freq=10000Hz	Freq=100000Hz	Freq=1000000Hz	Freq=2000000Hz
1mm	1 strip	4.64E-14	1.67E-13	9.39E-12	6.14E-11	1.38E-10
	2 strips	4.46E-14	2.17E-13	1.17E-11	4.19E-11	1.13E-10
	3 strips	4.75E-14	2.41E-13	1.24E-11	2.53E-11	6.28E-11
750 um	1 strip	4.90E-14	2.82E-13	1.58E-11	6.71E-11	1.32E-10
	2 strips	4.00E-14	2.86E-13	1.61E-11	6.09E-11	1.18E-10
	3 strips	4.66E-14	3.43E-13	1.75E-11	4.09E-11	9.47E-11
500 um	1 strip	5.09E-14	1.81E-13	8.28E-12	4.70E-11	1.10E-10
	2 strips	4.46E-14	2.12E-13	8.28E-12	4.37E-11	1.06E-10
	3 strips	4.73E-14	2.46E-13	1.04E-11	1.79E-11	3.10E-11

W22		Freq=1000Hz	Freq=10000Hz	Freq=100000Hz	Freq=1000000Hz	Freq=2000000Hz
1mm	1 strip	5.14E-14	7.00E-13	4.97E-11	2.65E-10	2.05E-10
	2 strips	7.19E-14	2.31E-12	1.46E-10	3.25E-10	2.14E-10
	3 strips	3.55E-14	4.01E-13	2.43E-11	7.82E-11	2.35E-10
750 um	1 strip	4.19E-14	5.03E-14	1.05E-14	-3.00E-13	-4.24E-12
	2 strips	4.79E-14	6.38E-13	3.34E-11	7.29E-11	1.85E-10
	3 strips	4.74E-14	7.21E-13	3.18E-11	7.64E-11	1.75E-10
500 um	1 strip					
	2 strips					
	3 strips					

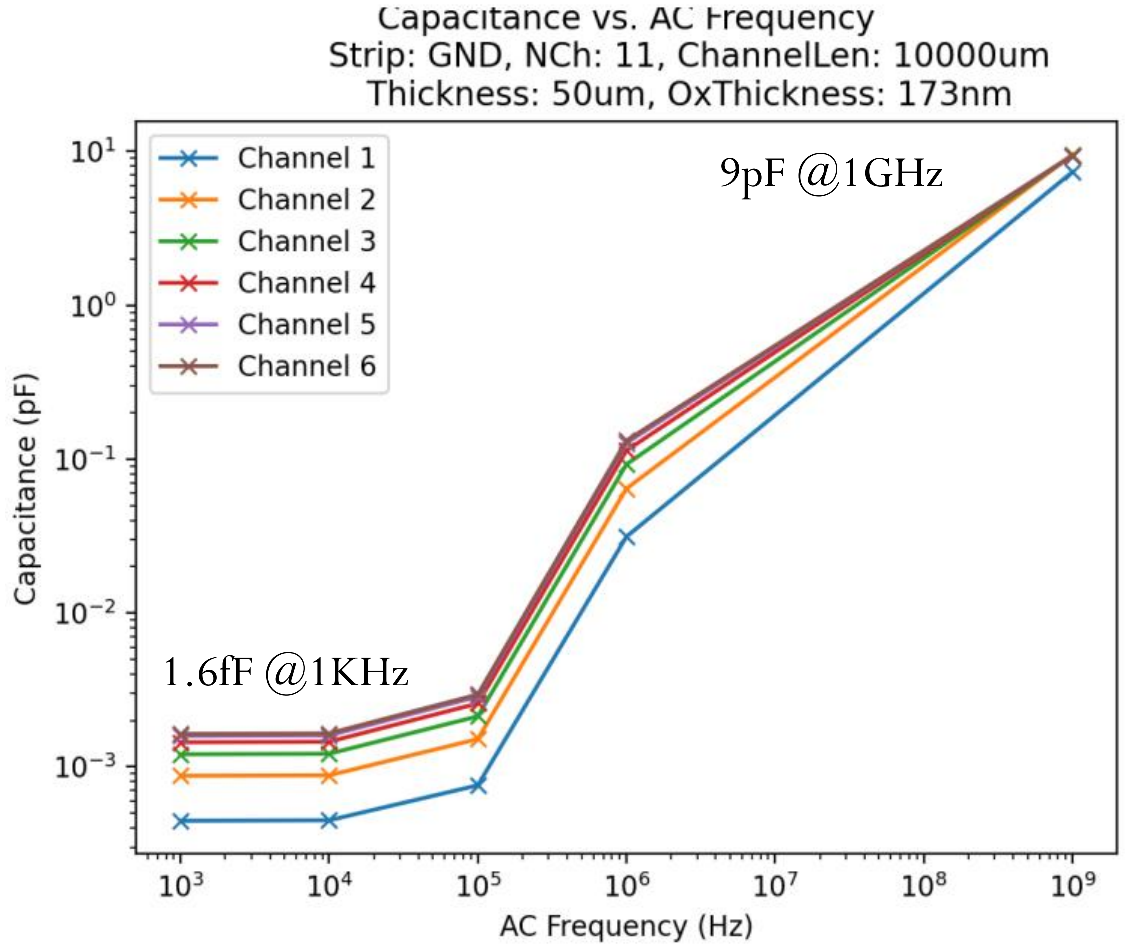
Student: M. Davis

TCAD study on capacitance

- 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 might be realistic

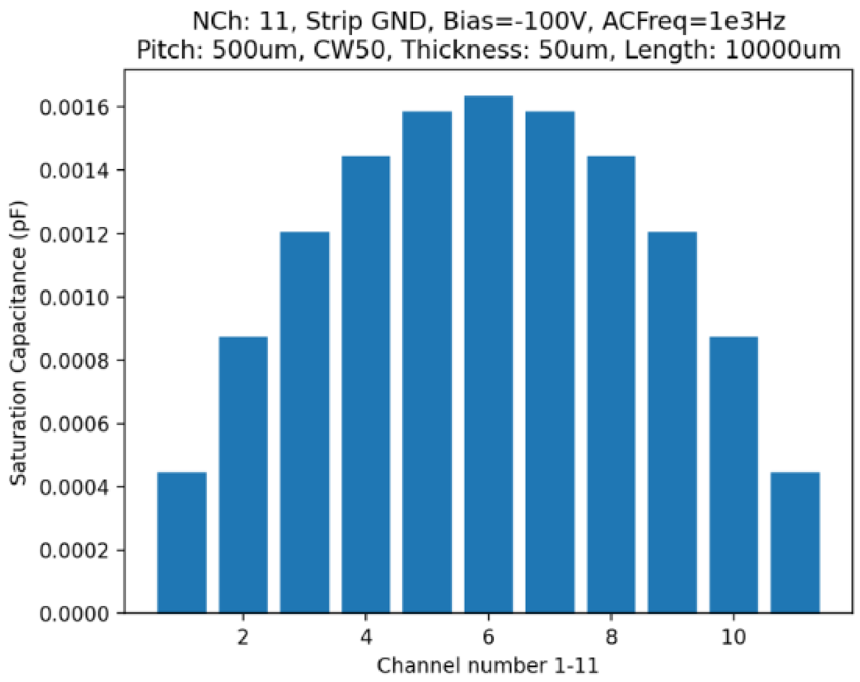
- 11 Channel Device
- Substrate Thickness: 50 um
- Channel Pitch: 500 um
- Channel Metal Width: 50 um
- Channel Length: 1 cm
- Oxide Thickness: 172.66 nm (600 pF/mm2)
- Single Backside (Anode) electrode
- Dual collection (Cathode) electrodes on the sides
- CVSweep Frequencies: 1e3, 1e4, 1e5, 1e6, 1e9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

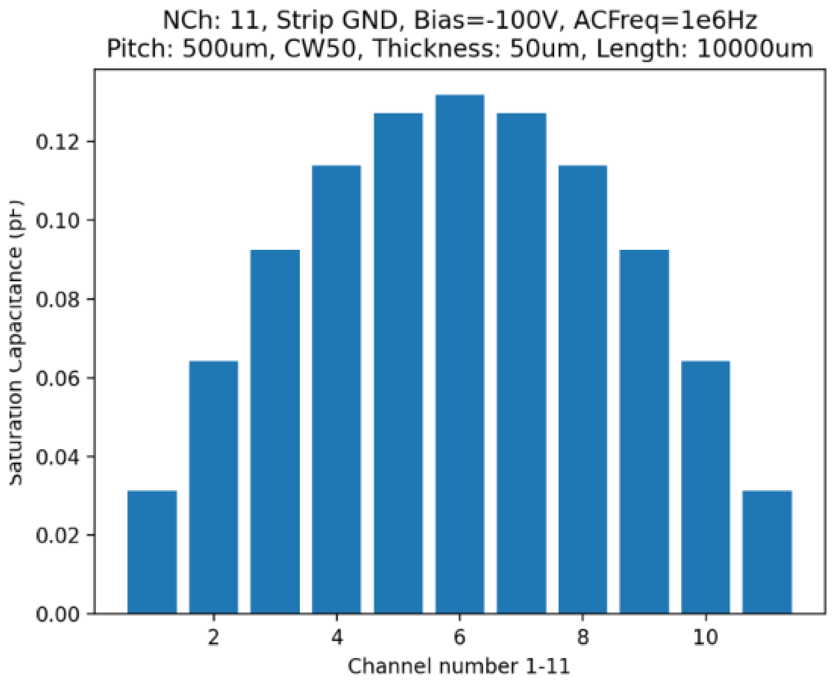


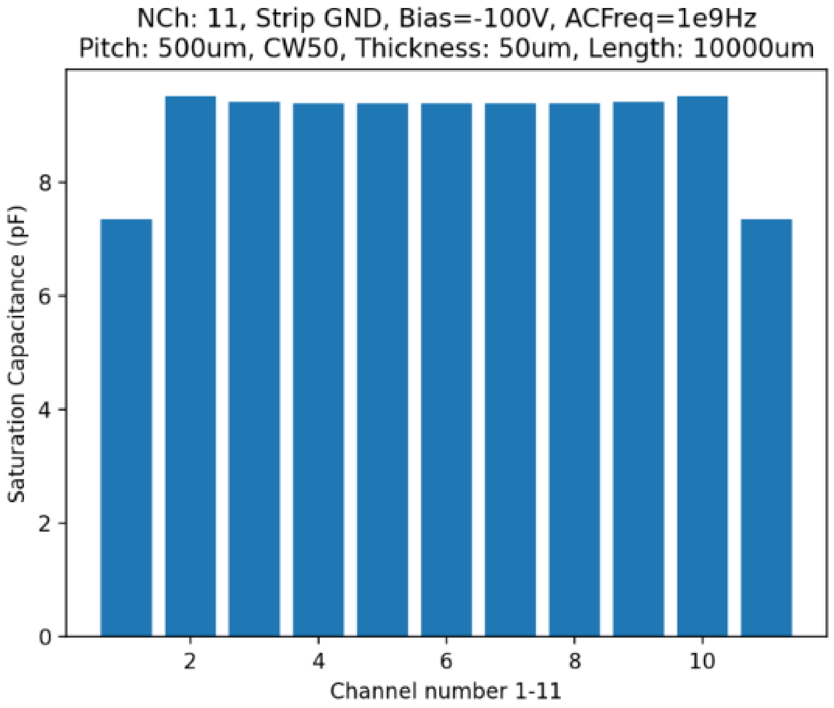
Credits:T. Shin

TCAD study on capacitance

- Interesting behavior: strip capacitance depends on position on the detector
  - Even though all strips are grounded
- Less effect for 1GHz frequency
- We'll test it soon on an actual detector



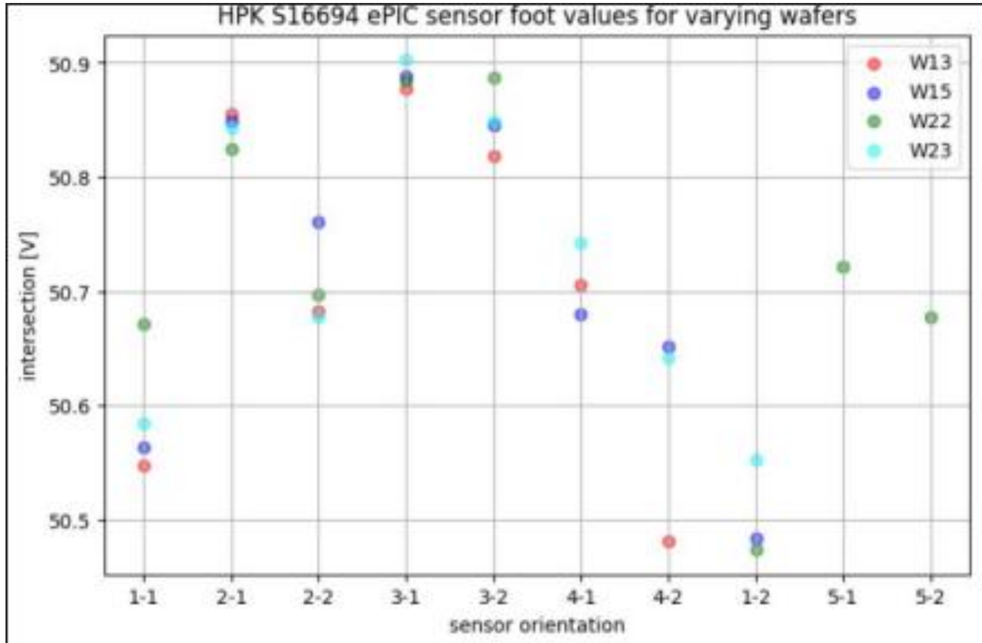


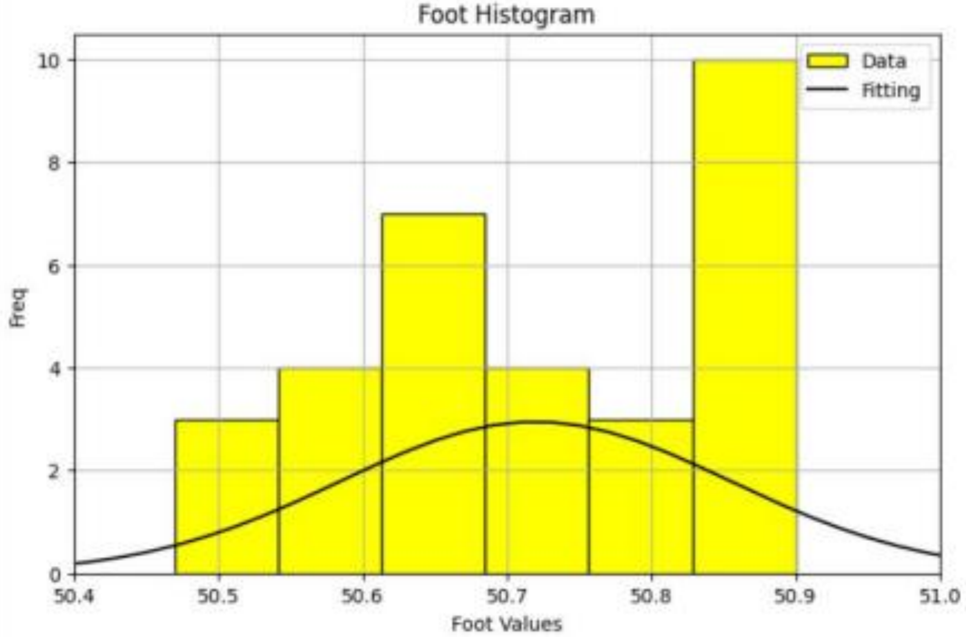


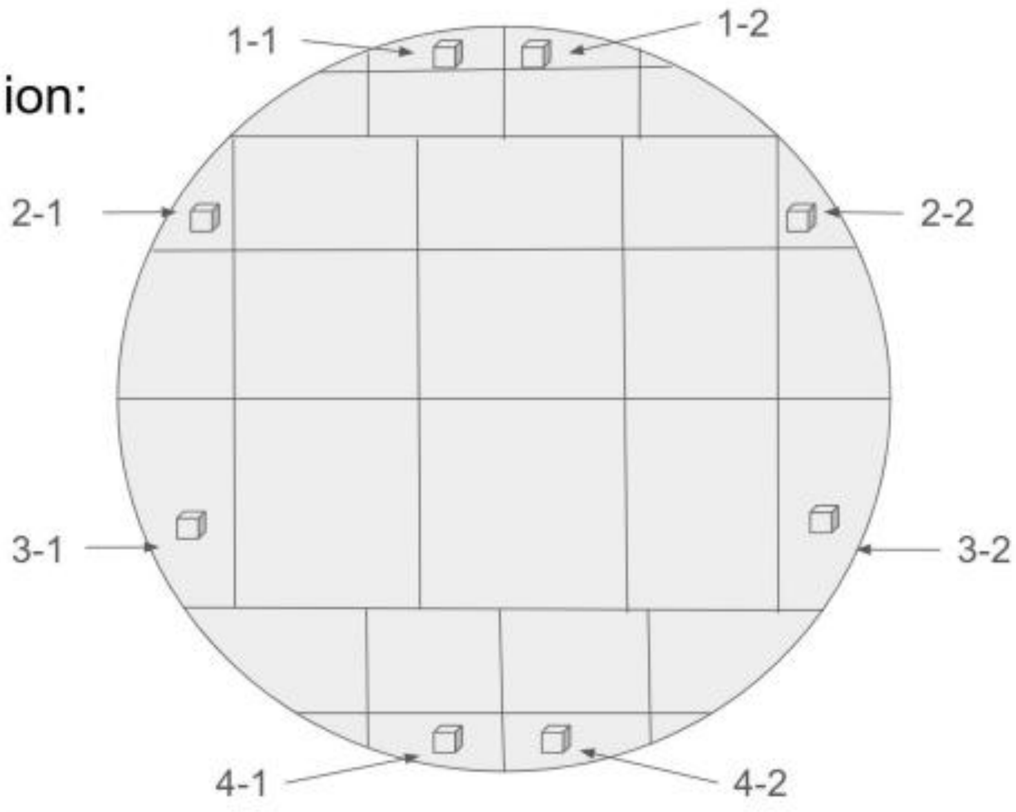
Credits: T. Shin

Gain test

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

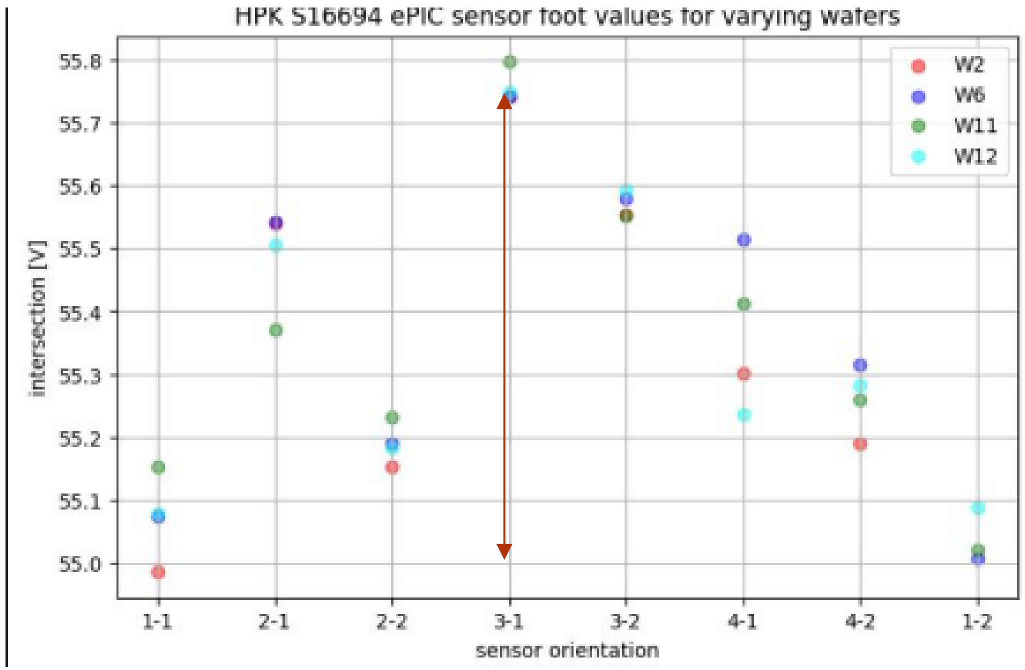






Mean = 50.72
Sigma = 0.13

Gain test

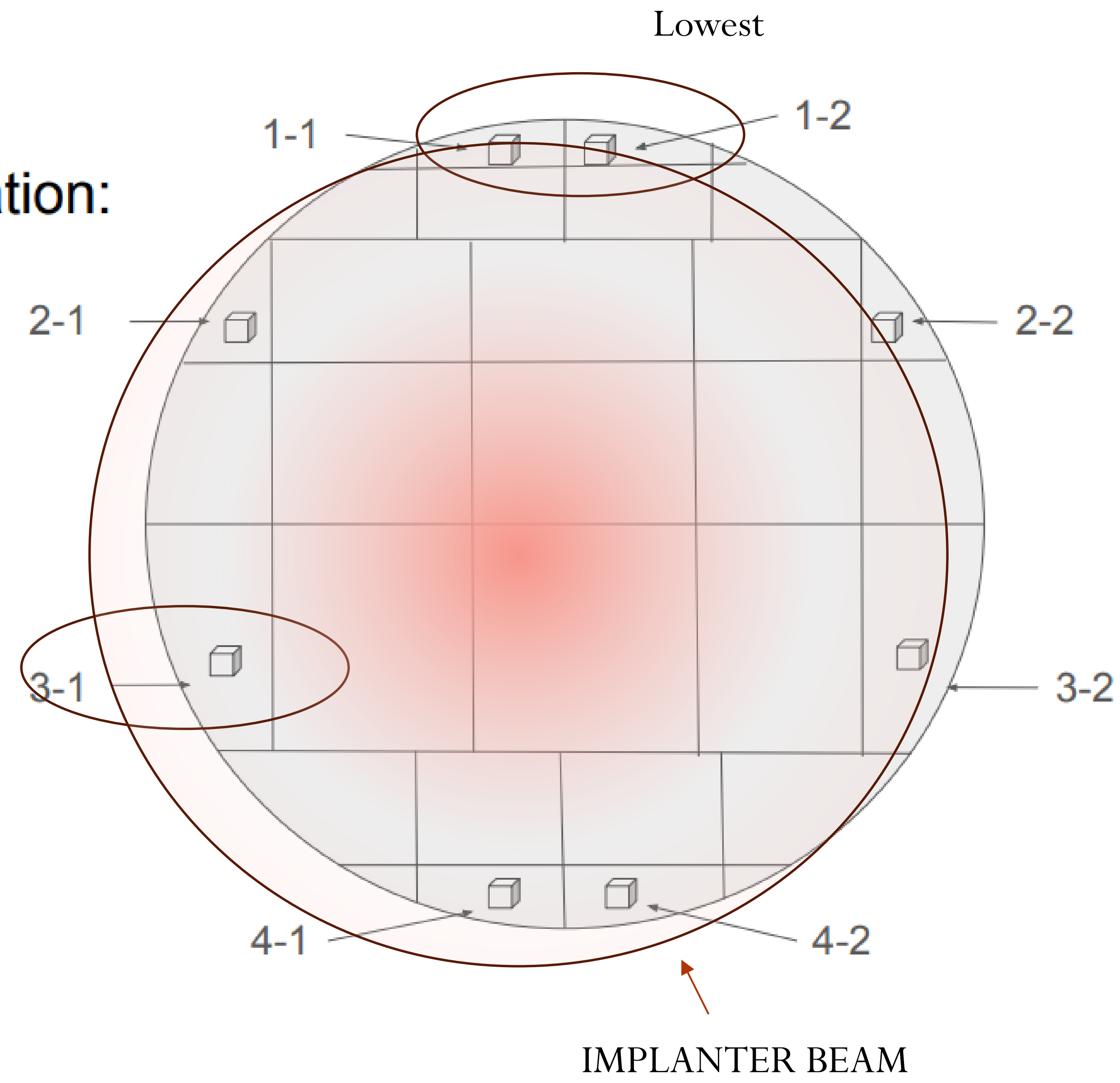


Max variation ~1%

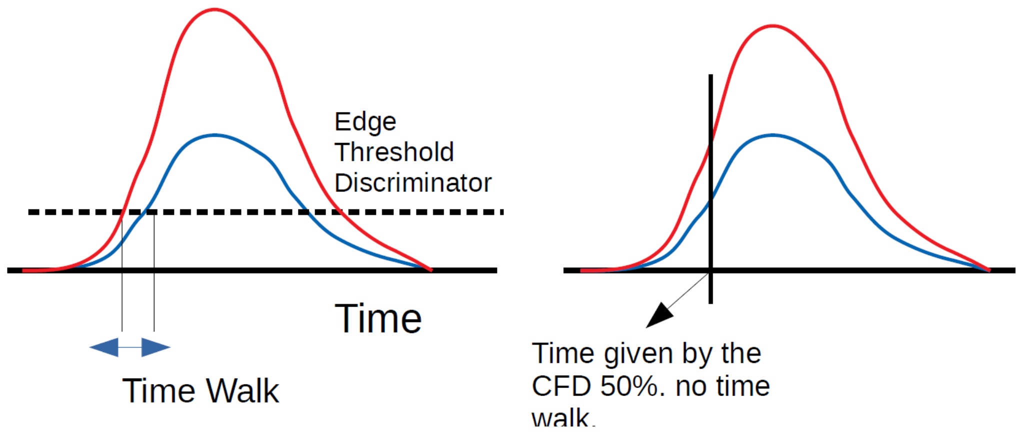
Very likely not an issue across the sensor

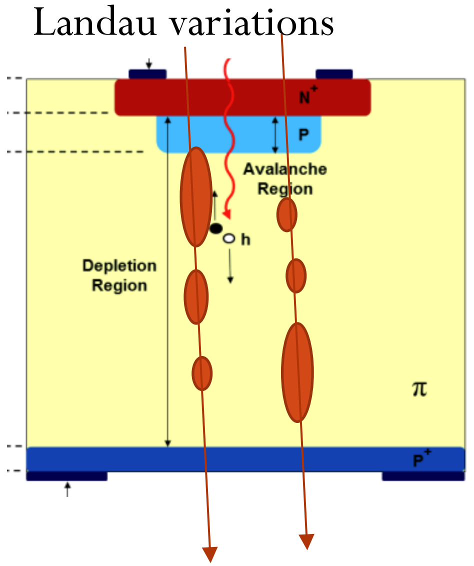
Might be valuable input to HPK

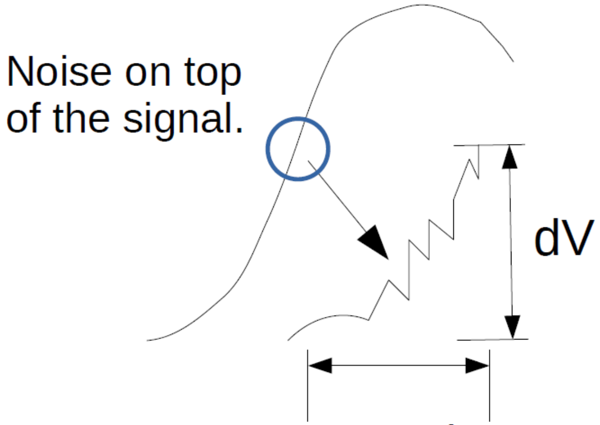
Orientation:



Time resolution







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

Sensor time resolution main terms

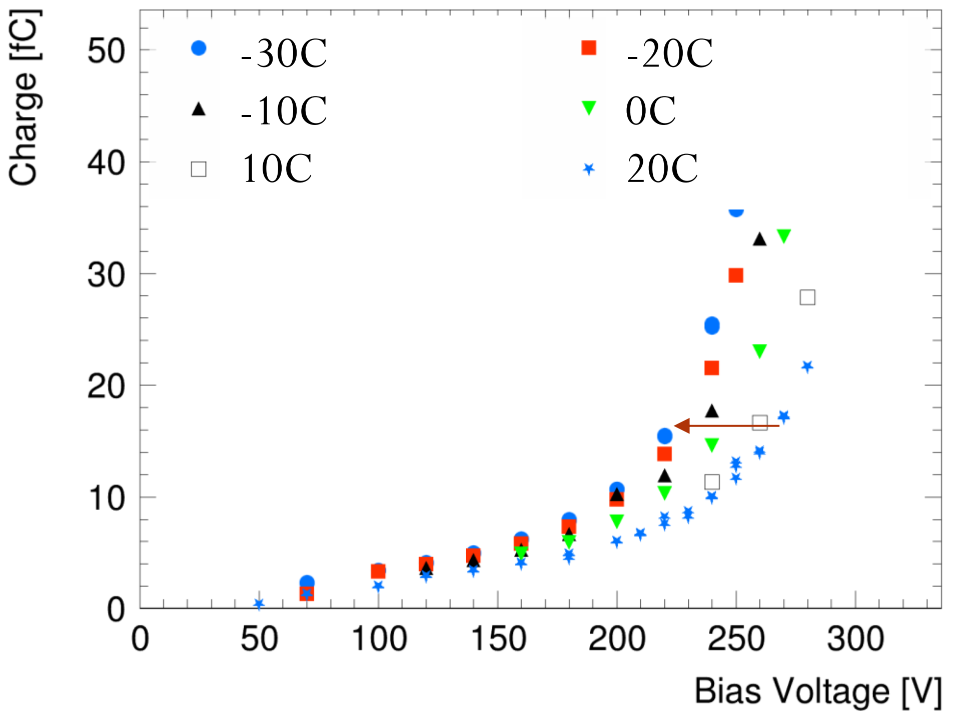
$$\sigma^2_{timing} = \sigma^2_{time\,walk} + \sigma^2_{Landau\,noise} + \sigma^2_{Jitter} + \sigma^2_{TDC}$$

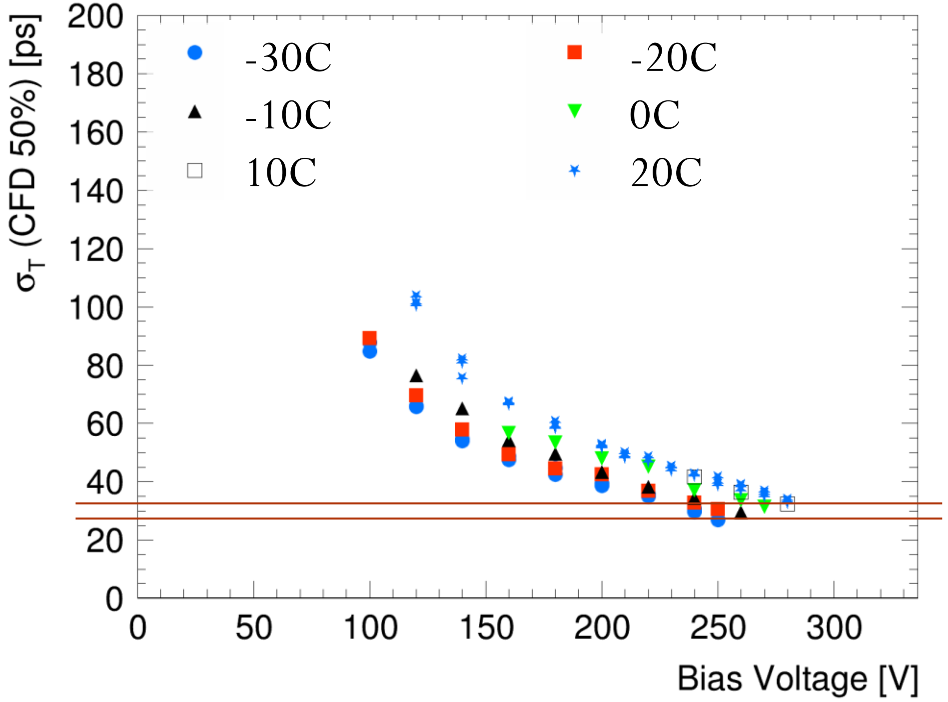
- **Time walk**:
  - Minimized by correcting the time of arrival using pulse width or pulse height (e.g., use 50% of the pulse as ToF)
- **Jitter**: from electronics
  - Proportional to $1/\frac{dV}{dt}$
  - Reduced by increasing S/N ratio with gain
- **TDC term**: from digitization clock (electronics)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

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

LGAD temperature dependence

- LGAD gain depends on temperature due to impact ionization dependence on e/h drift speed
- On a large temperature range the effect is significant
  - The same sensor has a ~50V breakdown variation over a 50C temperature change
  - Data from ATLAS/CMS prototype UFSD3.2 (FBK)
  - Similar study foreseen for ePIC AC-LGADs (laser station almost ready)
- The time resolution suffers slightly from the non-saturated drift velocity if the breakdown is too early (5ps worse for -30C)
  - Electric field in the bulk is too low between Gain layer depletion and breakdown
- In the case of ePIC the running temperature and temperature variation should not as extreme
  - However the breakdown voltage is <150V for most ePIC prototypes, (fairly low)
  - **Once the running temperature is set we should start testing devices at that temperature to measure realistic performance**
  - Then adjust the sensor design accordingly, a similar study happened for ATLAS with HPK (4 gain layer doping tunes)





Student: J. Ding