Performance of AC-LGADs for the ePIC TOF

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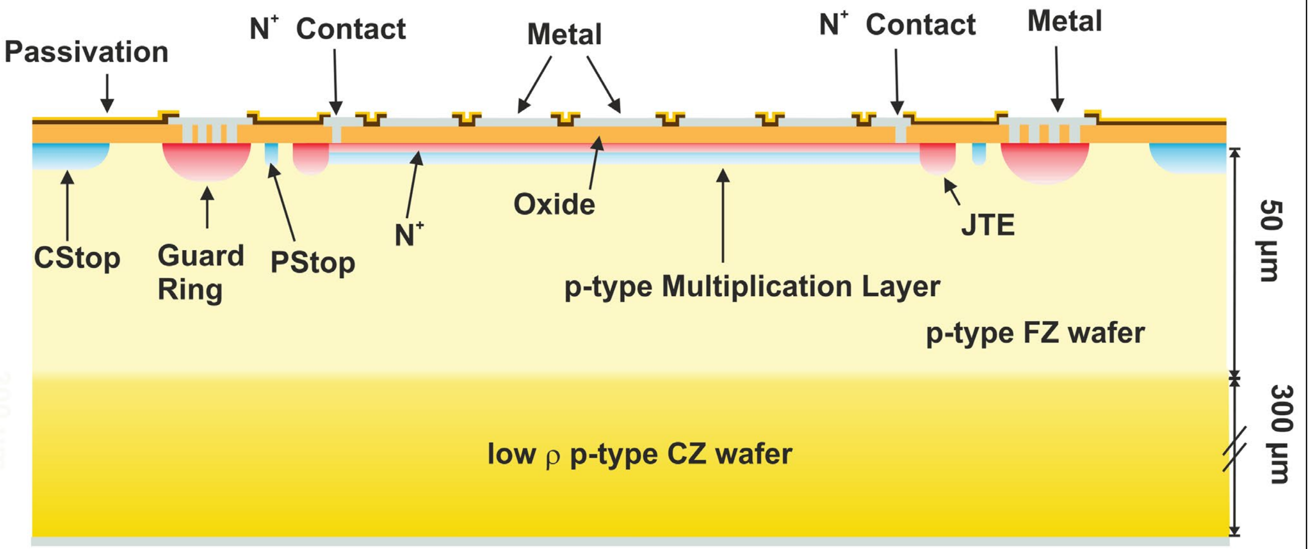
On behalf of SCIPP and ePIC TOF

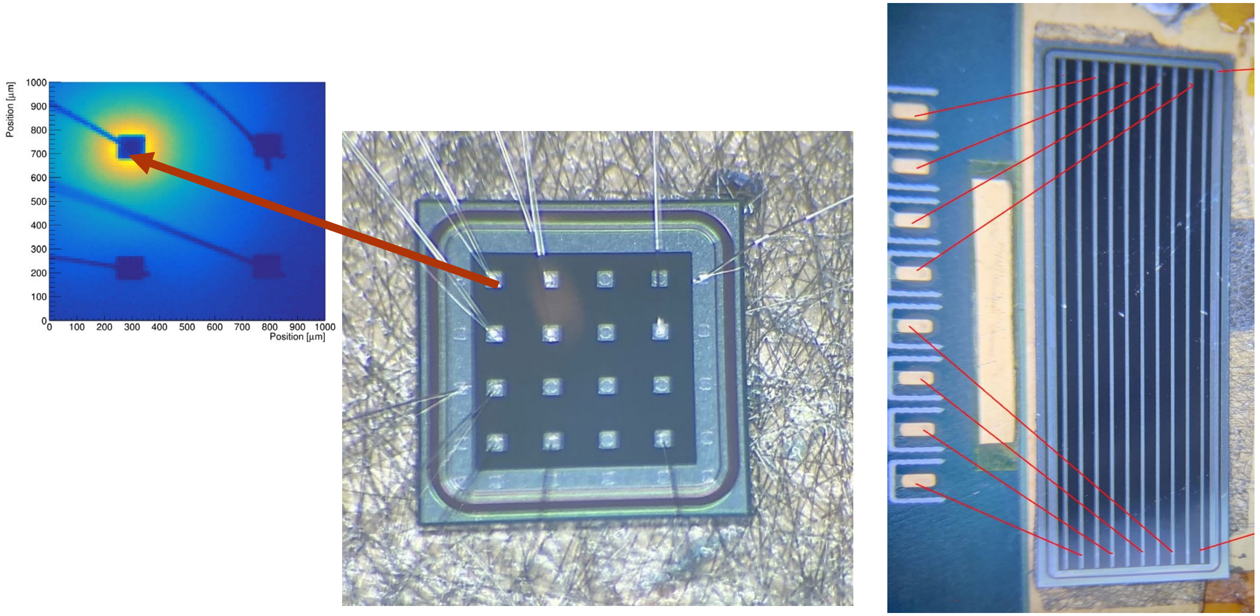
ePIC collaboration meeting, Aug. 2025, JLAB

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**
  - Finer segmentation and easier implantation process
- Continuous multiplication layer coupled with resistive (low doping) N+ layer
- **Readout pads are AC-coupled**, insulator (oxide) layer between N+ and pads
  - 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**

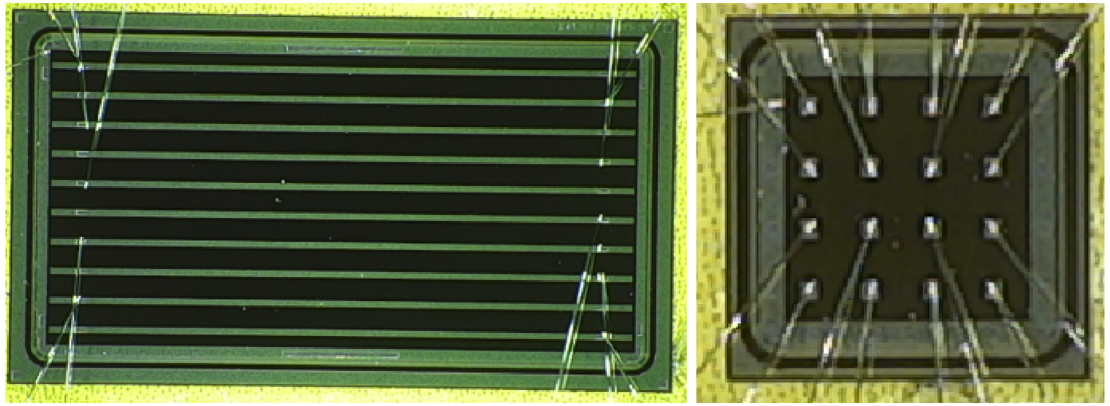


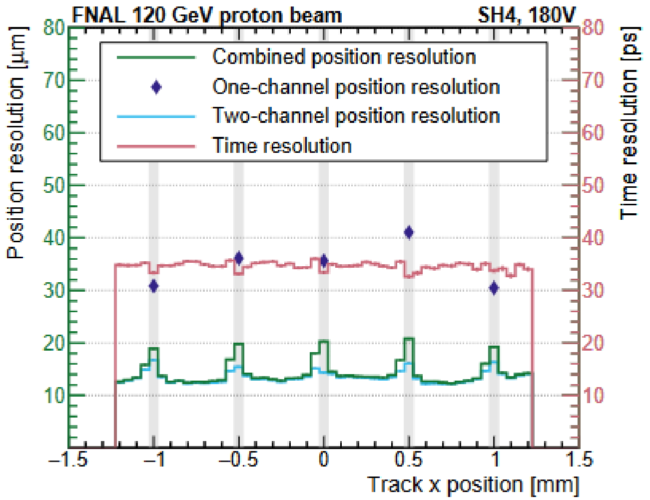


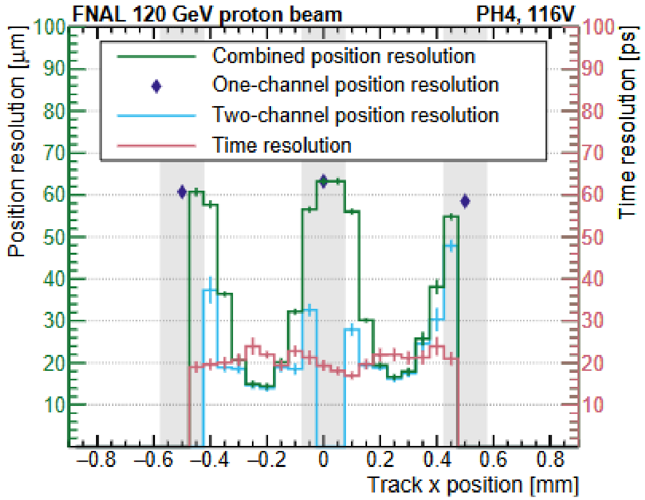
2023 HPK production

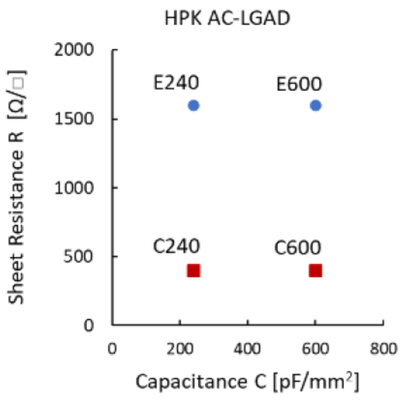
2023 HPK production

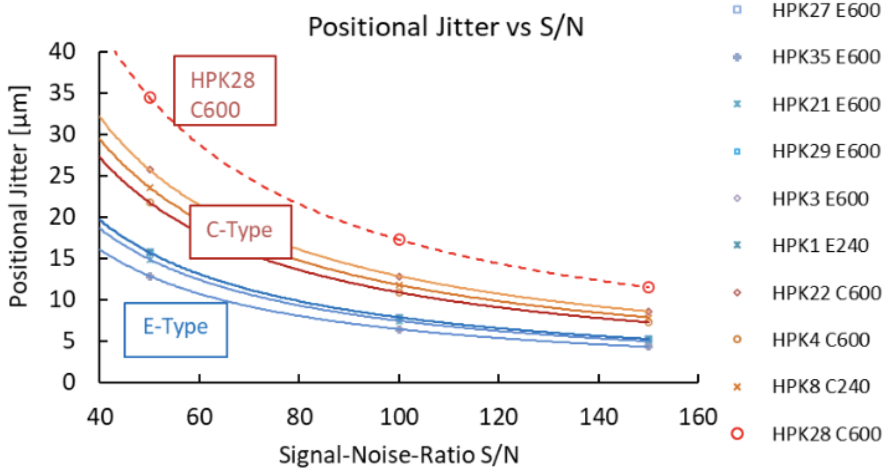
- Test beam and laboratory campaign to characterize HPK sample
  - Matrix of different pitch/size metal, different N+ resistivity and oxide thicknesses
- FNAL test beam results from HPK 2023 production, most ePIC requirements are met
  - Time resolution ~35ps for 1cm x 500um strips and ~20ps for 500um 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
  - 1cm strip length is the best compromise







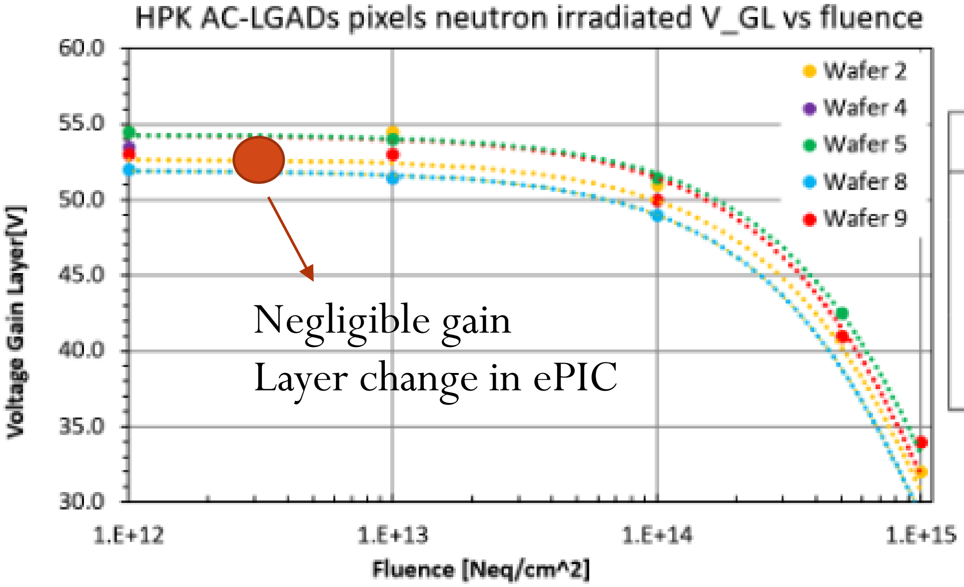




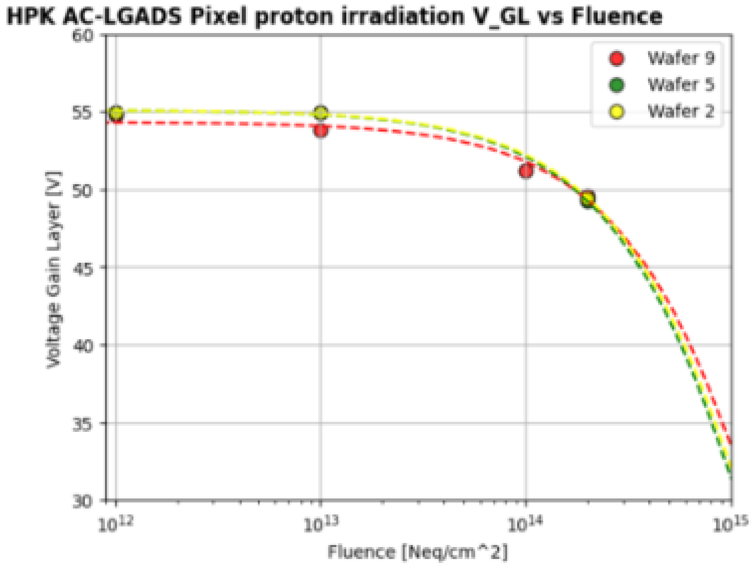
References: https://arxiv.org/abs/2407.09928 https://doi.org/10.1016/j.nima.2024.169478

Irradiation effects on AC-LGADs

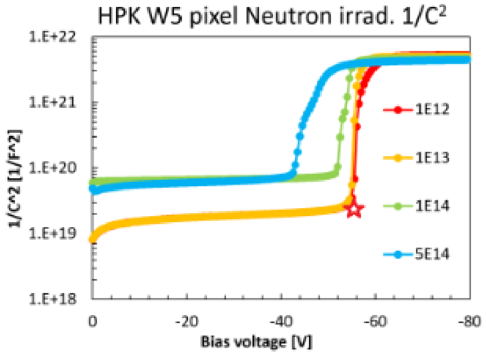
- Neutron (IJS) and proton (FNAL) irradiation on 2023 HPK production
- Up to 1e13 Neq, no significant change in sensor IV properties and gain layer doping
  - Leakage current scales with bulk volume
  - Current and breakdown voltage increases with fluence (as expected)
- Gain layer doping proportional 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
- 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}



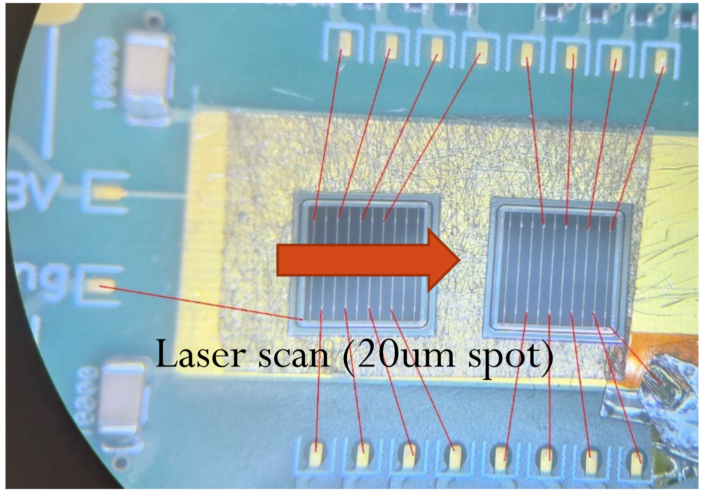
Wafer	C factor $\left[\frac{cm^2}{Neq}\right]$
W2	5.42×10^{-16}
W5	5.63×10^{-16}
W9	4.85×10^{-16}

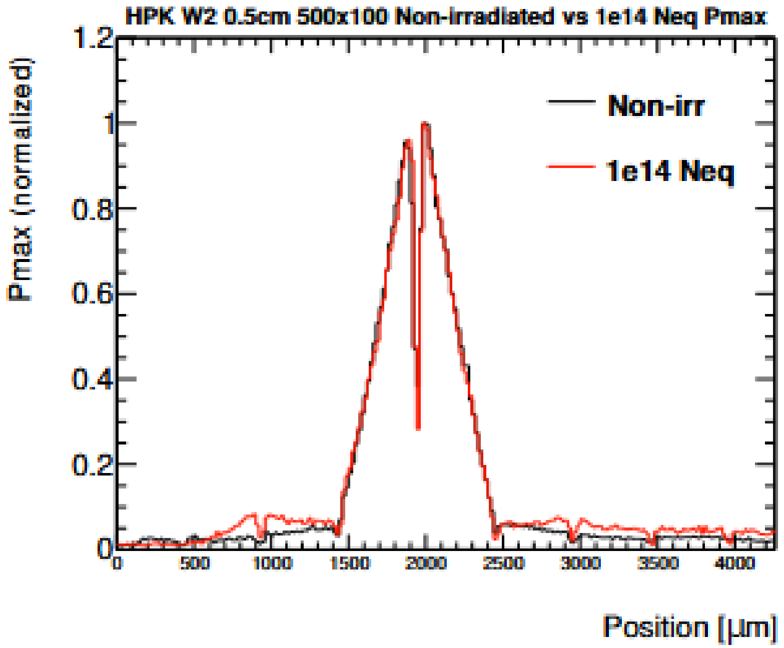


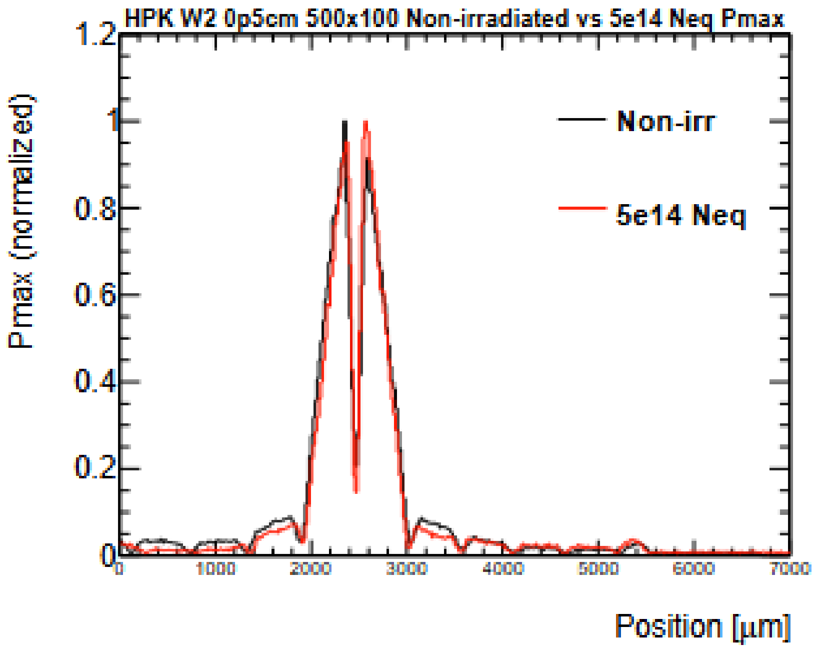
Student: J. Ding, M. Davis

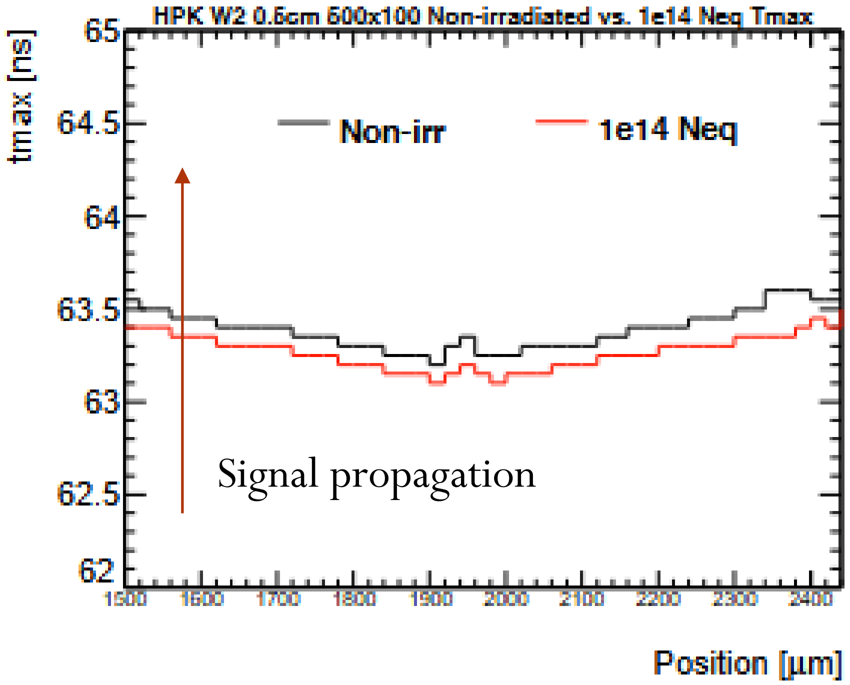
TCT laser studies - Neutrons

- 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**



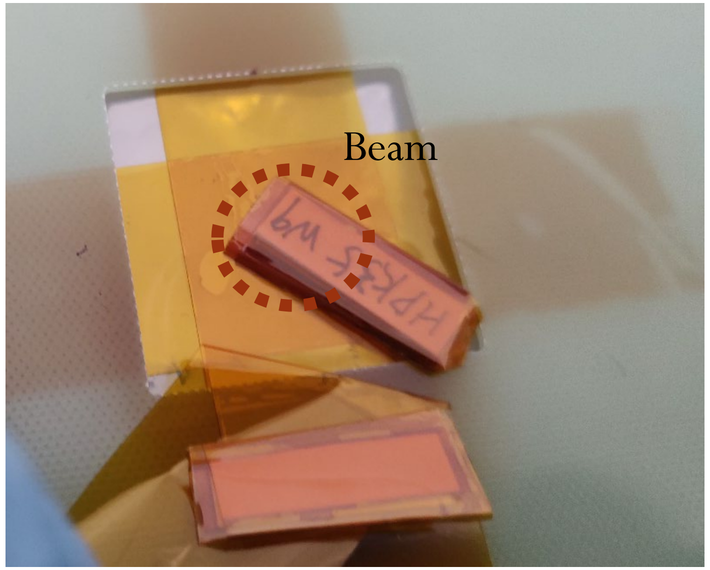




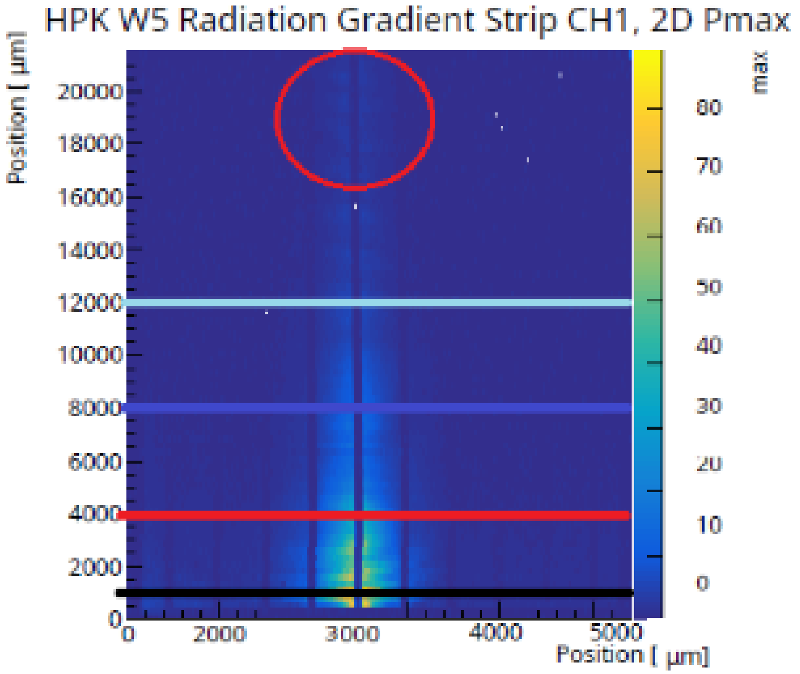


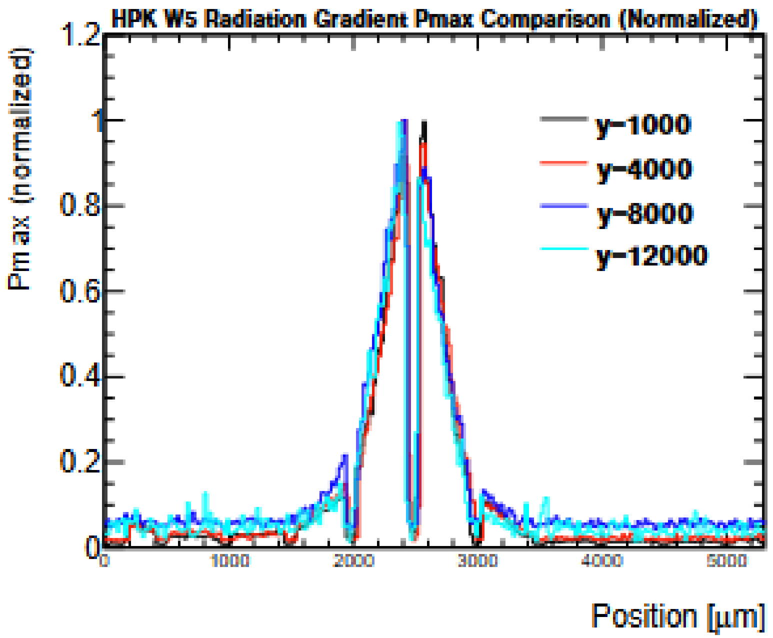
Student: G. Stage, A. Borgijin

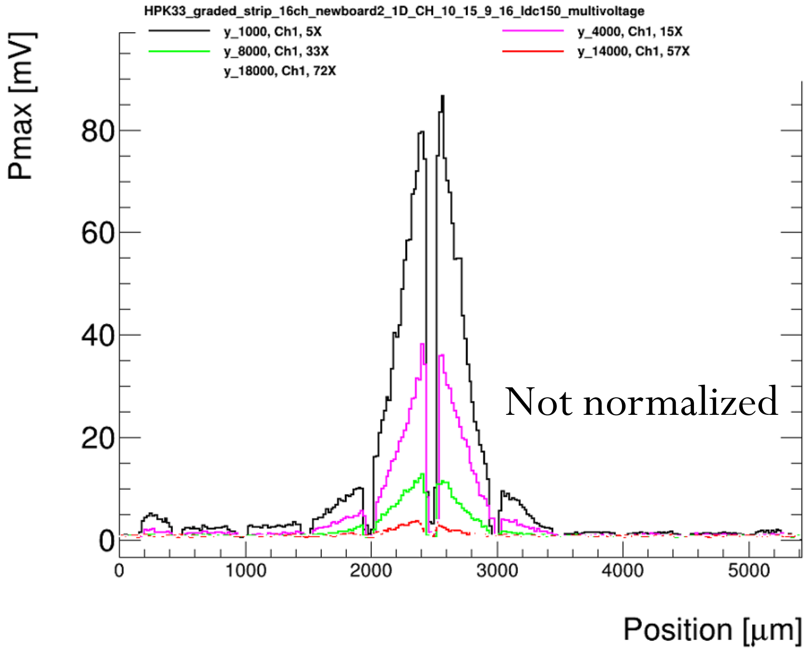
TCT laser studies - Protons



- 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!







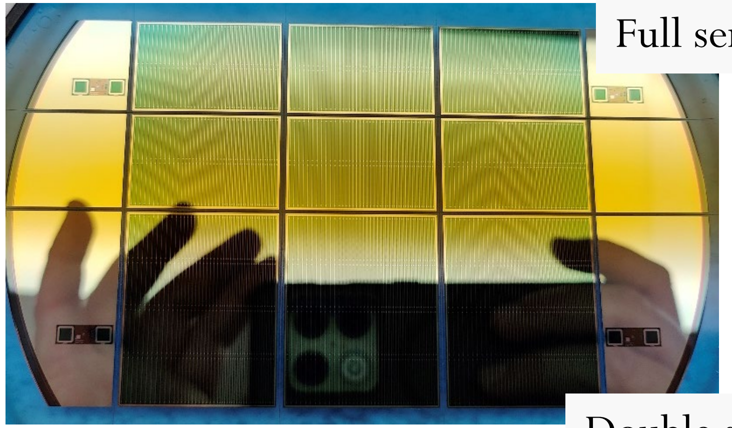
Student: G. Stage, A. Borgijin

2024 HPK production

Strip production

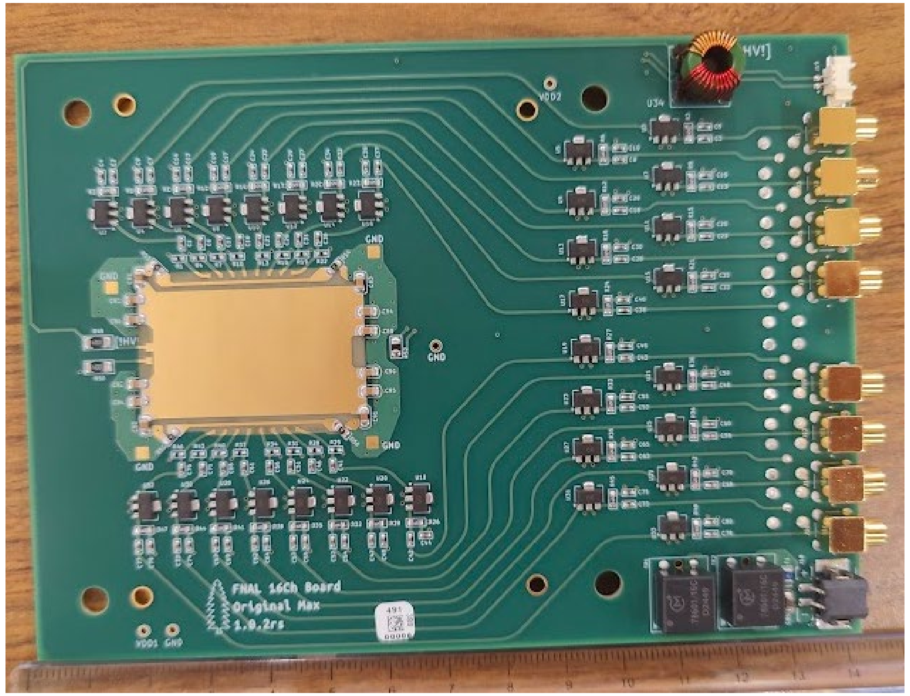
- ePIC full-size production of HPK strip AC-LGADs with devices up to 3.2x4.2 cm
  - Nominal size 3.2x2.2 cm with 1cm strip ‘segments’
  - Strip width: 50um, strip pitch 500, 750, 1000 um
- 8 wafers in hand, four 50um thick and four 30um thick
- Database: https://docs.google.com/spreadsheets/d/1J7IuZuRaYmpDjLfzsFhHAh88glab9uHFaDUo3HoOE1o/edit?usp=sharing
  - Also a log of distribution to collaborators

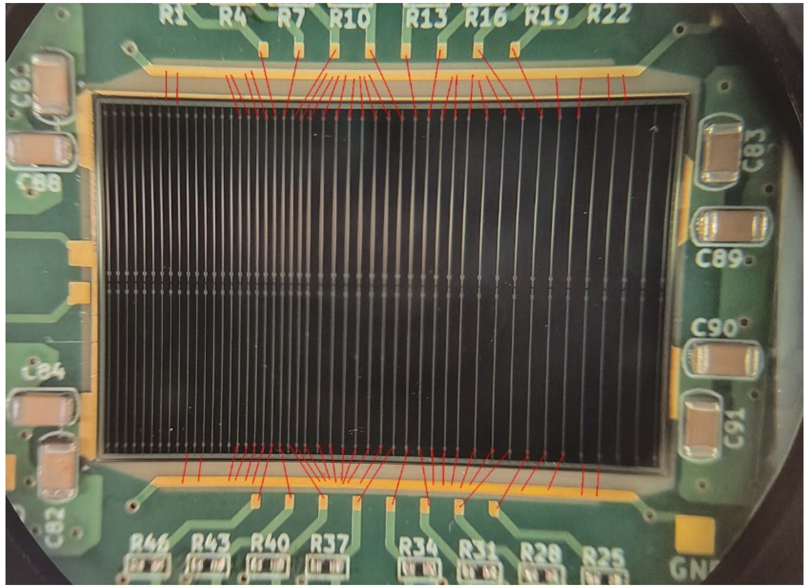
Half sensors

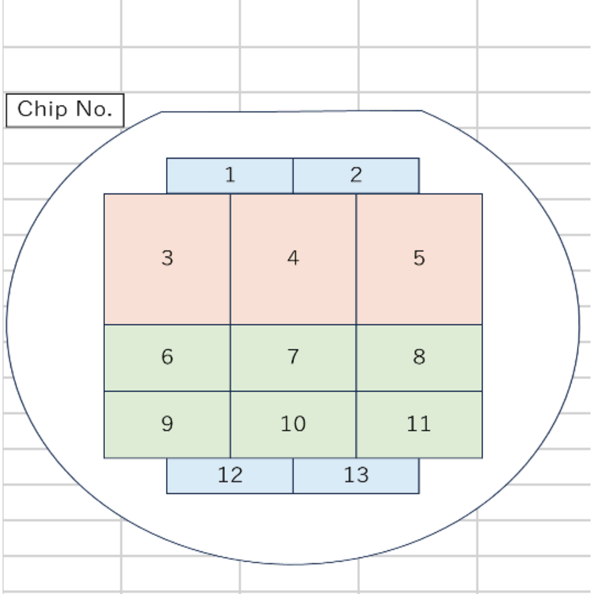


Full sensors

Double sensors







AC-LGAD sensor inventory

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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	
HPK s16694	HPK	October 2024	11	5-1	strips	half size multipitch	50 um	FNAL	March 2025	5.72.E-06	190	OK	IV, CV	
HPK s16694	HPK	October 2024	11	5-2	strips	half size multipitch	50 um	UCSC	March 2025	6.84.E-05	200	OK	IV	
HPK s16694	HPK	October 2024	2	1-1	strips	half size multipitch	50 um	UCSC	March 2025	-1.09E-06	190	OK	IV	
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	
HPK s16694	HPK	October 2024	2	4-2	strips	double size multipitch	50 um	UCSC	March 2025	-	30	NG	IV	
HPK s16694	HPK	October 2024	2	4-3	strips	double size multipitch	50 um	Hawaii	March 2025	-	40	NG	IV	
HPK s16694	HPK	October 2024	2	5-1	strips	half size multipitch	50 um	UCSC	March 2025	-4.38E-07	185	OK	IV	
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
HPK s16694	HPK	October 2024	6	1-1	strips	half size multipitch	50 um	UCSC	March 2025	-	85	NG	IV	
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	
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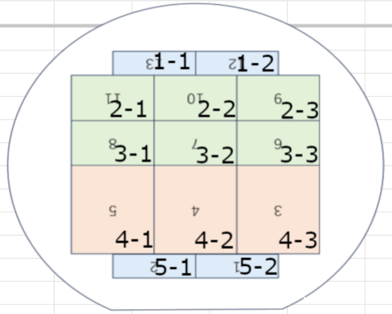
HPK s16694	HPK	October 2024	6	5-1	strips	half size multipitch	50 um	Hawaii	March 2025	-2.10E-06	190	OK	IV	
HPK s16694	HPK	October 2024	6	5-2	strips	half size multipitch	50 um	FNAL	March 2025	-1.10E-06	190	OK	IV	
HPK s16694	HPK	October 2024	12	1-1	strips	half size multipitch	50 um	UCSC	March 2025	-1.20E-05	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

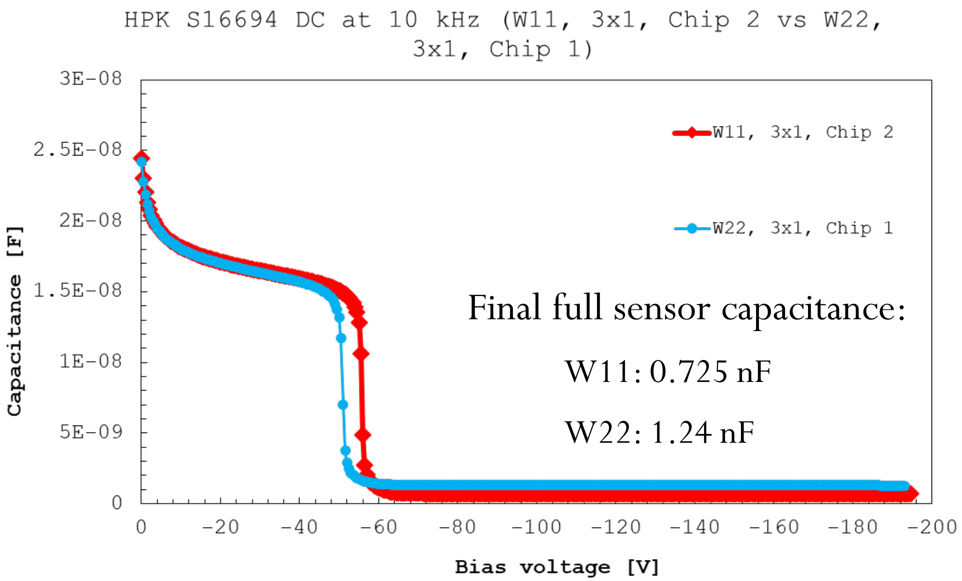
NG		OK
NG	OK	High current
NG	NG	NG
NG	NG	NG
OK		OK

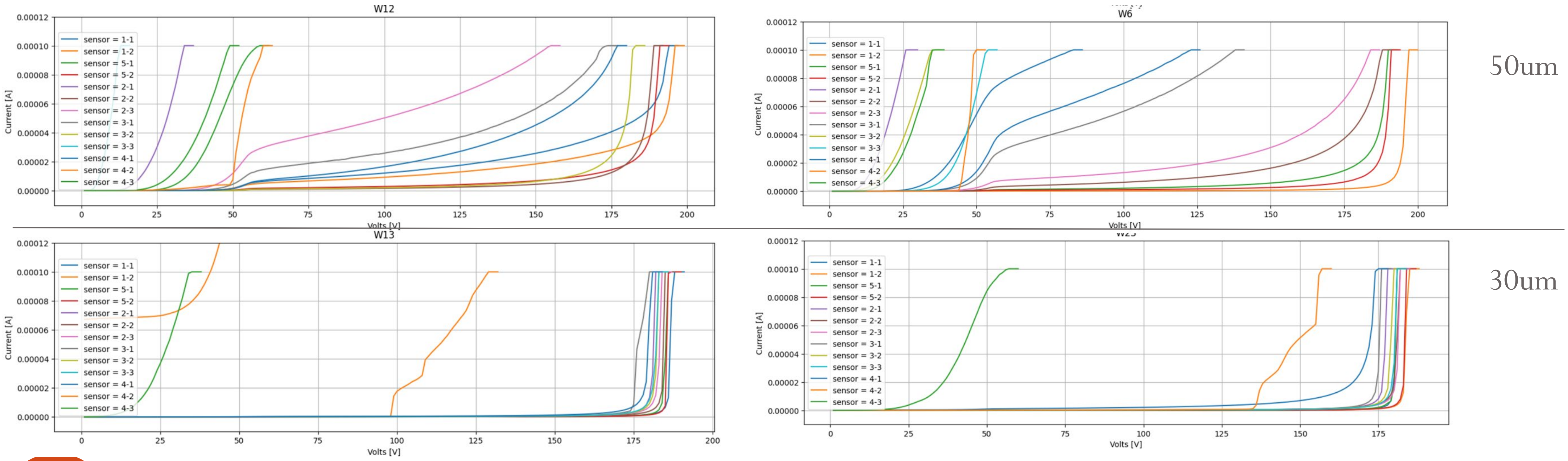
OK		OK
NG	OK	High current
High current	OK	NG
High current	NG	NG

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

HPK strip production results – IV/CV

- Yield is not optimal, better for 30um wafer
- Capacitance of full detector scales with thickness
- Measurement of strip capacitance (input capacitance to the amplifier) is not an easy task
  - Significantly changing with probing frequency





50um

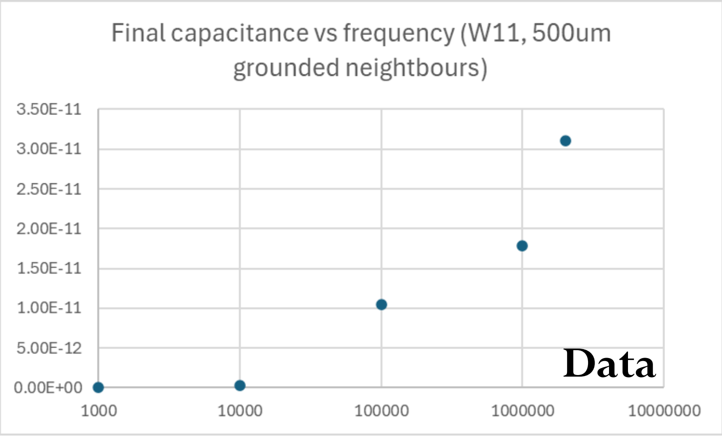
30um

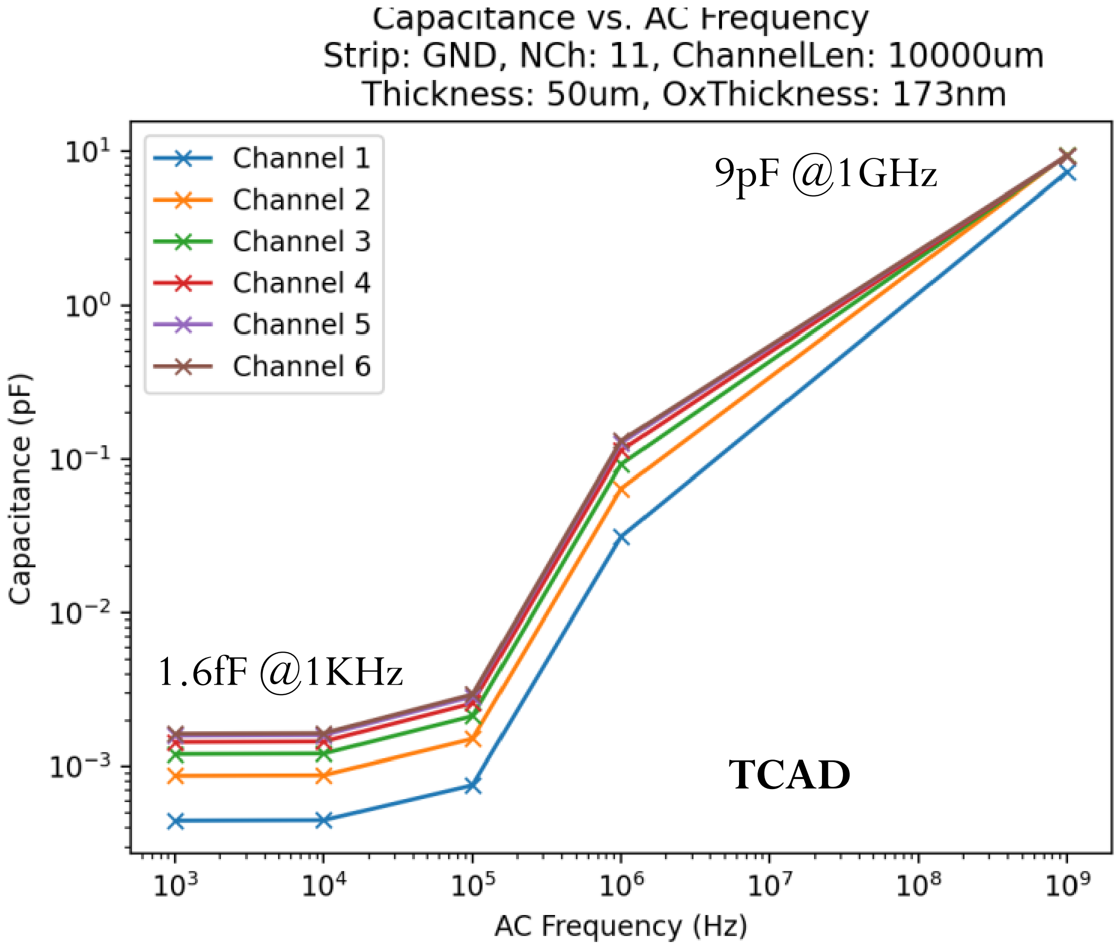
Student: G. Stage, A. Borgijin

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

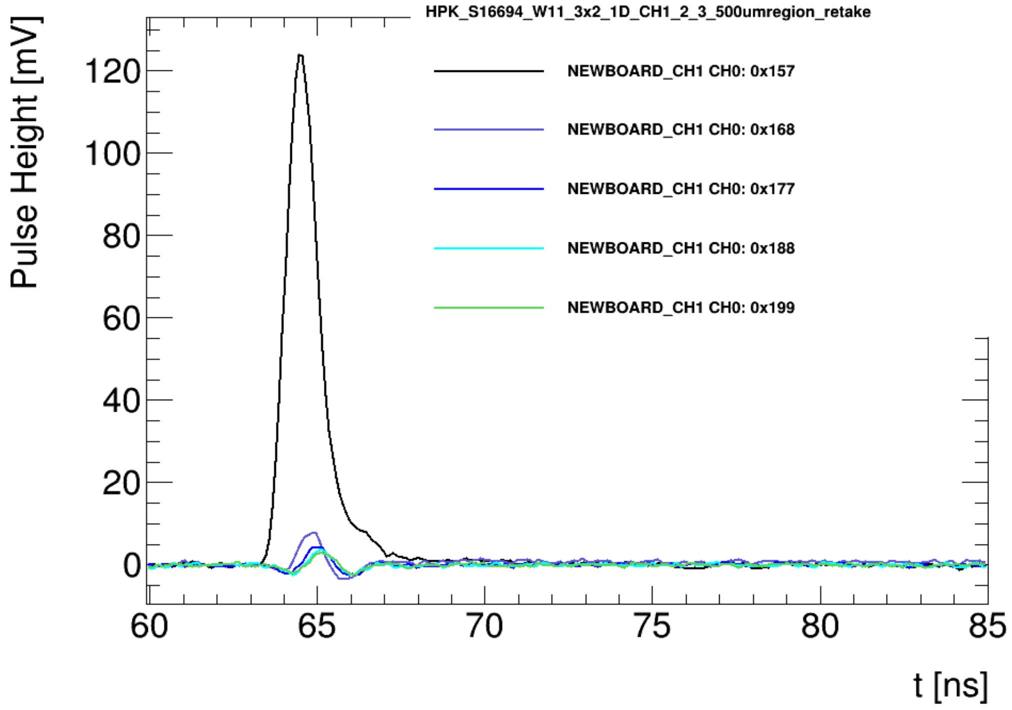


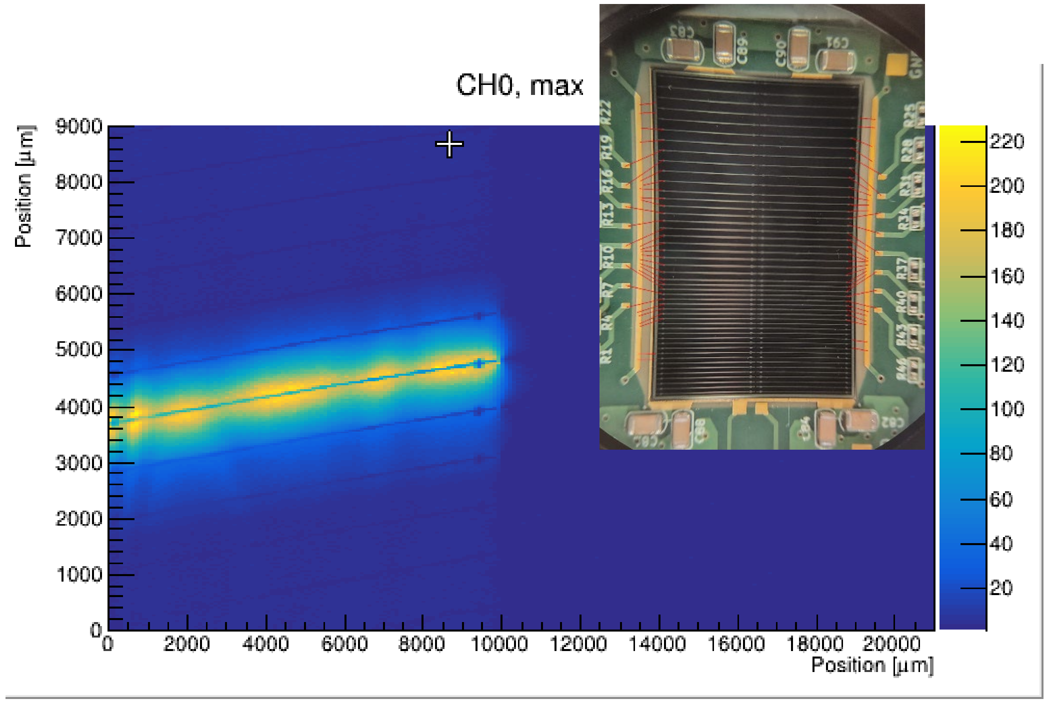


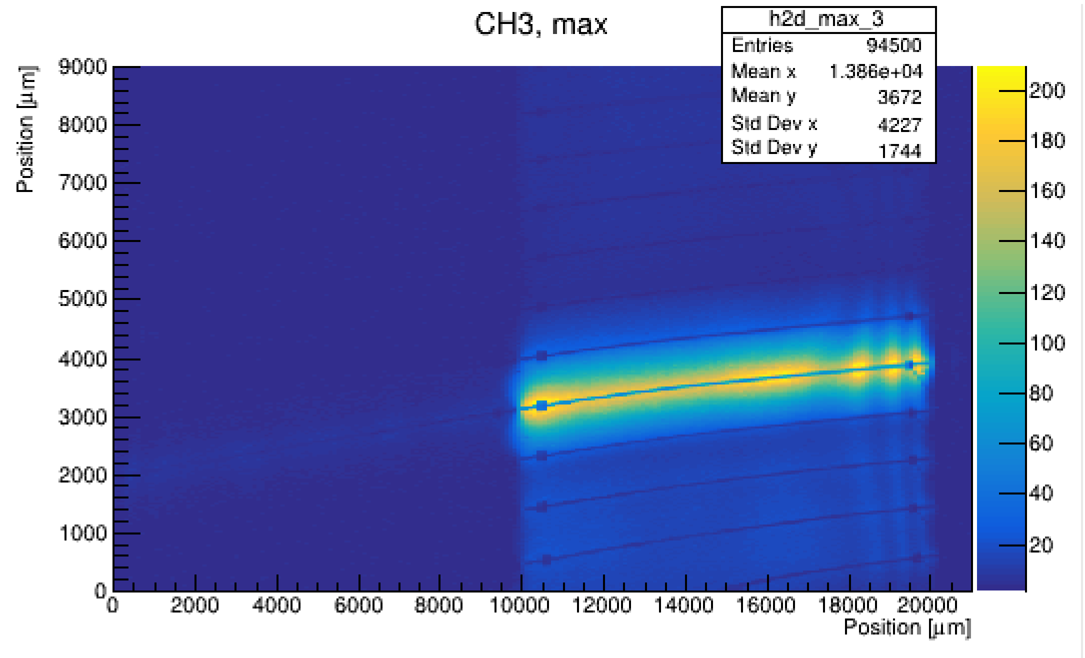
Credits: T. Shin

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)



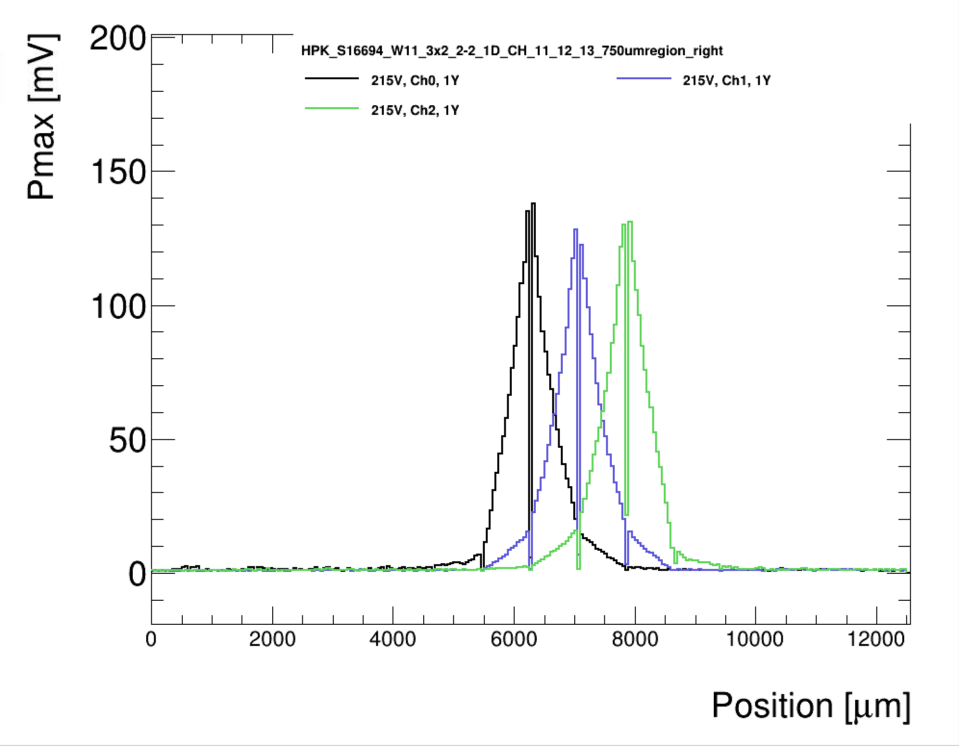


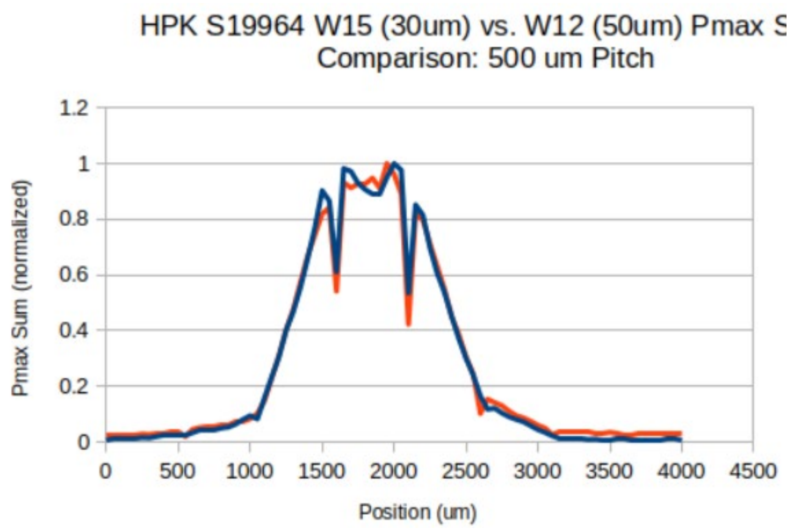


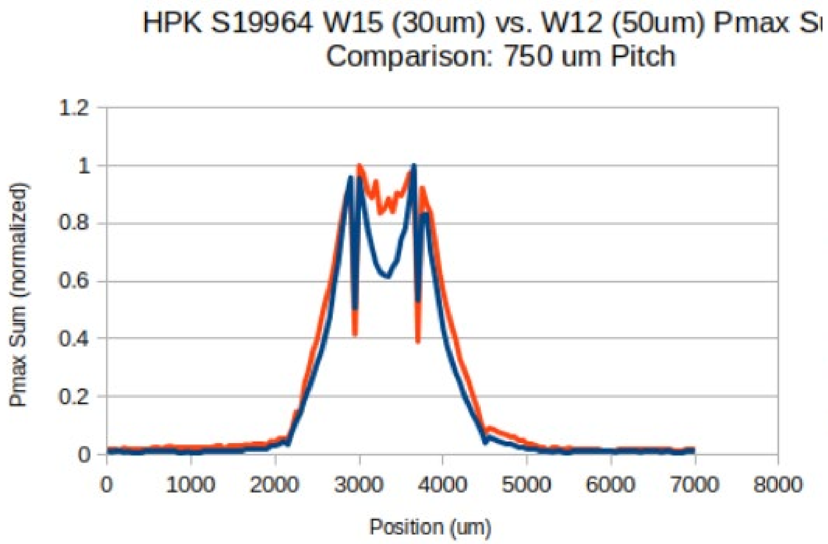
Student: G. Stage, A. Borgijin

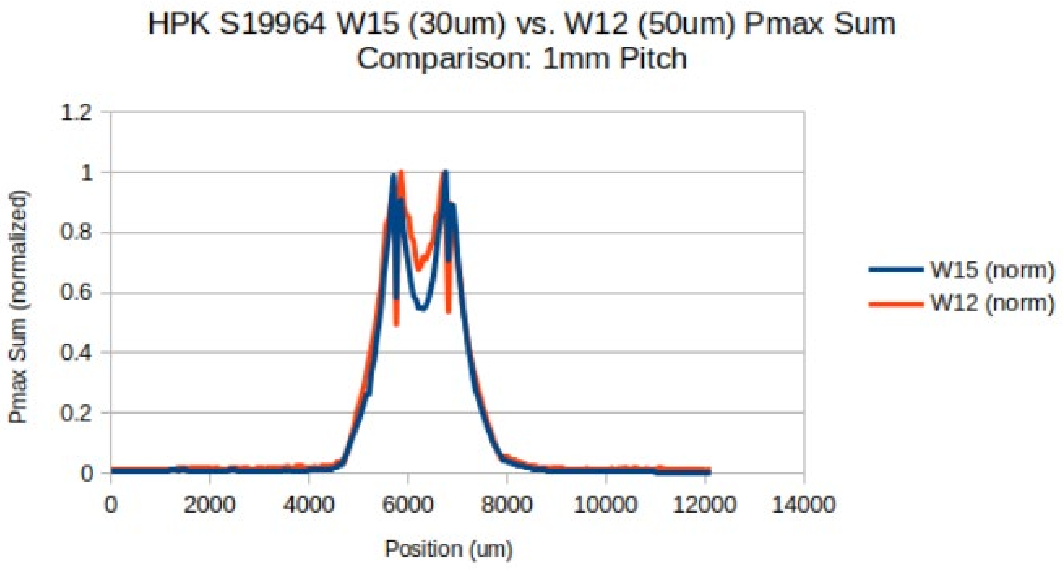
HPK production results - TCT

- Signal for 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





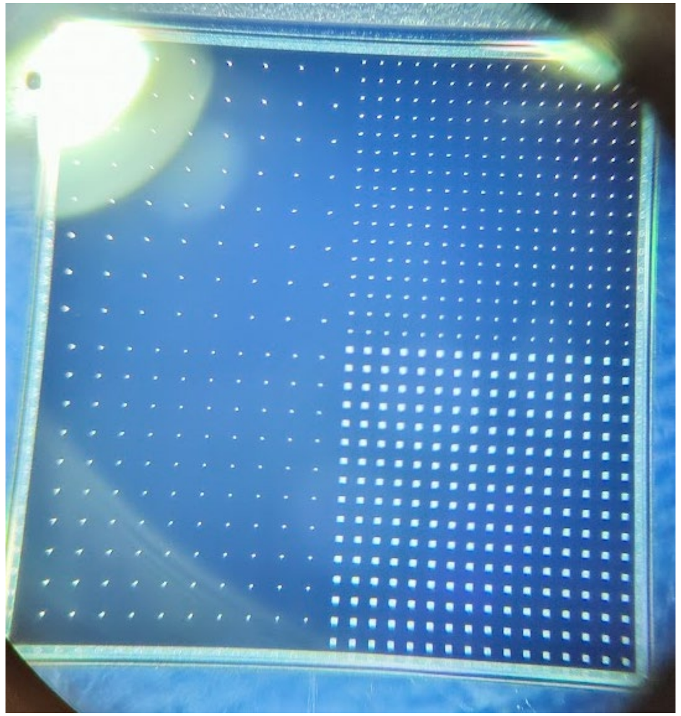


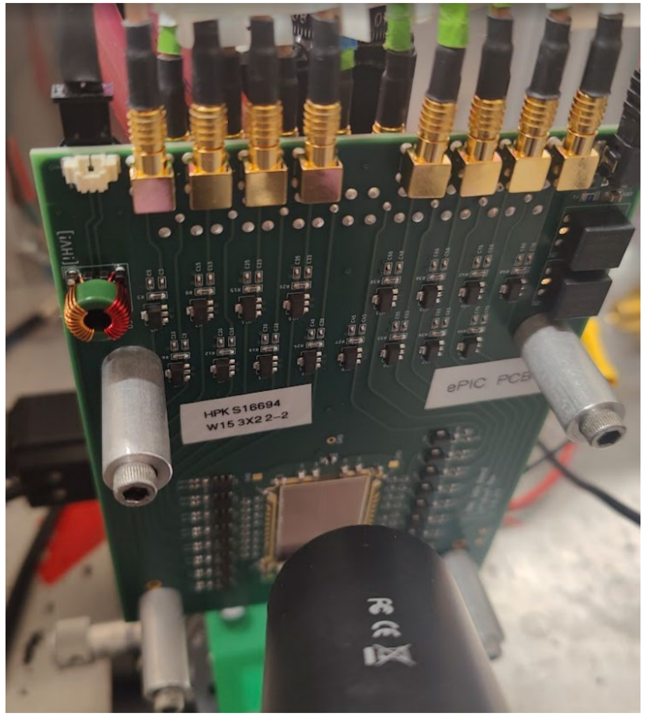


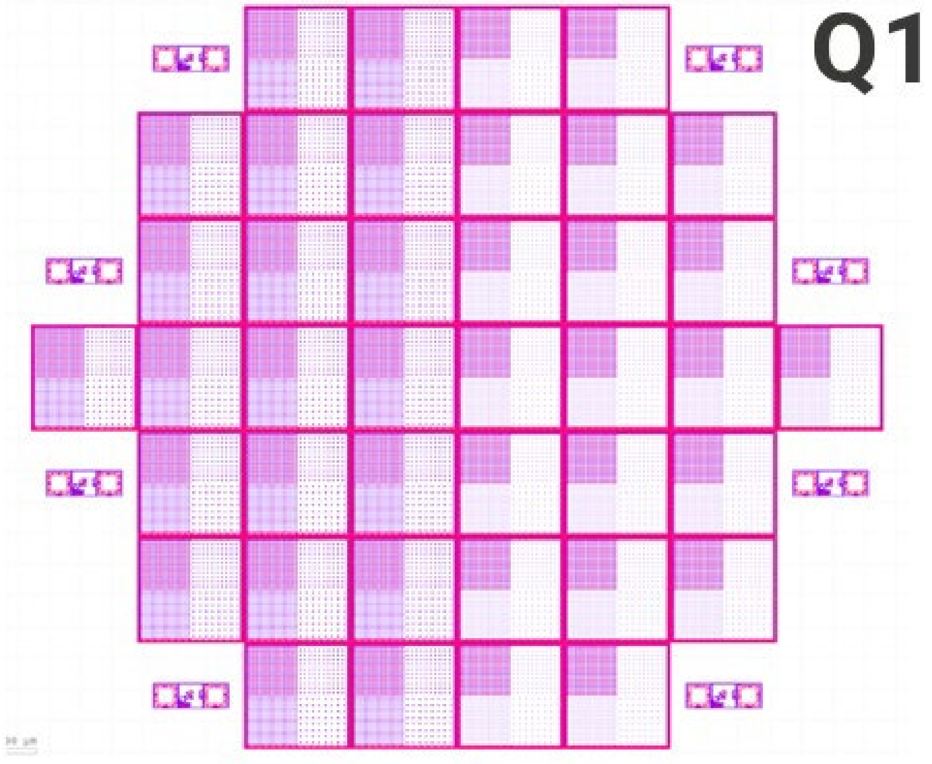
Student: G. Stage, A. Borgijin

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





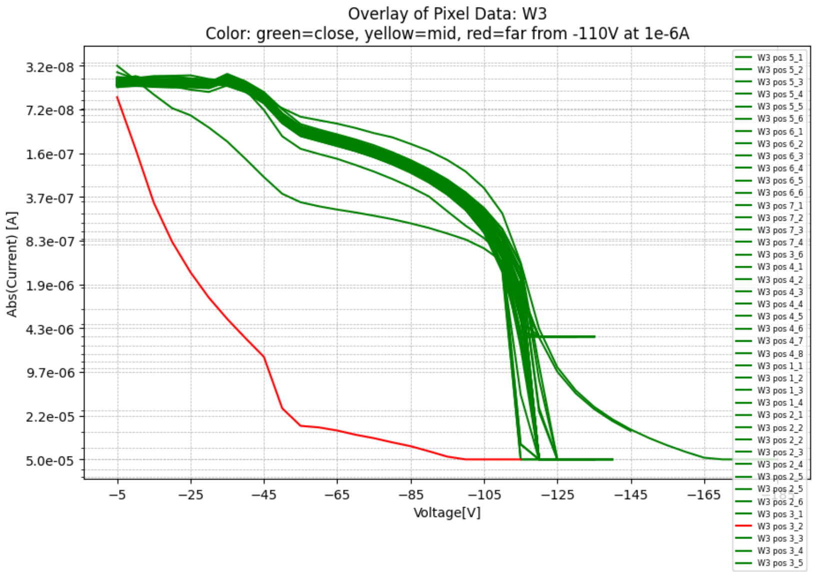


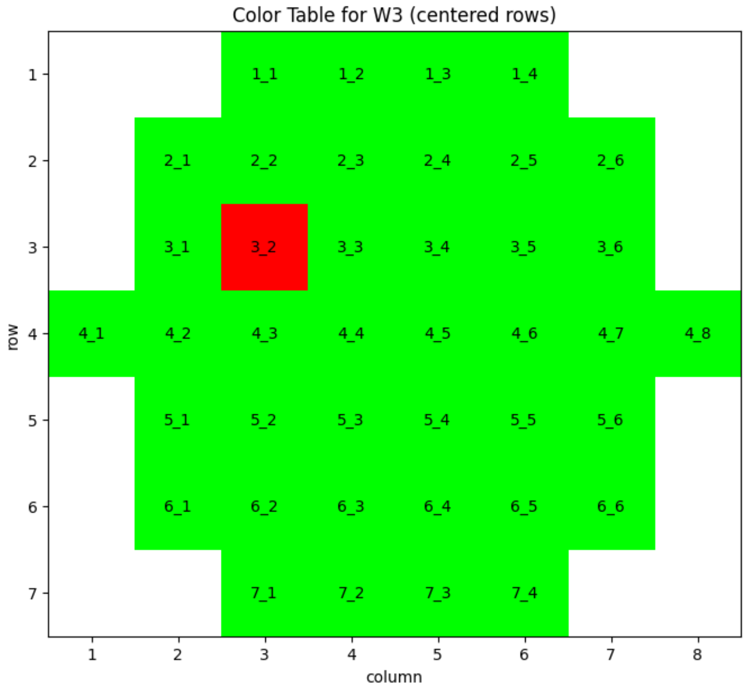
HPK Sensor production for pixel ongoing, first trials with EICROC1 when available (Q4 2025)

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

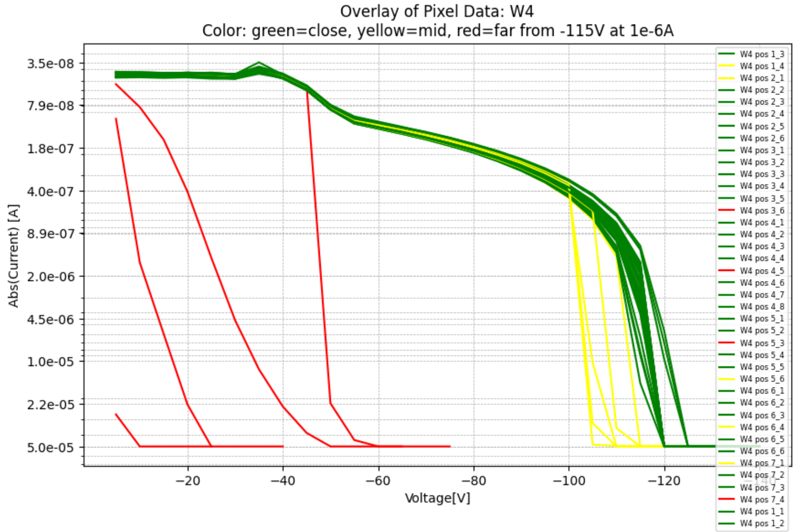
Pixel sensors – 2 wafers for now

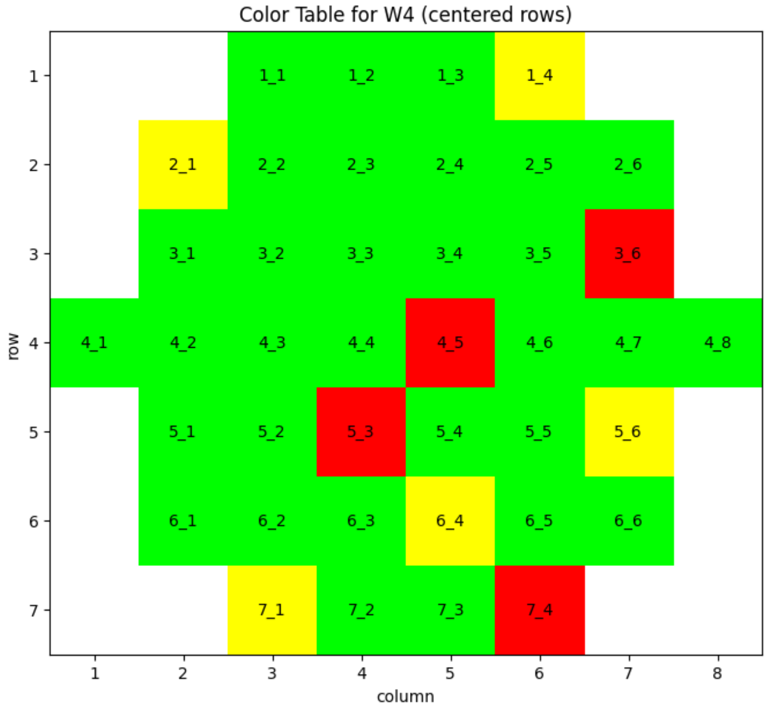
- W3 - 20um thick





- W7 - 30um thick

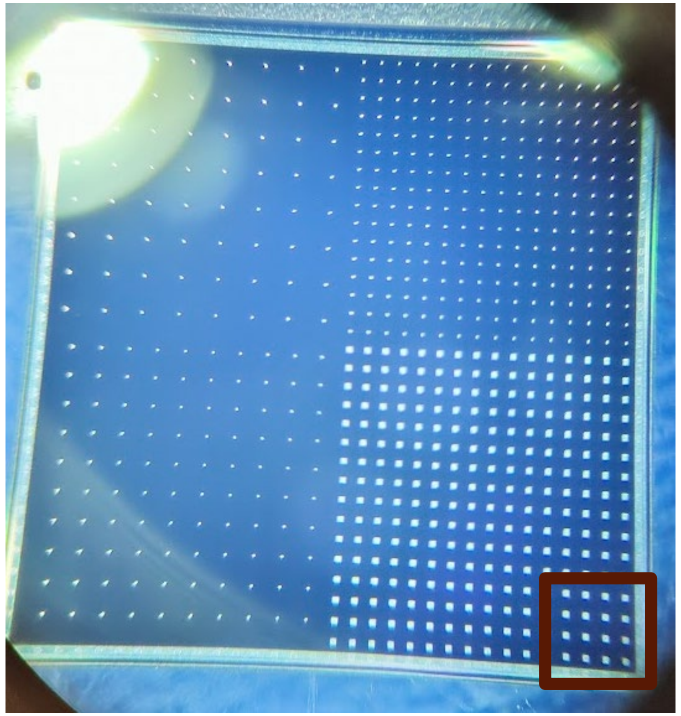


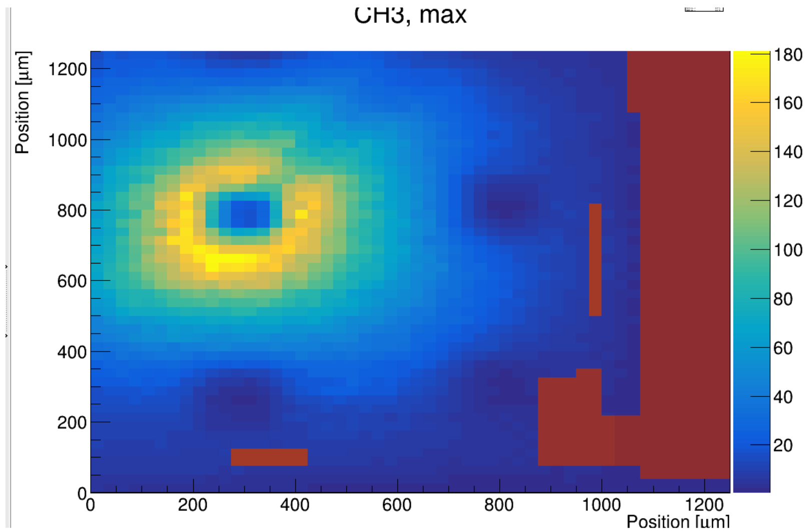


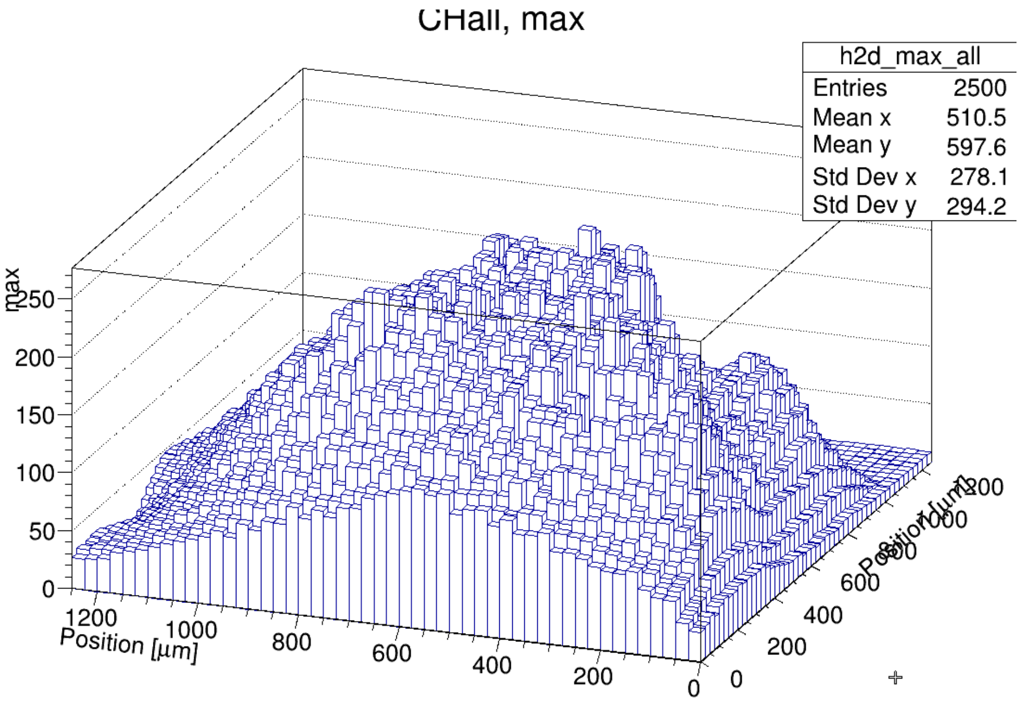
- More data here (almost complete)
  - https://docs.google.com/spreadsheets/d/1J7IuZuRaYmpDjLfzsFhHAh88glab9uHFaDUo3HoOE1o/edit?usp=sharing

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



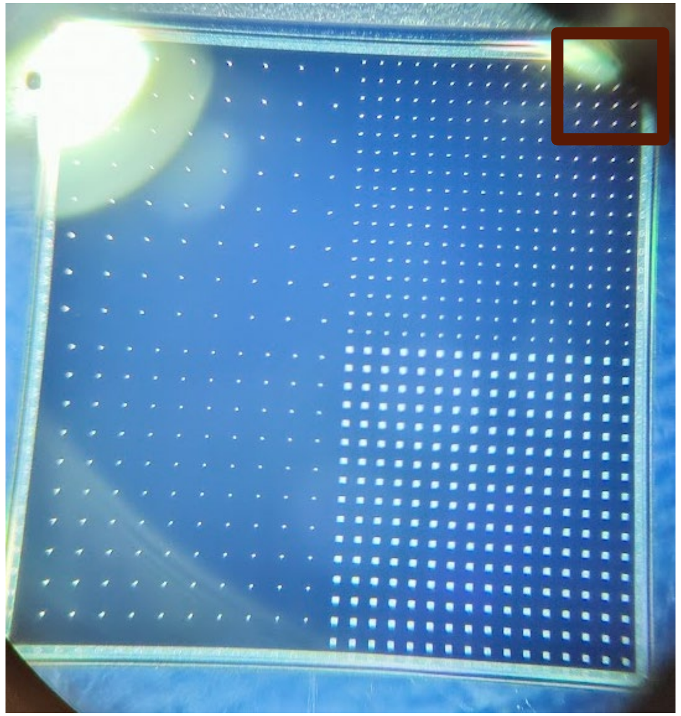


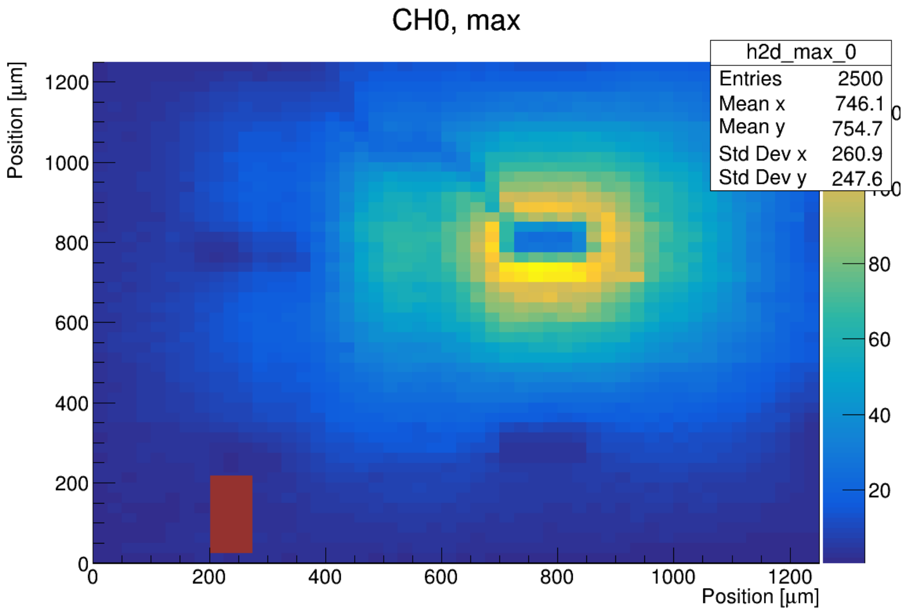


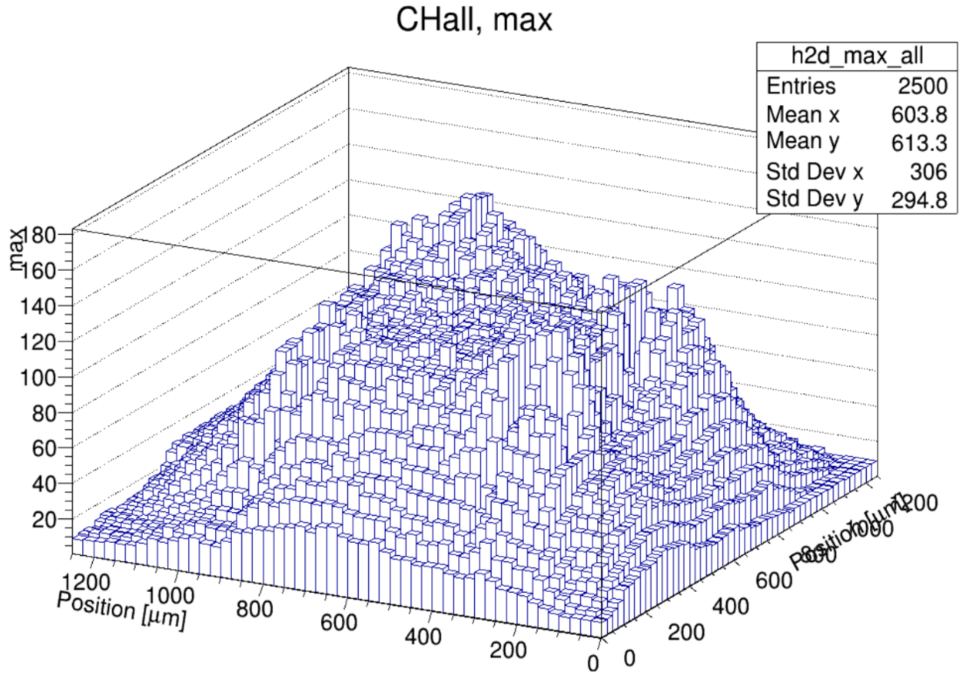
Students: N. Lynch, A. Drumm, Y. Spinos, O. Khandelwal

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



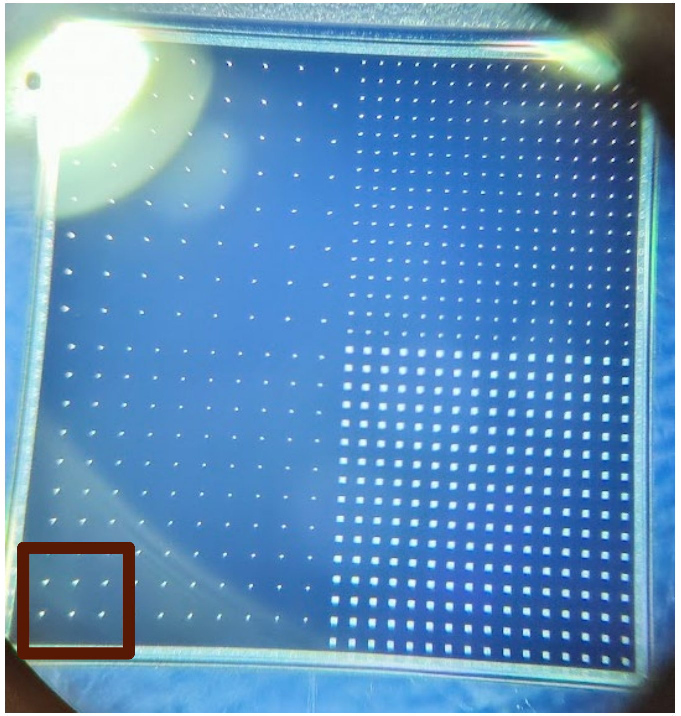


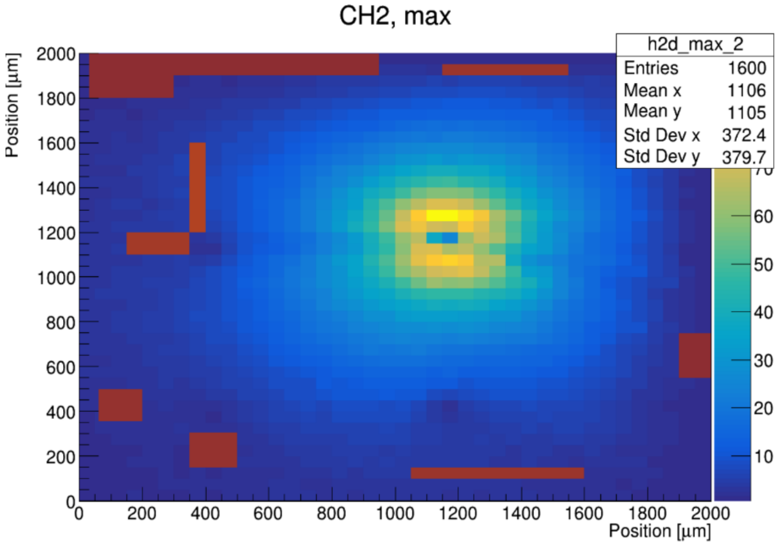


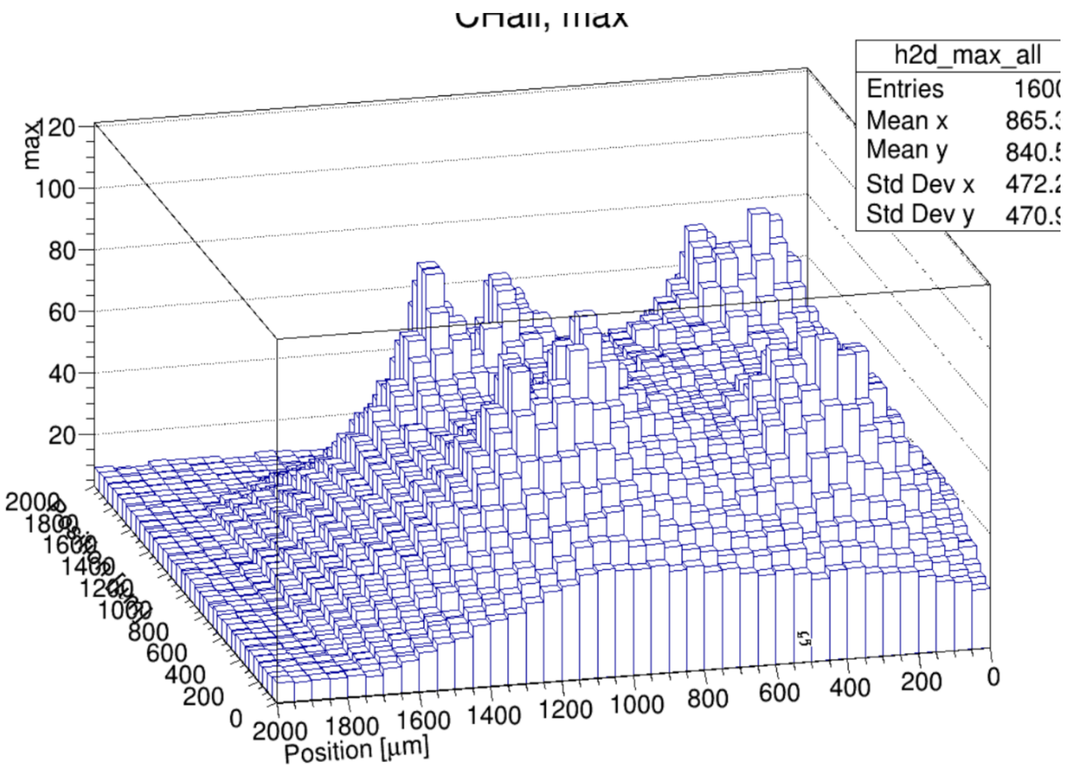
Students: N. Lynch, A. Drumm, Y. Spinos, O. Khandelwal

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



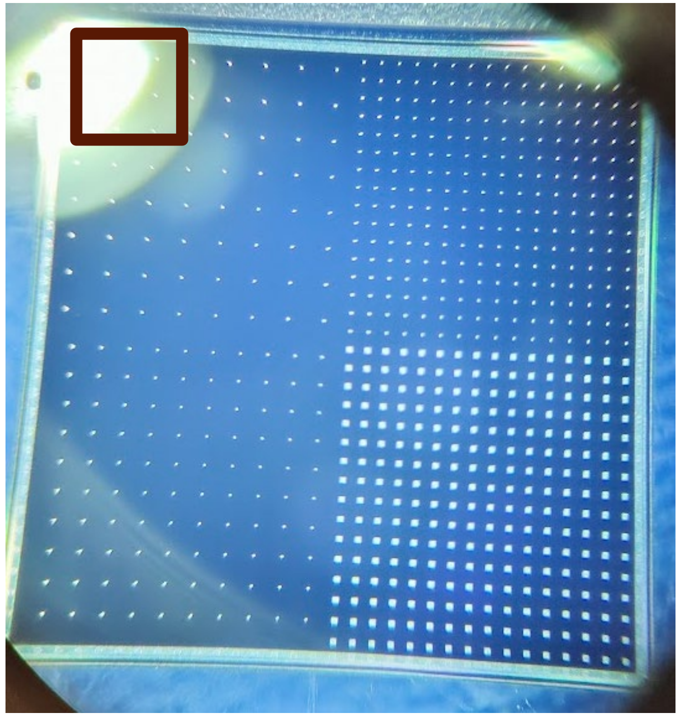


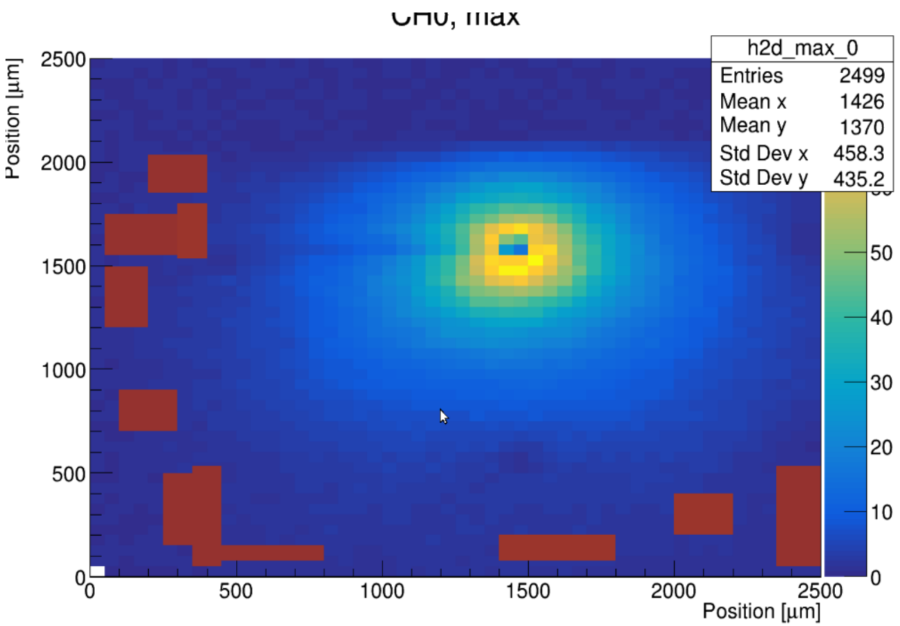


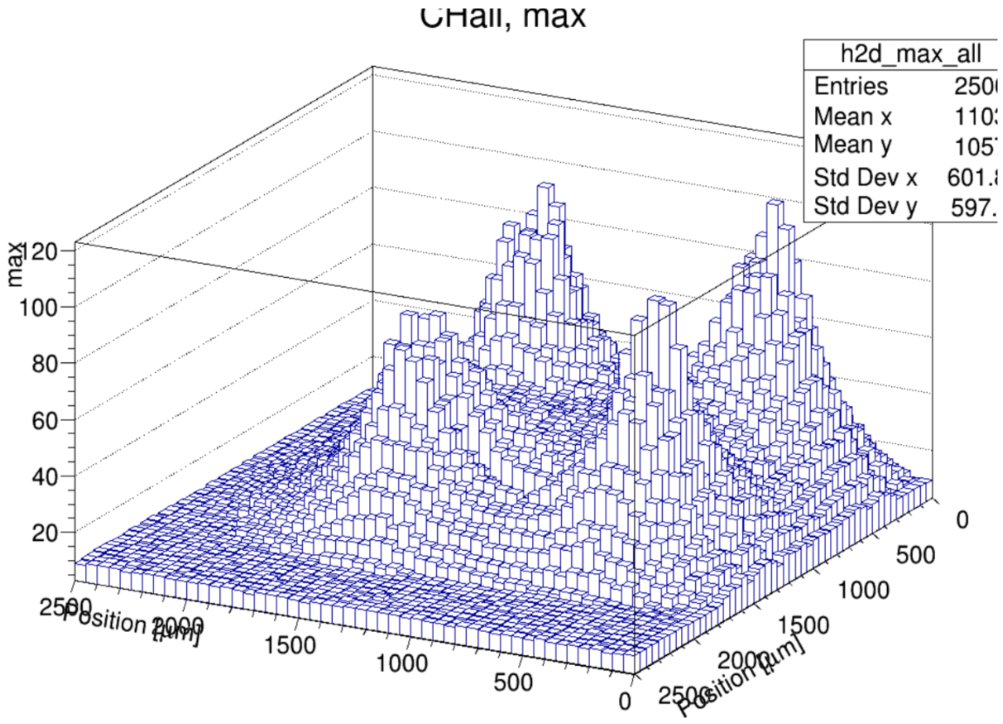
Students: N. Lynch, A. Drumm, Y. Spinos, O. Khandelwal

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



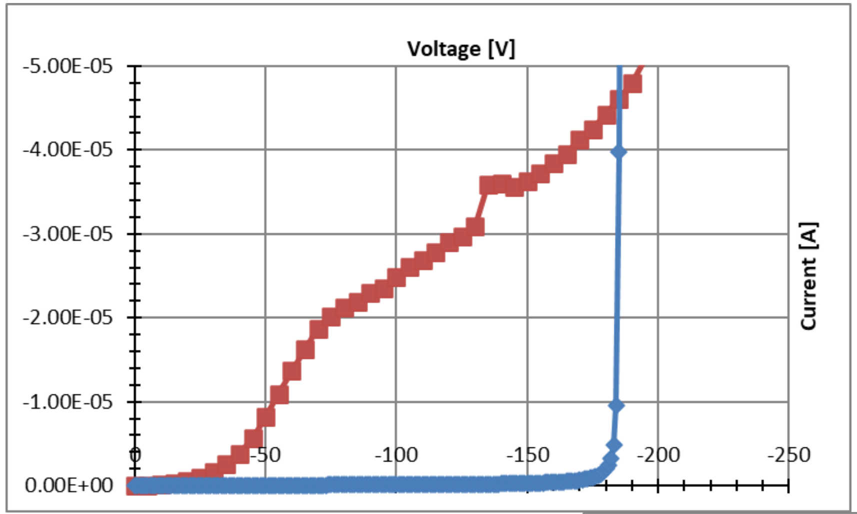




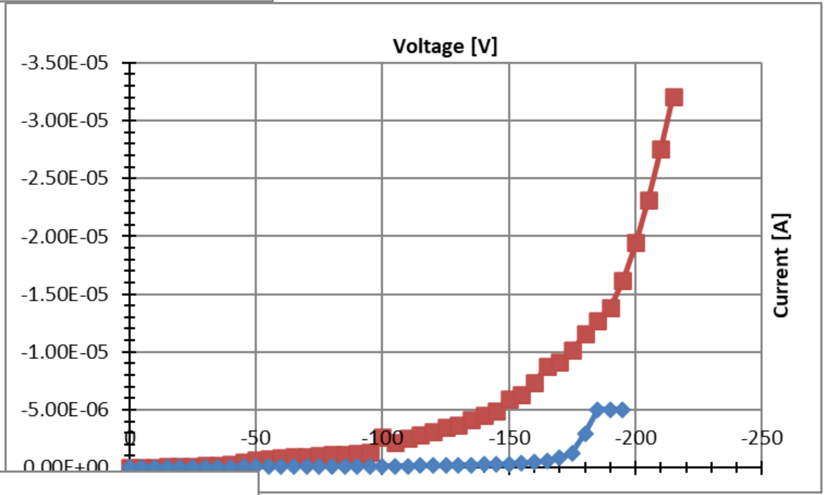
Students: N. Lynch, A. Drumm, Y. Spinos, O. Khandelwal

Assembled sensors issue

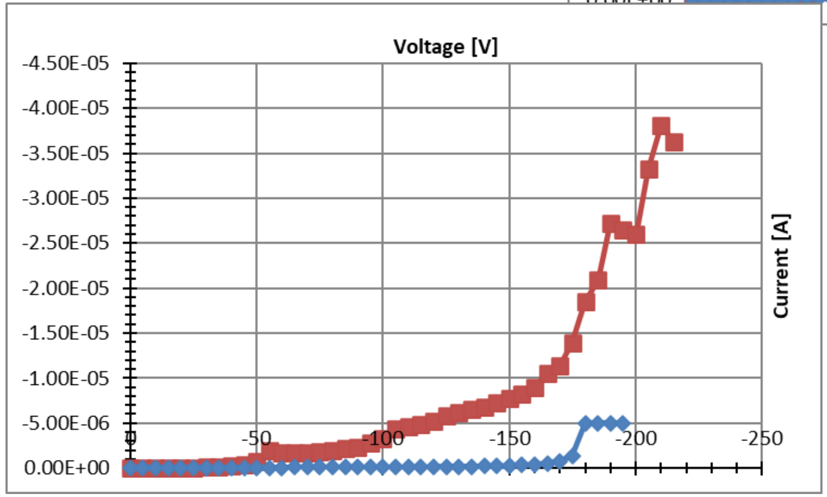
- With the assembly of many sensors an issue is arising
  - For all the assembled 3x2 strips there was no issue
  - For some assembled 3x1 strips there was an increased current after wire-bonding
  - Same issue with pixel sensors (~50% of the time)
- Possible cause: AC-LGADs have thin oxide, wire bonding might cause defects that increase current
  - Also reported by other groups with BNL and FBK sensors
- Wire bonding (UCSC) and bump bonding (ORNL) tests are planned to study this
- Urgent matter to communicate HPK and find a workaround
  - E.g. thicker oxide for strips under the connection
  - It might be tricky to solve for pixels (connection is on a 'bump'?)



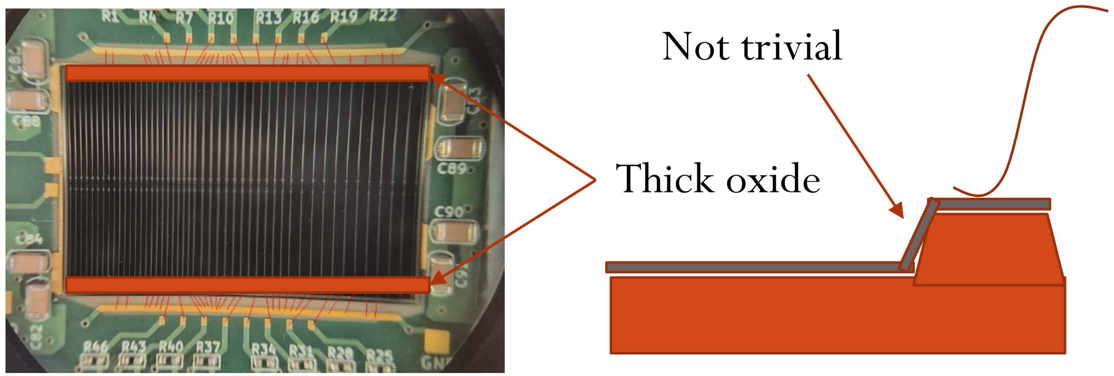
HPK W13 30um
Strips 3x1 5-1
Before assembly
After assembly



HPK W7 30um
Pixel "SMOL" 2-2
Before assembly
After assembly



HPK W7 30um
Pixel "BIG" 2-5
Before assembly
After assembly

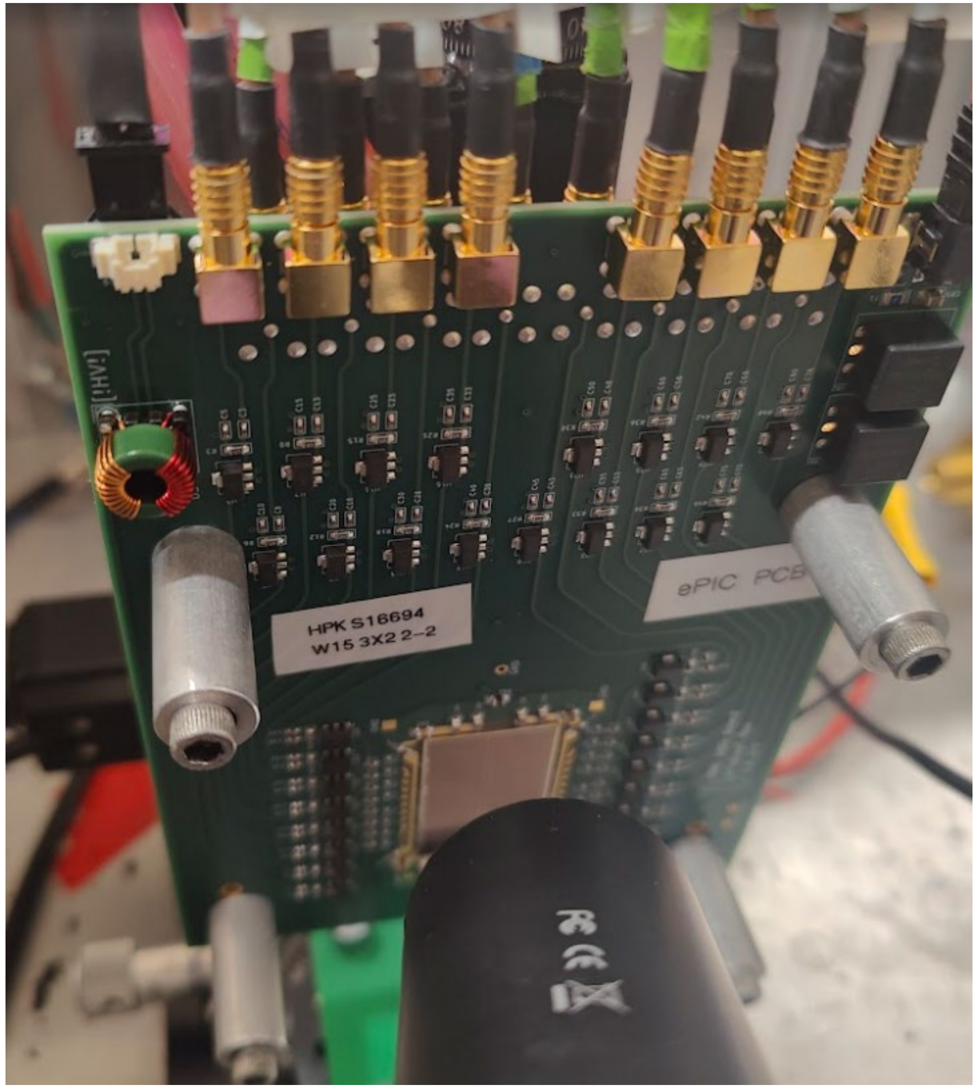


Sensors mounted for JLAB test beam

- Strip sensors mounted on boards
  - W12 50um 2-2 3x2 – ePIC PCB1 – laser tested
  - W13 30um 3-2 3x2 – ePIC PCB2 – laser tested
  - W12 50um 3-2 3x2 – ePIC PCB3 – laser tested
  - W15 30um 2-2 3x2 – ePIC PCB11 – laser tested
  - W2 50um 5-2 3x1 – ePIC PCB6 – laser tested
  - W13 30um 5-1 3x1 – ePIC PCB5 – laser tested

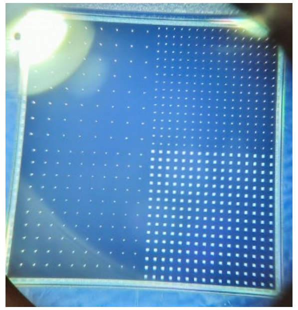
- Pixel sensors mounted on board
  - Pixel W7 30um "BIG" 2-5 – ePIC PCB7 – laser tested
  - Pixel W3 20um "BIG" 2-5 – ePIC PCB8 – to test (IV OK)
  - Pixel W7 30um "SMOL" 2-2 – ePIC PCB9 – laser tested
  - Pixel W3 20um "SMOL" 2-2 – ePIC PCB10 – to test (IV OK)
  - Pixel W7 30um "BIG" 4-5 - ePIC PCB13 – to test (IV OK)
  - Pixel W3 20um "BIG" 2-4 - ePIC PCB12 – to test (IV OK)

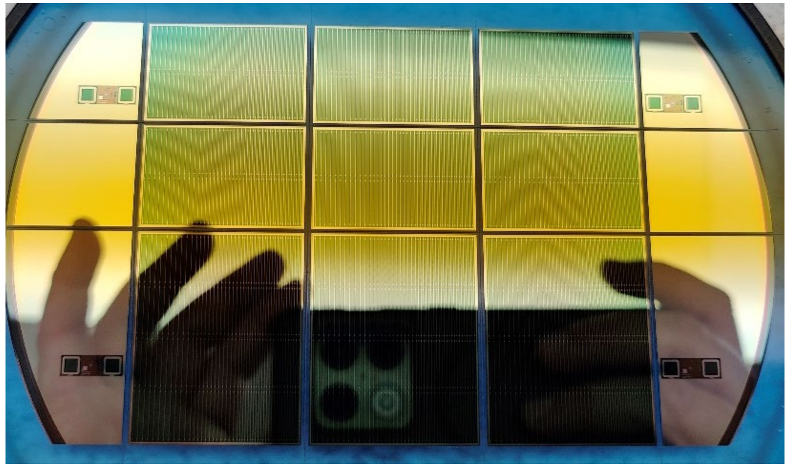
- **Mounting setup tomorrow, running until Aug 13**



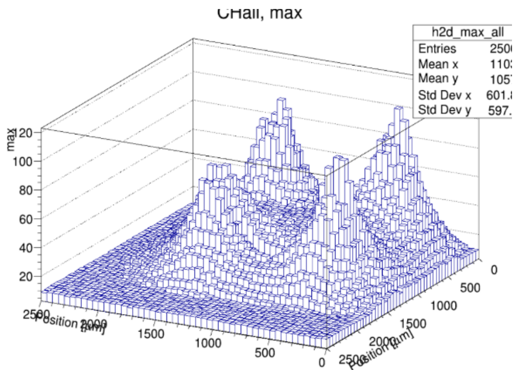
Conclusions

- Sensors for the ePIC TOF layer 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>
- **Running a test beam here & now!**
- Additional test beam planned this year at KEK for full-size sensor testing and readout electronic testing





- An additional HPK production is ongoing
- 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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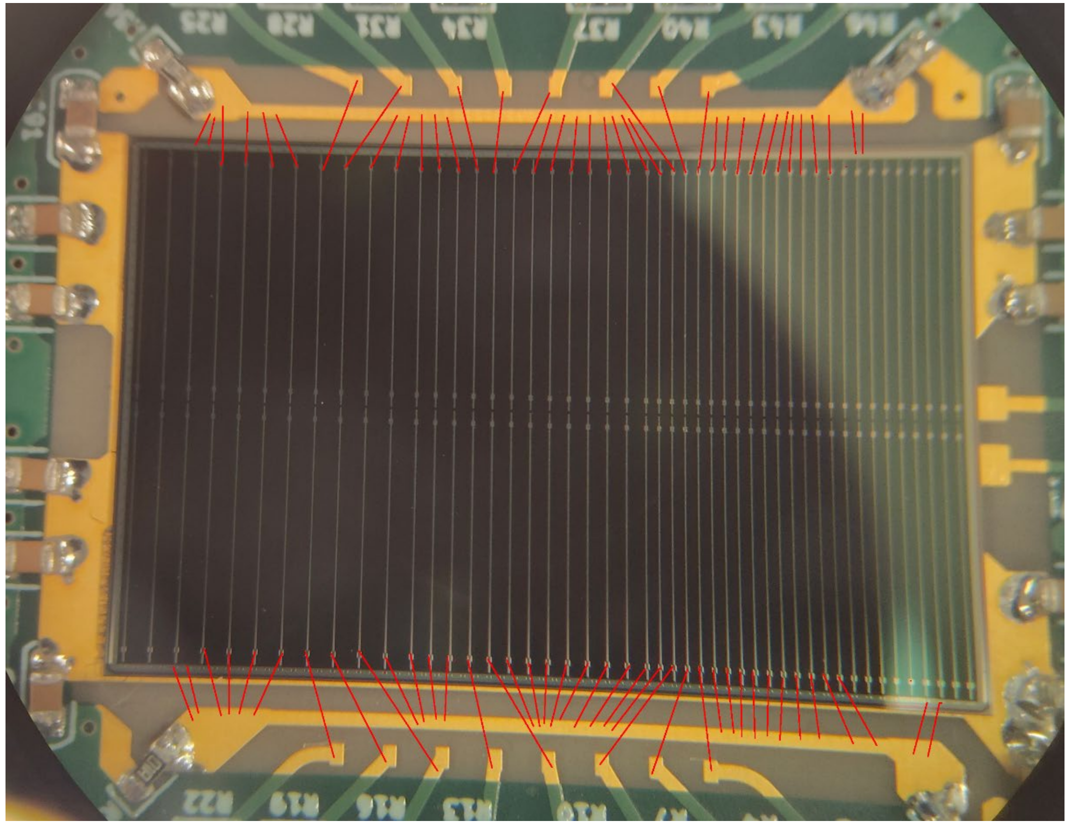
Thanks to IJS (G. Kramberger, I. Mandic) and UNM (S. Seidel) for providing sensor irradiation at Lubjiana and FNAL ITA

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

Backup

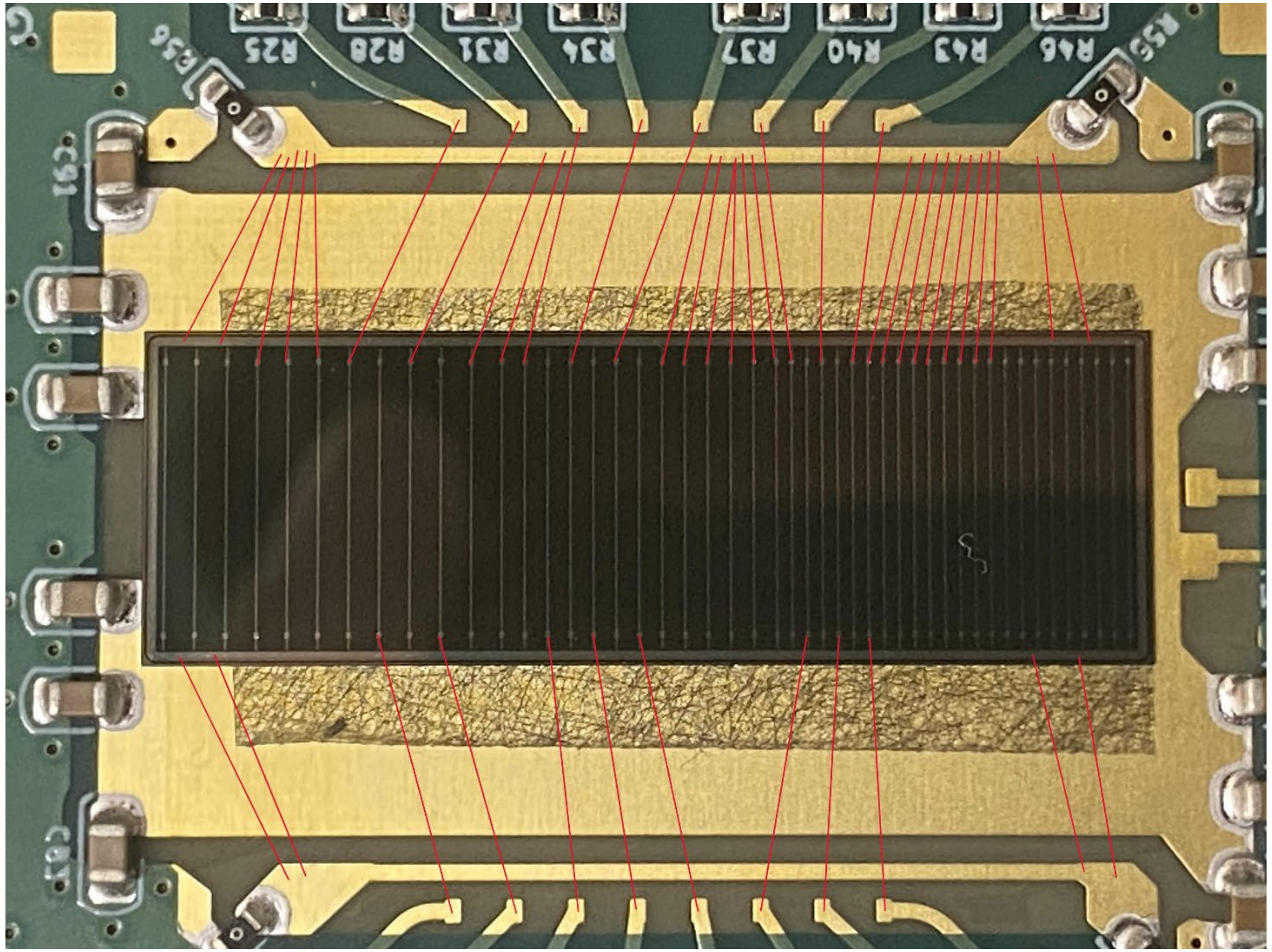
Boards wire bonding

2 3 3



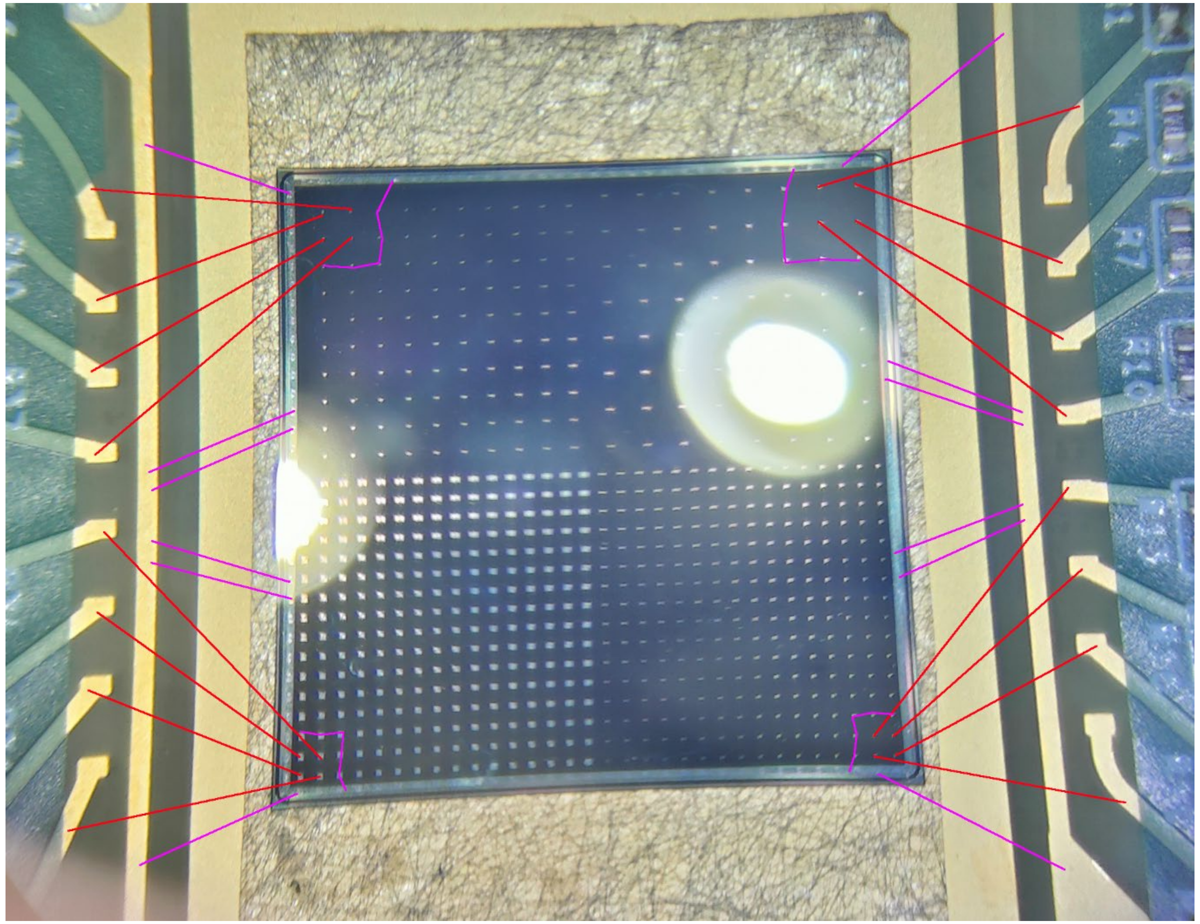
3 2 3

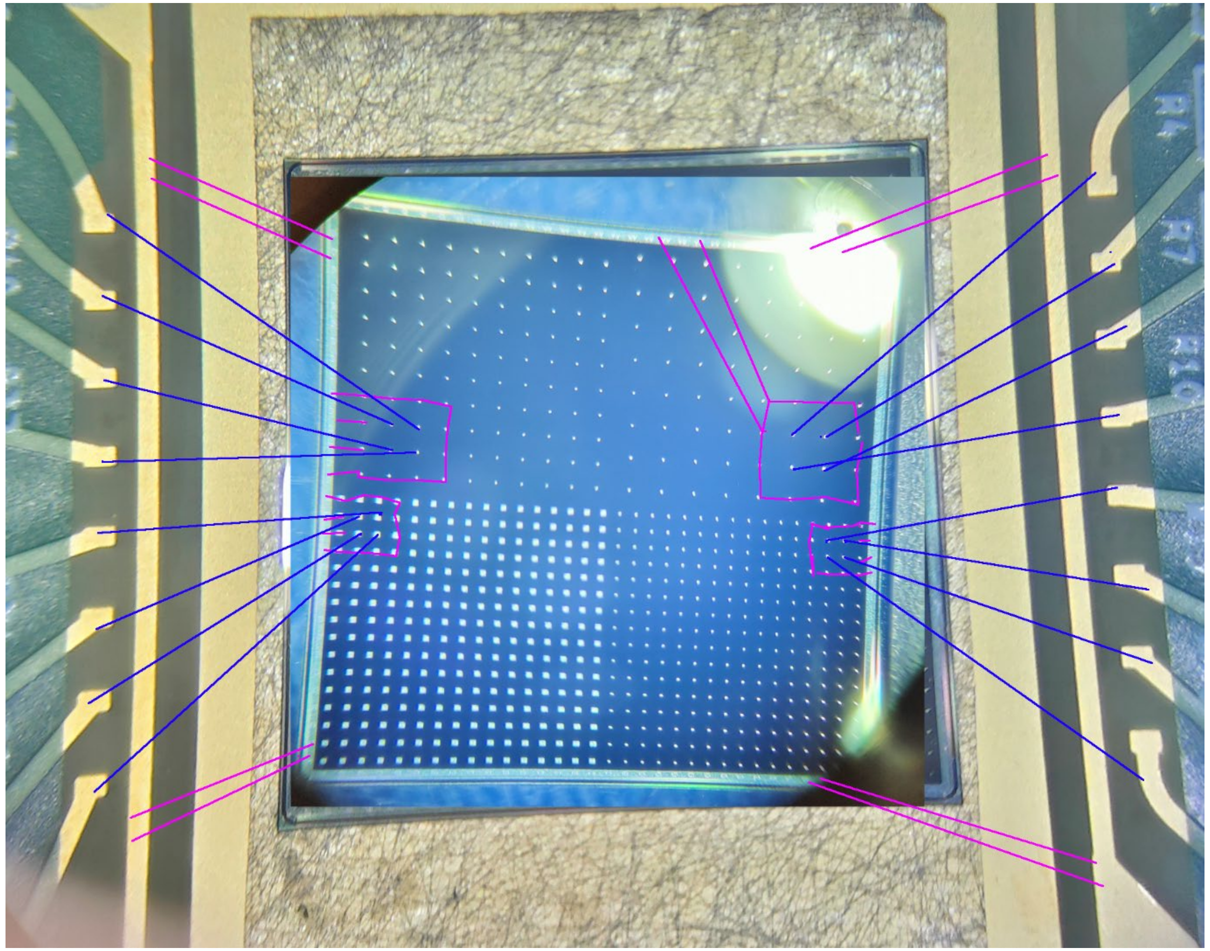
Alternating connection



4 6 6

Boards wire bonding

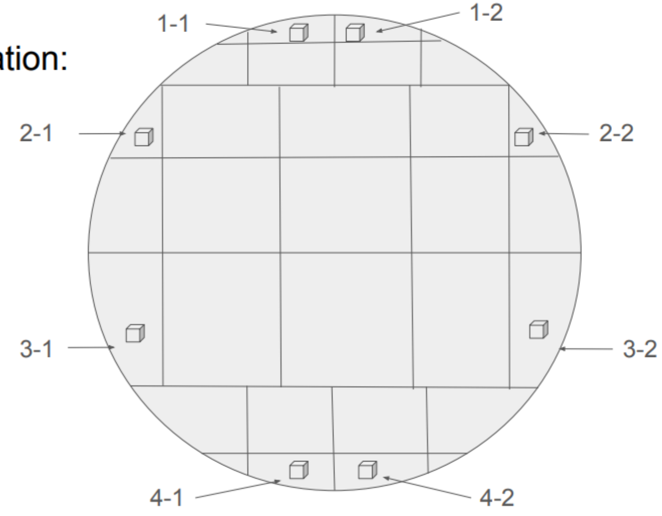


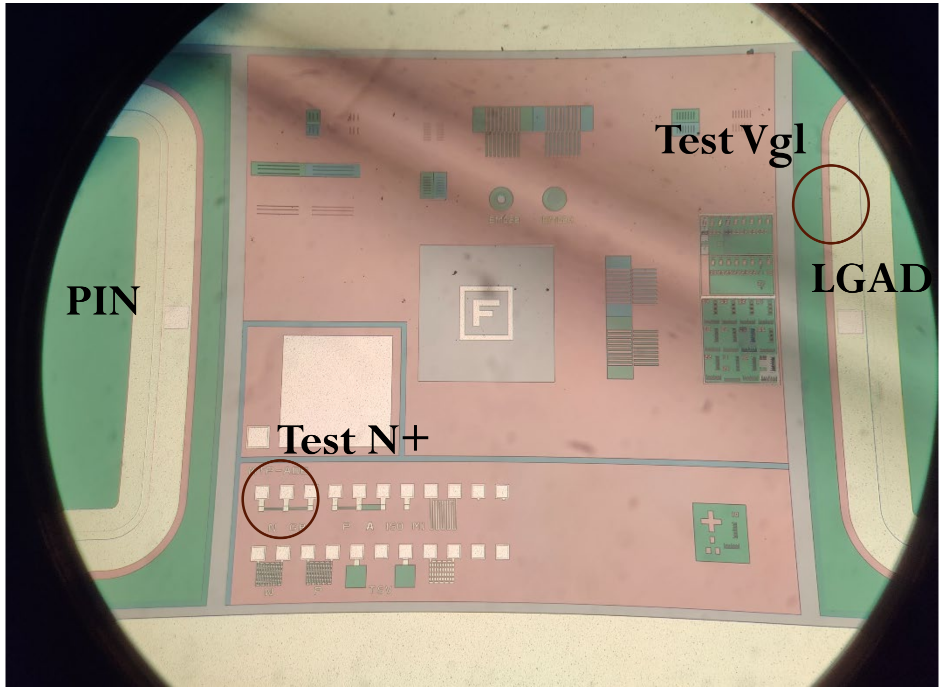


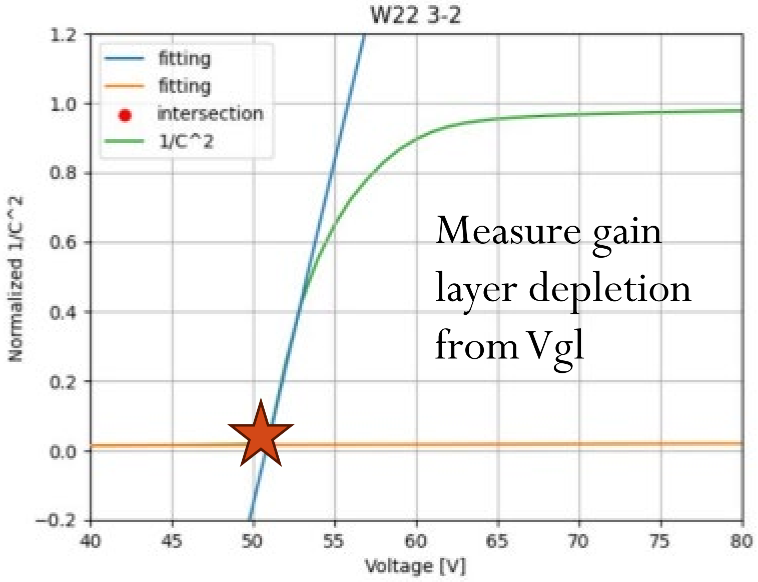
HPK production testing

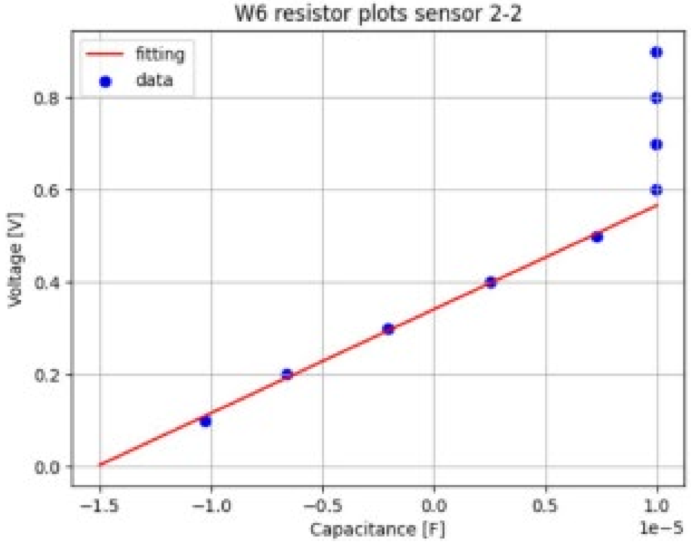
- **Check gain and N+ homogeneity** across the wafer and between the wafers
  - Wafer edge is usually the most sensible
- Using test structures at the edge of the wafer to test gain and N+ resistivity
  - Measure Vgl of the LGAD test structure
  - Measure current vs voltage for N+ test

Orientation:







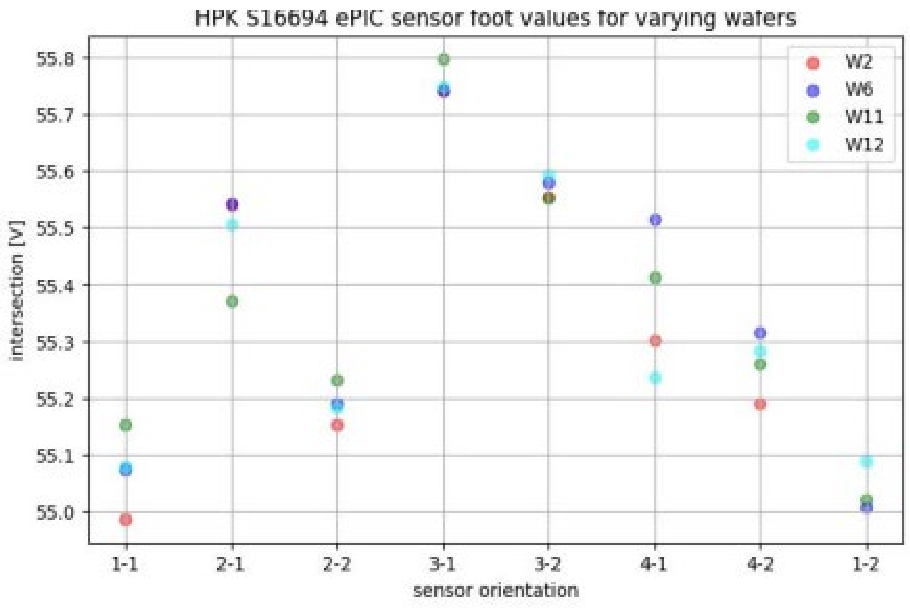


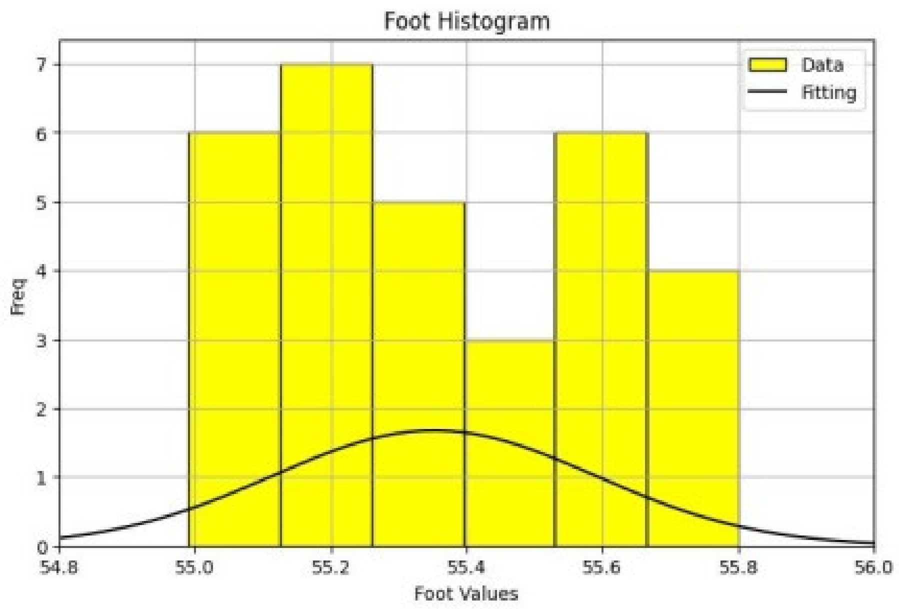
V(I) = 22504*I + 0.341

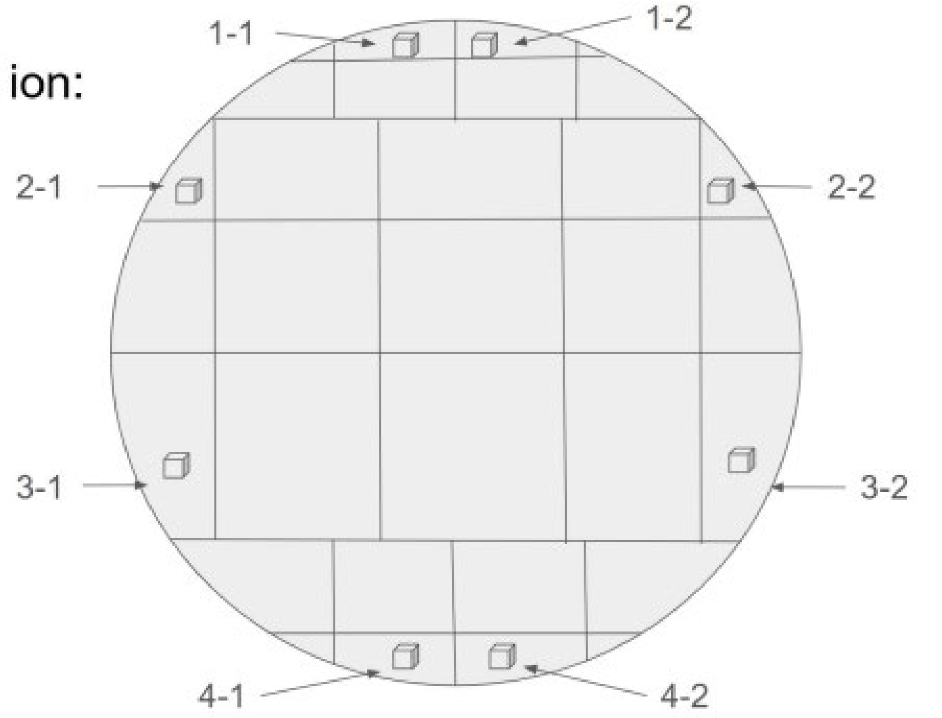
Student: M. Davis, S. Beringer

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?



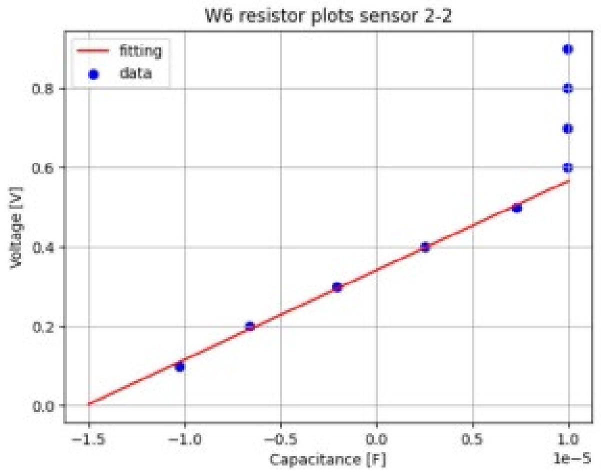


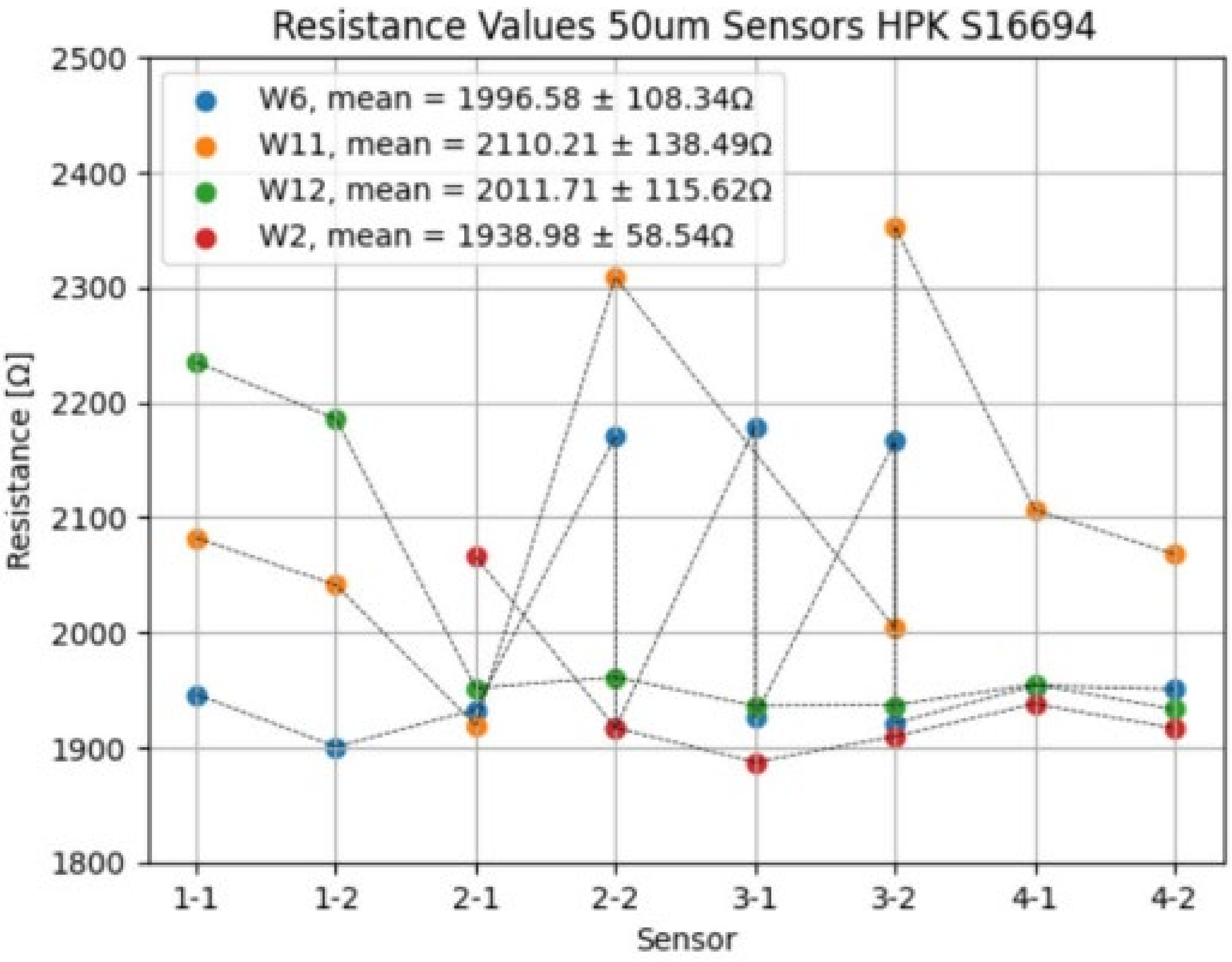


Mean = 55.26
Sigma = 0.23

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%

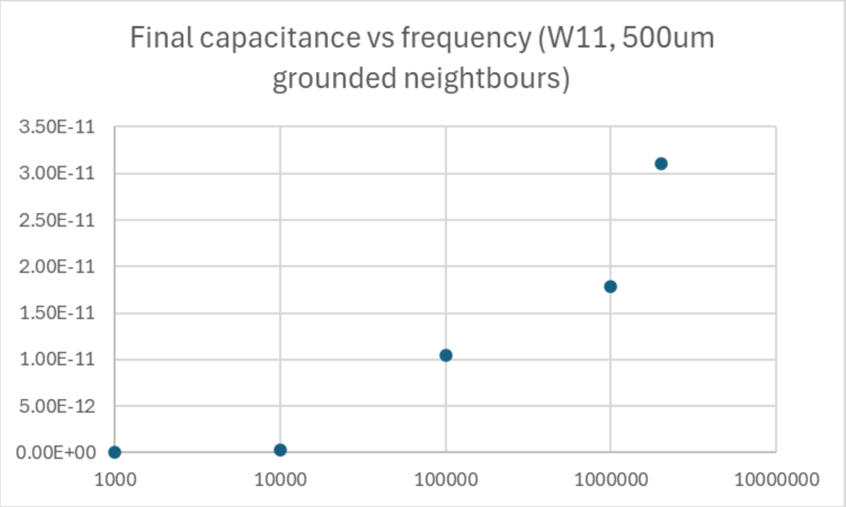


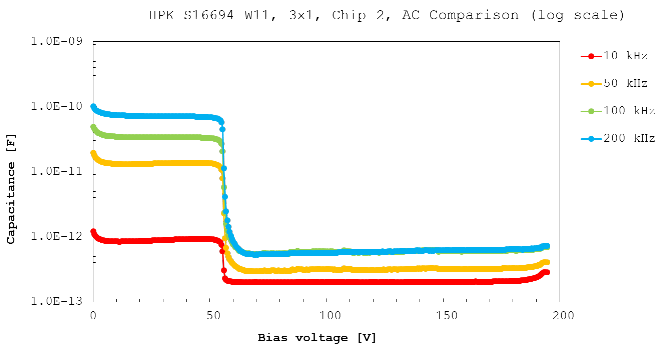


V(I) = 22504*I + 0.341 → R = 2250 Ω

Strip capacitance

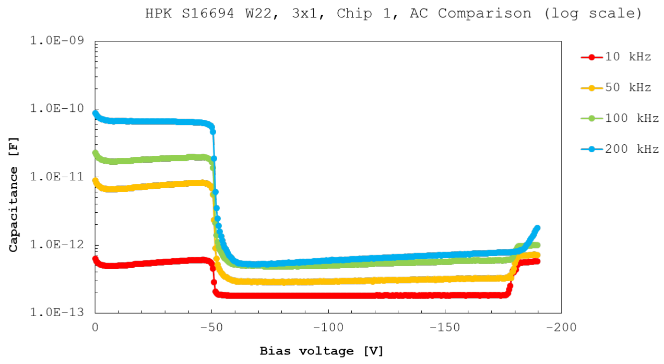
- Capacitance of AC strips with backside measurements, test on strip grounding neighbors
- Final capacitance measured the order of few pF for both wafers → remeasured
- As always it's tricky to pinpoint a number as result vary wildly with frequency
  - Value goes to 10-100 pF for higher frequencies
-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

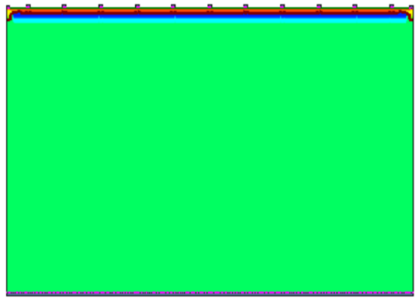
Student: M. Davis

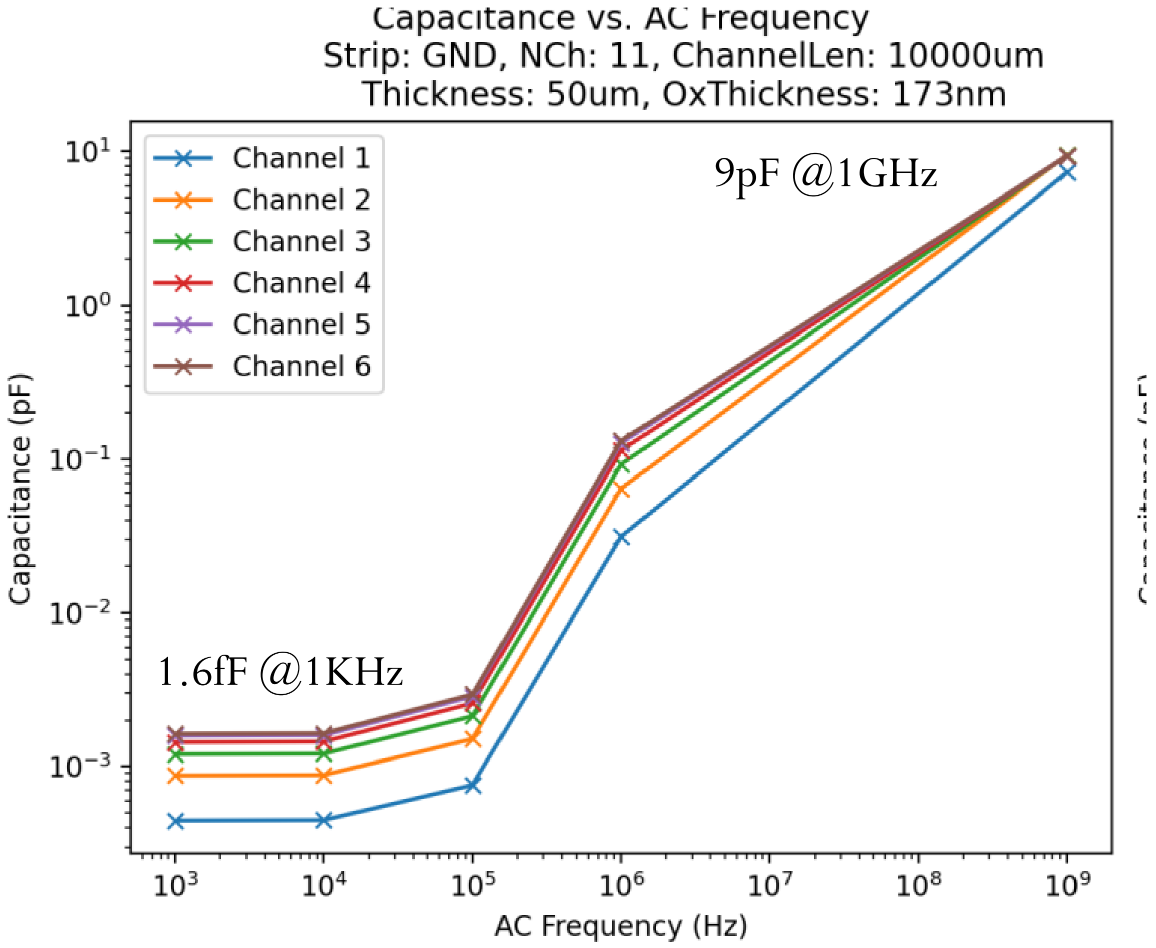
TCAD study on capacitance

- 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

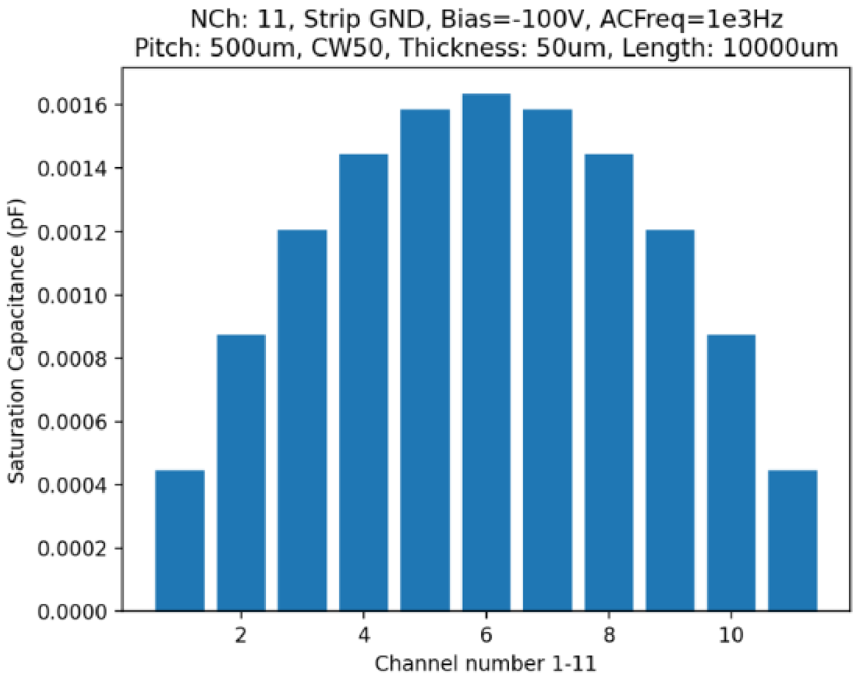


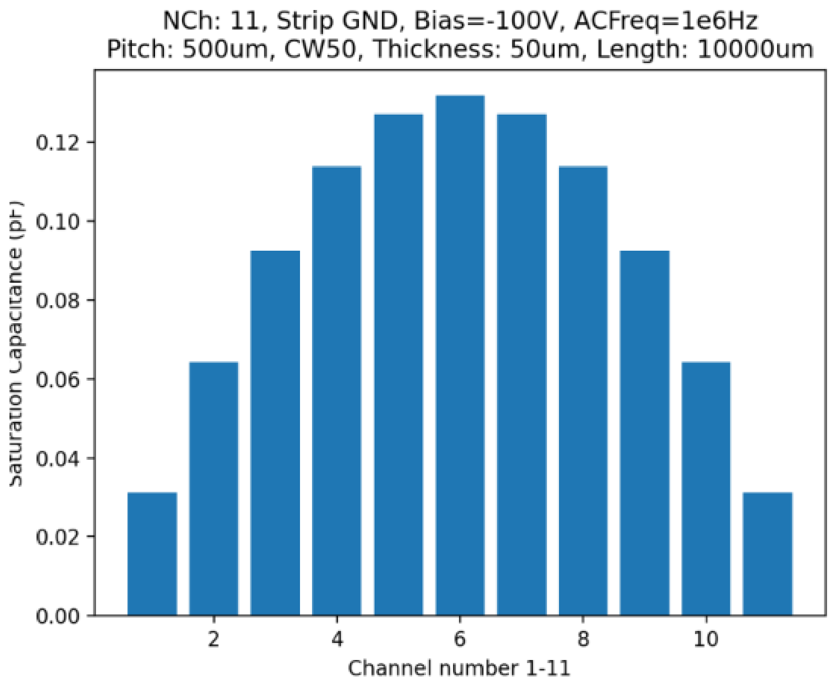


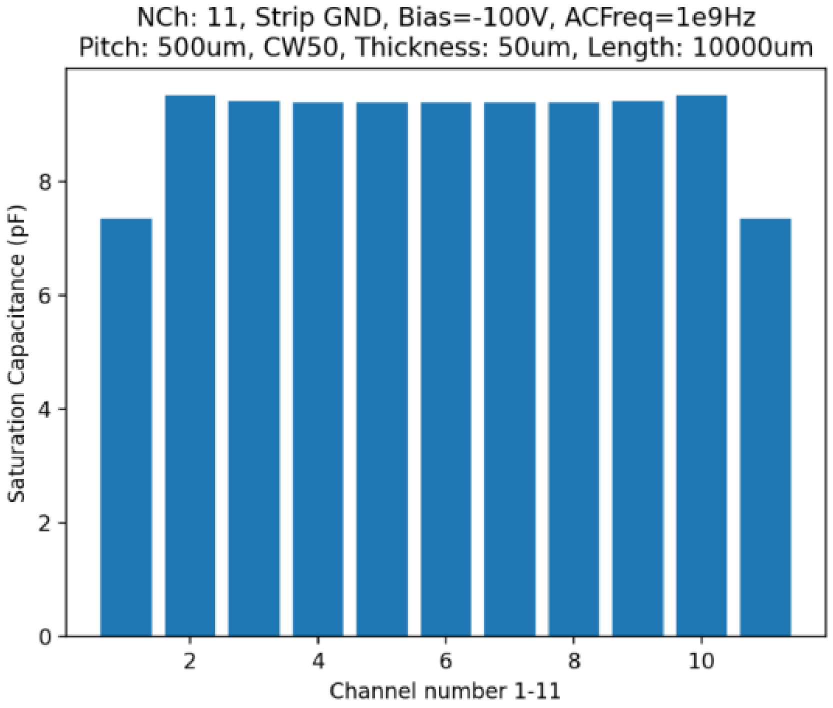
Credits:T. Shin

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



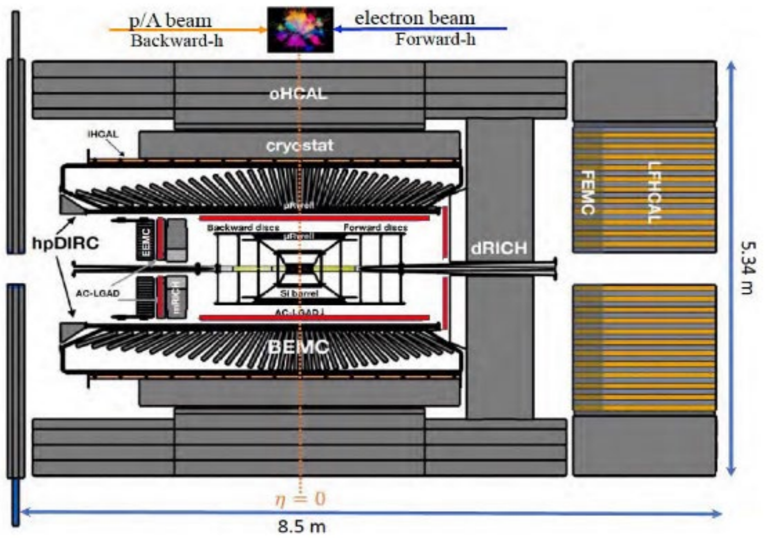


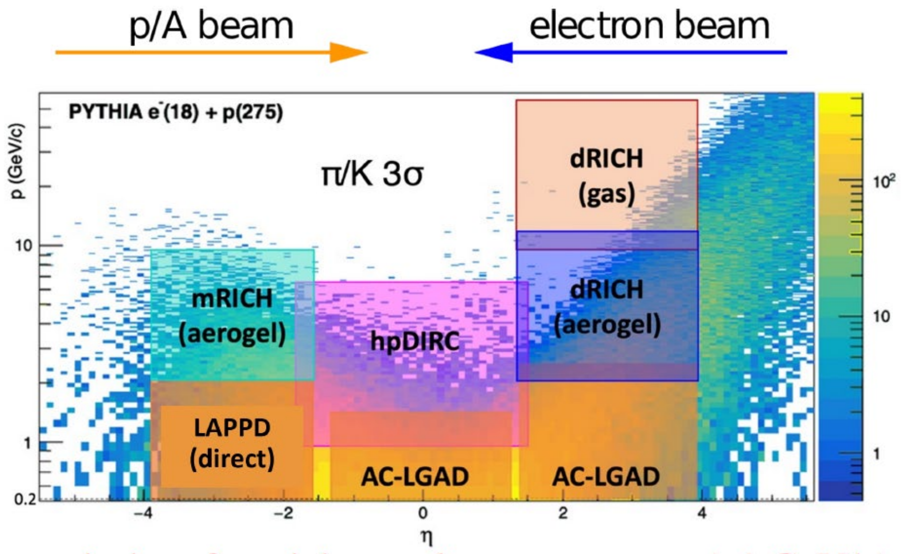


Credits:T. Shin

The ePIC detector

- **4D tracking** is of great interest in the ePIC collaboration
- **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
- **Particle identification with time of flight (TOF)**
  - For e/π/K/p at low/intermediate momentum
  - Require good time resolution and meaningful flight distance

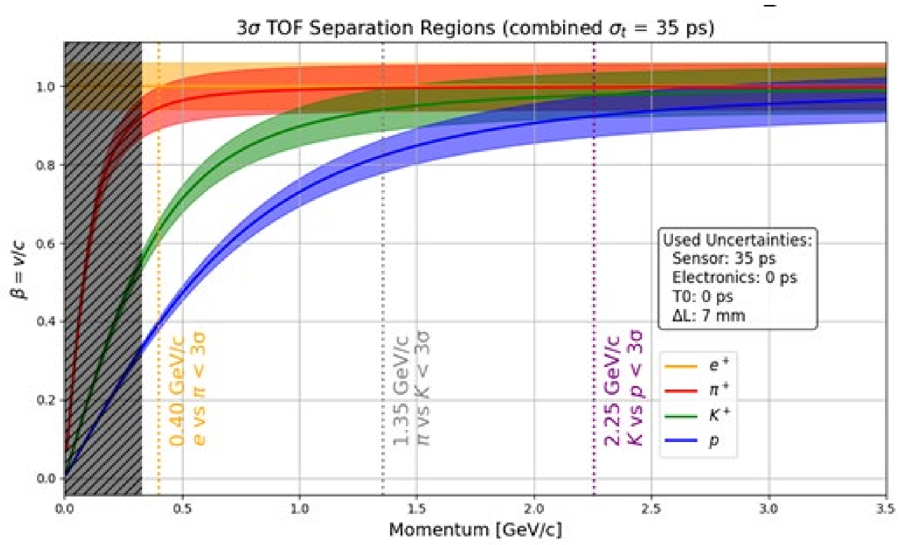


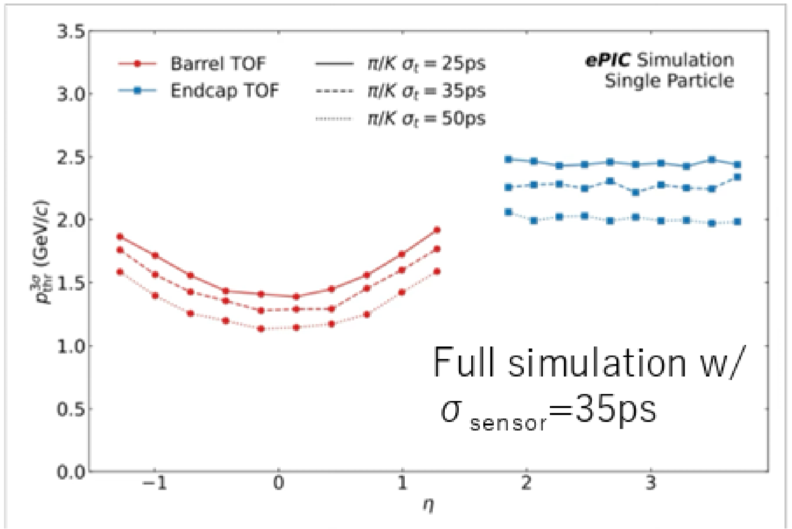


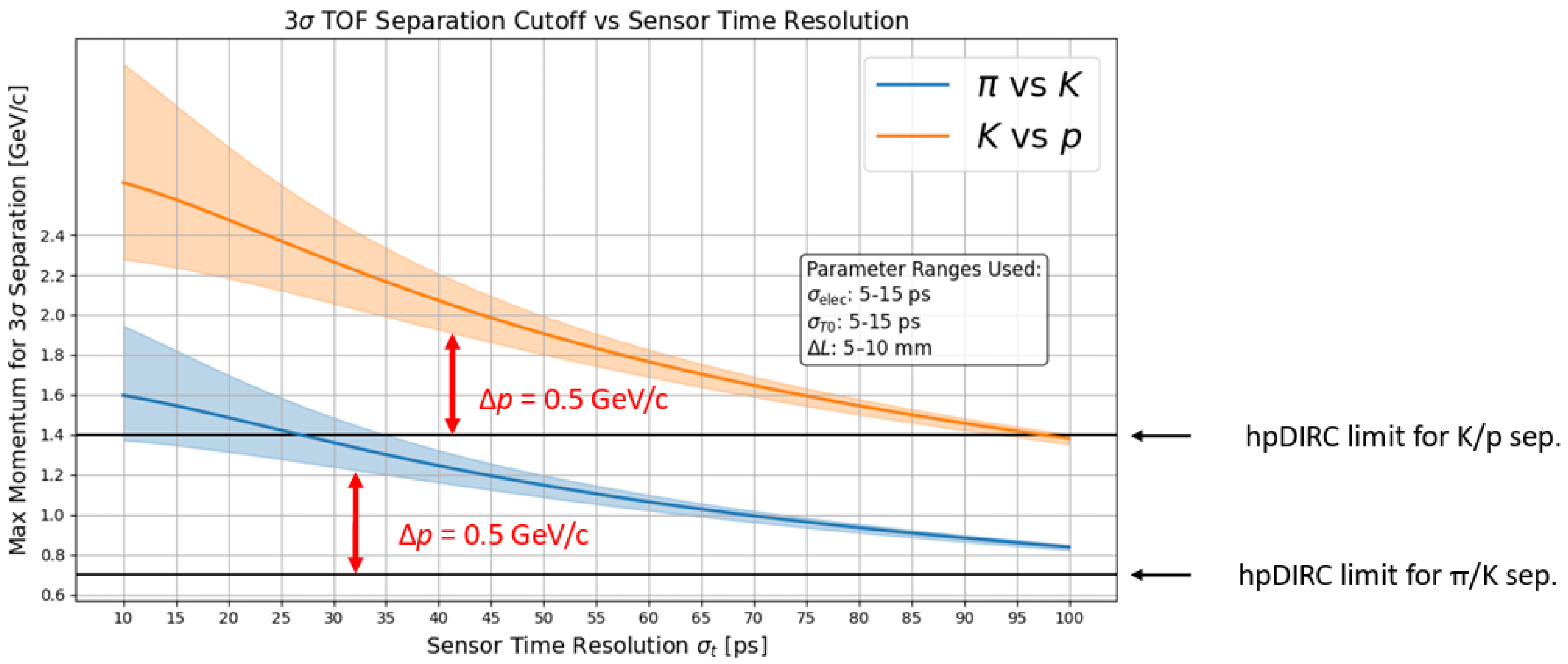
Subsystem	Area (m^2)	dimension (mm^2)	channel count	timing σ_t (ps)	spatial σ_x (μm)	material budget (X/X_0)
Barrel TOF	12	0.5*10	2.4M	35	30 ($r \cdot \phi$)	3%
Forward TOF	1.1	0.5*0.5	3.2M	25	30 (x, y)	5%

Why TOF?

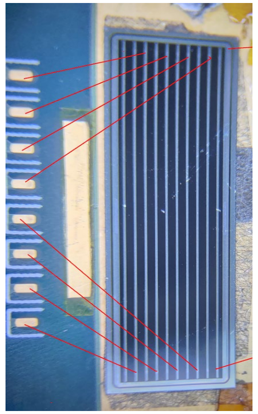
- Heavy flavor (HF) measurement is the most important subject at EIC
  - Identification of HF hadrons decay products with TOF PID
- BOTF default performance: 35ps
  - e/PI separation up to 0.4 GeV
  - Pi/K separation up to 1.35 GeV
  - K/P separation up to 2.25 GeV
- Improves the hpDIRC particle ID by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

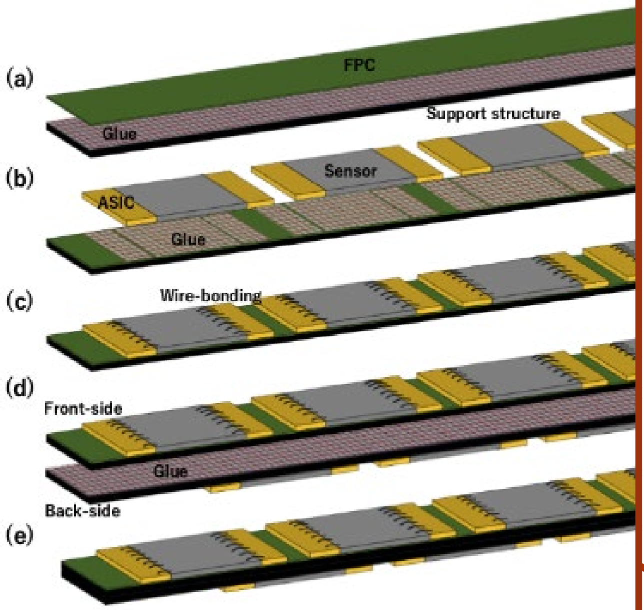




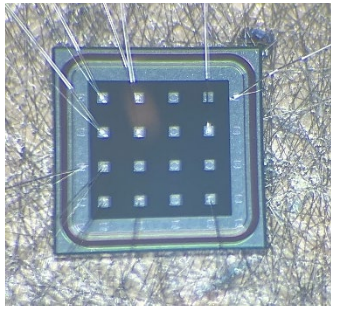


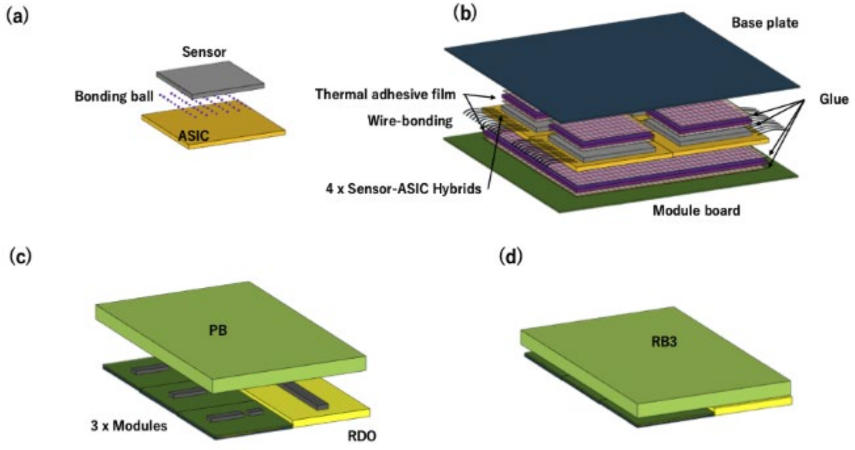
TOF layout in ePIC





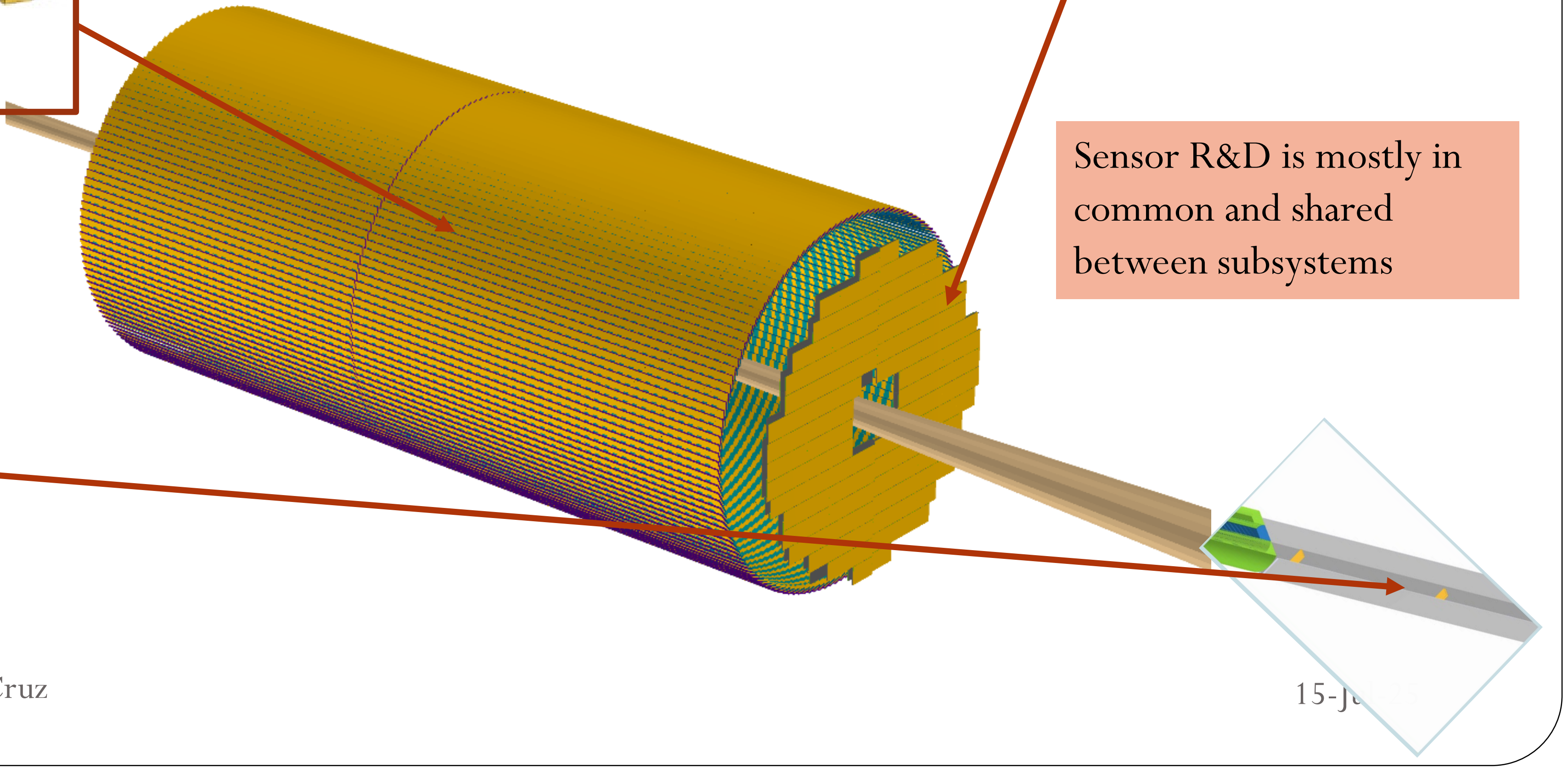
Sensors: strips
Readout: FCFD

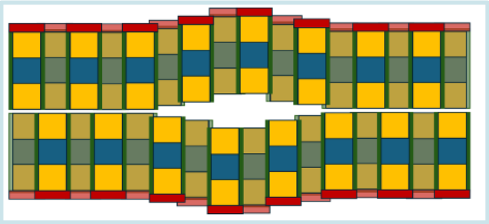




Sensors: pixels
Readout: EICROC

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



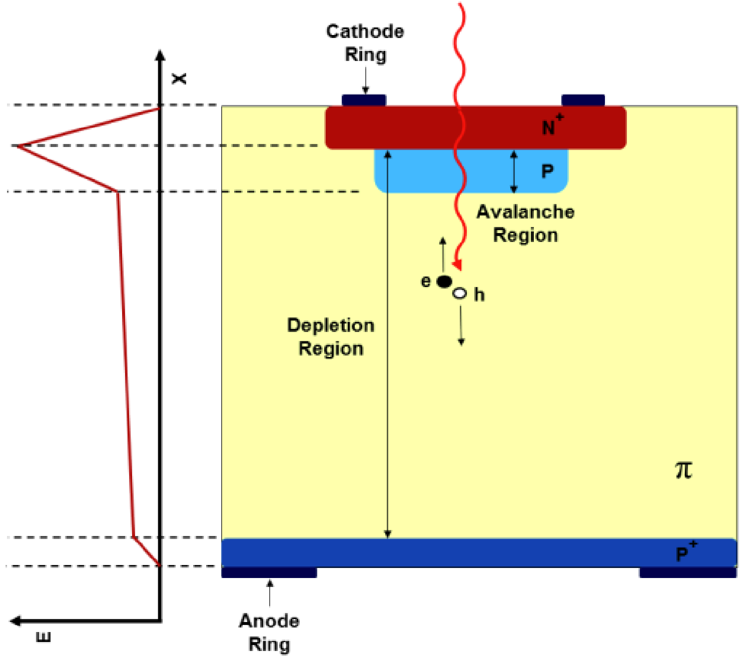


Sensors: pixels
Readout: EICROC

Off-Momentum Detectors (OMD)

Low Gain Avalanche Detectors, LGADs

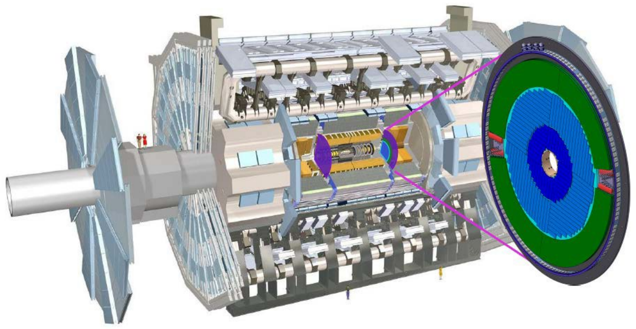
- LGAD: silicon detector with a thin (<5 μm) and highly doped (~10^{16}) multiplication layer
  - High electric field in the multiplication layer
  - Field is high enough for electron multiplication but not hole multiplication
- LGADs have intrinsic modest internal gain (10-50)
  - Gain $= \frac{Q_{LGAD}}{Q_{PiN}}$ (collected charge of LGAD vs same size PiN)
  - Not in avalanche mode → controlled tunable gain with applied bias voltage
  - Thanks to gain LGADs can be thin (20um, 50um)
- **Great hit time resolution reach: <20 ps!**
- LGADs are a great device to allow 4D tracking (x,y,z,t)



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

First application HL-LHC timing layers for ATLAS and CMS

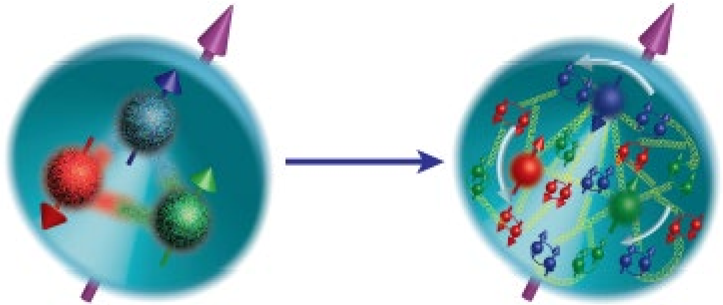
- Several producers of experimental LGADs around the world
  - CNM (Spain), HPK (Japan), FBK (Italy), BNL (USA), NDL (China)



https://cds.cern.ch/record/2719855
https://cds.cern.ch/record/2667167

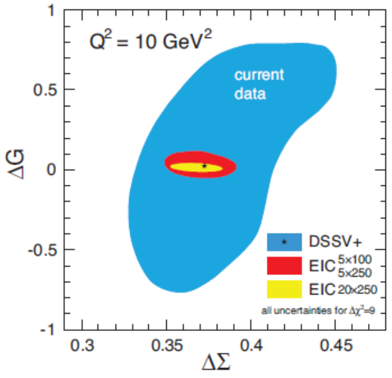
Electron-Ion collider

- Electron-Ion collider will be the biggest NP effort in the U.S. at BNL
  - Running conditions will be from 20-100 GeV c.d.m. to 140 GeV with polarized nucleon and electron beams and 10^{34} $cm^{-2}s^{-1}$ luminosity
- **ePIC** is the detector 1 design currently under review

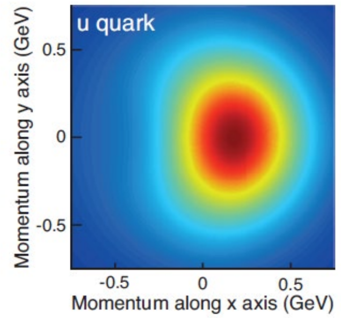


ePIC will provide key measurements:

- **Proton spin**: decisive measurements on how much the intrinsic spin of quarks and gluons contribute to the proton spin. Only 30% proton spin is accounted for by quark-antiquark!
- **The motion of quarks and gluons in the proton**: study the correlation between the spin of a fast-moving proton and the transverse motion of both quarks and gluons. Nothing is currently known about the spin and momentum correlations of the gluons and sea quarks.
- **The tomographic images of the proton**: detailed images of the proton gluonic matter distribution as well as images of sea quarks. Reveal aspects of proton structure that are connected with QCD dynamics at large distances.
- **QCD matter at an extreme gluon density**: first unambiguous evidence for a novel QCD matter of saturated gluons, Color Glass Condensate.

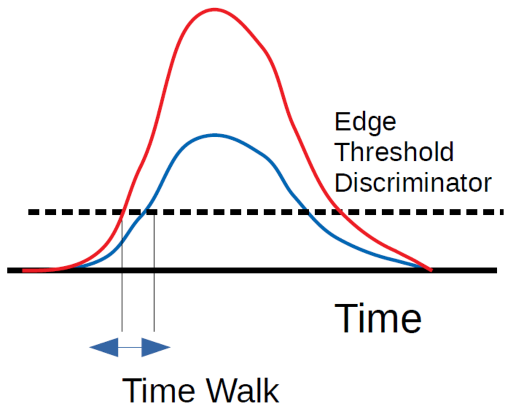


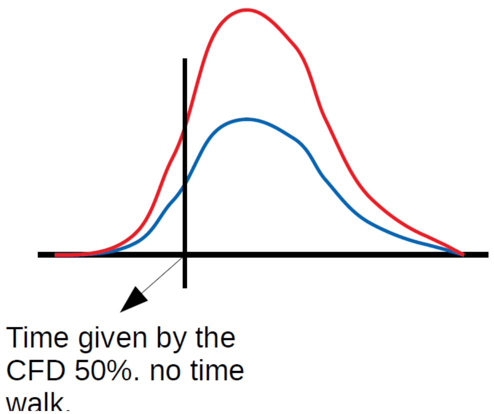
Gluon helicity contribution vs quark helicity contribution

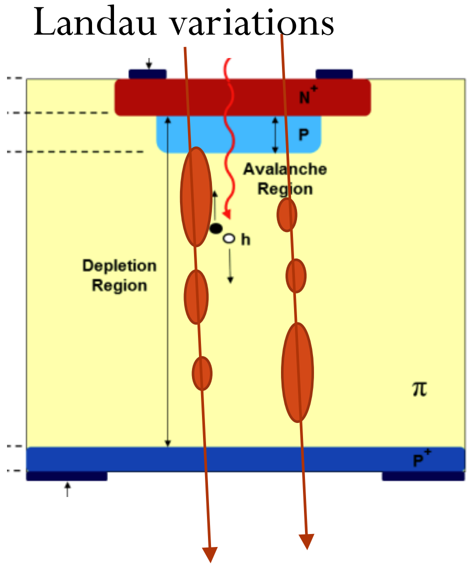


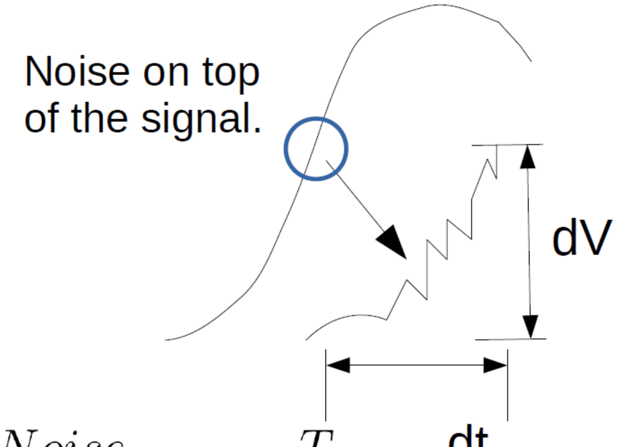
X-Y u quark motion
For proton traveling in Z

Time resolution









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

Sensor time resolution main terms

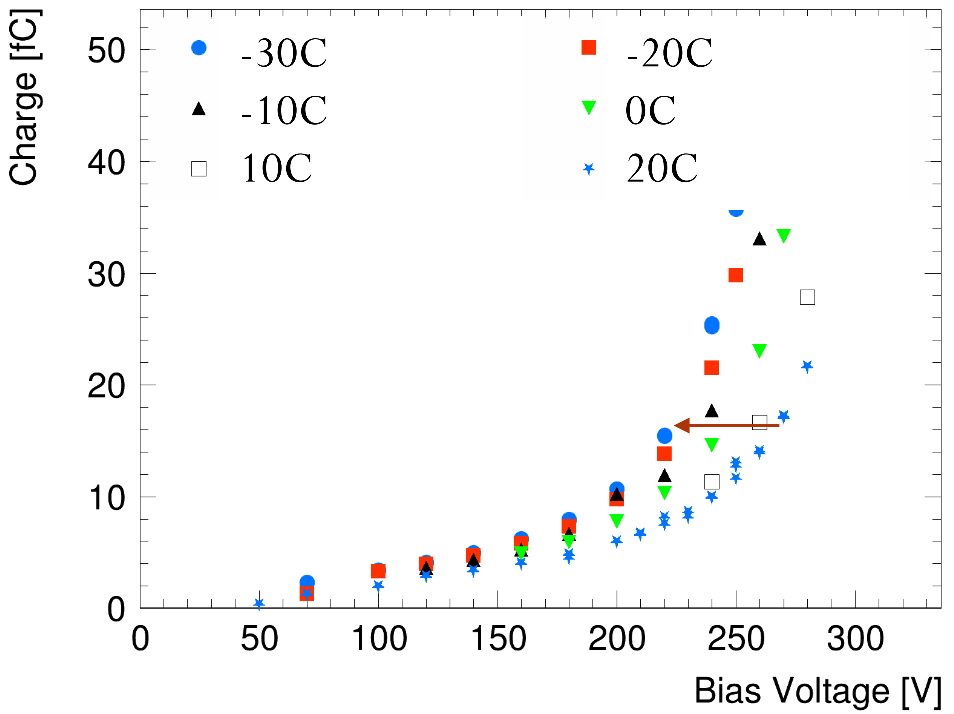
$$\sigma^2_{timing} = \sigma^2_{time\,walk} + \sigma^2_{Landau\,noise} + \sigma^2_{Jitter} + \sigma^2_{TDC}$$

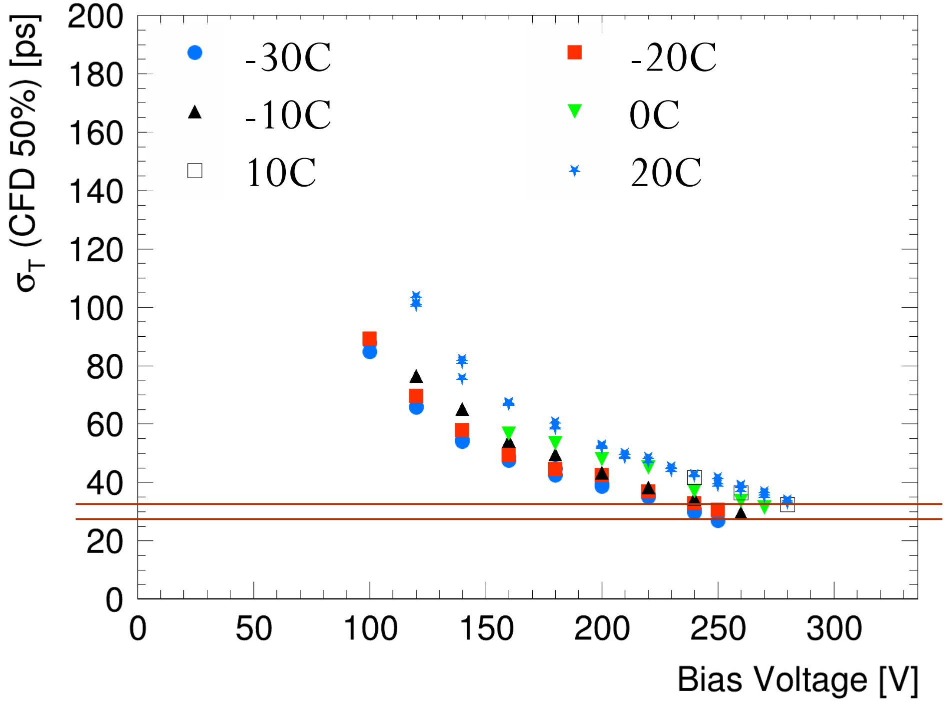
- **Time walk**:
  - Minimized by correcting the time of arrival using pulse width or pulse height (e.g., use 50% of the pulse as ToF)
- **Jitter**: from electronics
  - Proportional to $^1/_{\frac{dV}{dt}}$
  - Reduced by increasing S/N ratio with gain
- **TDC term**: from digitization clock (electronics)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

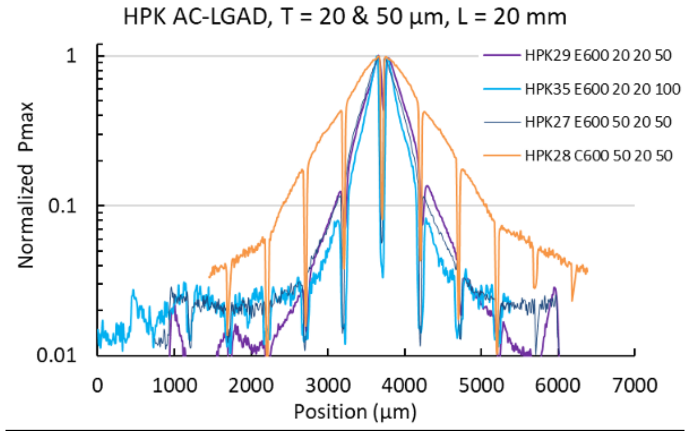


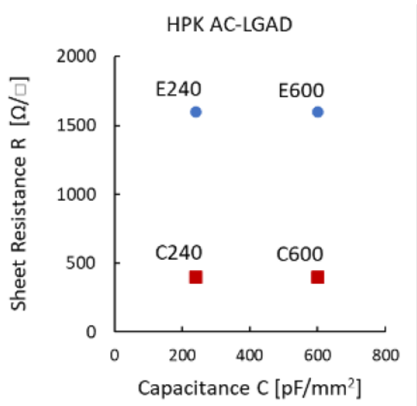


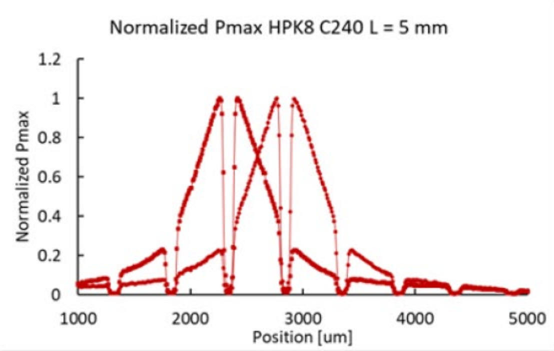
Student: J. Ding

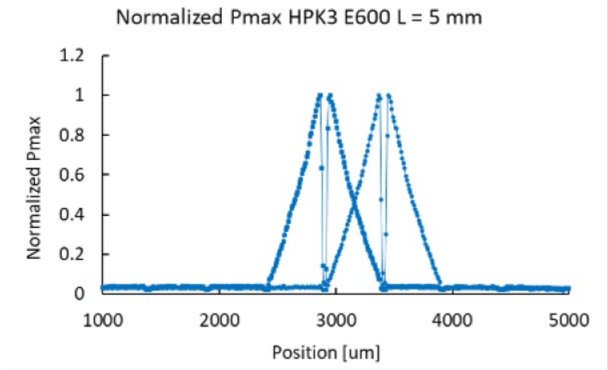
HPK 2023 lab studies

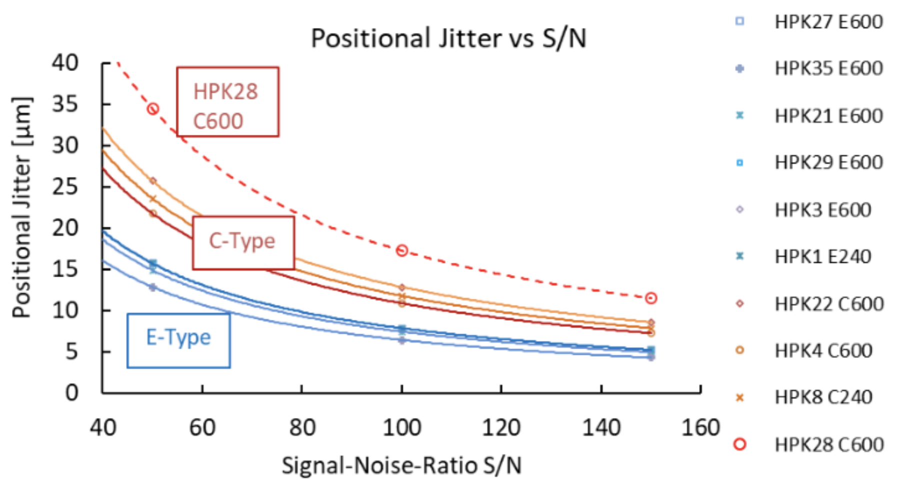
- Previous lab results from 2023 HPK production
  - https://doi.org/10.1016/j.nima.2024.169478
  - Based on laser TCT studies
- Conclusions:
  - Type E strips (more resistive) perform much better, oxide thickness has less impact but thinner is better.
  - Long strip length degrades both signal (rise time, Pmax) and has worse charge sharing. 1cm length was best compromise.
  - Another issue is the input capacitance which degrade the ASIC performance
    - 20um strips were abandoned for now due to decreased signal and increased input capacitance
- Pitch of 500um → ~20um hit precision (<5% of pitch)





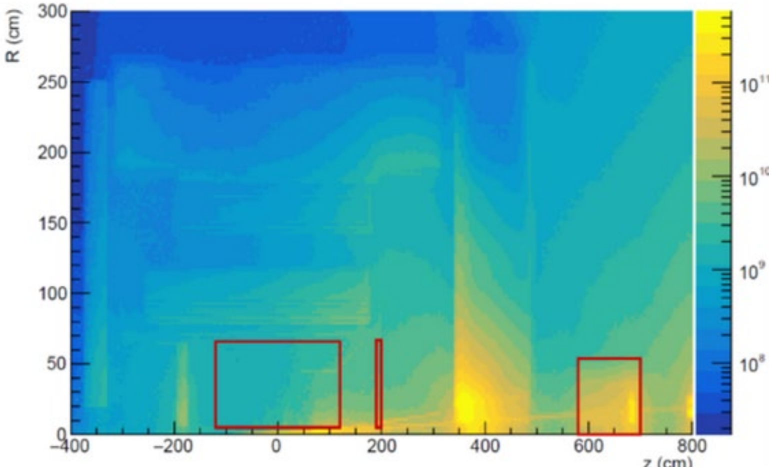






Radiation levels at ePIC

- 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.

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

Pixels

Strips W2

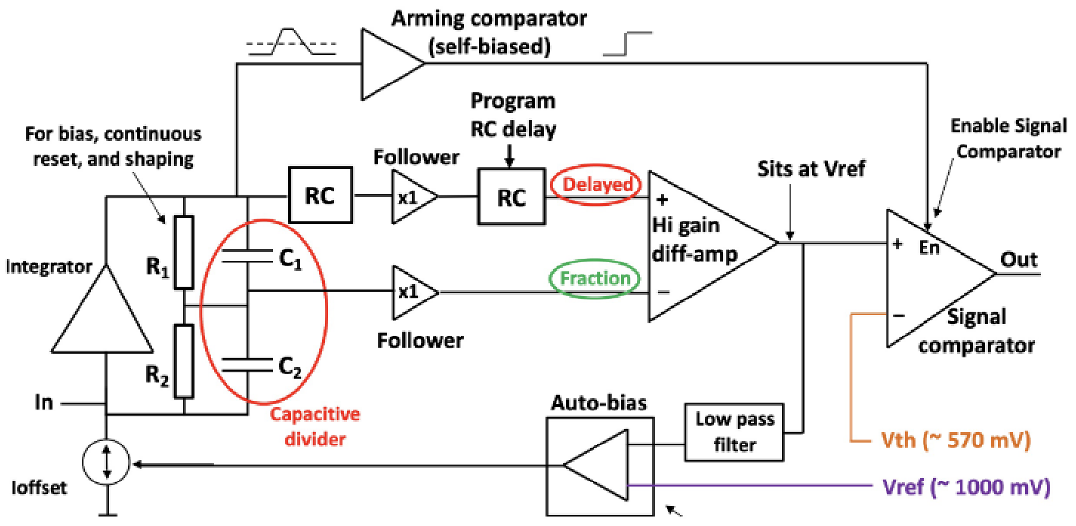
Fluence	0.5 cm	1 cm	2 cm
1.00E+14	52	52	
5.00E+14	44		48
1.00E+15		38	42

Strips W5

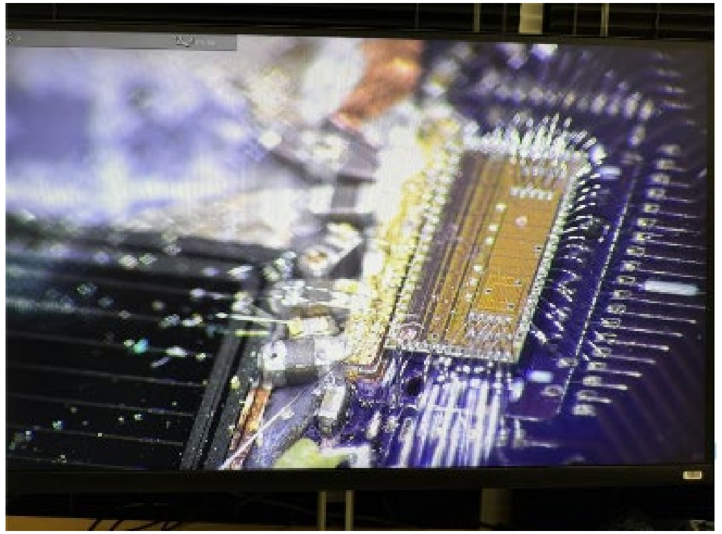
Fluence	0.5 cm	1 cm	2 cm
1.00E+12	54	54	
1.00E+13	42		54
1.00E+14		52	53

FCFD

- FCFDv1 – 6 channel received Jan 2024.
- Tested at FNAL in May/June 2024, AC & DC-LGAD (1 mm):
  - DC-LGAD @ 50 ps; AC-LGAD @ 52 ps
  - AC-LGAD should get ~35 ps with improved comparator.
- FCFDv1.1 – TSMC May 2025; DESY tests in July 2025.



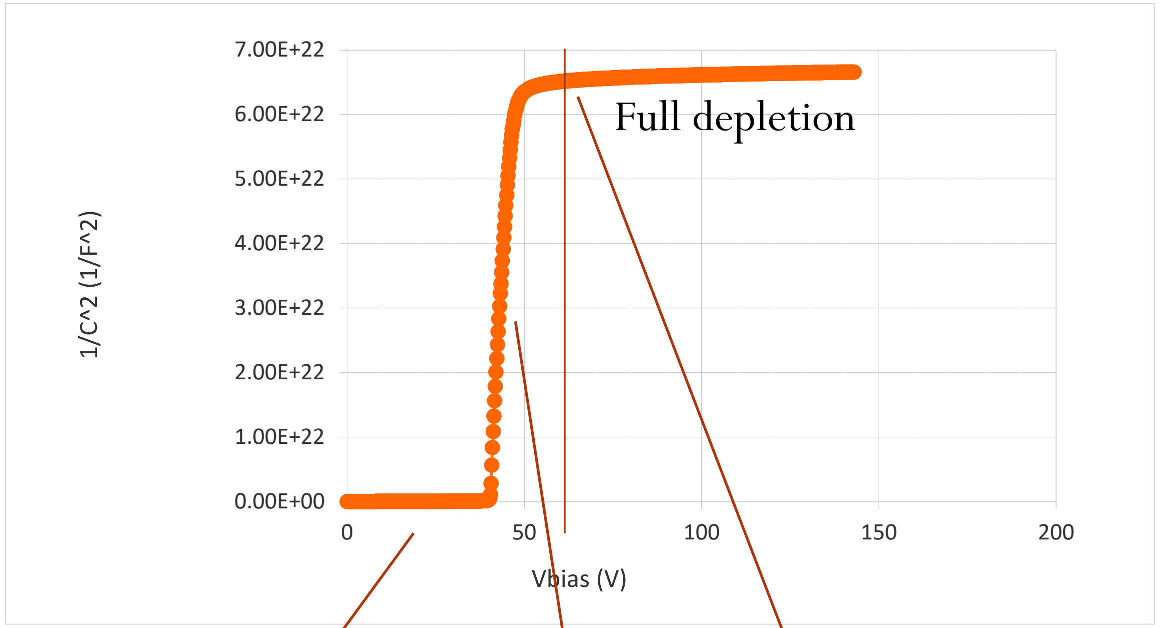
- 128 ch strip readout
- 65 nm CMOS
- Constant Fraction Discriminator
- Plus TDC, ADC, interfaces
- Cdin: <15 pF
- Dynamic Range: 5-40 fC
- Timing: 10-30 ps
- Links: ~Gbps, multiple
- Radiation tolerant.

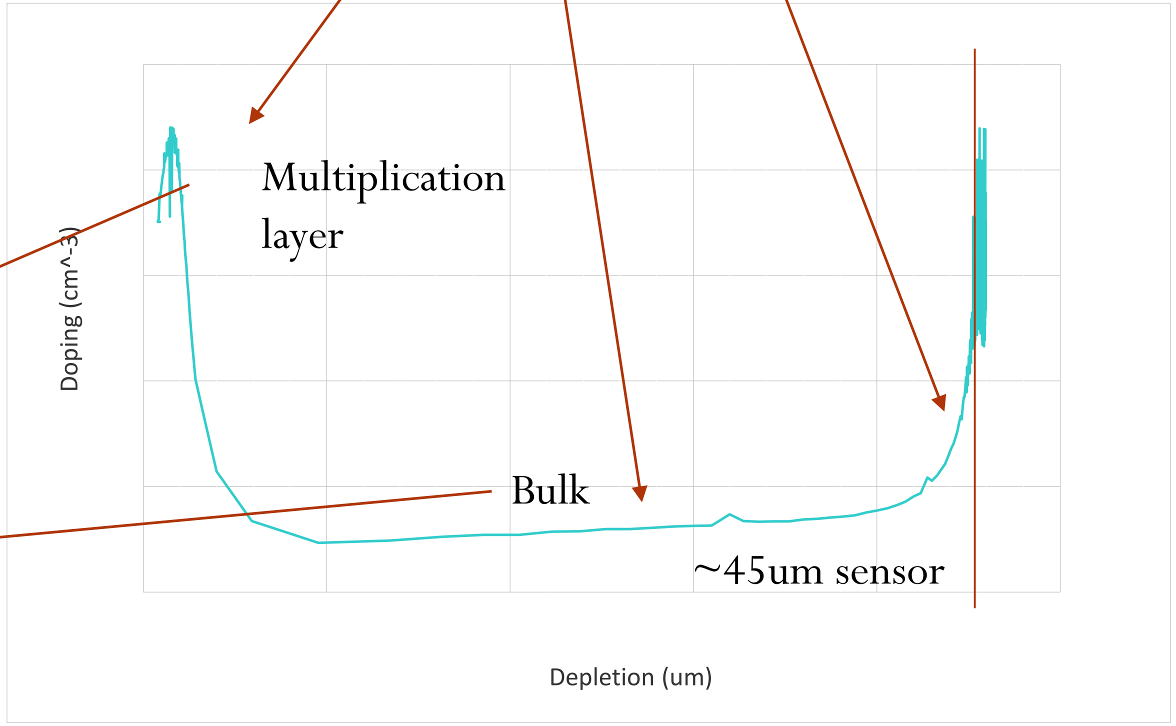


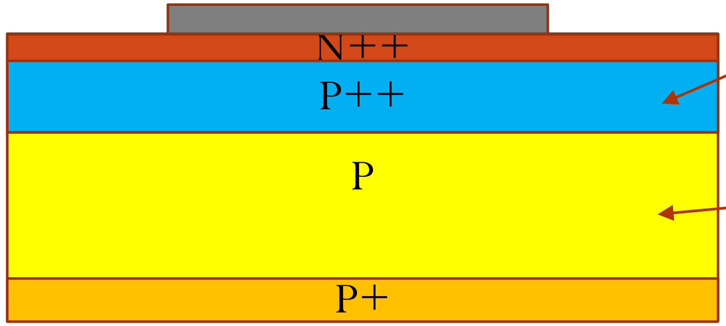
- FCFDv1 (6 ch): FY23 – FY24
- FCFDv1.1 (6ch): May 2025
- FCFDv2: FY25 – FY26
- FCFDv3: FY27 Production

Sensor testing – IV/CV

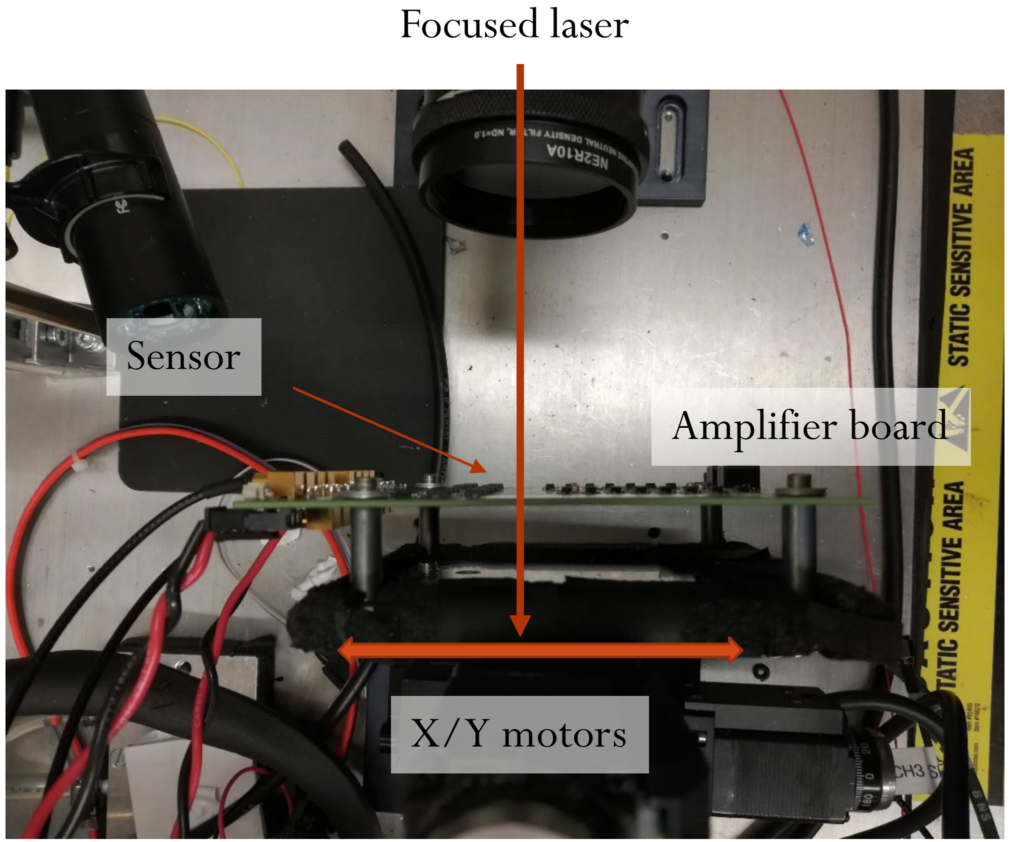
- Capacitance over voltage (CV)
  - Study doping concentration profile and full depletion of the sensor
  - Doping profile can be extracted from the $1/C^2$ derivative
- Study of the “foot” for LGADs on $1/C^2$
  - $1/C^2$ is flat until depletion of multiplication layer because of the high doping concentration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







Sensor testing –Laser TCT setup

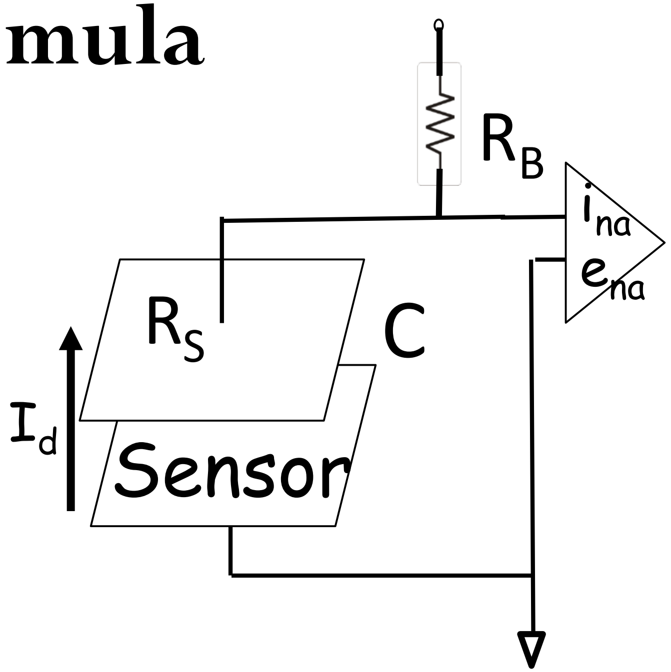


- Sensors are mounted on a multi-channel analog amplifier board with bandwidth ~1 GHz
  - Response is readout by 2 GHz/20 Gs oscilloscope
- **IR laser (1064 nm)** mimics charge deposit of a Minimum Ionizing Particle (MiP)
  - Focused laser beam with spot width ~20 um
- Amplifier board is mounted on X/Y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

Readout noise master formula

Define some quantities that are associated with sources of **readout noise**:

C = Sensor capacitance
R_S = electrode resistance
i_{na} = amplifier current noise
e_{na} = amplifier voltage noise
R_B = bias resistance
I_d = Sensor leakage current
4kT = temperature term



Noise level in equivalent electrons

- Strictly speaking, applies to "lumped elements" (separate C, R_S)

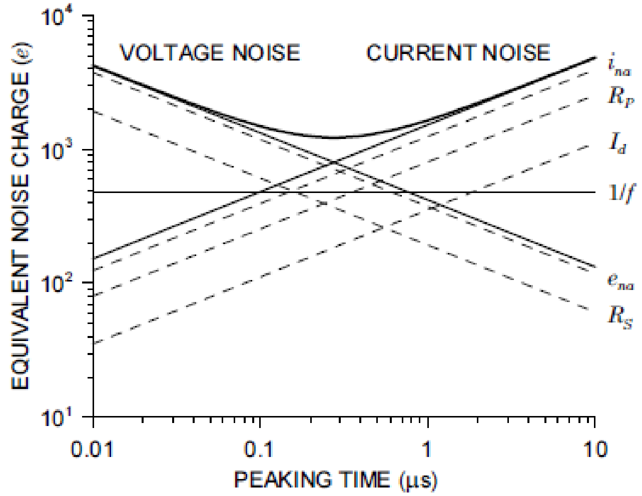
General rule of thumb: signal-to-noise of 12:1 for efficient operation

Signal-shape parameters (of order 1)

Noise current sources | Noise voltage sources

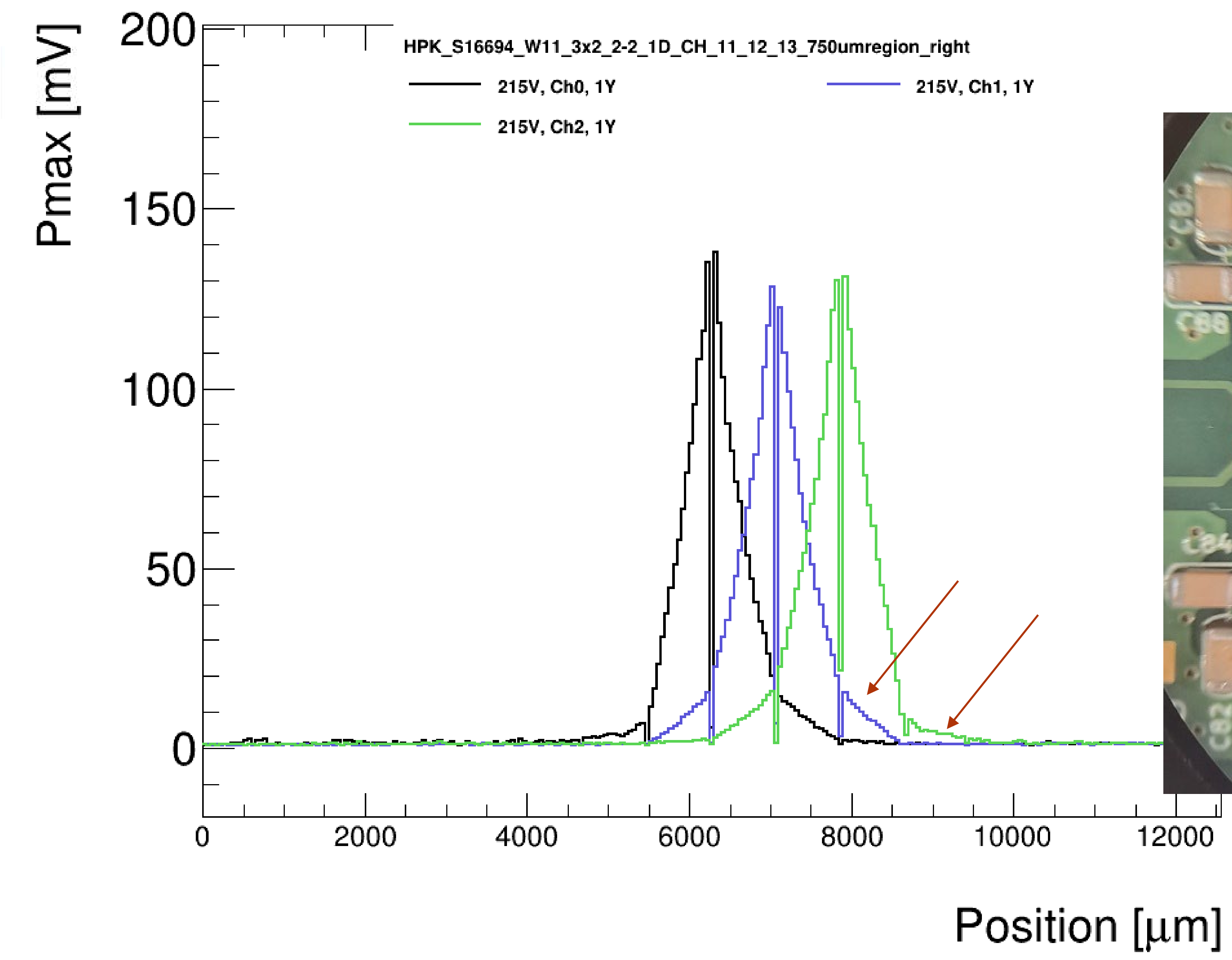
$$Q^2 = \boxed{F_i \tau \left(2eI_d + \frac{4kT}{R_B} + i_{na}^2\right)} + \boxed{\frac{F_v C^2}{\tau}\left(4kTR_s + e_{na}^2\right)}$$

Amplifier shaping time (1/Bandwidth)

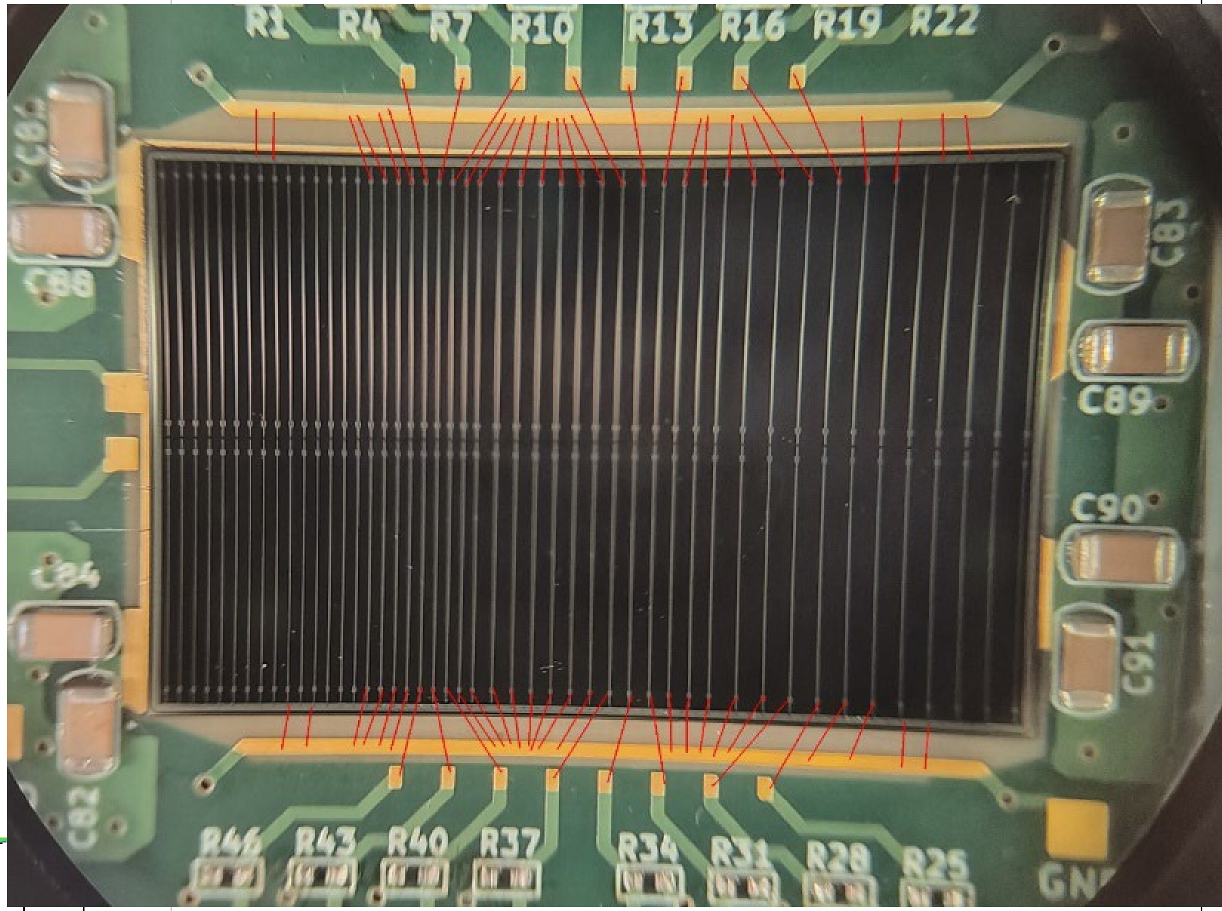


(For a particular set of parameters)

(F_v/τ) C^2 e^2_{na} → Beware of sensor capacitance, esp. for fast signals!



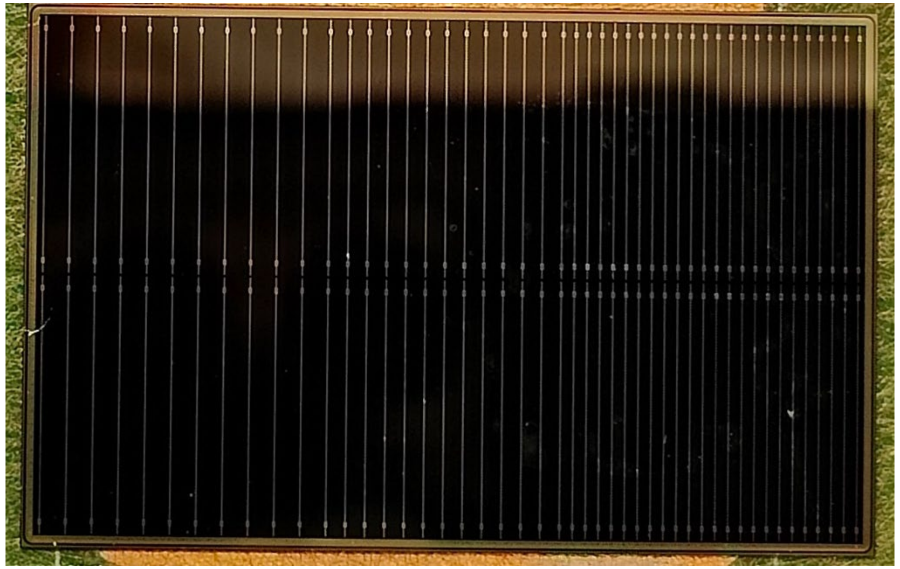
HPK_S16694_W11_3x2_2-2_1D_CH_11_12_13_750umregion_right
215V, Ch0, 1Y
215V, Ch1, 1Y
215V, Ch2, 1Y
Pmax [mV]
Position [µm]

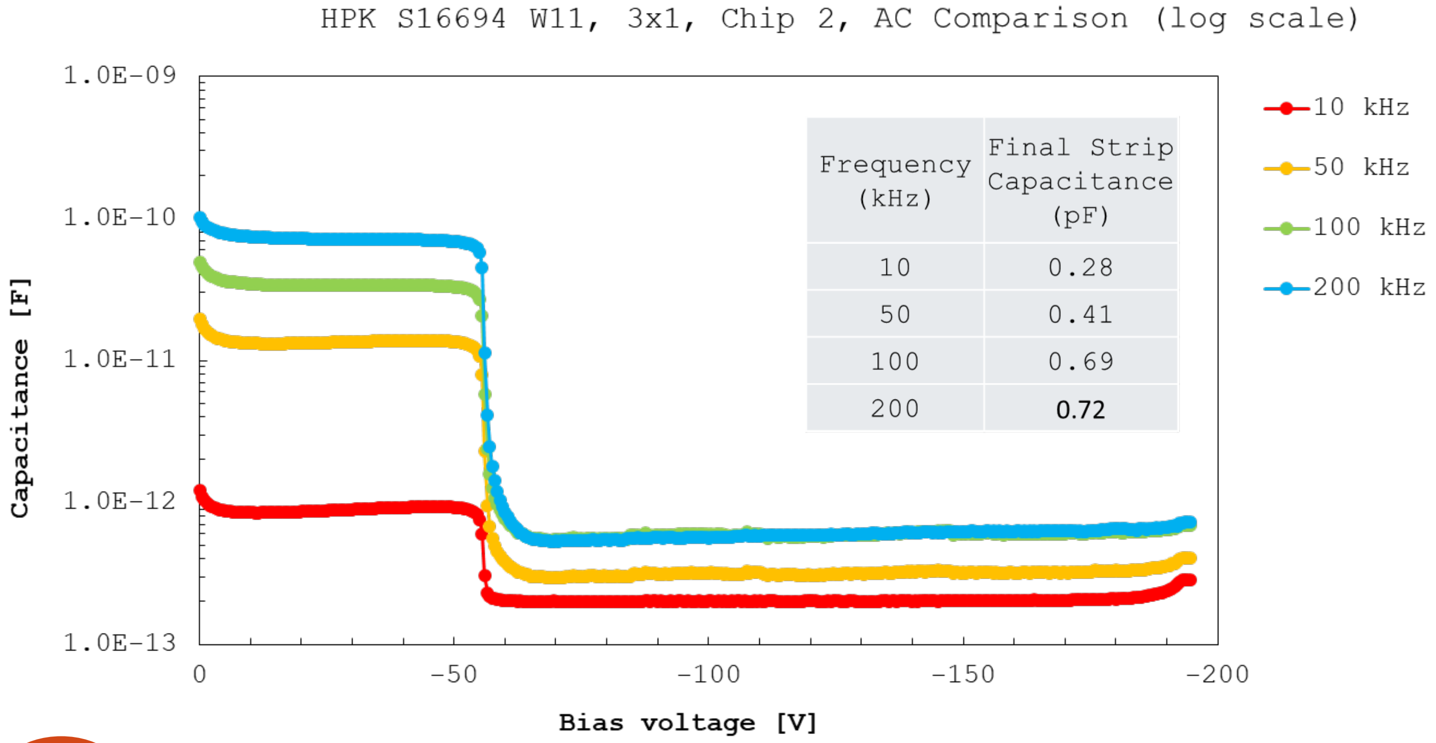


New HPK production

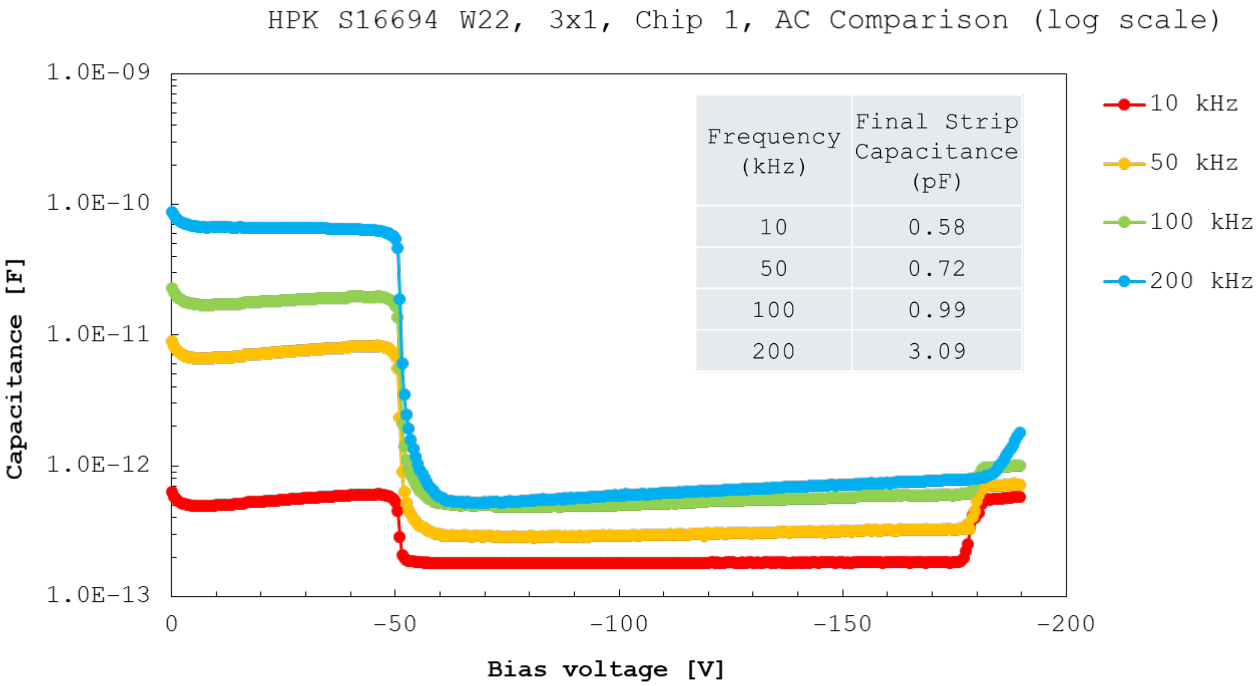
- Capacitance of AC strips with backside measurements, test on edge strip near N+ connection
- As always it's tricky to pinpoint a number as result vary wildly with frequency
- Final capacitance of the order of few pF for both wafers
  - This seems suspiciously low, studies ongoing

Full sensors





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

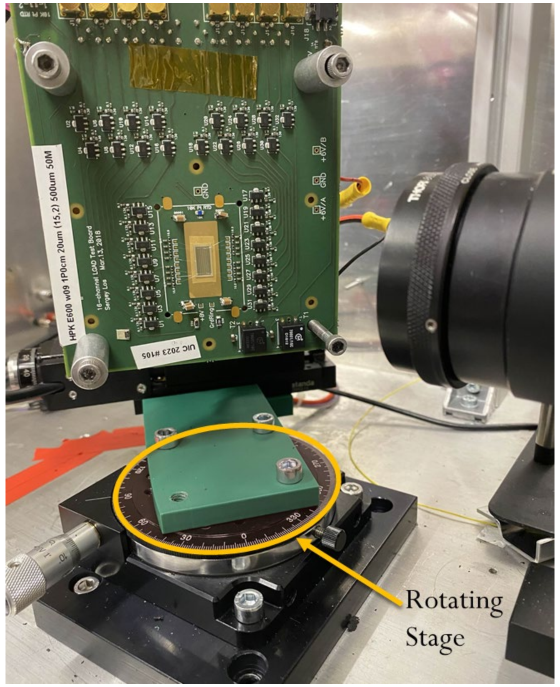


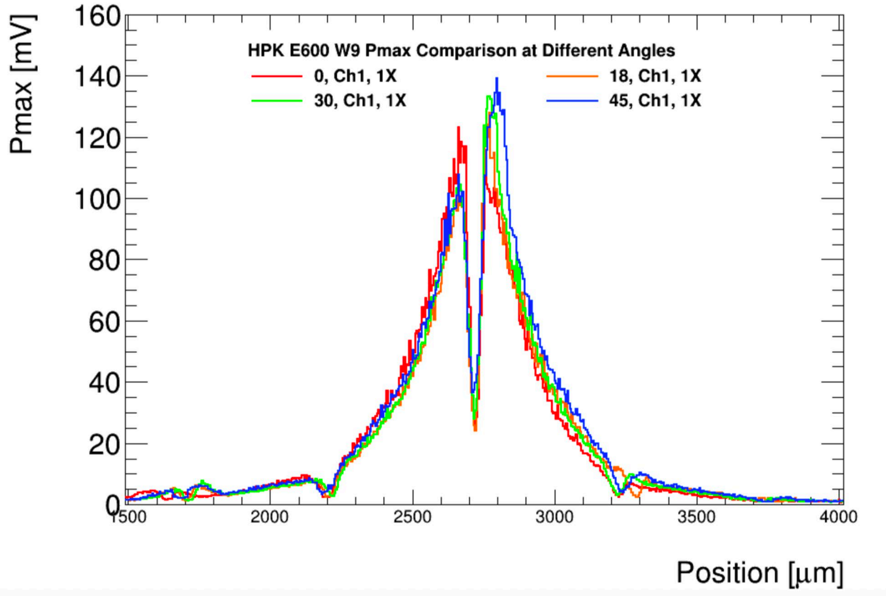
Frequency (kHz)	Final Strip Capacitance (pF)
10	0.58
50	0.72
100	0.99
200	3.09

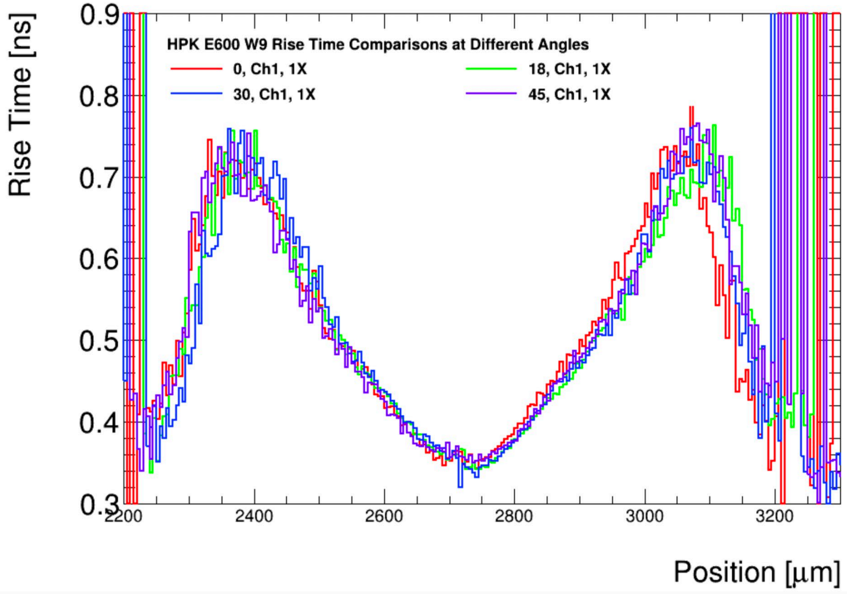
Student: J. Ding

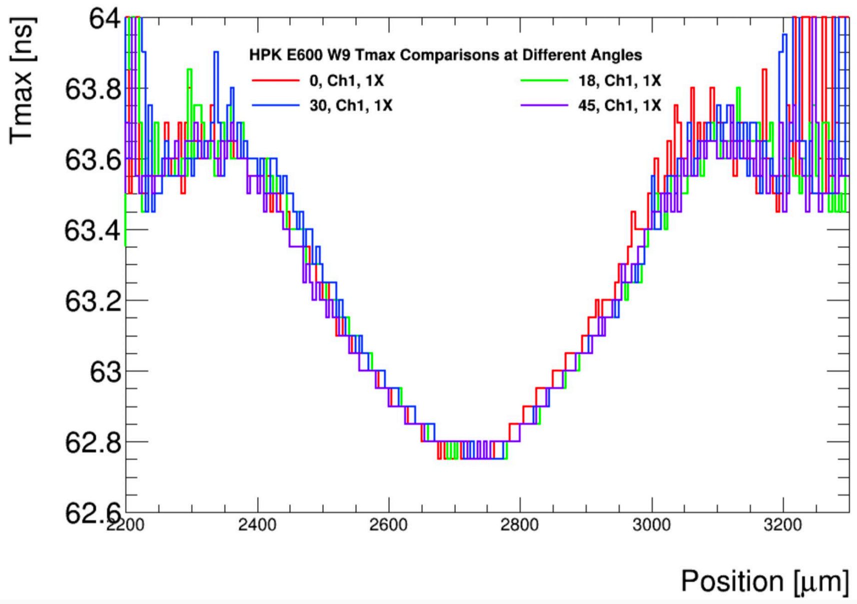
Angled charge injection

- 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



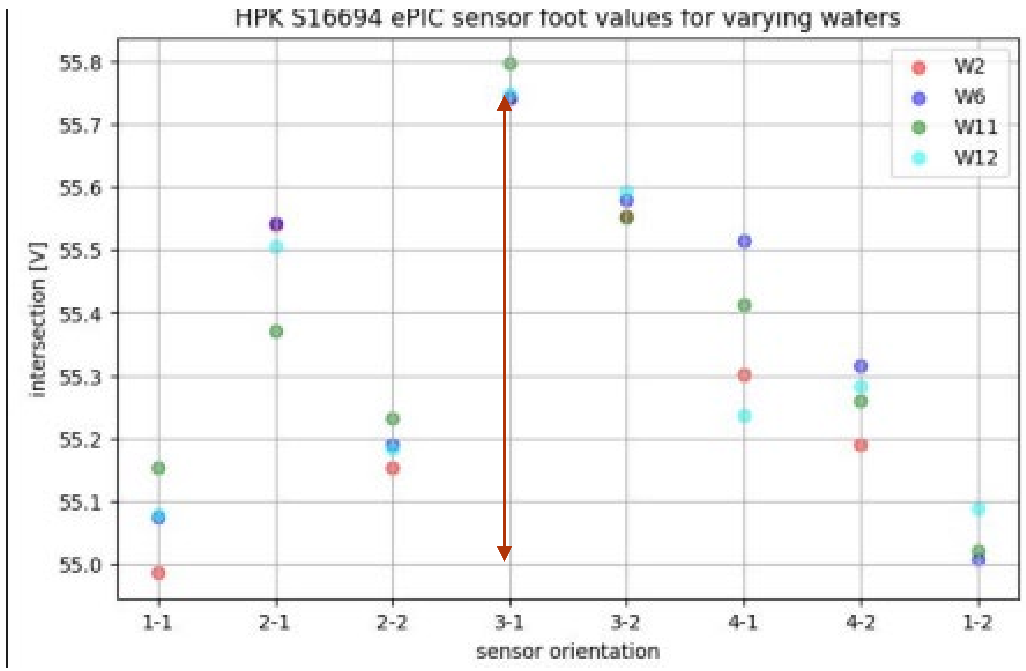






Student: J. Ding

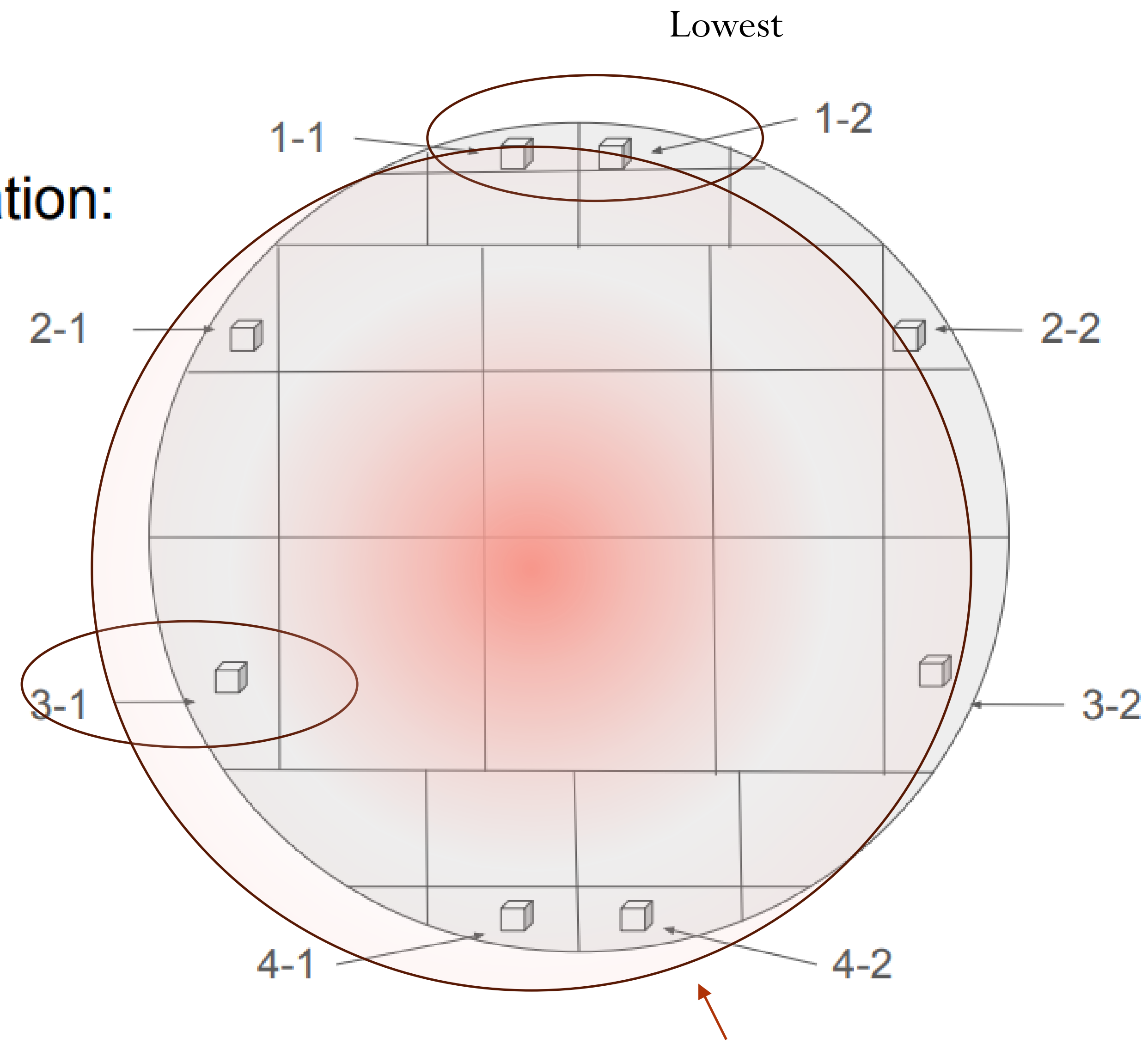
Gain test



Max variation ~1%

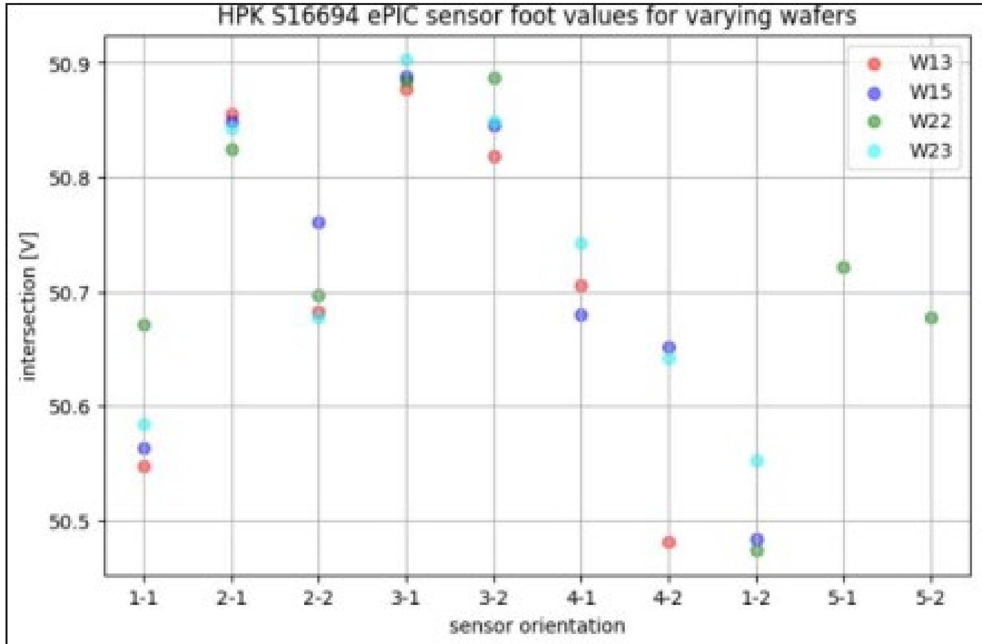
Very likely not an issue across the sensor

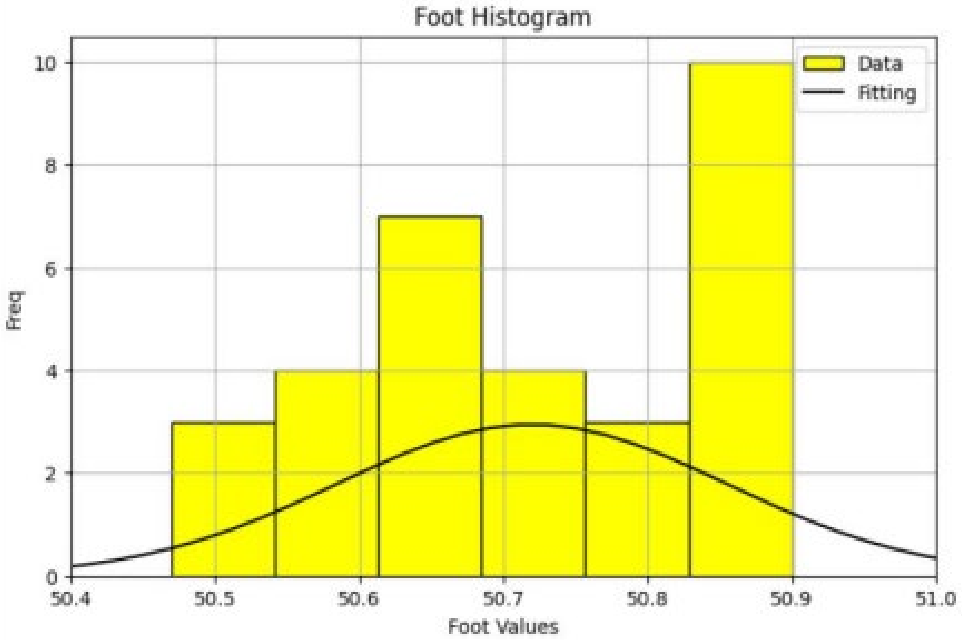
Might be valuable input to HPK

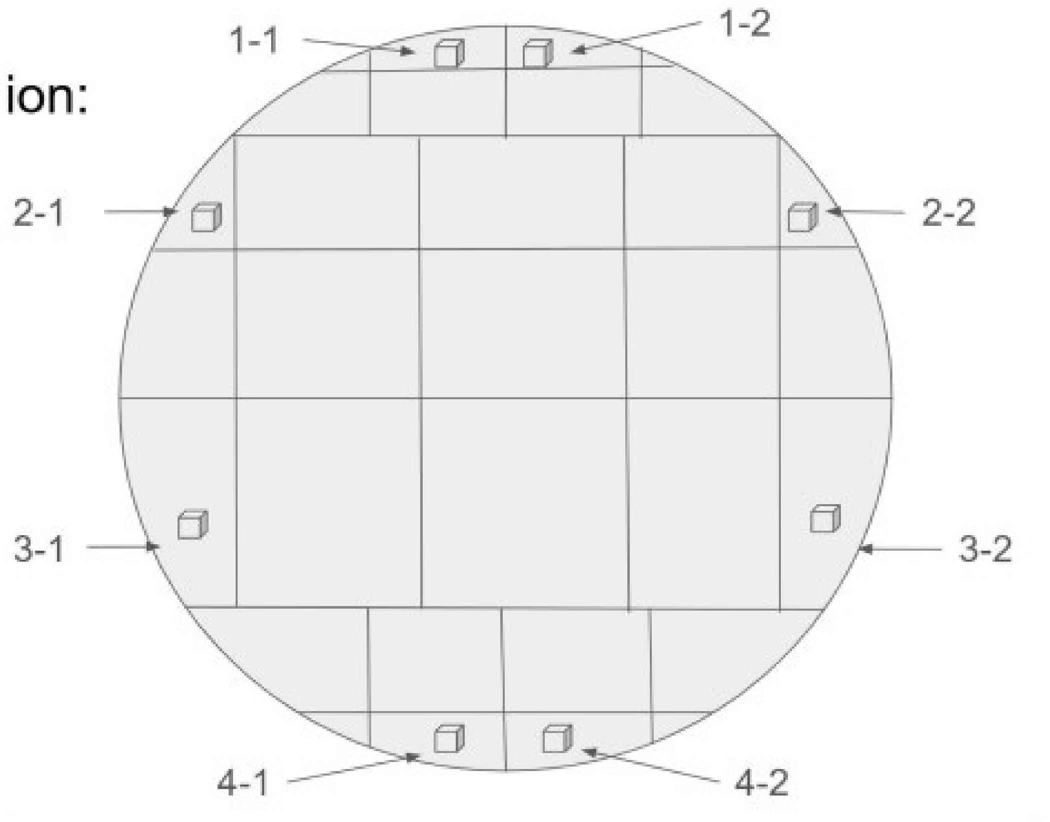


Gain test

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







Mean = 50.72
Sigma = 0.13