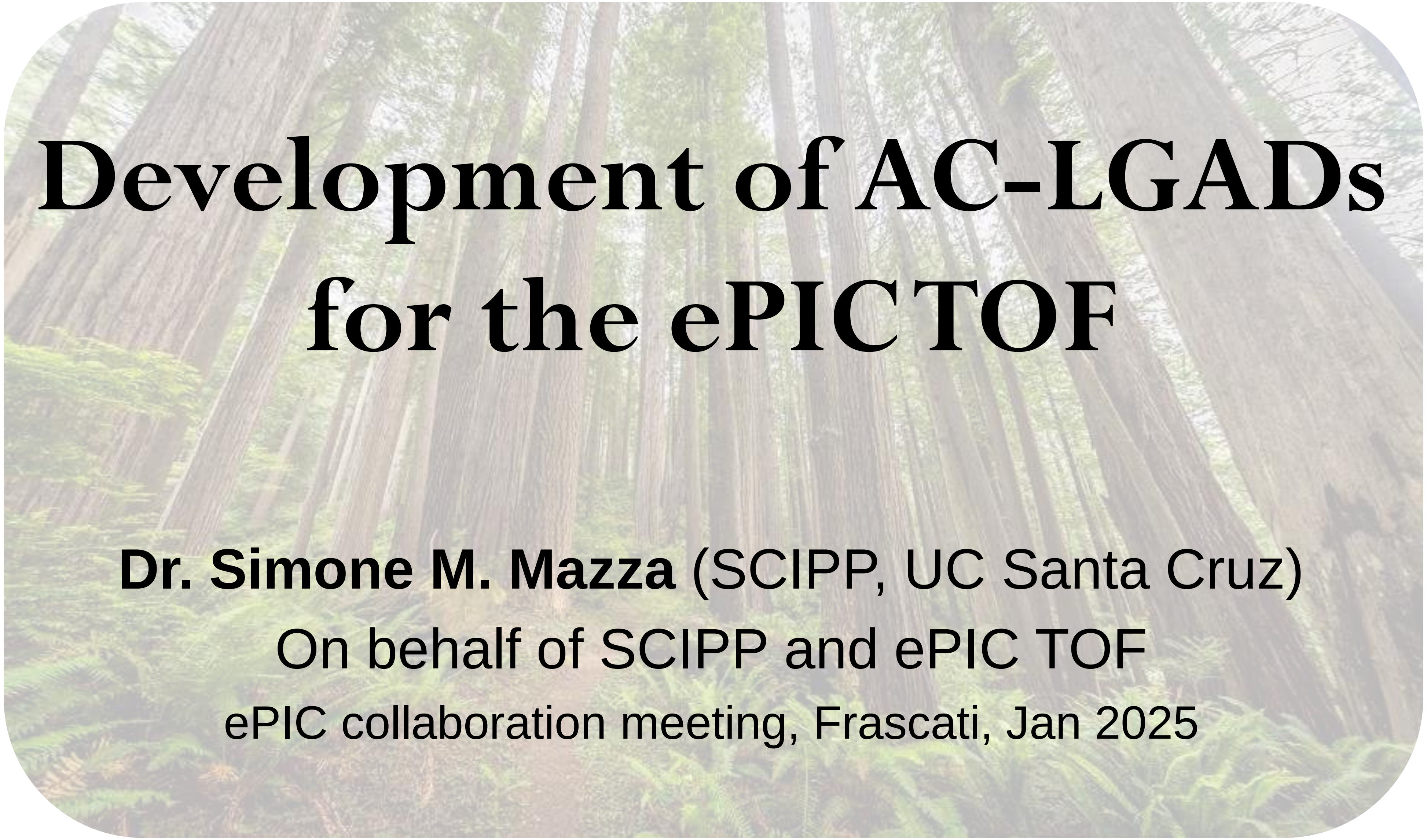


Development of AC-LGADs for the ePIC TOF

Dr. Simone M. Mazza (SCIPP, UC Santa Cruz)

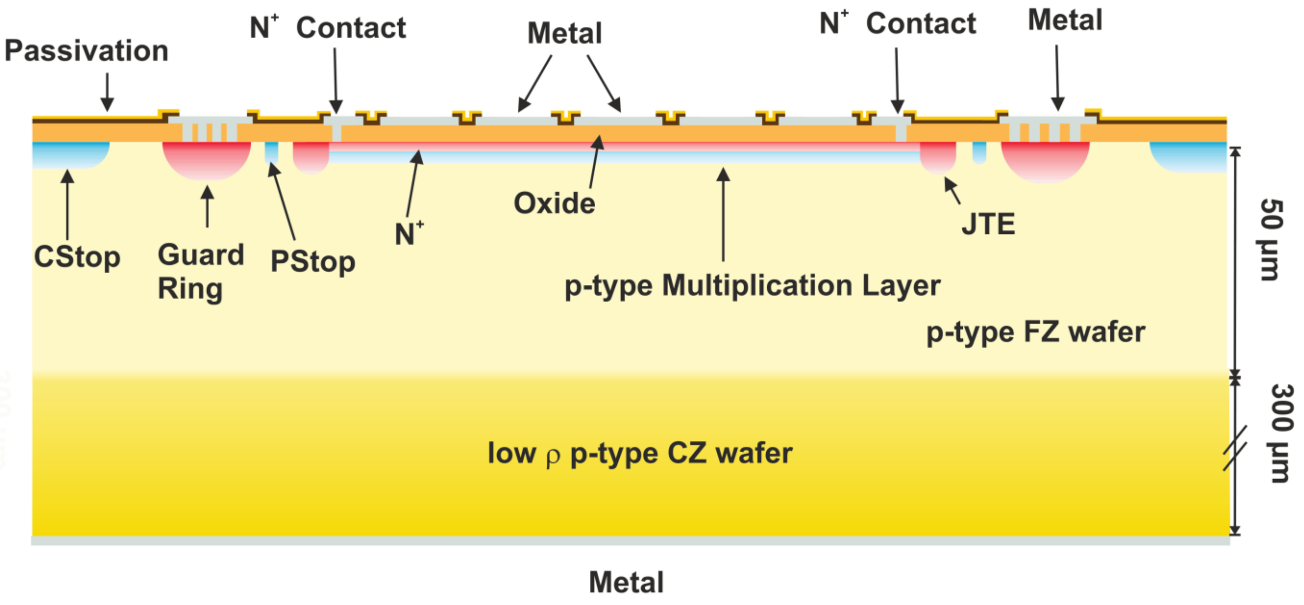
On behalf of SCIPP and ePIC TOF

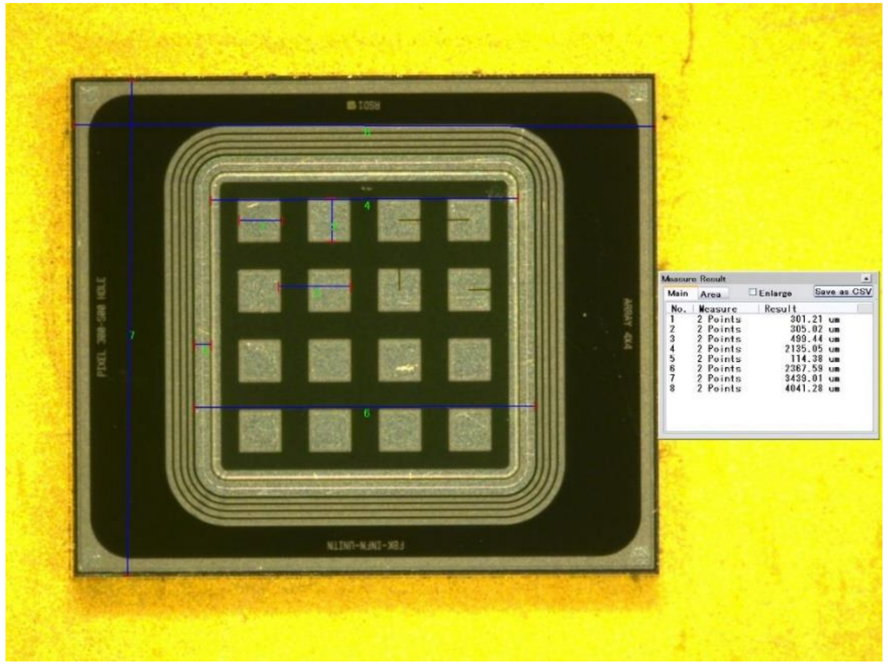
ePIC collaboration meeting, Frascati, Jan 2025

AC-LGADs

- Most advanced high-granularity prototype is AC coupled LGAD
  - Finer segmentation and easier implantation process
- Continuous sheets of multiplication layer and N+ layer
- **N+** layer is **resistive** and grounded through side connections
- **Readout pads are AC-coupled**
  - Insulator layer between N+ and pads
- Prototypes produced by CNM, FBK, BNL, HPK

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



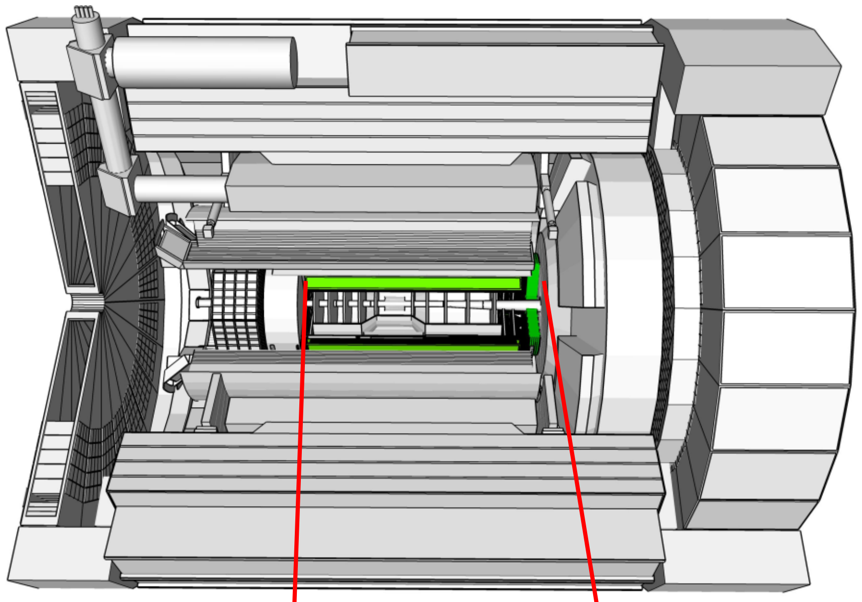


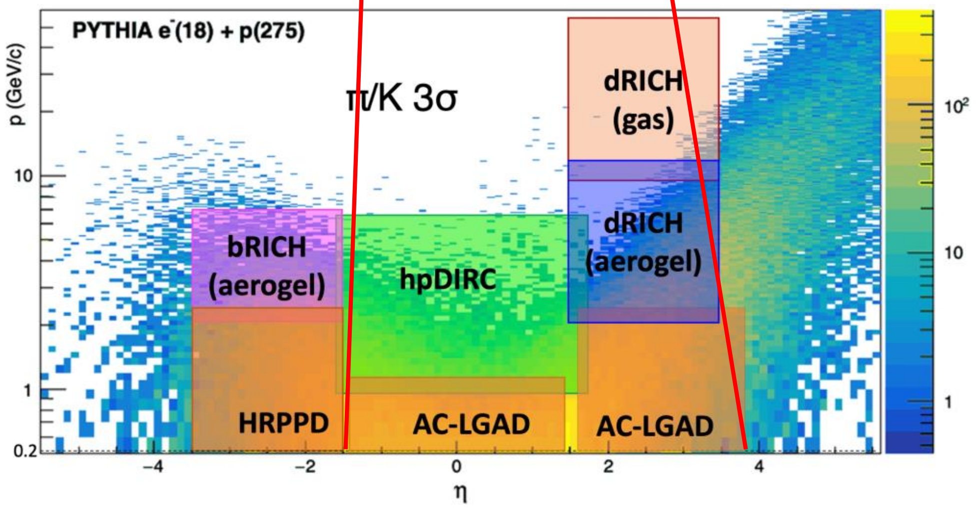
Measure Result

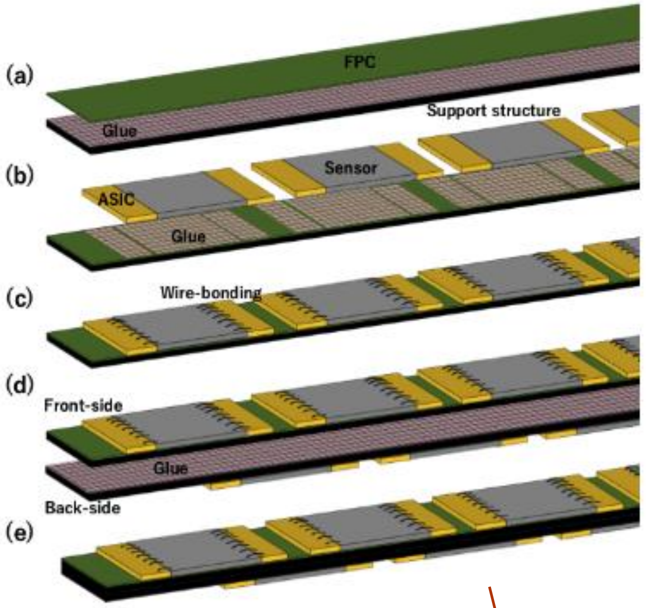
Main | Area | ☐ Enlarge | Save as CSV

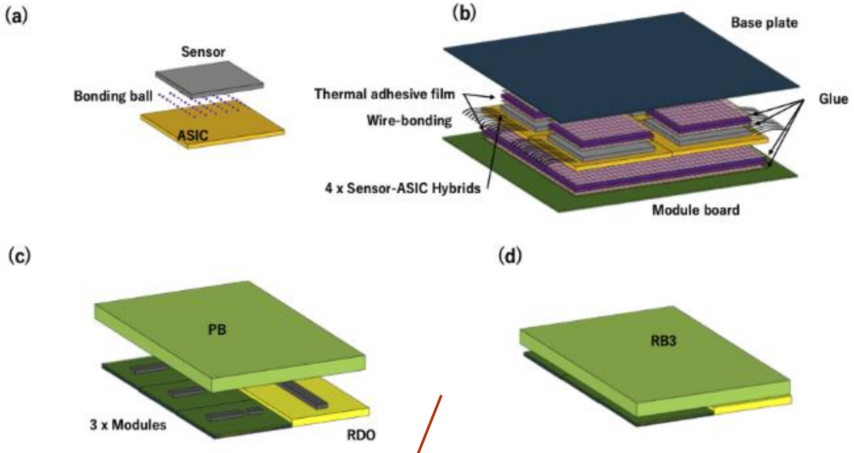
No.	Measure	Result
1	2 Points	301.21 um
2	2 Points	305.02 um
3	2 Points	499.44 um
4	2 Points	2135.05 um
5	2 Points	114.38 um
6	2 Points	2367.59 um
7	2 Points	3439.01 um
8	2 Points	4041.28 um

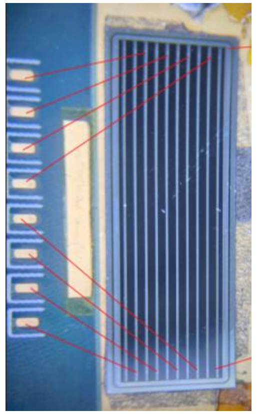
AC-LGAD TOF layout

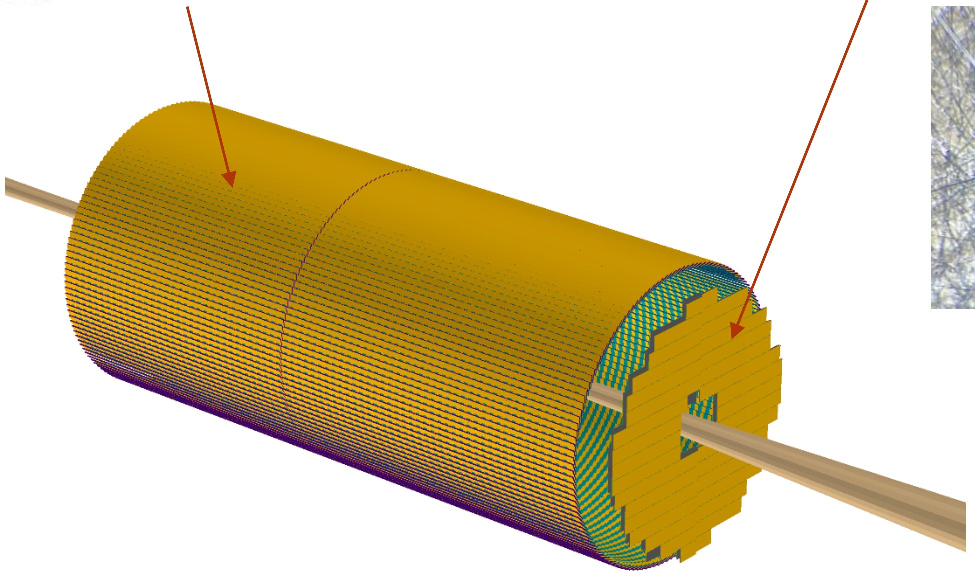


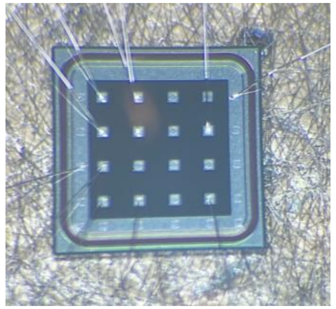






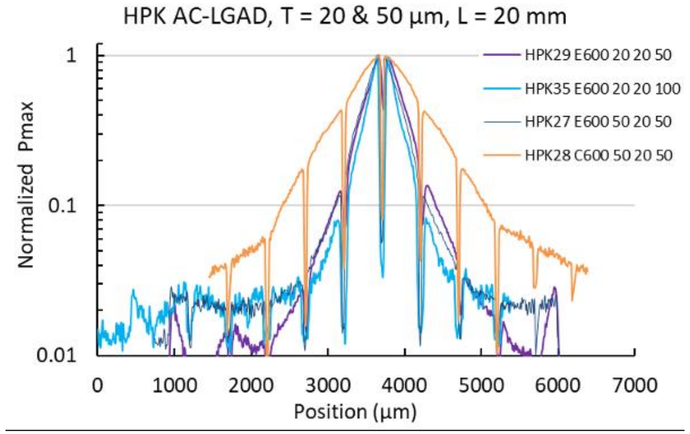


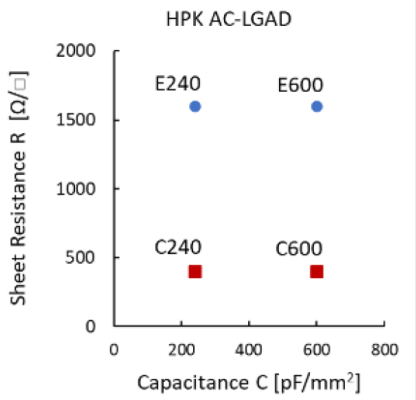


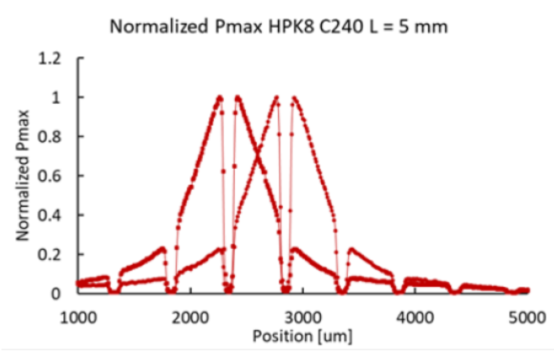


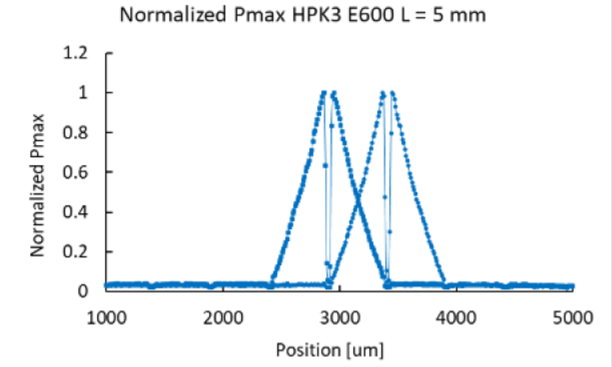
Previous Laboratory studies

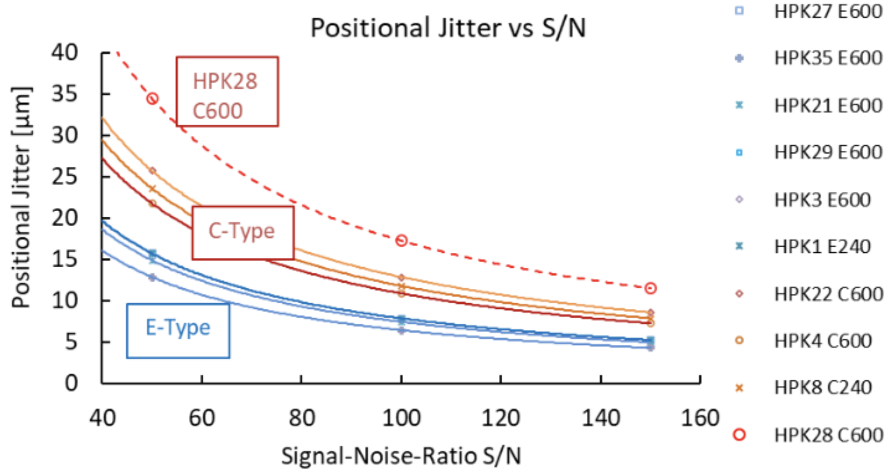
- Previous lab results from 2023 HPK production
  - https://doi.org/10.1016/j.nima.2024.169478
  - Base of laser TCT studies
- Conclusions:
  - Type E strips (more resistive) perform much better, oxide thickness has less impact but thinner is better.
  - Long strip length degrades both signal (rise time, Pmax) and has worse charge sharing. 1cm length was selected.
  - 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







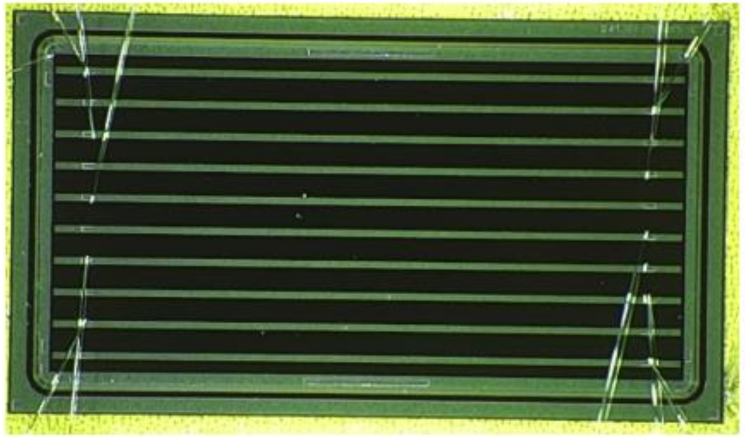


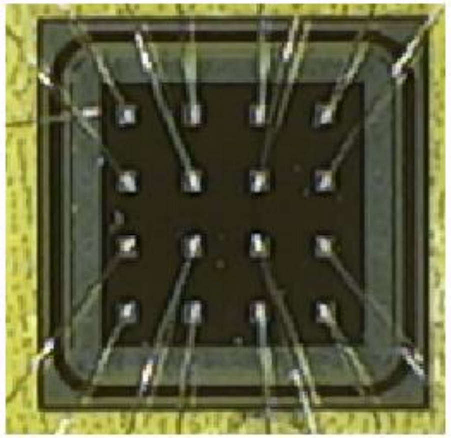


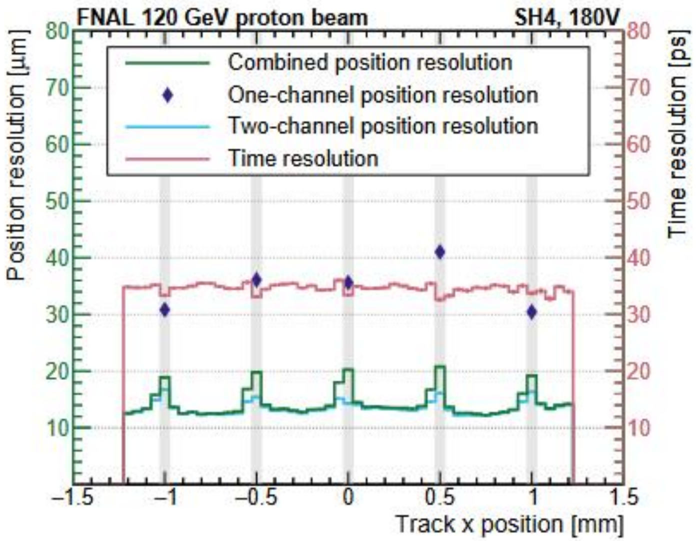
Previous FNAL test beam results

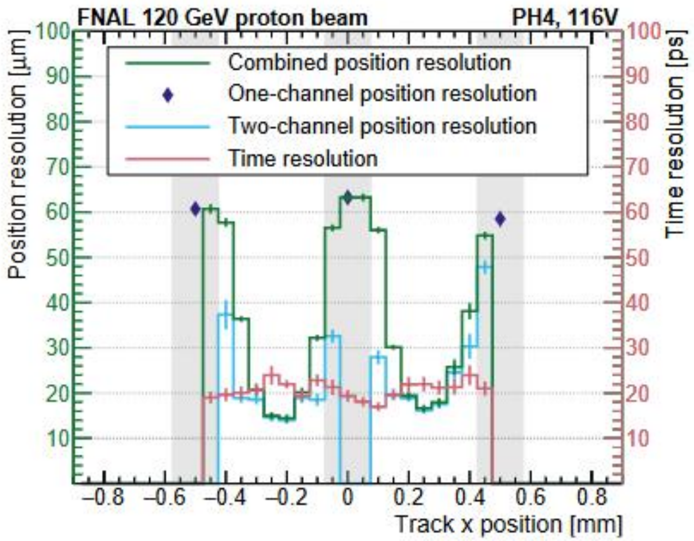
- Previous results from 2023 HPK production from the FNAL test beam
  - https://arxiv.org/abs/2407.09928

- Conclusions:
  - 50um strip detector 1cm long reach the 35ps time resolution requirement and have 10-20um position resolution
  - Pixel detector needs to have large pitch and small pixel size or position resolution is bad under metal, however this degrades S/N in between pixels.
    - Increasing pixel distance might help but could mean a large signal loss in between
    - Cross metal design is under investigation and showed promising results during the test beam and in the lab (see backup slides)
  - **Both pixel and strips have the required time resolution but current pixel design has shortfall in position resolution under metal**







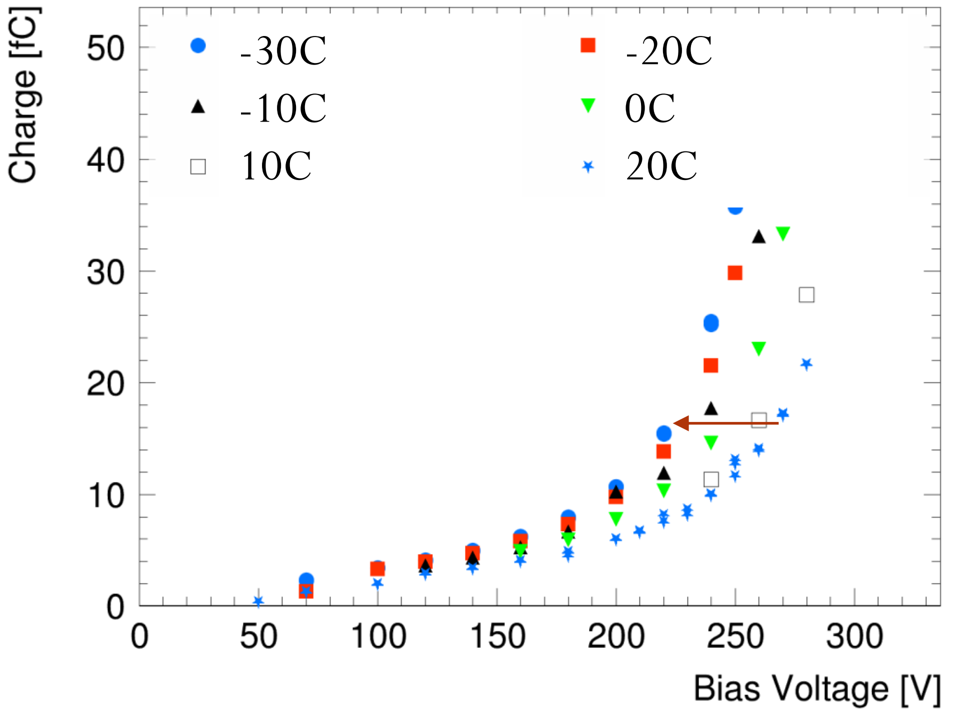


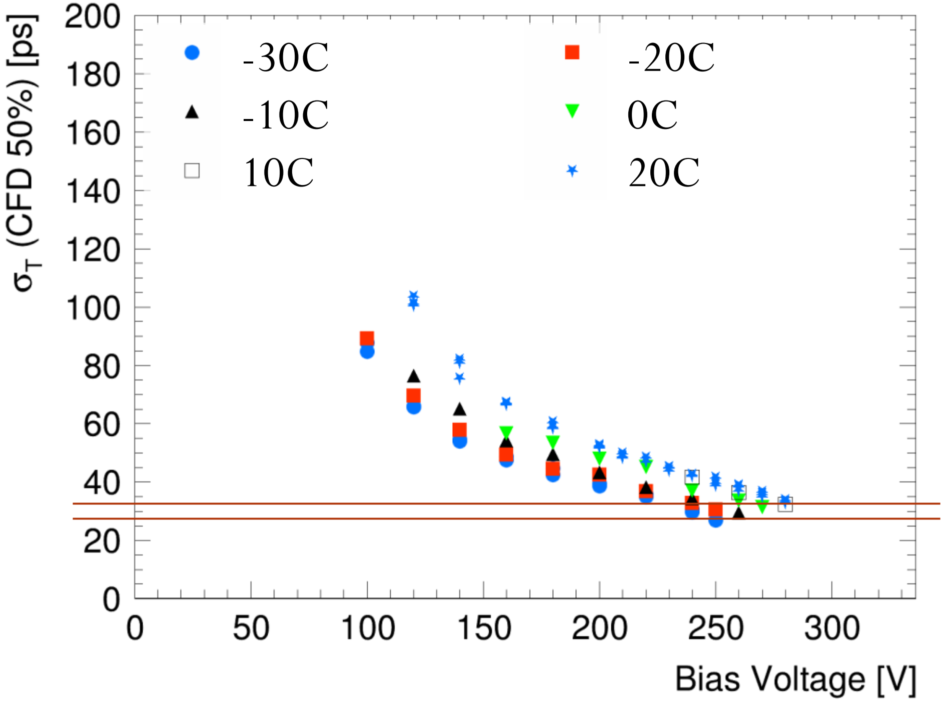
https://arxiv.org/abs/2407.09928

LGAD temperature dependence

- LGAD gain depends on temperature due to impact ionization dependence on 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, which is 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)

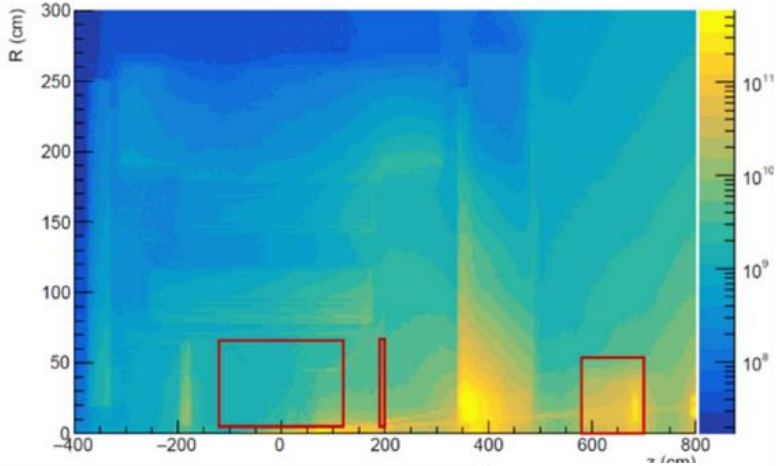


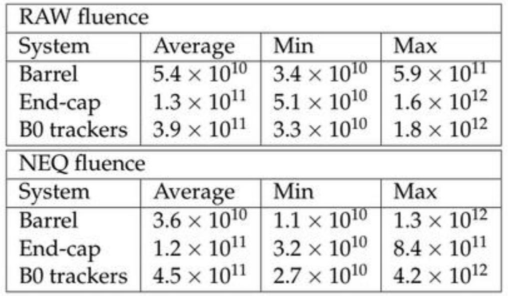


Student: J. Ding

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**
  - Focus on acceptor removal, gain layer doping deactivation
  - Relatively large-pad, conventional (DC-coupled) LGADs
- At the EIC: radiation levels will be much lower than at the LHC: under certain assumptions, sensors should receive < 5e12 cm^{-2} over their lifetime
- However, ePIC will feature AC-LGADs with resistive n^{+} layer, which may be susceptible to radiation damage by changes in the n^{+} electrode and the coupling dielectric
- HPK (and BNL) sensors were irradiated with reactor neutrons at JSI/Ljubljana and at FNAL ITA
  - Focus on E type and 50 µm thickness for strips – include 0.5, 1, 2 cm lengths
  - Focus on 150 µm pad size – include more wafers
- Total fluences between 1e12 and 1e15 Neq – some much higher than envisioned at the EIC over the full time of life, but better to have more margin, also taking into account the different doses especially in the forward high-η region
- **Thanks to G. Kranberger and I. Mandic for the JSI irradiation**
- **Thanks to S. Seidel and J. SI (UNM)**

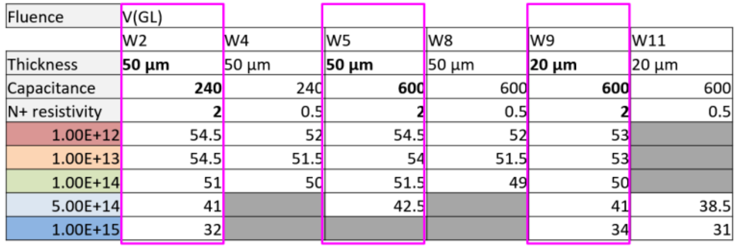




RAW fluence			
System	Average	Min	Max
Barrel	5.4×10^{10}	3.4×10^{10}	5.9×10^{11}
End-cap	1.3×10^{11}	5.1×10^{10}	1.6×10^{12}
B0 trackers	3.9×10^{11}	3.3×10^{10}	1.8×10^{12}

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}

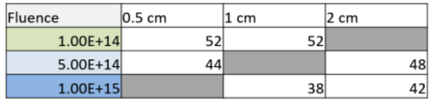
Table 8.2: RAW and NEQ fluence per system for the lifetime of the ePIC experiment, assuming 10 years of data taking at 50% time.



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

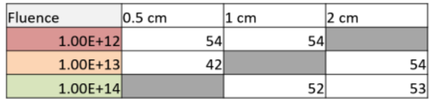
Pixels

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

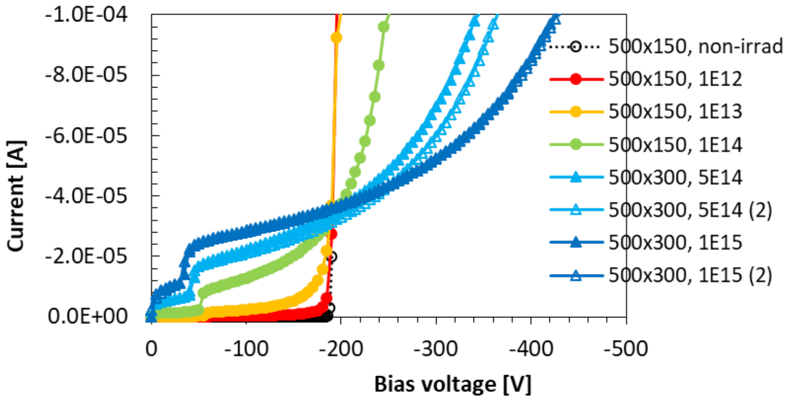


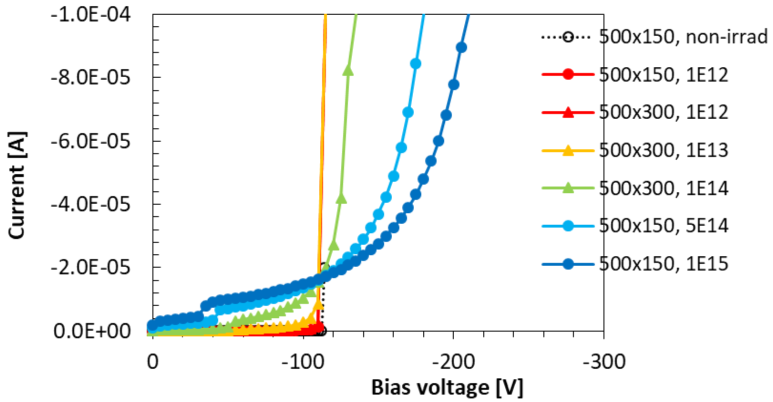
Fluence	0.5 cm	1 cm	2 cm
1.00E+12	54	54	
1.00E+13	42		54
1.00E+14		52	53

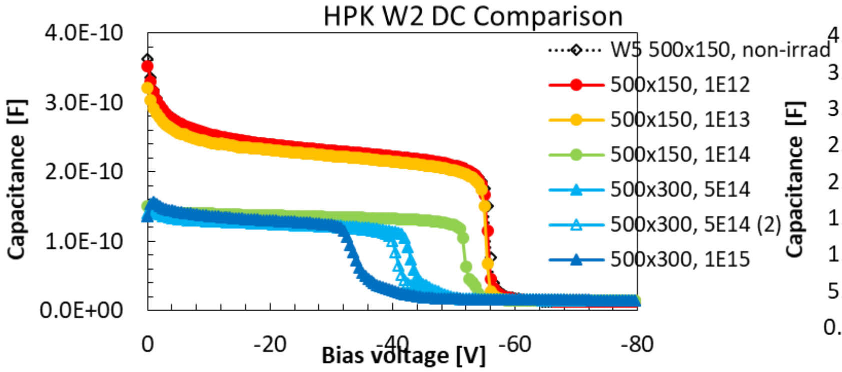
Pixels - Neutrons

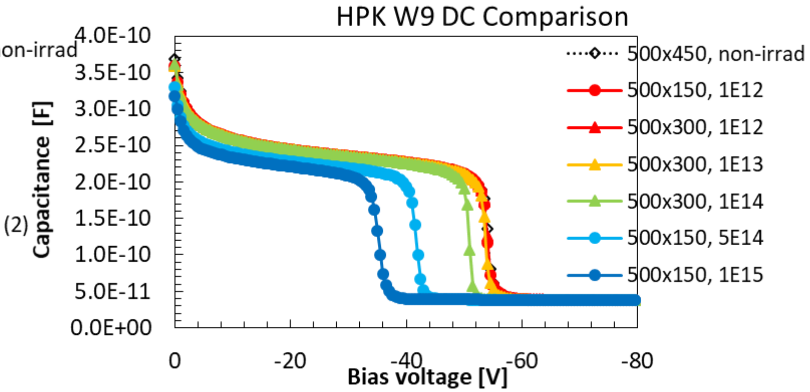
- Up to 1e13 Neq, no significant change in sensor properties
  - Shift in gain layer depletion voltage is recognizable even in IV measurement
  - Leakage current scales with bulk volume: 50 µm thick sensor has higher leakage currents and more prominent ‘step’ at gain layer depletion
- Breakdown voltage increases with fluence

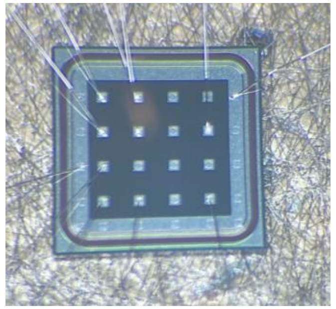
- Up to 1e13 Neq, no significant change in gain layer depletion voltage = gain layer active doping concentration
  - Shift in gain layer depletion voltage with fluence is very clear
- Behavior across wafers is consistent
  - Note higher full depletion capacitance for thinner sensor
  - More trapping / higher drift time in thicker bulk: affects capacitance before depletion

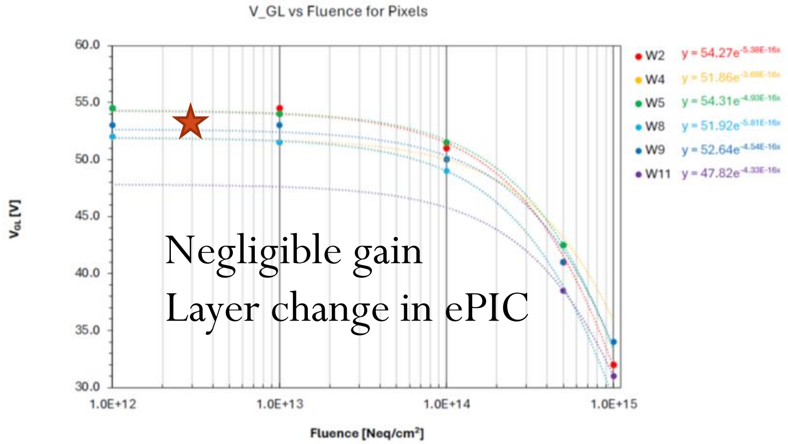












Negligible gain
Layer change in ePIC

Formula for Fit: $\mathbf{N_D = N_0 e^{-c\phi}}$

c factors:

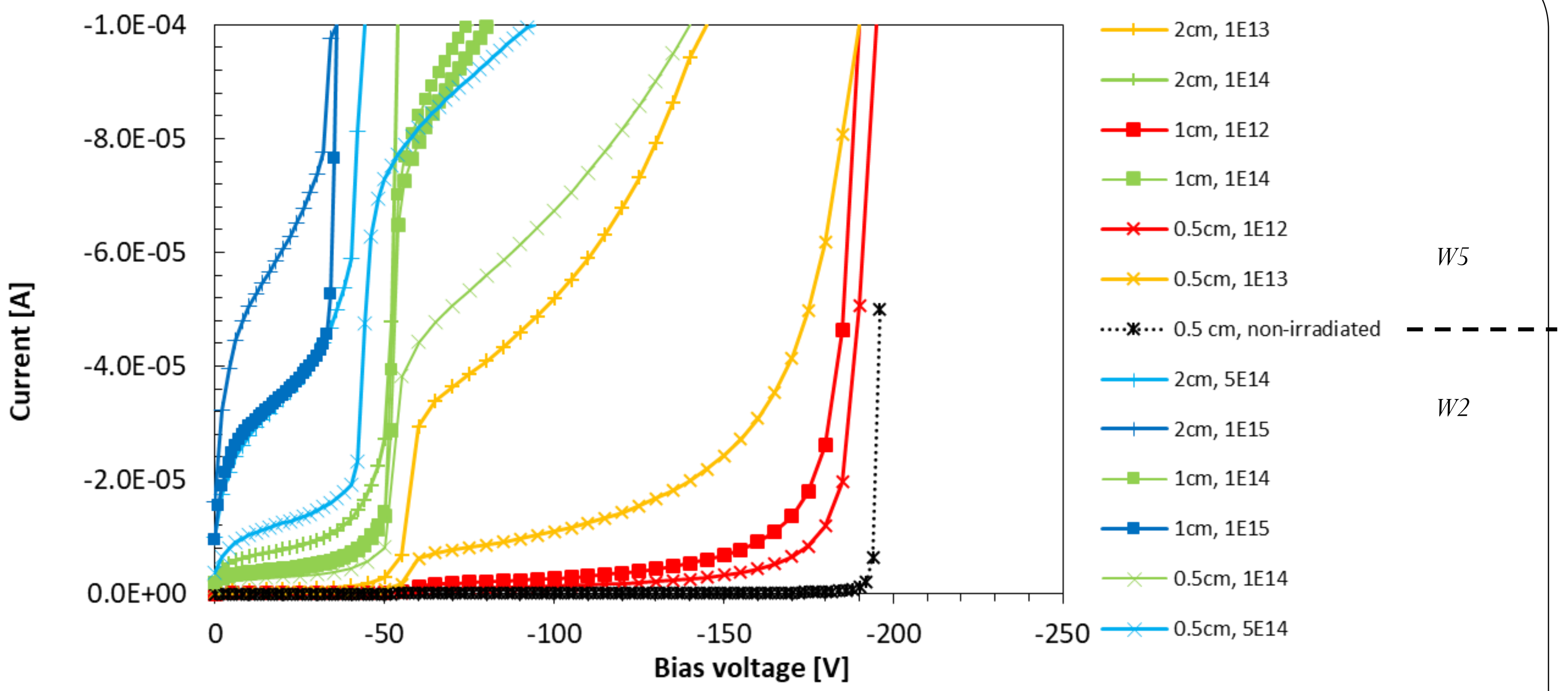
- W2: $5.38\cdot10^{-16}$
- W4: $3.69\cdot10^{-16}$
- W5: $4.93\cdot10^{-16}$
- W8: $5.81\cdot10^{-16}$
- W9: $4.54\cdot10^{-16}$
- W11: $4.33\cdot10^{-16}$

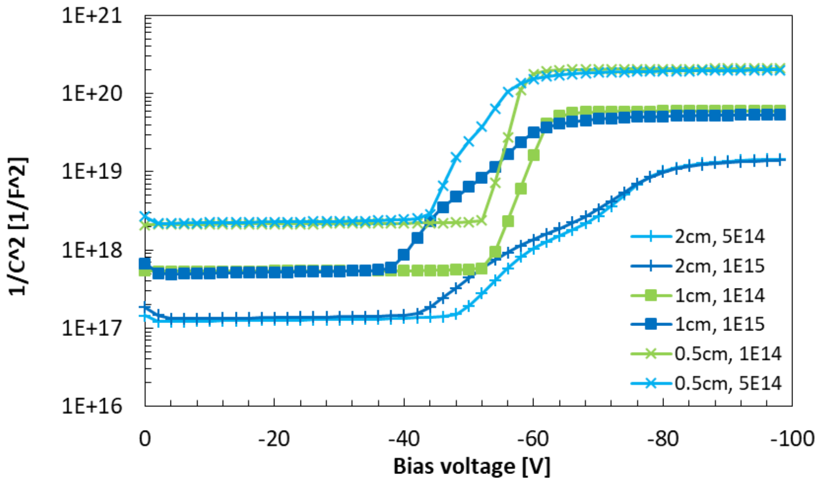
Student: J. Ding

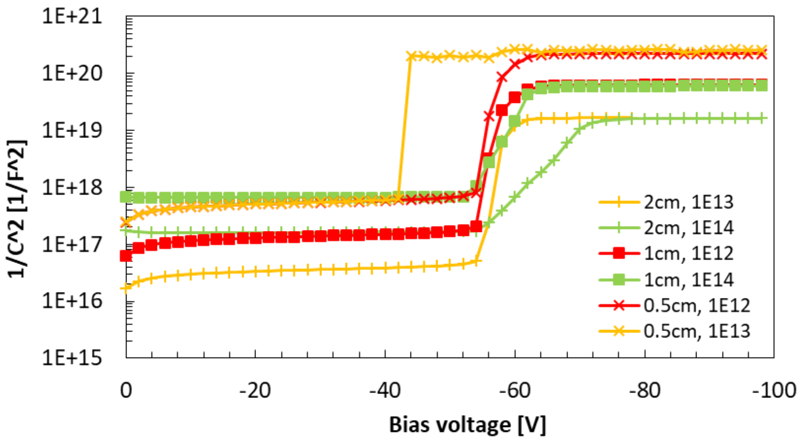
Strips - Neutrons

- Strip sensors have larger area, also scales up with strip lengths: changes in leakage current more prominent, already at low fluences after 1e12Neq
- Shift in gain layer depletion voltage is recognizable even in IV measurement
- (Soft) breakdown voltage may increase with fluence – is overshadowed by too high leakage currents

- Up to 1e13 Neq, no significant change in gain layer depletion voltage = gain layer active doping concentration
- Shift in gain layer depletion voltage with fluence is very clear
- Capacitance scales with surface area / strip length
- Larger sensor: more bulk effects visible after gain layer depletion



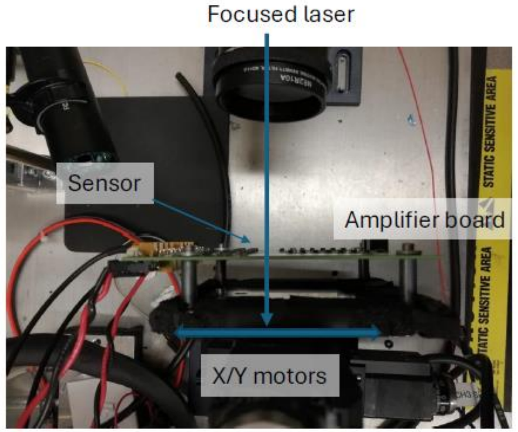


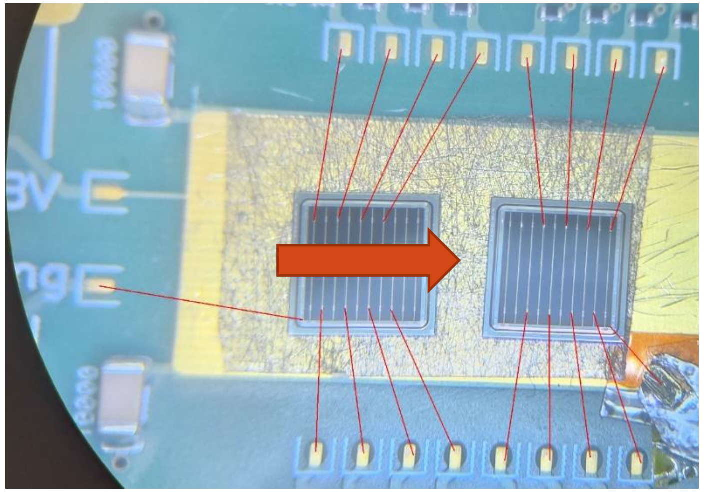


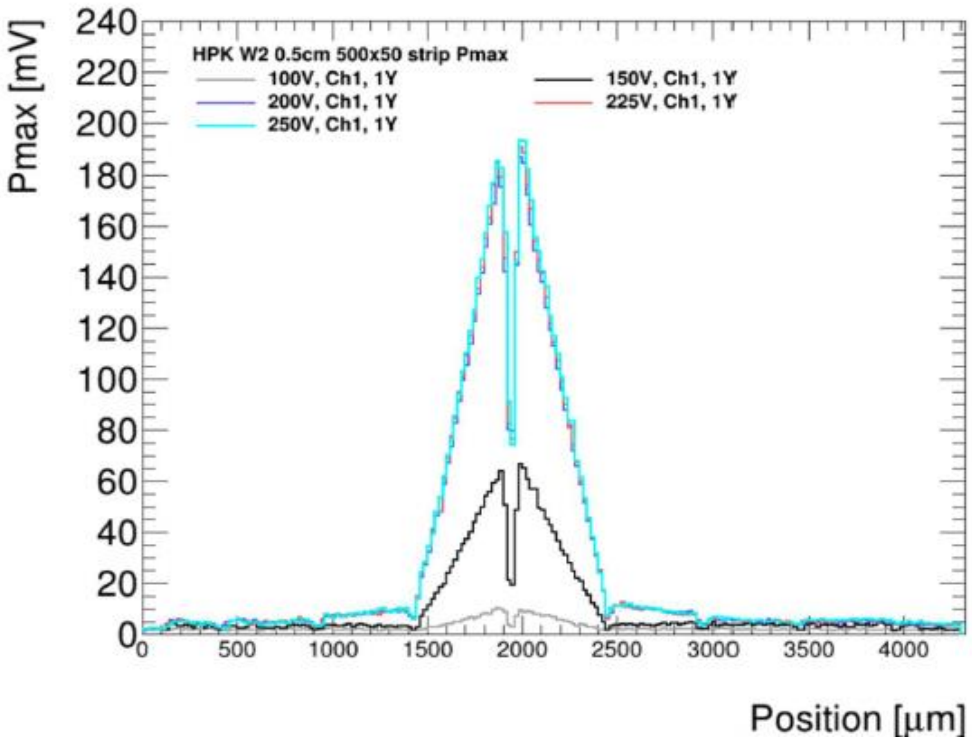
Student: J. Ding

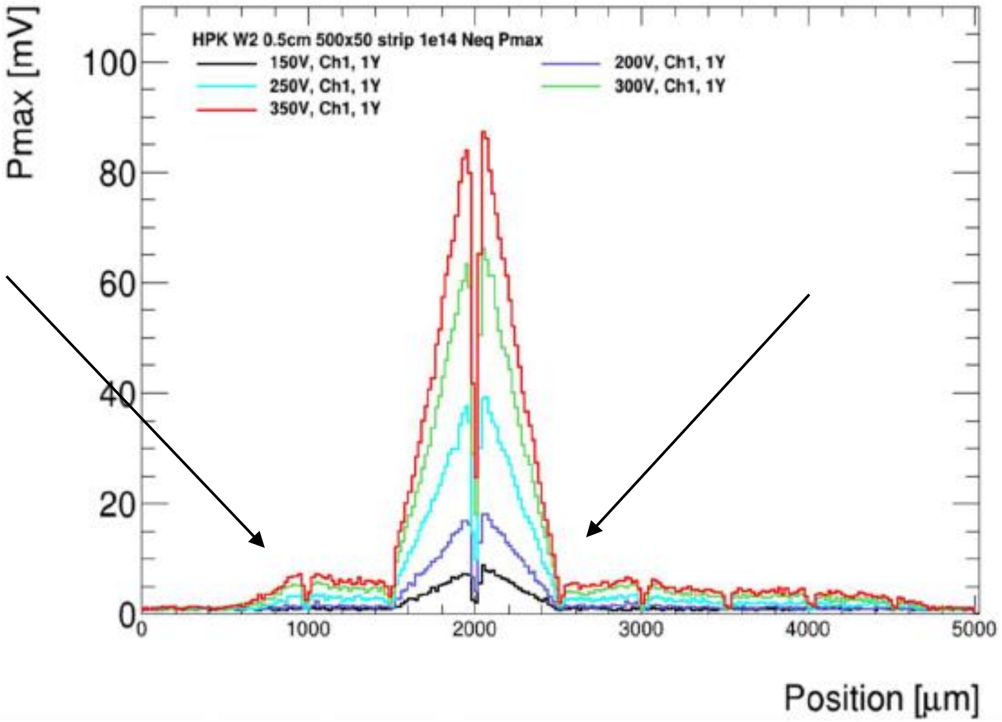
Strip laser studies - Neutrons

- Using laser TCT setup with cooling plate and FNAL 16ch board
- W2 0.5 cm strip, non-irradiated sensor and irradiated to 1e14 n/cm2
  - Cooling with chiller to ~10 C
  - Irradiated sensor was biased to higher voltages
- Pmax profile of the main strip is very similar, but increases beyond the first neighboring strip and at longer distances
- Effect is unexplained, could be radiation damage to dielectric
- Other sensors in testing to verify if it's a common change





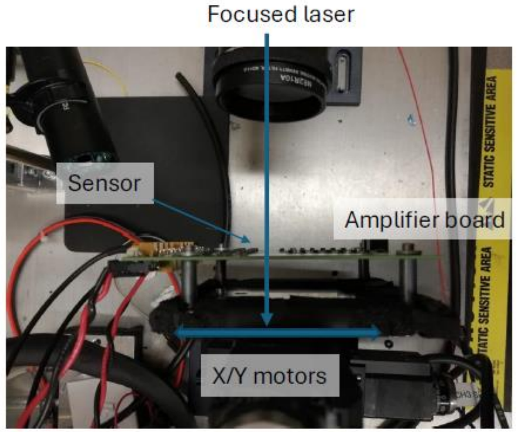


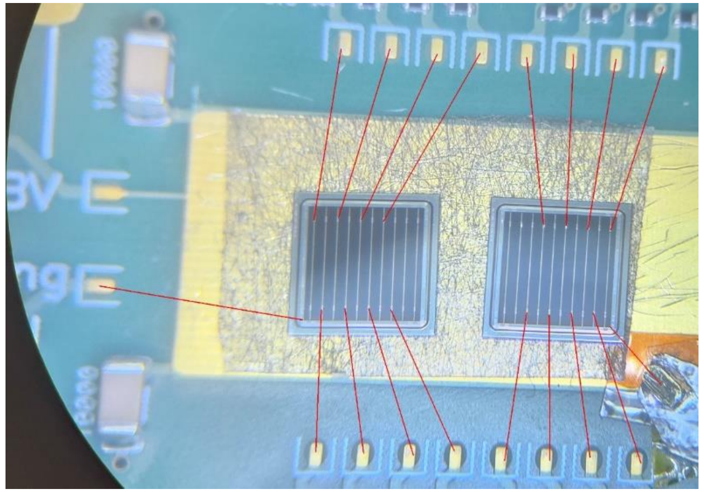


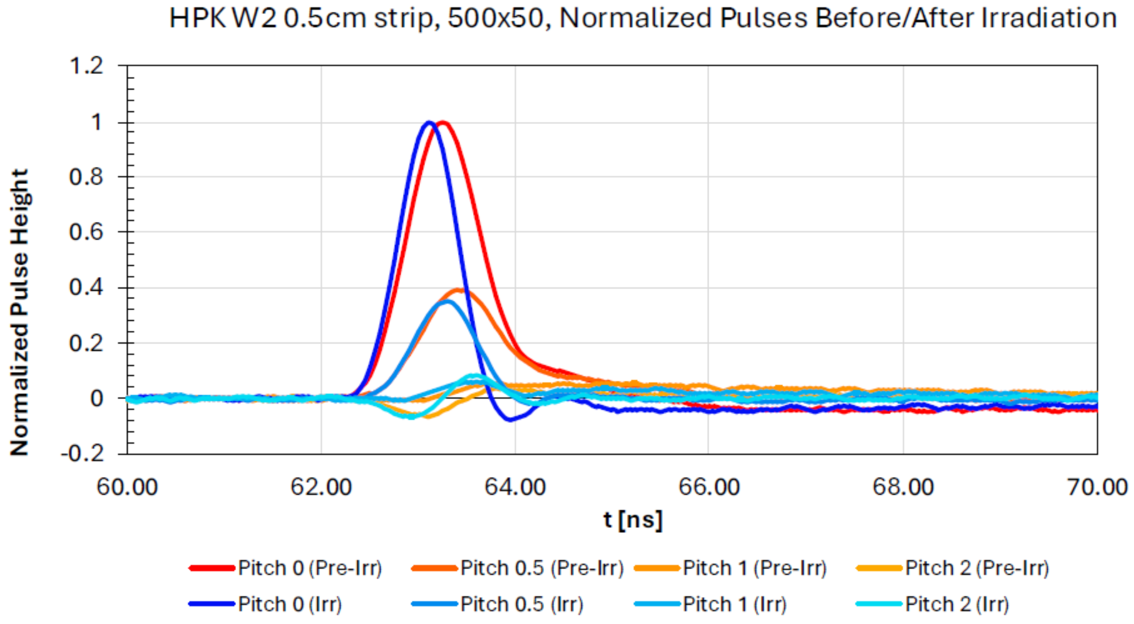
Student: G. Stage, A. Borgijin

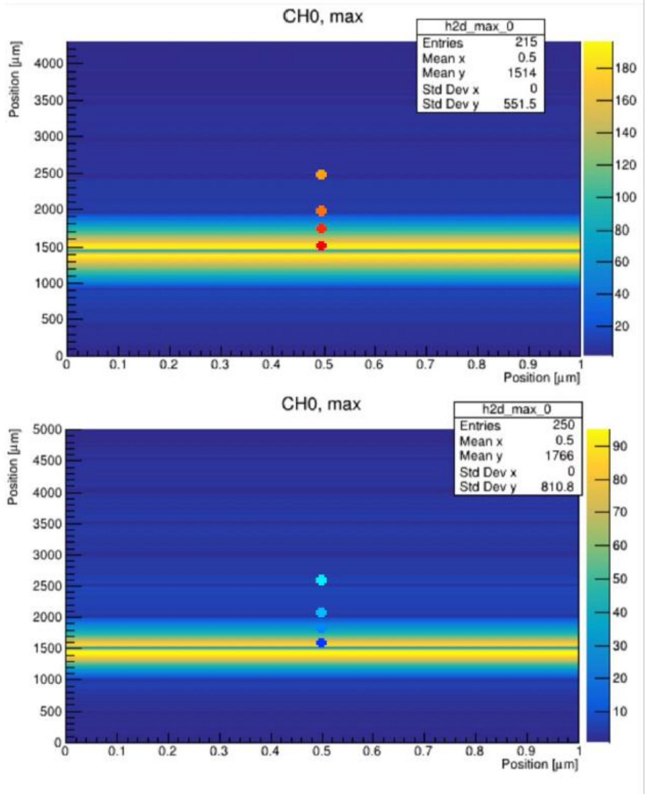
Strip laser studies – Neutrons

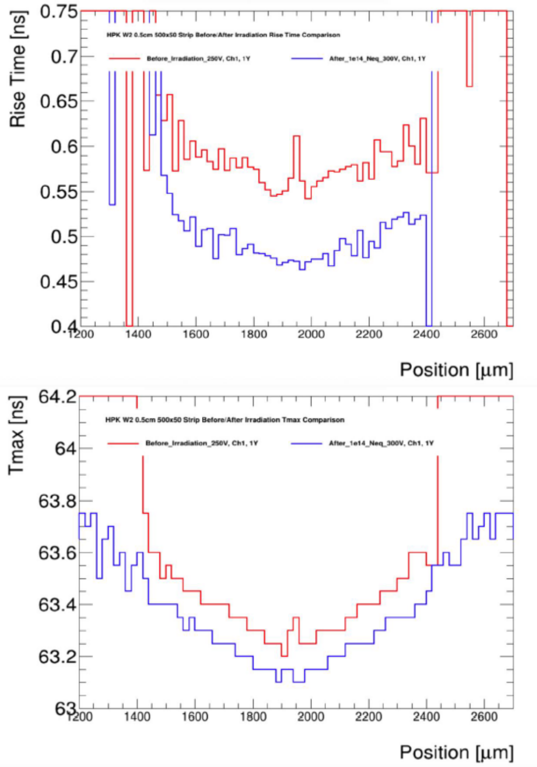
- Higher leakage current, higher breakdown voltage, **lower gain** in irradiated sensors at 1e14 n/cm^2
- **Faster rise time and shorter pulse in irradiated sensor**
  - More distinct rise and fall as opposed to 'tail' after main pulse





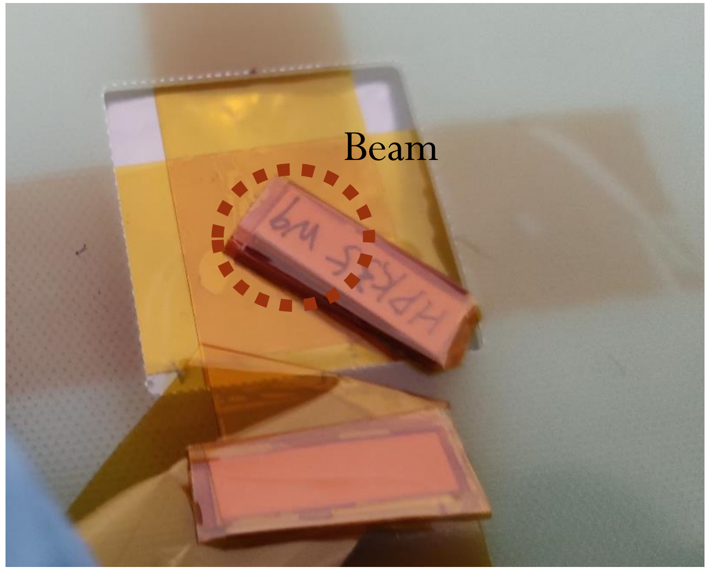




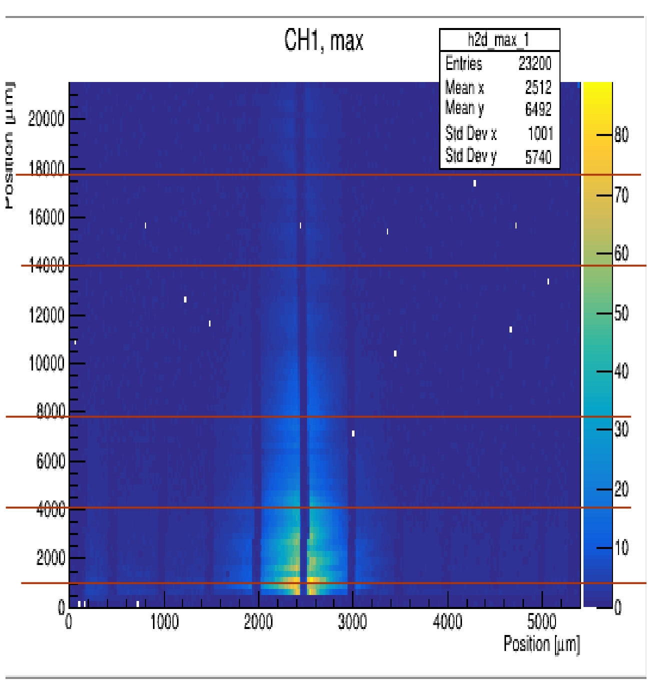


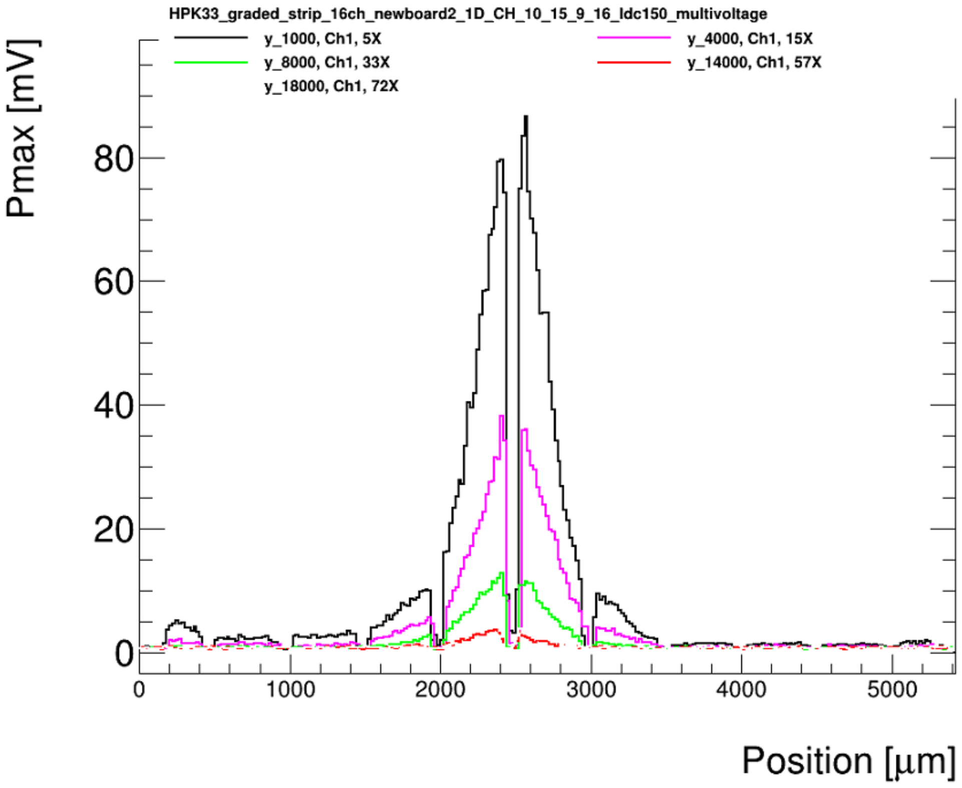
Student: G. Stage, A. Borgijin

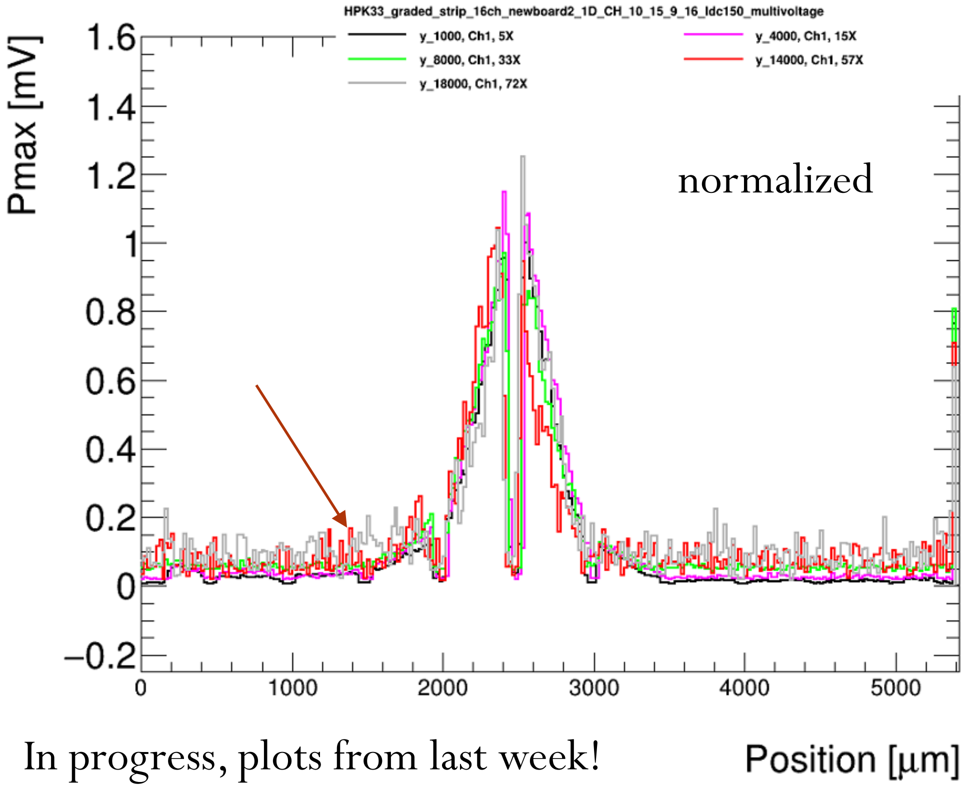
FNAL proton irradiated sensor results



- Graded irradiation on an HPK 2cm long strip sensor (500um pitch, E600, 50um)
  - Fluence each ~0.5cm: 4.4E+14Neq, 3.5E+14Neq, 1.8E+14Neq, 7.8E+13Neq
- Testing with laser TCT with cold plate (~0C)
- Effect of the irradiation clear in the gain layer signal degradation
  - However, the charge sharing profile doesn't change → good!
  - Interesting to see the 'baseline' single change slightly with irradiation
- This will be interesting to see in the 'other' direction now that full scale sensors are available



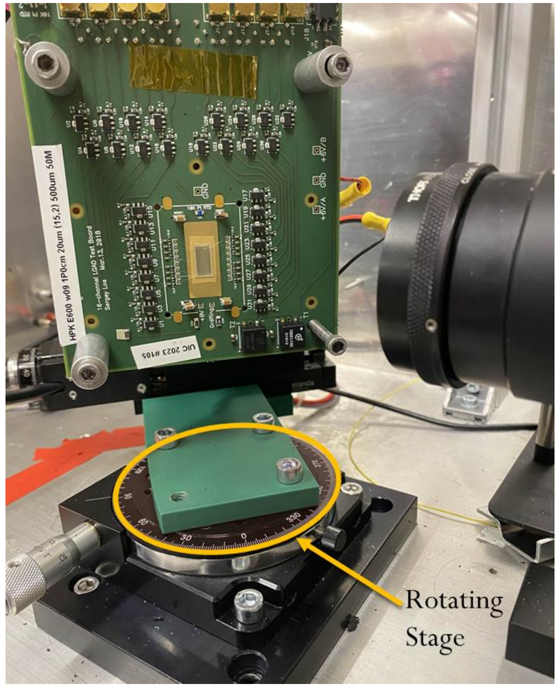




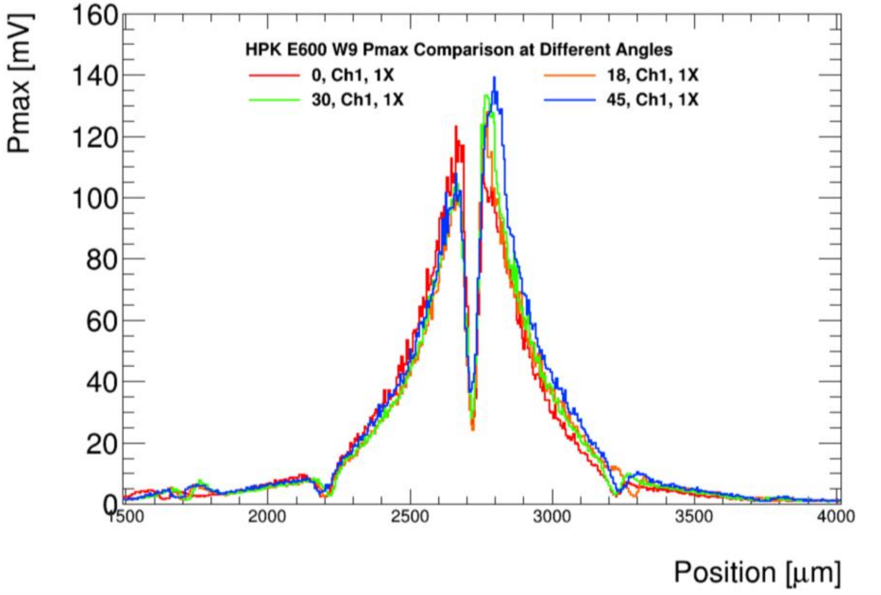
In progress, plots from last week!

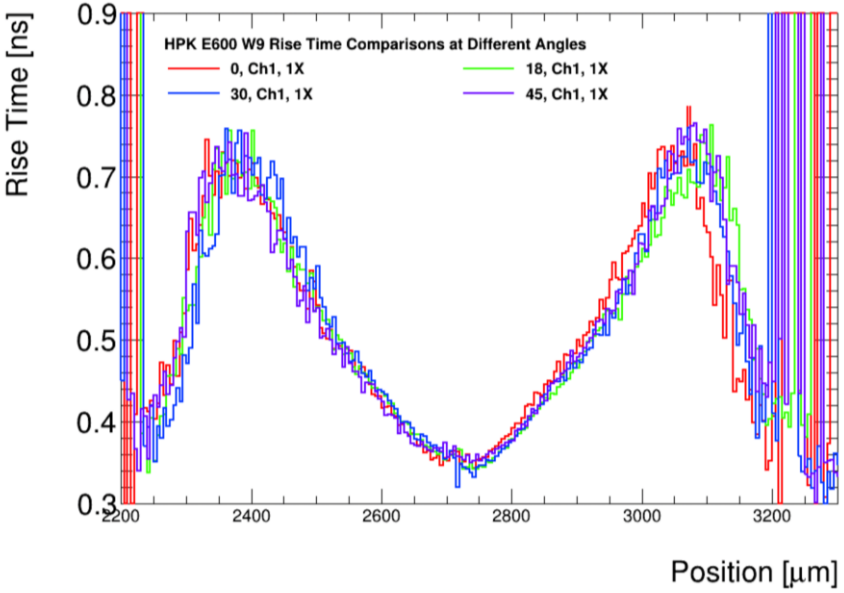
Student: G. Stage, A. Borgijin

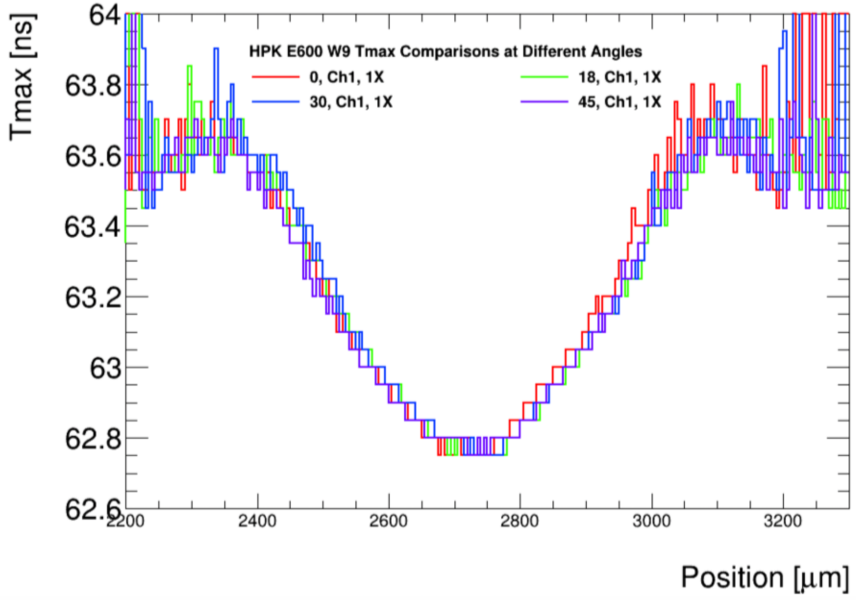
Angled charge injection



- 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





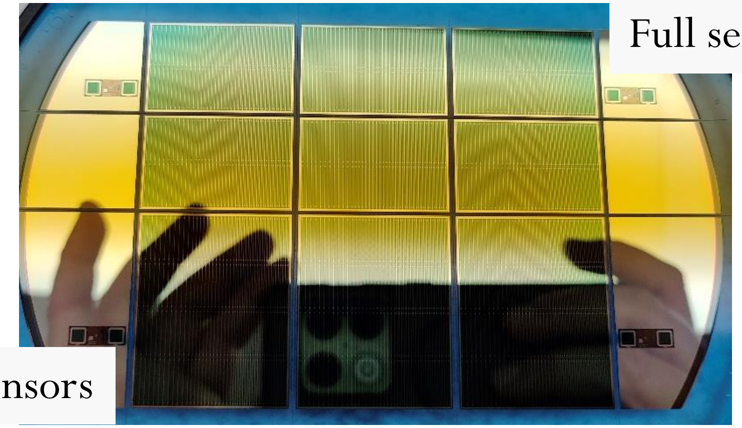


Student: J. Ding

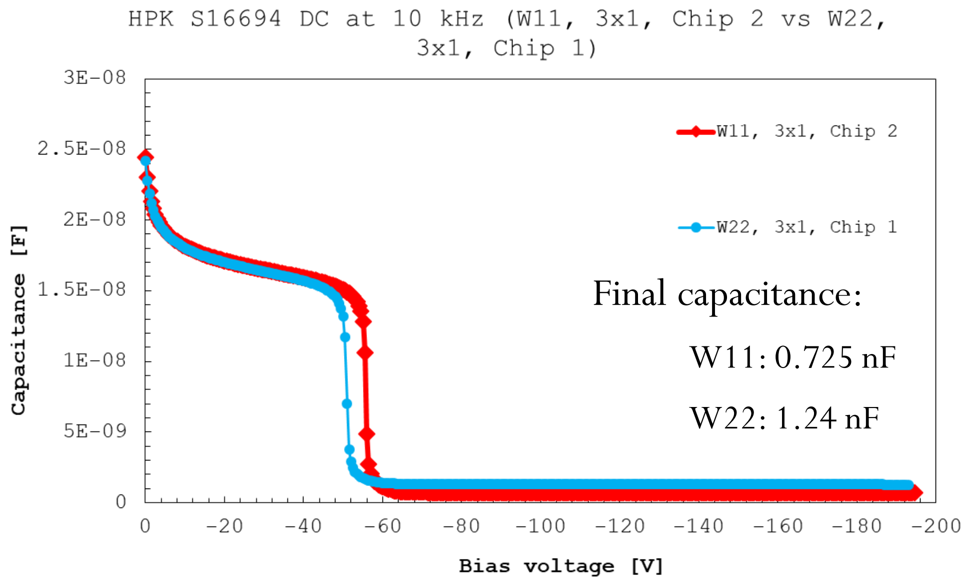
New HPK production

- Received first ePIC full-size production of strip AC-LGADs from HPK with devices up to 3.2x4 cm
  - Nominal size 3.2x2.2 cm with 1cm strip ‘segments’
- Produced a new 16ch board that can house larger sensors, v1 with many problems, v2 working well available now (will produce for collaborators as well)
- For now 2 wafers in hand (8 total), one 50um thick (W11) and one 30um thick (W22)
  - Yield is not optimal, somehow better for 30um wafer
  - Strip width: 50um, strip pitch 500, 750, 1000 um
- We’ll received pixel AC-LGADs wafers (4 total) production soon as well
  - With different pitch and pixel size
- Capacitance of full detector scales with thickness


Half sensors


Full sensors

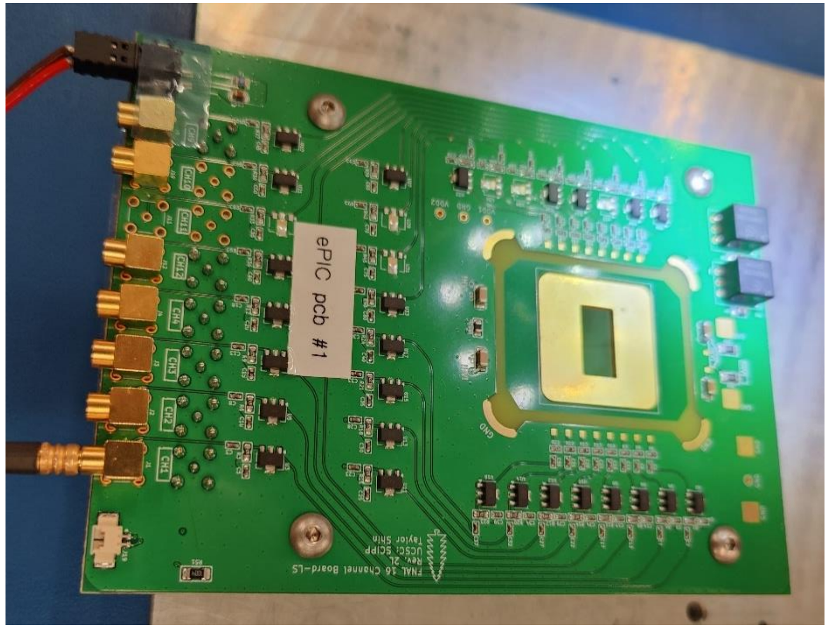
Double sensors

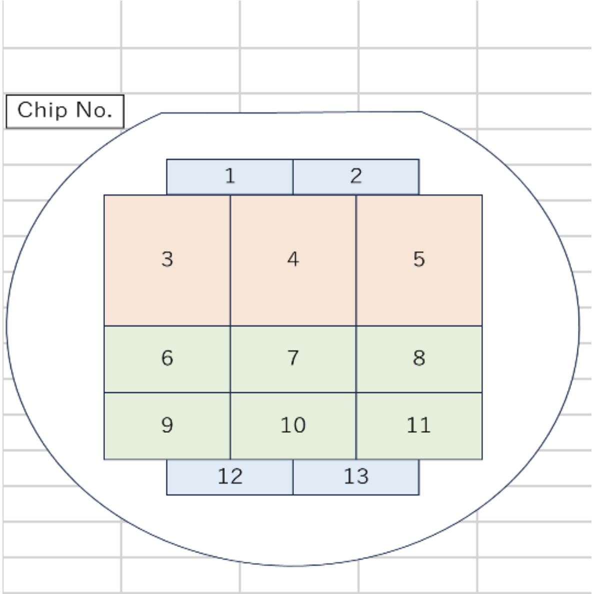


Final capacitance:

W11: 0.725 nF

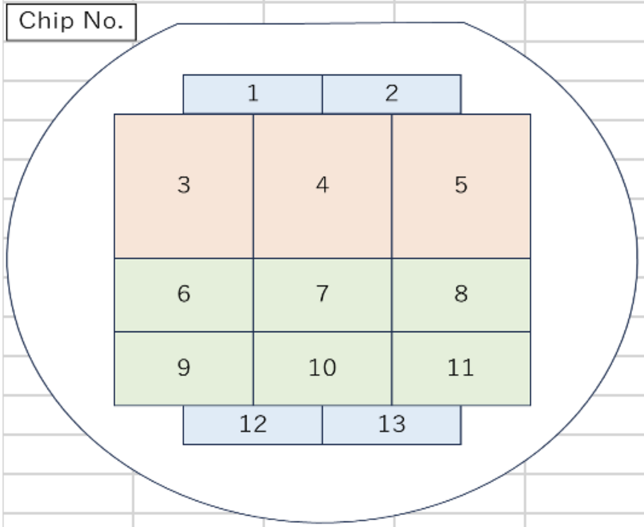
W22: 1.24 nF





Student: G. Stage, A. Borgijin

HPK Sensors Received - Yield



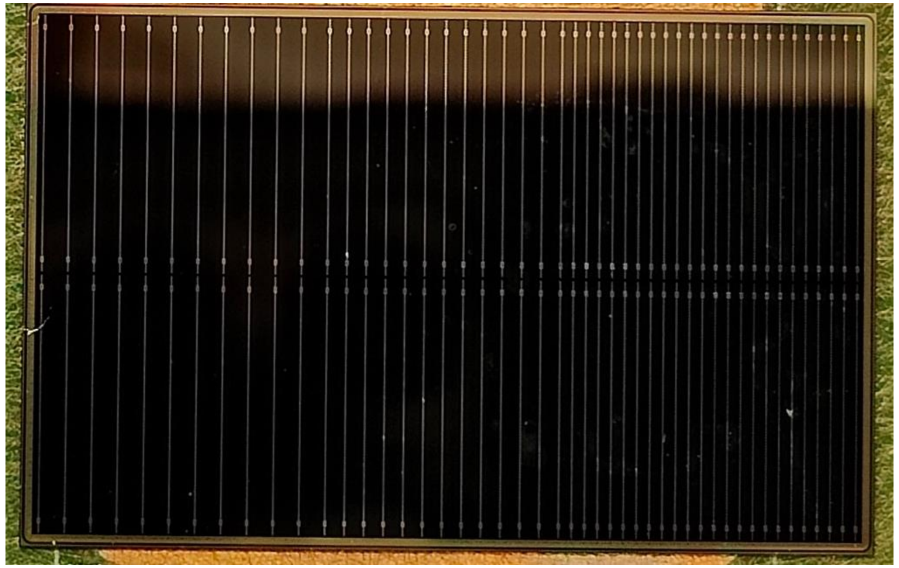
Type	50um											
W/No.	2			6			11			12		
Chip No.	VB (V)	ID@VB-35V (A)	OK or NG	VB (V)	ID@VB-35V (A)	OK or NG	VB (V)	ID@VB-35V (A)	OK or NG	VB (V)	ID@VB-35V (A)	OK or NG
1	195	3.79.E-07	OK	194	5.90.E-07	OK	40	-	NG	194	7.65.E-06	OK
2	193	1.02.E-06	OK	193	6.53.E-06	OK	192	7.54.E-06	OK	59	-	NG
3	50	-	NG	40	-	NG	53	-	NG	50	-	NG
4	40	-	NG	50	-	NG	183	1.91.E-05	NG	61	-	NG
5	67	-	NG	123	6.64.E-05	NG	116	6.68.E-05	NG	181	3.90.E-05	NG
6	30	-	NG	54	-	NG	51	-	NG	20	-	NG
7	80	-	NG	40	-	NG	183	2.54.E-05	NG	185	5.13.E-06	OK
8	160	5.96.E-05	NG	140	6.00.E-05	NG	40	-	NG	174	4.54.E-05	NG
9	10	-	NG	10	-	NG	10	-	NG	10	-	NG
10	54	-	NG	191	1.73.E-05	NG	192	8.57.E-06	OK	191	3.94.E-06	OK
11	50	-	NG	30	-	NG	50	-	NG	40	-	NG
12	199	3.63.E-06	OK	199	3.85.E-07	OK	198	5.72.E-06	OK	198	2.19.E-05	NG
13	198	3.57.E-06	OK	84	-	NG	191	6.84.E-05	NG	197	3.04.E-05	NG

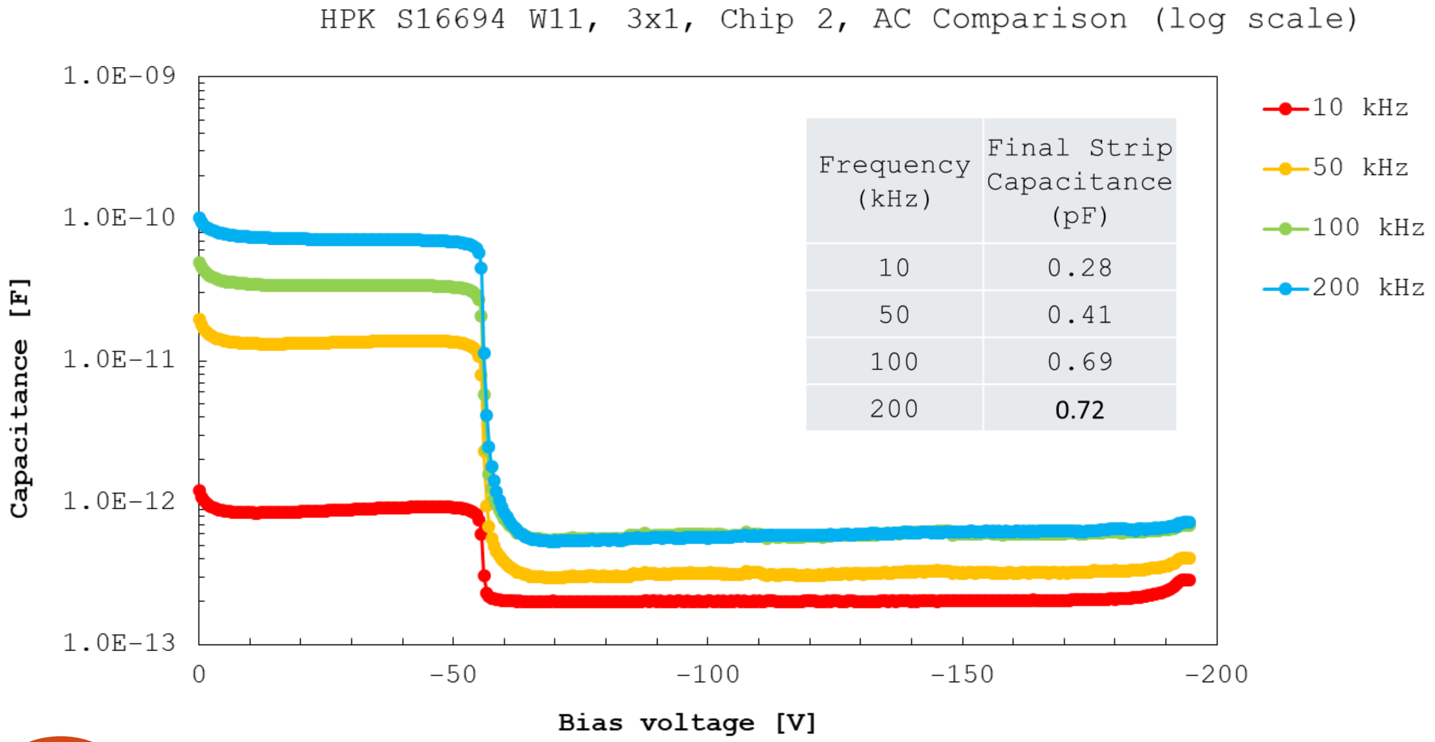
Type	30um											
W/No.	13			15			22			23		
Chip No.	VB (V)	ID@VB-35V (A)	OK or NG	VB (V)	ID@VB-35V (A)	OK or NG	VB (V)	ID@VB-35V (A)	OK or NG	VB (V)	ID@VB-35V (A)	OK or NG
1	188	9.57.E-09	OK	183	8.95.E-09	OK	186	8.65.E-09	OK	180	7.72.E-09	OK
2	188	1.00.E-08	OK	185	9.46.E-09	OK	182	7.71.E-09	OK	183	8.59.E-09	OK
3	40	-	NG	50	-	NG	58	-	NG	180	3.45.E-08	OK
4	185	3.56.E-08	OK	178	2.92.E-08	OK	156	3.70.E-05	NG	182	3.47.E-08	OK
5	182	2.91.E-08	OK	180	3.24.E-08	OK	177	2.93.E-08	OK	184	3.70.E-08	OK
6	185	1.96.E-08	OK	178	1.63.E-08	OK	183	1.83.E-08	OK	183	1.86.E-08	OK
7	186	1.93.E-08	OK	178	1.49.E-08	OK	181	1.55.E-08	OK	183	1.83.E-08	OK
8	183	1.86.E-08	NG	180	1.72.E-08	OK	177	1.45.E-08	OK	185	1.94.E-08	OK
9	10	-	NG	10	-	NG	20	-	NG	10	-	NG
10	188	1.90.E-08	OK	182	1.61.E-08	OK	183	1.58.E-08	OK	185	3.11.E-08	OK
11	185	1.87.E-08	OK	182	1.77.E-08	OK	179	1.44.E-08	OK	187	1.91.E-08	OK
12	190	1.05.E-08	OK	186	9.34.E-09	OK	186	8.52.E-09	OK	189	9.82.E-09	OK
13	124	2.55.E-09	NG	184	8.95.E-09	OK	182	7.53.E-09	OK	188	9.61.E-09	OK

New HPK production

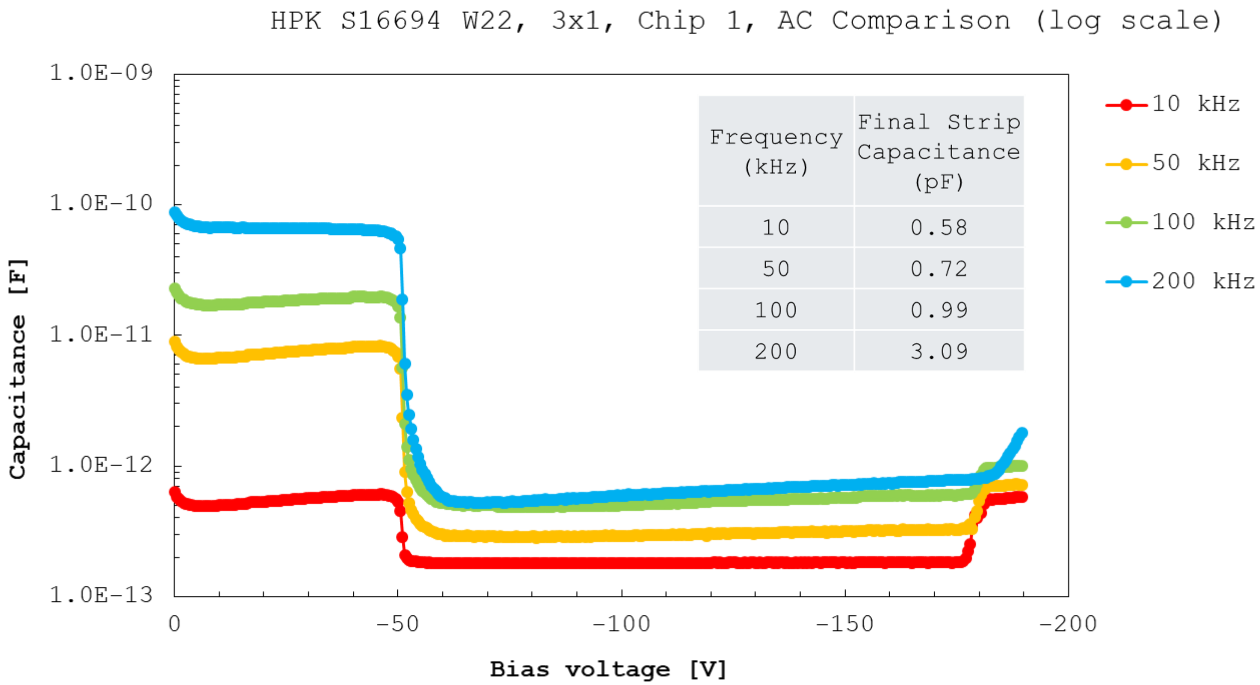
- Capacitance of AC strips with backside measurements, test on edge strip near N+ connection
- As always it’s tricky to pinpoint a number as result vary wildly with frequency
- Final capacitance of the order of few pF for both wafers
  - This seems suspiciously low, studies ongoing

Full sensors





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

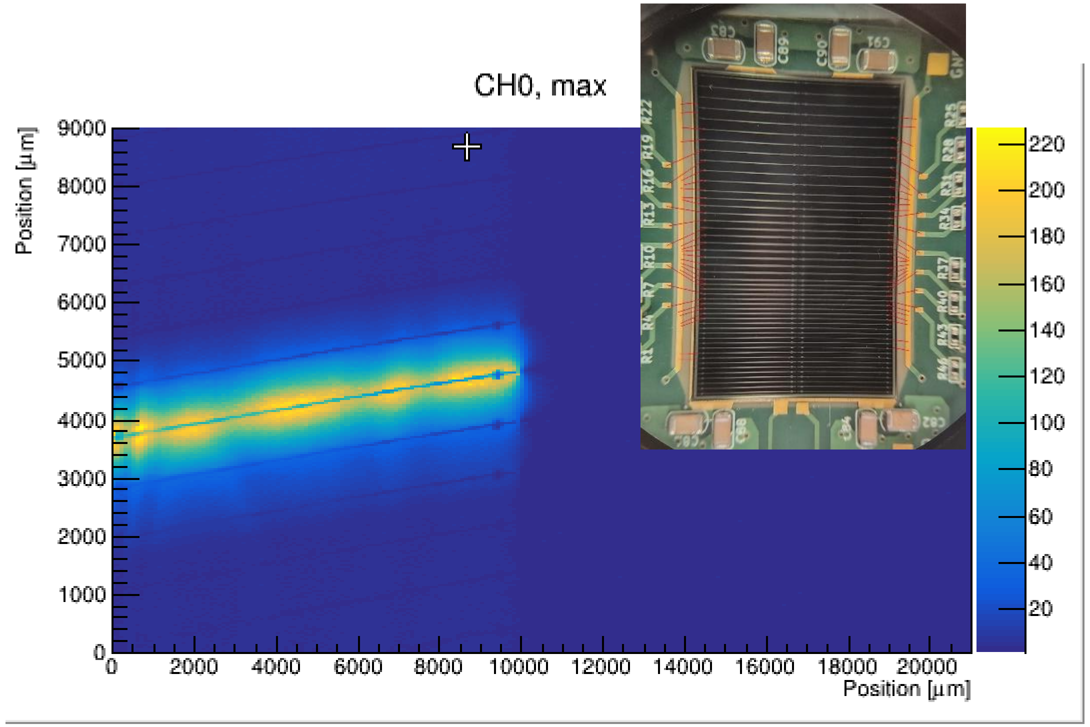


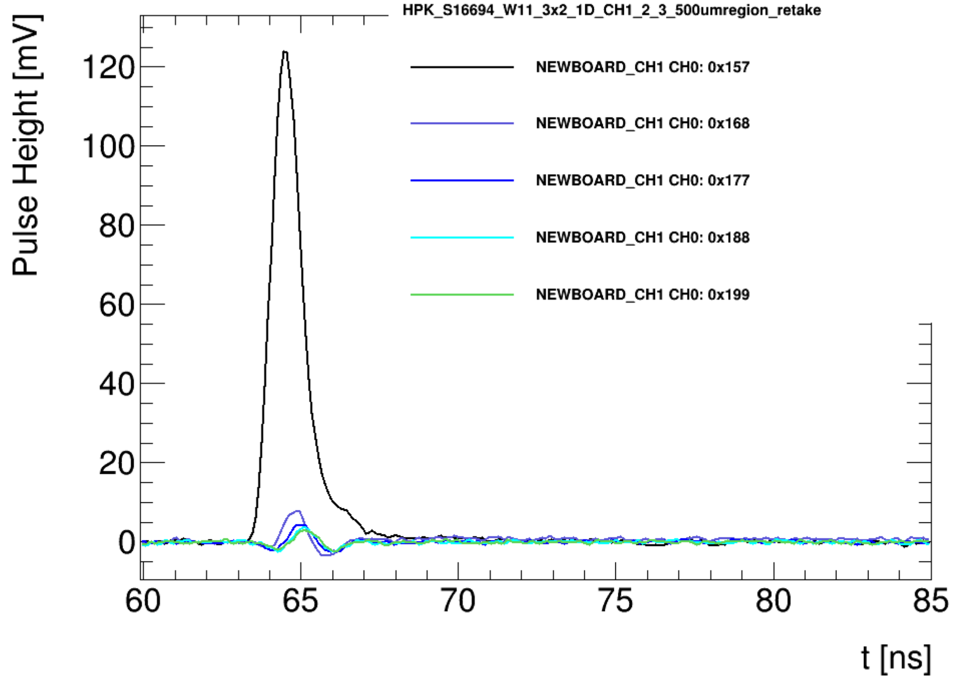
Frequency (kHz)	Final Strip Capacitance (pF)
10	0.58
50	0.72
100	0.99
200	3.09

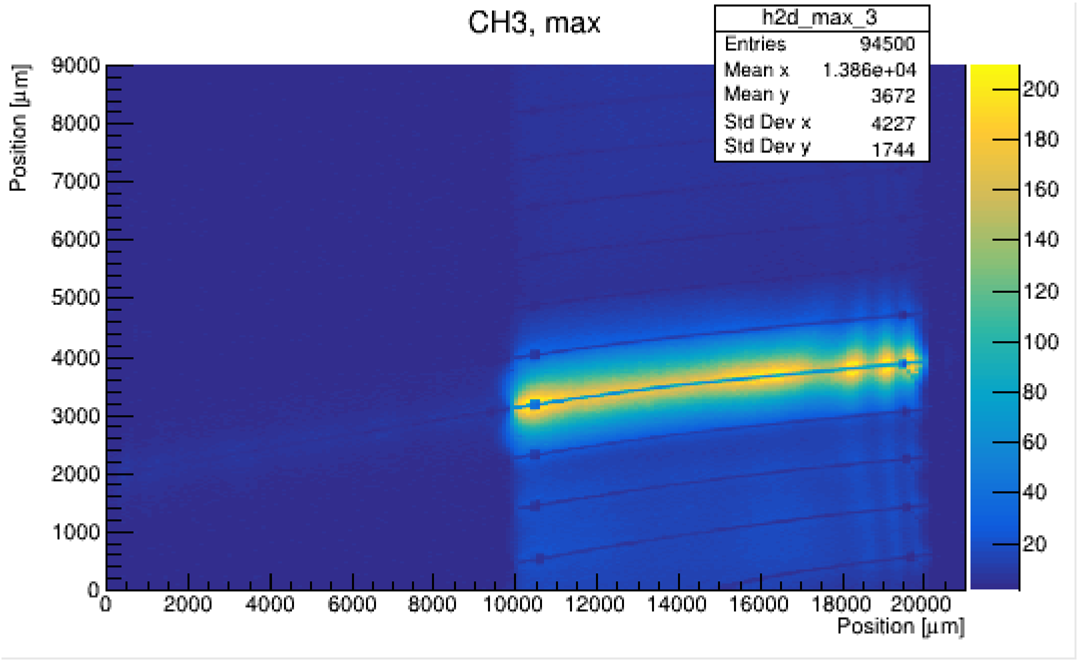
Student: J. Ding

HPK production results

- First full-scale sensor tested on a large board
    - W11, 50um thickness
- Sensor works well, some gain variation across strip but it's unclear if due to laser reflections, need test beam to verify
- Pulse as expected with rise-time 600-700 ps



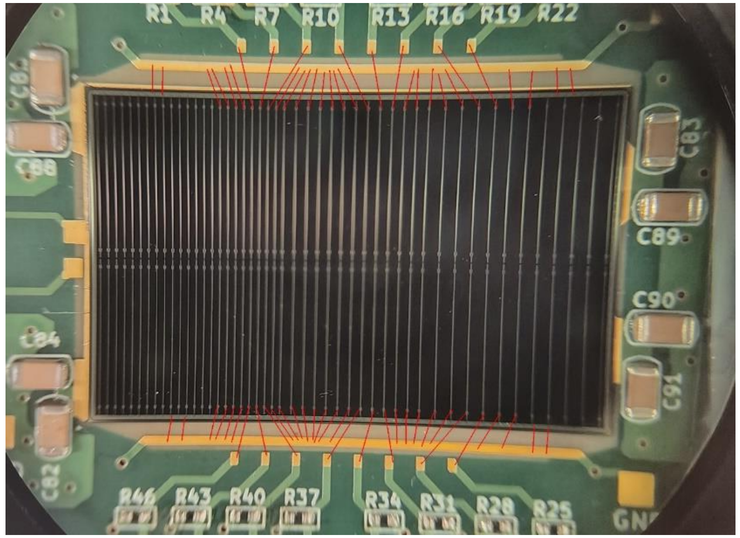


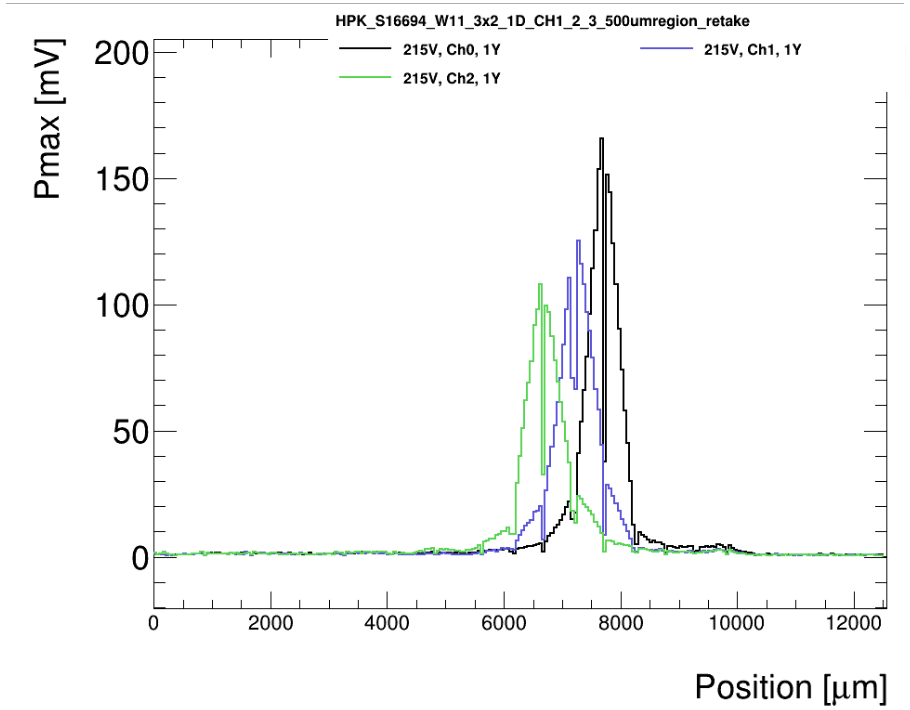


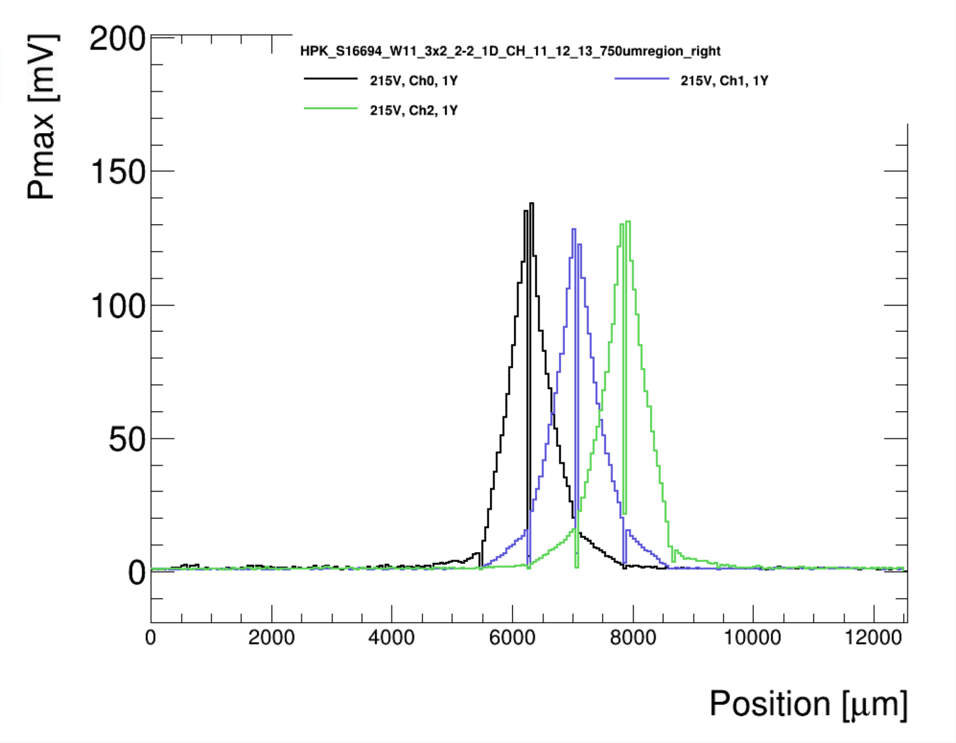
Student: G. Stage, A. Borgijin

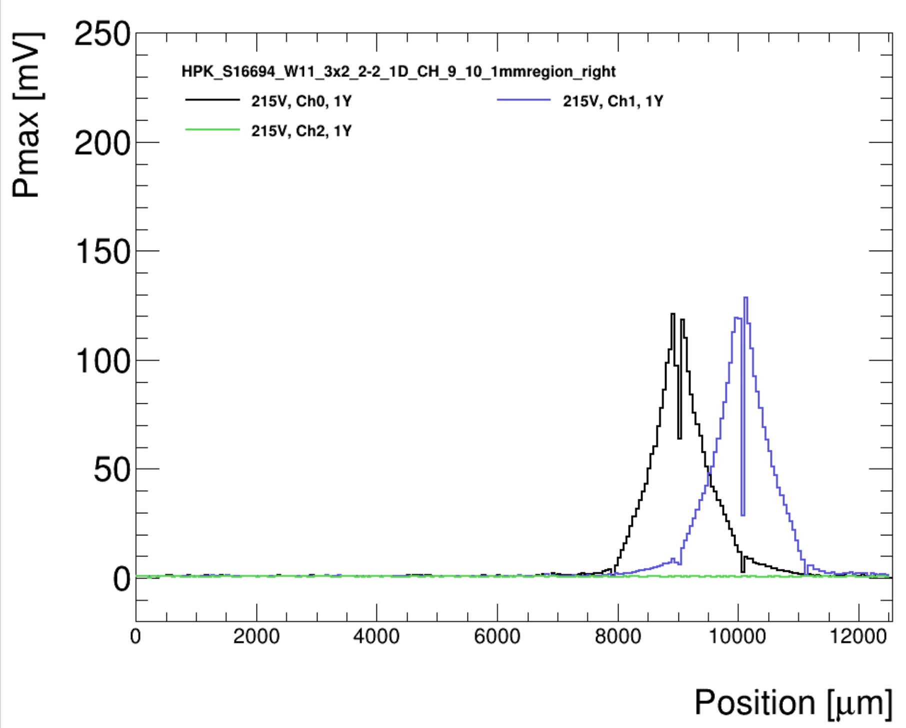
HPK production results

- Signal for 1000um, 750um and 500um is very similar (100-150mV)
- Some difference in charge sharing if strip is grounded or connected to board
  - Could be cross talk induced in the board
- The S/N loss is small even for 1000um pitch, could be a viable solution
  - Need to check time of arrival delay, in progress
- Next: test the same sensor geometry for 30um thickness





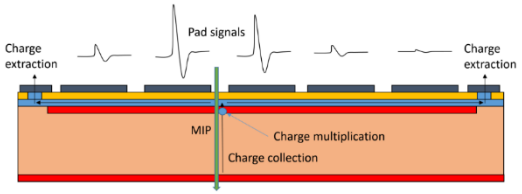


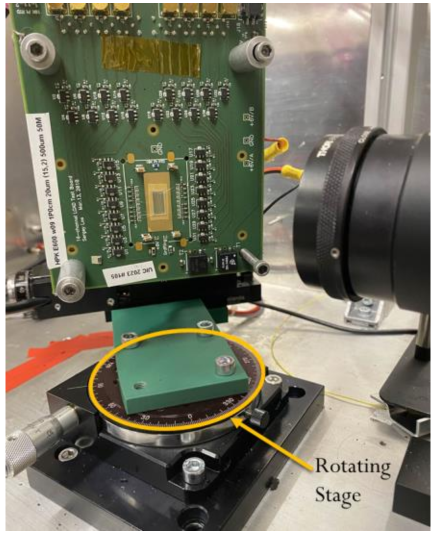


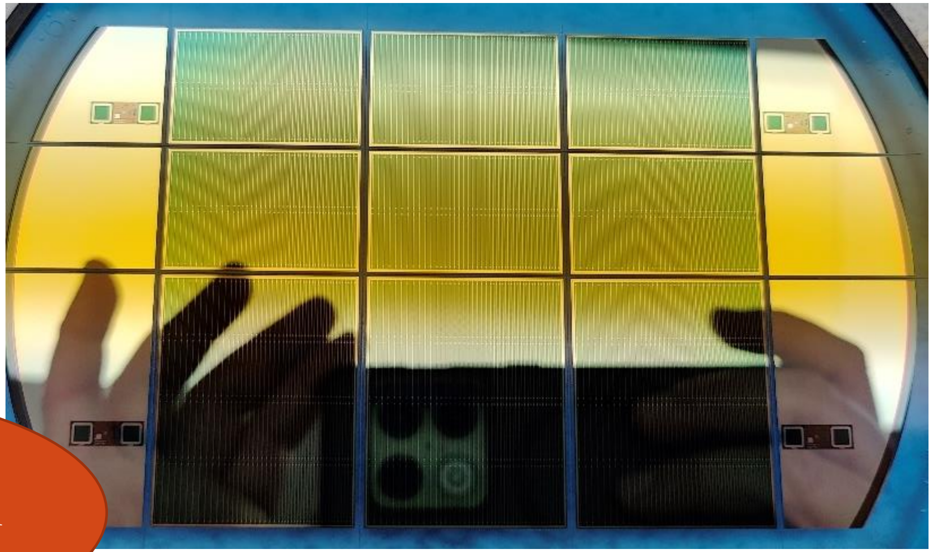
Student: G. Stage, A. Borgijin

Conclusions

- Ongoing development of AC-LGADs for the ePIC TOF layers
- First production showed the importance of N+ resistivity, especially for strip geometry
  - 500um pitch 50um width strip are adequate for ePIC requirements
  - Tested pixels with 500um pitch and 150um width have shortfall in position resolution under metal (need design update), new geometries are expected in the new production
- Tested neutron and proton irradiated AC-LGADs
  - No unforeseen effects in breakdown of gain layer degradation
  - Strange secondary effects seen in charge sharing profile
  - Testing of several sensors ongoing
- Tested sensors with angled charge injection
  - Effects are small with the tested geometries
- Received first large-scale AC-LGAD production from HPK
  - First results show low yield but good performance







Let us know if you want to get involved in sensor testing!

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

Thanks to HPK, BNL for providing sensors for this study

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This work was supported by eRD112 funds from EIC

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

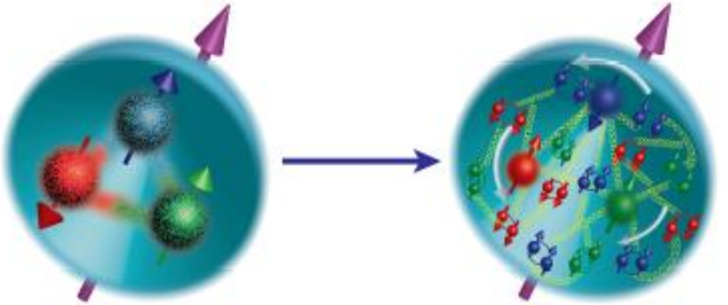
Backup

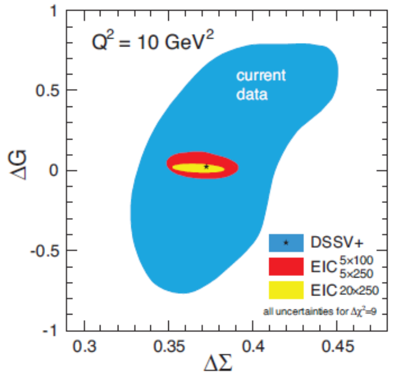
Electron-Ion collider

- 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

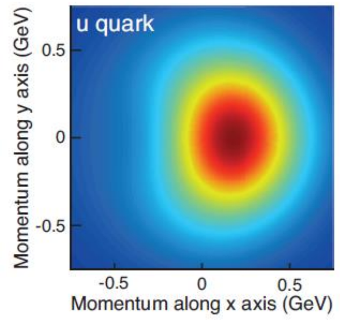
ePIC will provide key measurements:

- **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.



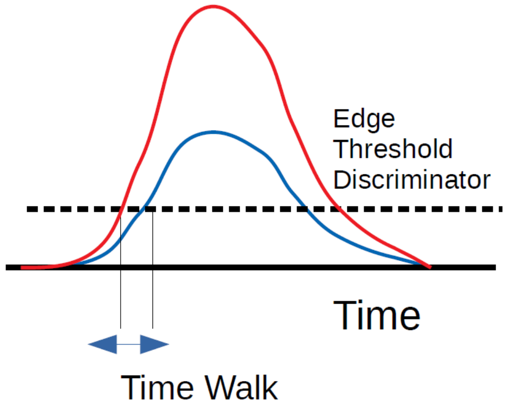


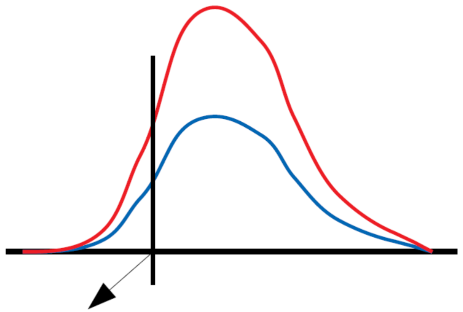
Gluon helicity contribution vs quark helicity contribution



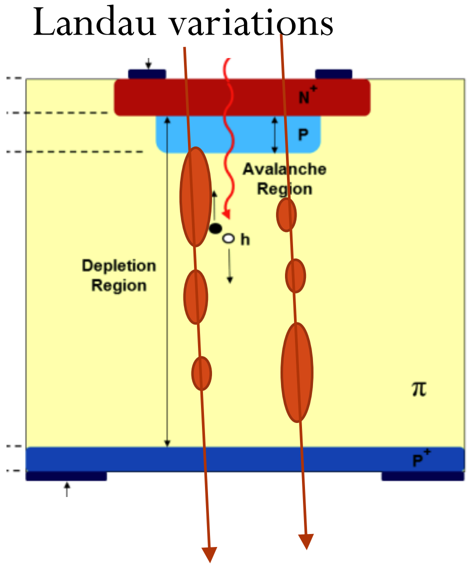
X-Y u quark motion
For proton traveling in Z

Time resolution

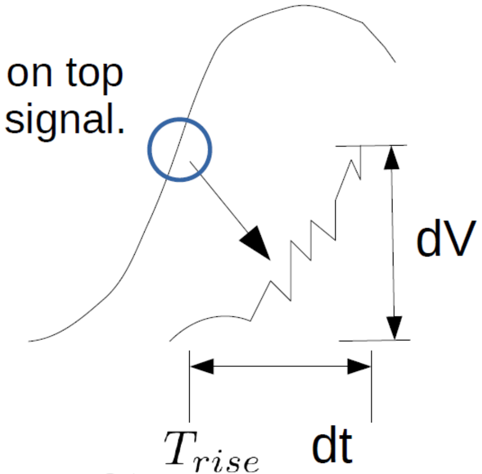




Time given by the CFD 50%. no time walk.



Noise on top of the signal.



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

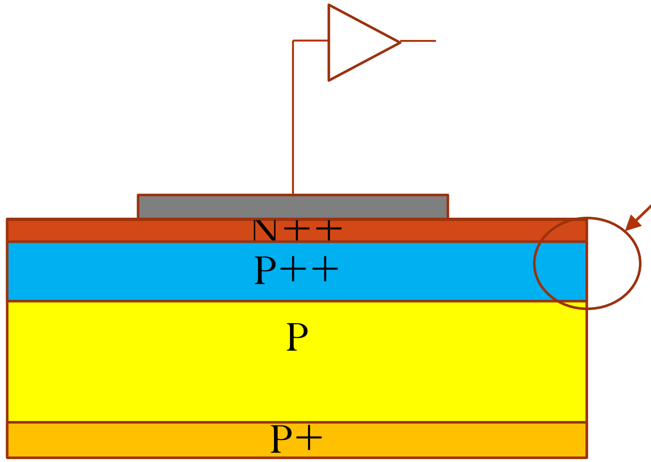
Sensor time resolution main terms

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

- **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

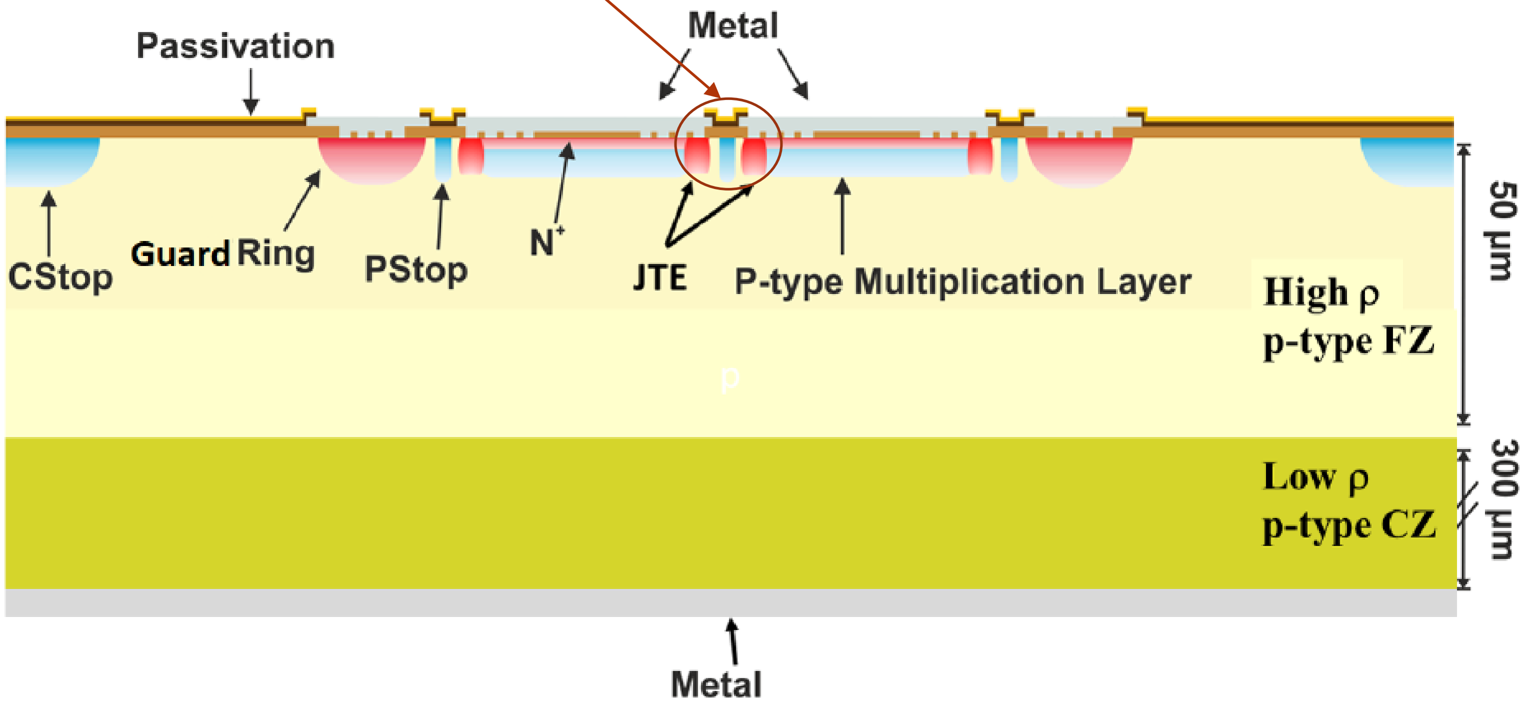
- **Bottom line: thin detectors with high S/N**

LGAD arrays structure



Very high field area, induces early breakdown

Structure to avoid high field line concentration at the edges
Junction Termination Extension (JTE)
Separation between the pads of an array **~50-100 um**



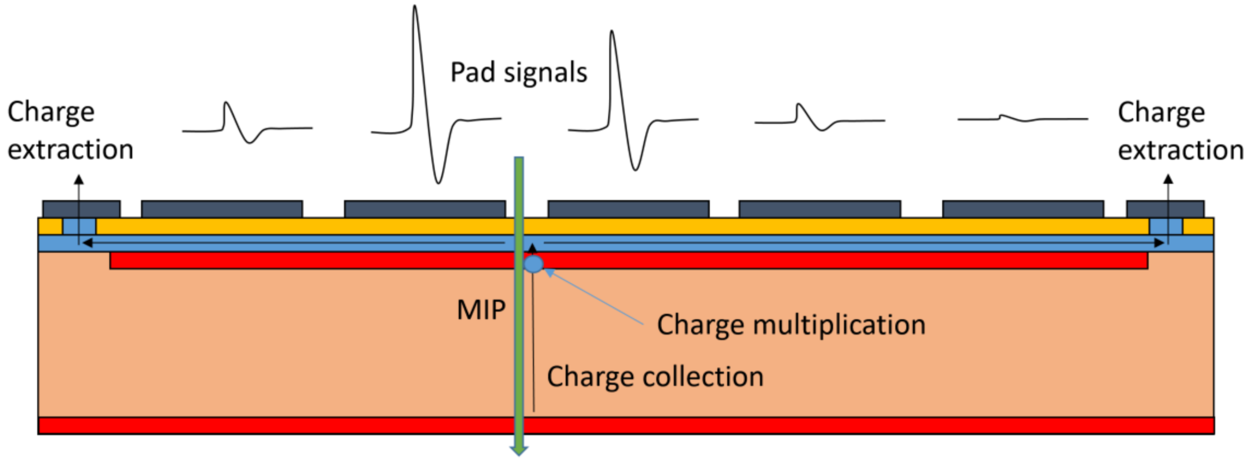
- Protection structures limit the current granularity of LGADs
- ~100 um pixel size would mean ~50% active area
- But intensive R&D is ongoing to overcome this limitation

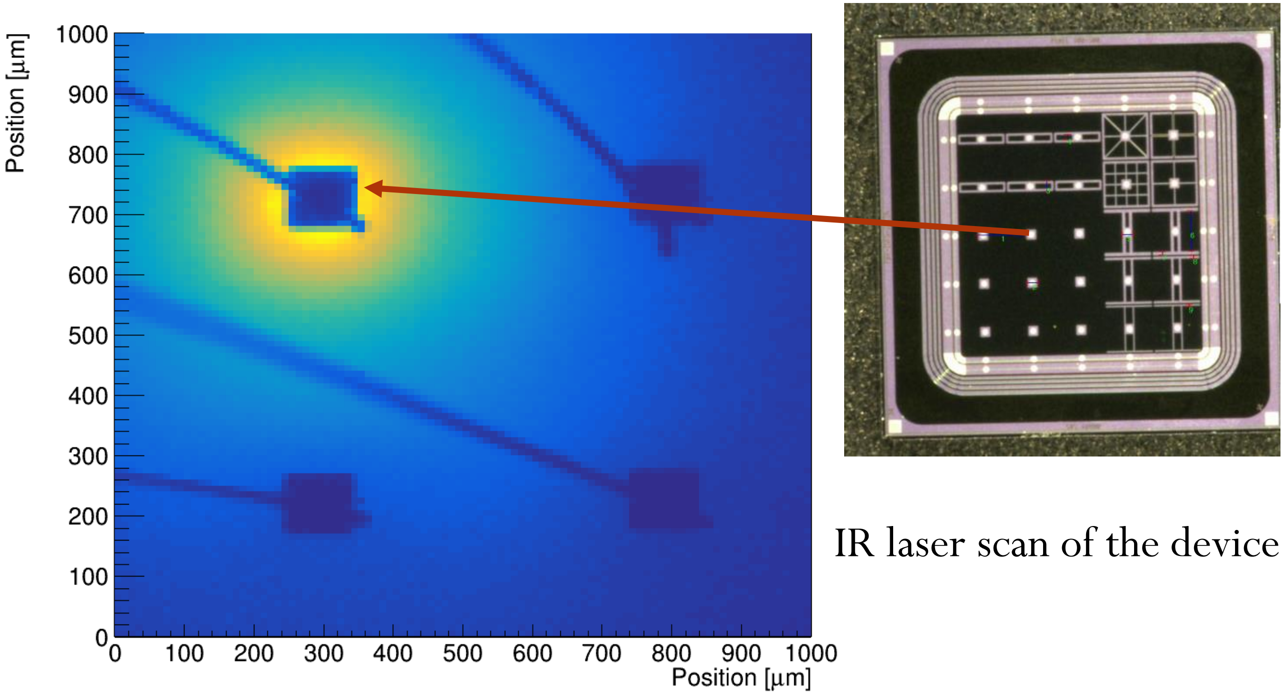
AC-LGAD hit reconstruction

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

- AC-LGAD has **intrinsic charge sharing**
  - Gain increases the S/N and allows for smaller metal pads
- Charge sharing can be a great feature for low density tracking environment
  - Using information from multiple pixels for hit reconstruction
- **With a sparse pixelation of 300 um a <10 um hit precision can be achieved!**
  - Combination of time of arrivals as well
- **Sparse readout is extremely useful for channel density and power dissipation**
- Metal layout can be in any shape and size

- Technology being consider for
  - The PIONEER experiment at PSI
  - ePIC, future detector at Electron-ion collider (EIC) at BNL

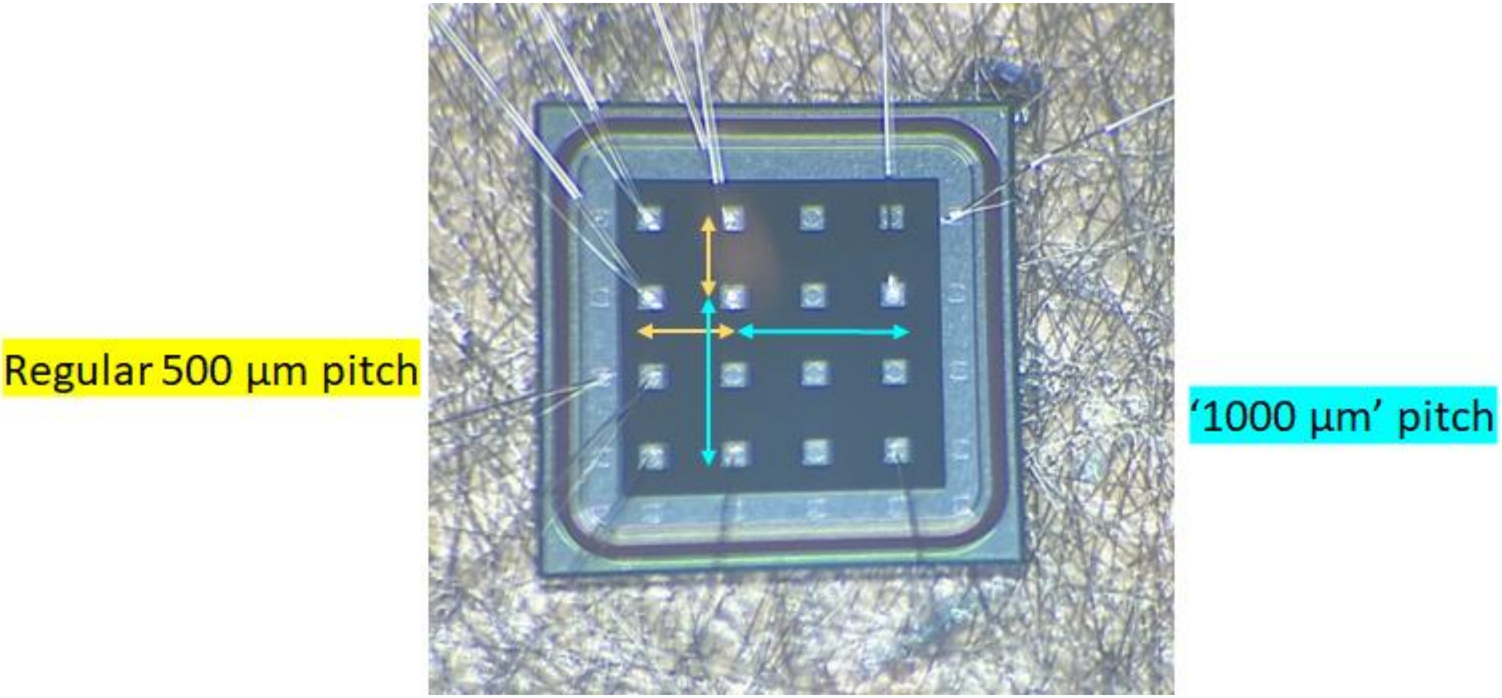




IR laser scan of the device

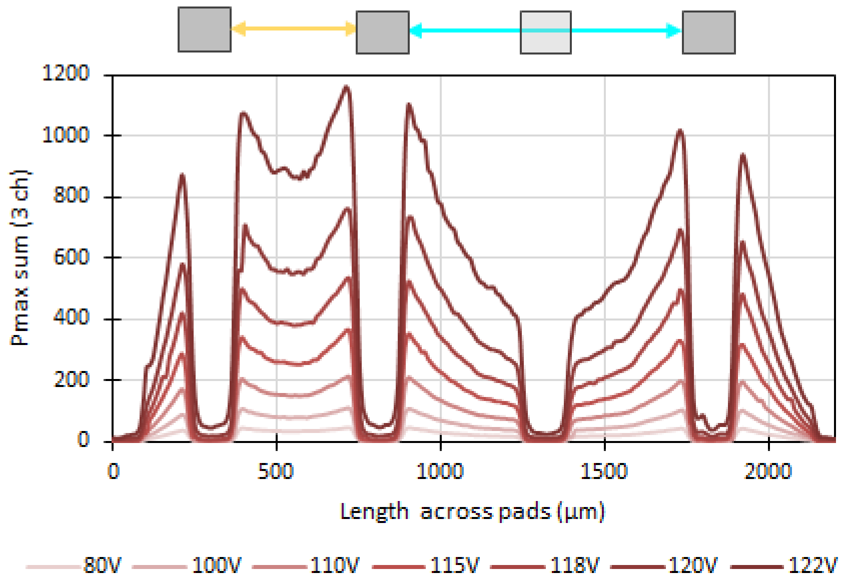
Standard square pad AC-LGAD

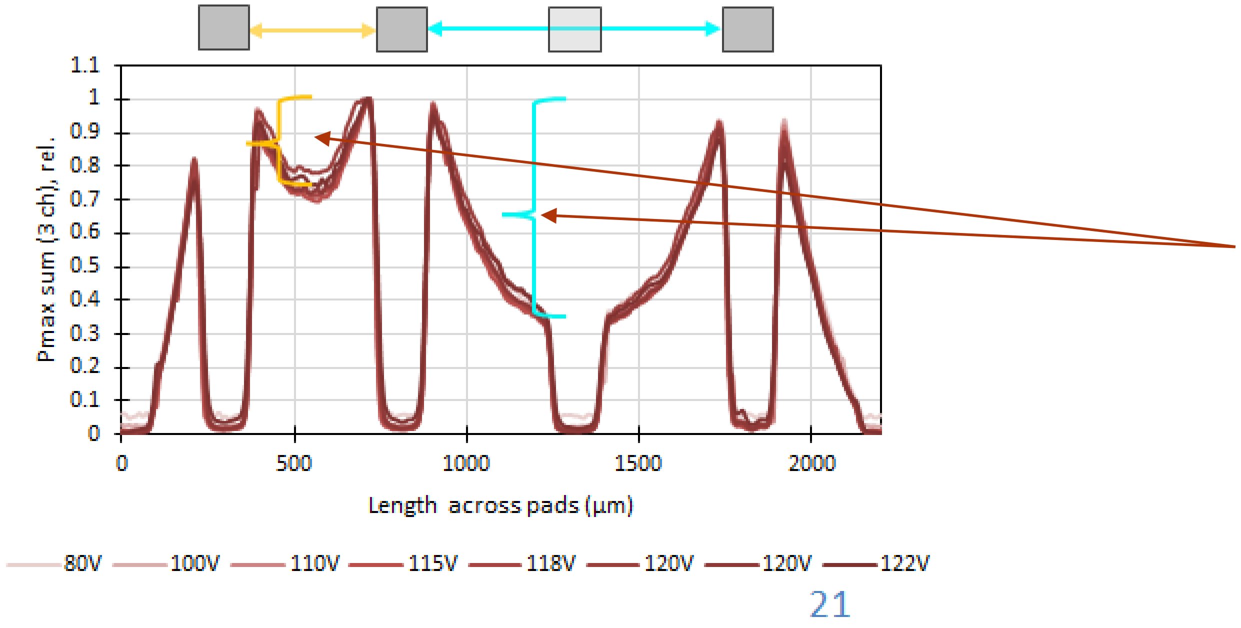
- Presented at TOF-PID meeting a few weeks ago
- Approach: leave some pads in a 4x4 pad array with 500 µm pitch unbonded and floating to mimic 1000 µm pitch, monitor pulse maximum as function of distance
- Using smallest currently available pad size in the HPK production: 150x150 µm. Here, a C600 sensor (more signal sharing) with bulk thickness 20 µm (faster rise time)



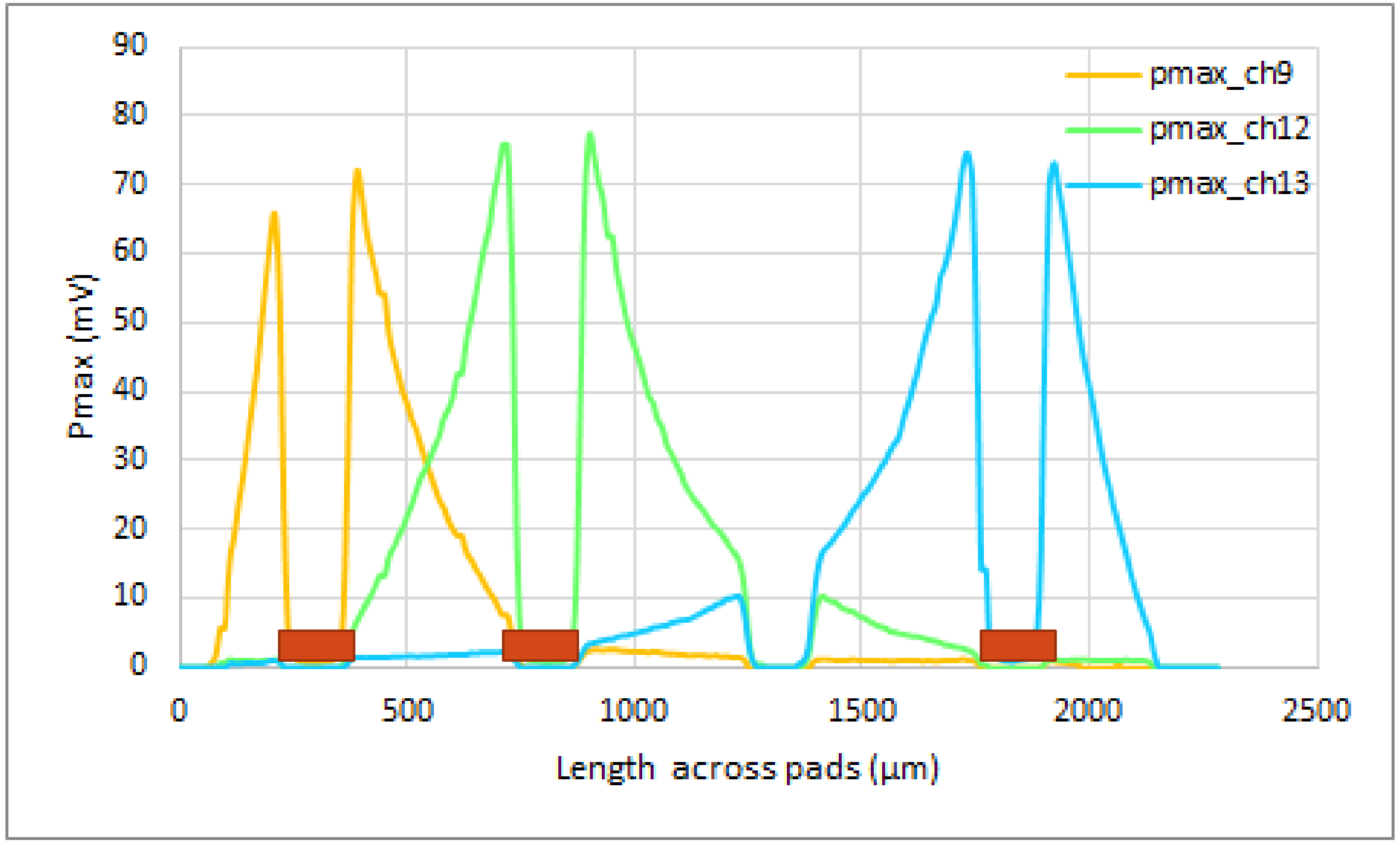
Standard square pad AC-LGAD

- Significant **loss of signal amplitude** between pads at 500 µm, more pronounced for the double distance: in this sensor, ca. 27% at the center point between adjacent pads, **ca. 65% for '1000 µm' pitch**
- The effect of the bias voltage on relative signal sharing is minimal (observed throughout this production)
- Whether smaller signal, worse SNR and jitter are acceptable depends on what gain the sensor is operated at = what absolute signal remains, and how critical the reduction of the metal size or channel count is finally determined to be

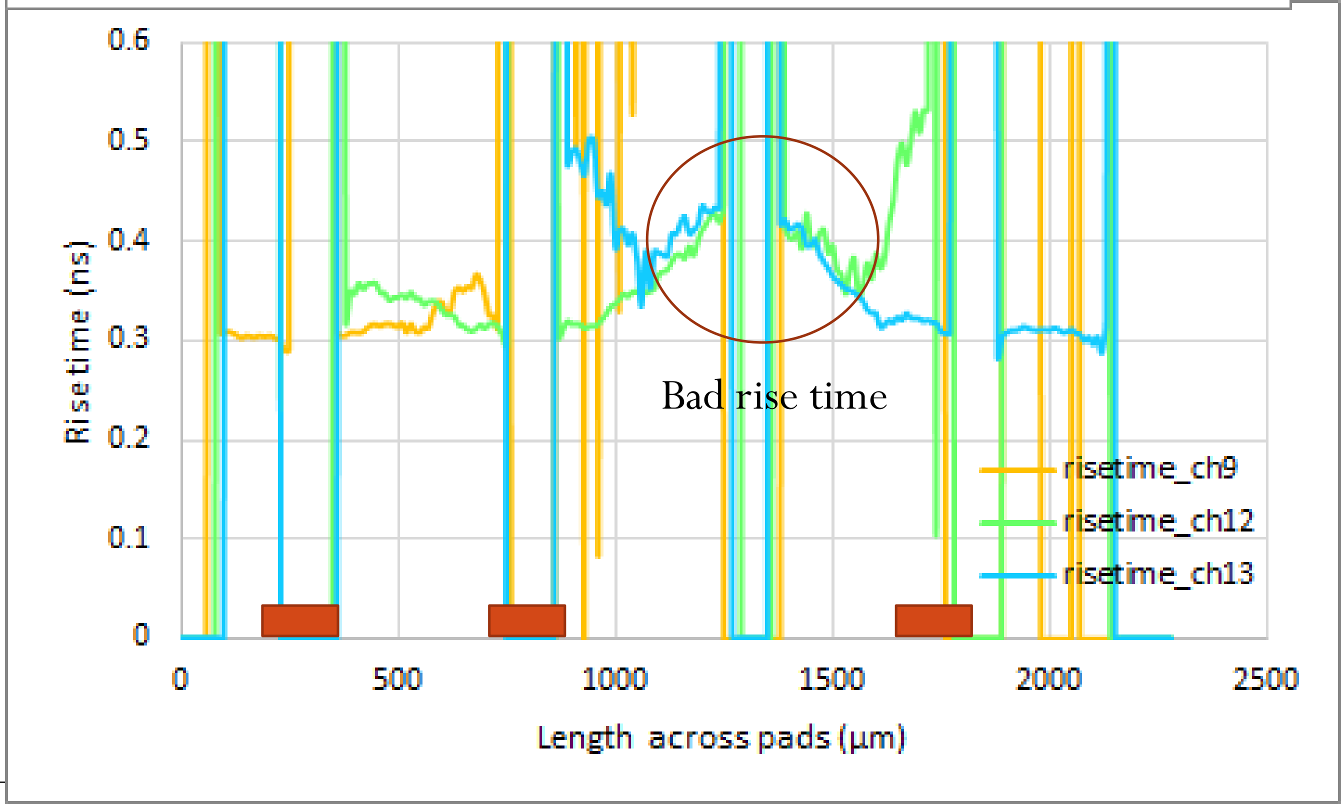




How to minimize the 'dip' in between pads?

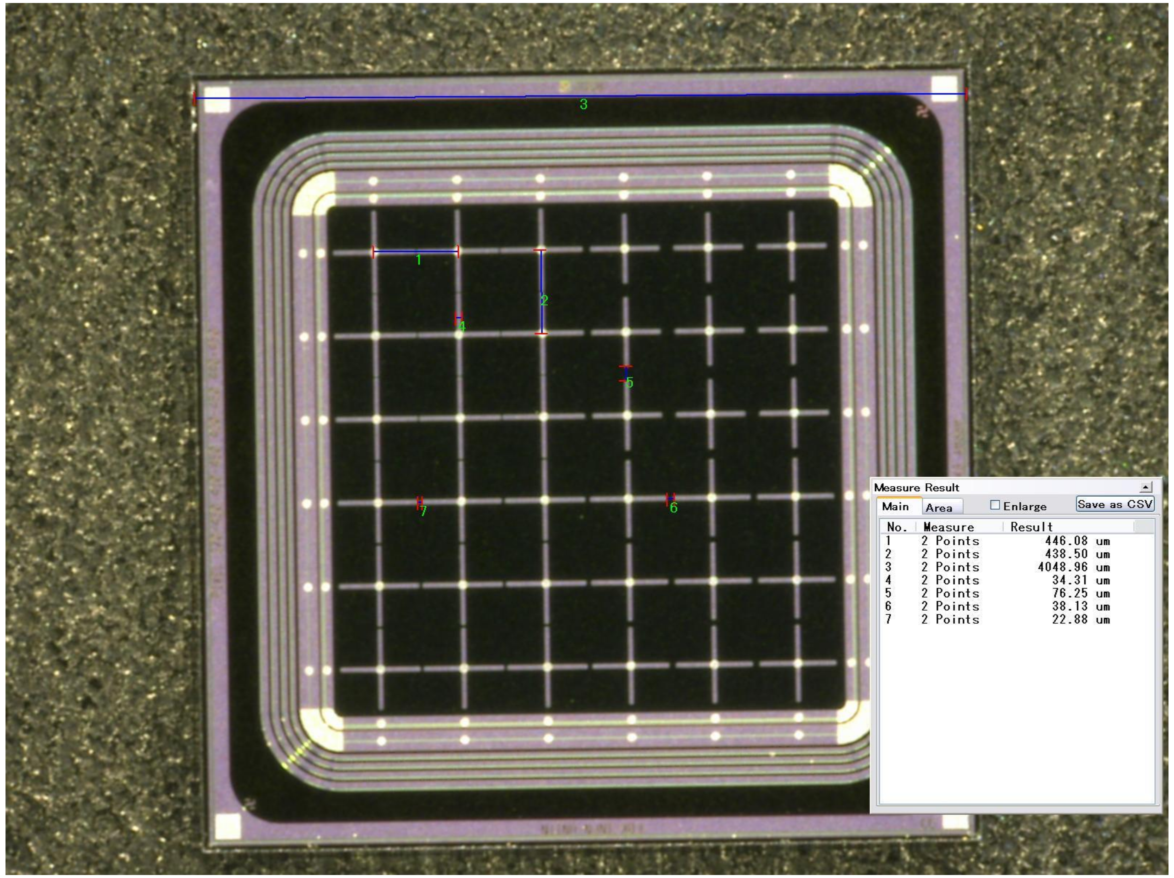

90
80
70
60
50
40
30
20
10
0
Pmax (mV)
0
500
1000
1500
2000
2500
Length across pads (µm)
pmax_ch9
pmax_ch12
pmax_ch13

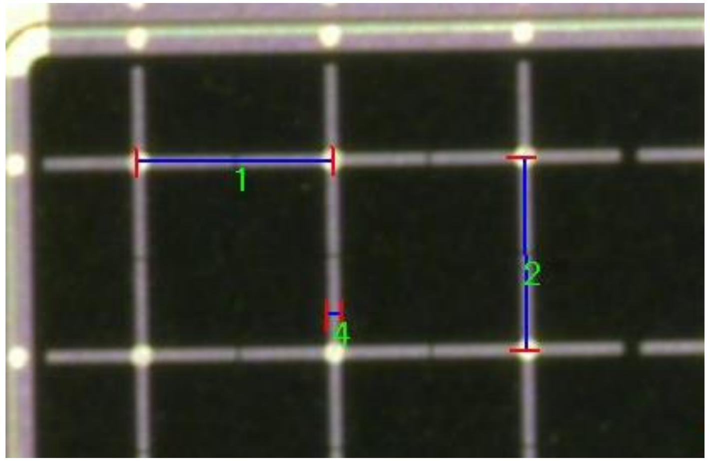

48
47.5
47
46.5
46
45.5
45
Time of arrival / CFD50 (ns)
0
500
1000
1500
2000
2500
Length across pads (µm)
ToA_ch9
ToA_ch12
ToA_ch13

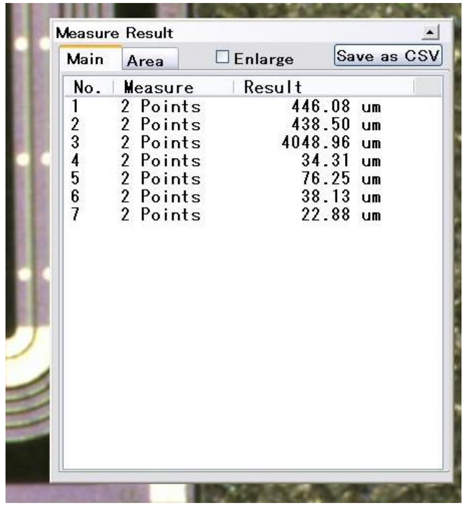

0.6
0.5
0.4
0.3
0.2
0.1
0
Risetime (ns)
0
500
1000
1500
2000
2500
Length across pads (µm)
Bad rise time
risetime_ch9
risetime_ch12
risetime_ch13

New geometries - crosses

- FBK sensor from RSD2 production
  - Pitch 450um
  - Bond pad size ~50x50um
  - Metal arm width ~35um
- Using metal ‘arms’ to collect the charge in a cross-like pattern
- Reduce the signal reduction in between thanks to the more efficient charge collection
  - Tested with laser TCT and compared with standard square pad sensor
- Only relative for now, no absolute comparison

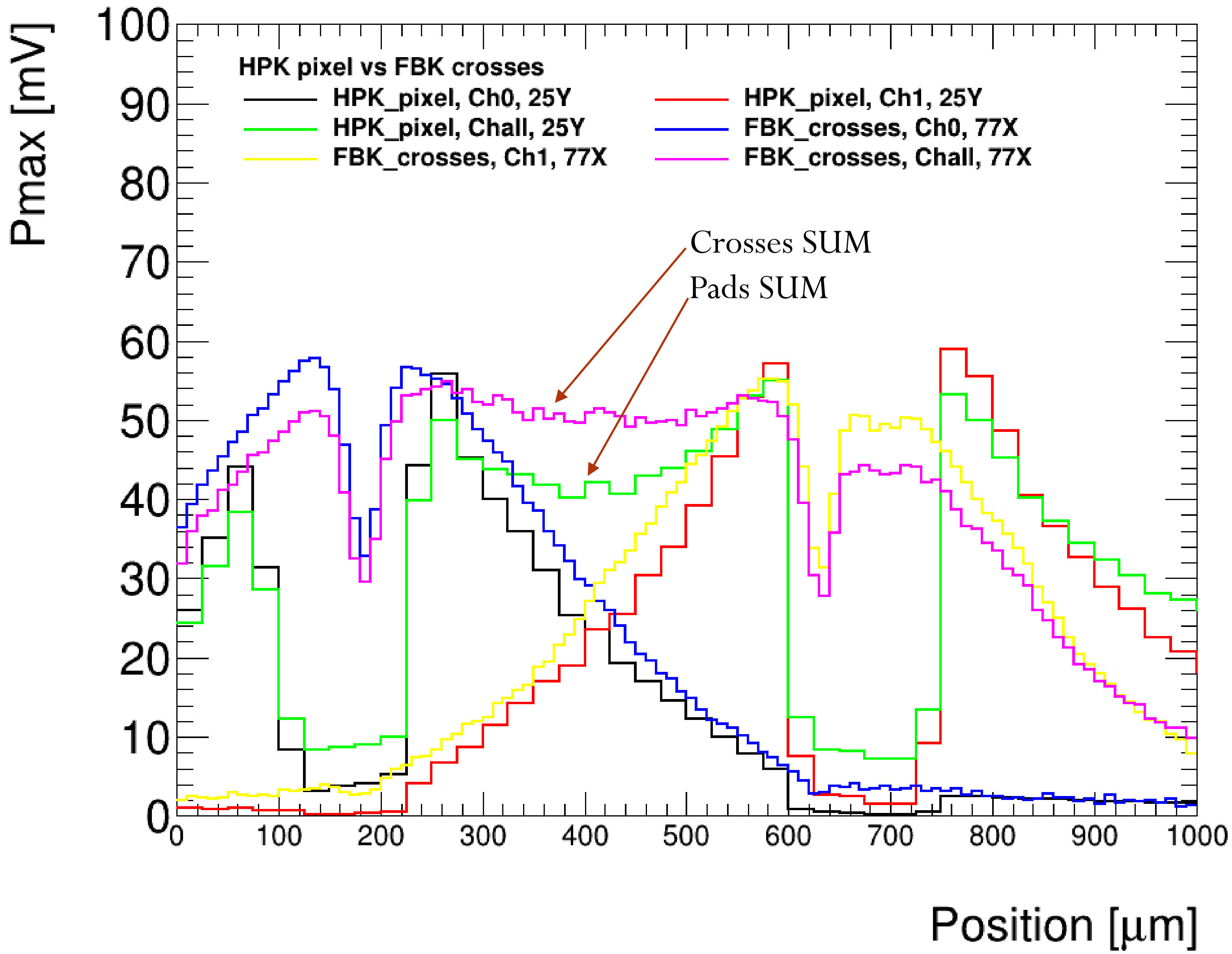






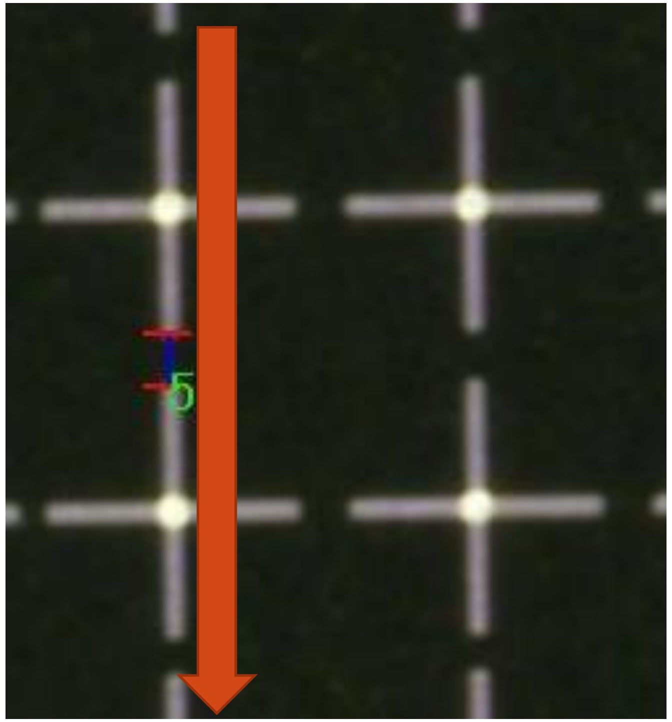
No.	Measure	Result
1	2 Points	446.08 um
2	2 Points	438.50 um
3	2 Points	4048.96 um
4	2 Points	34.31 um
5	2 Points	76.25 um
6	2 Points	38.13 um
7	2 Points	22.88 um

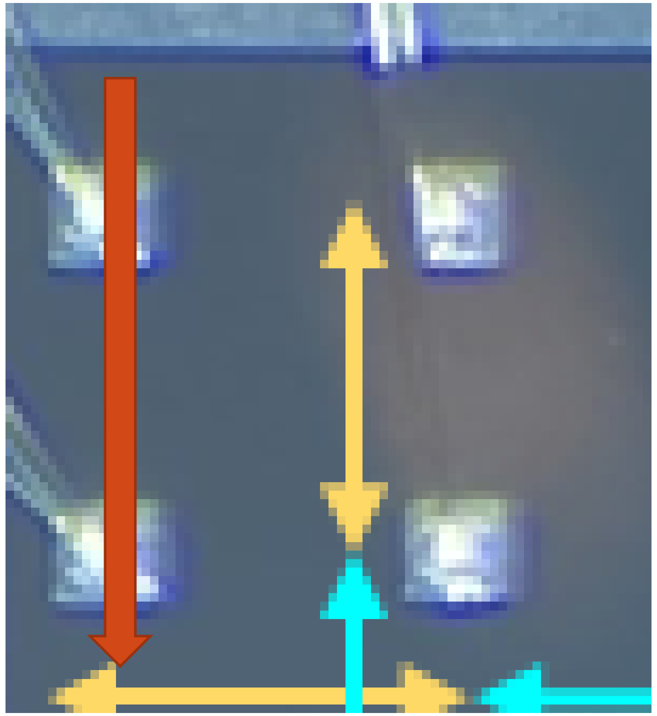
New geometries - crosses



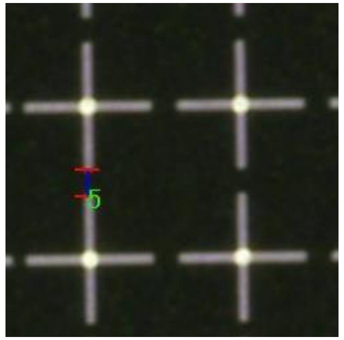
Crosses SUM

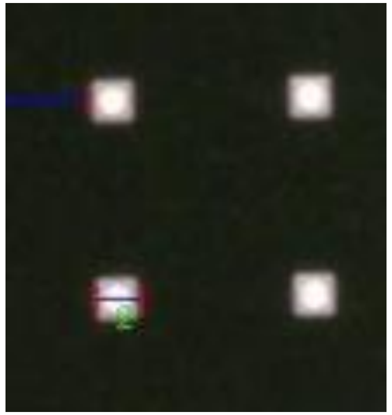
Pads SUM

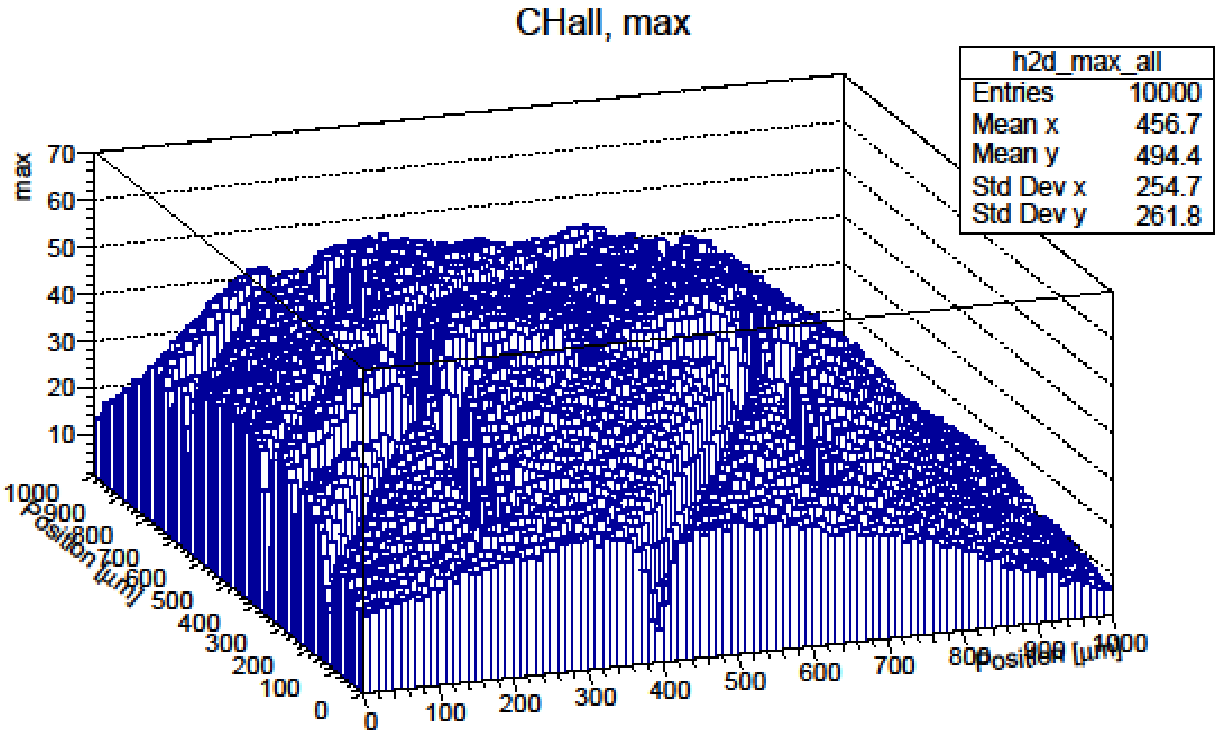


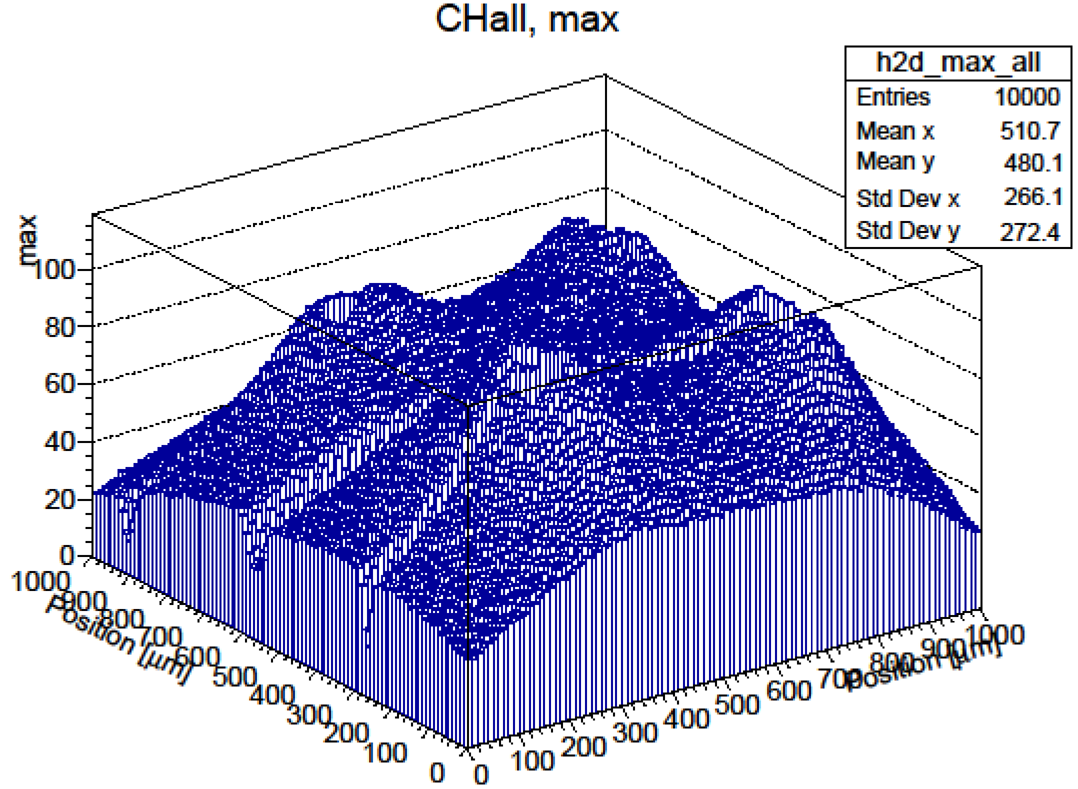


New geometries - crosses



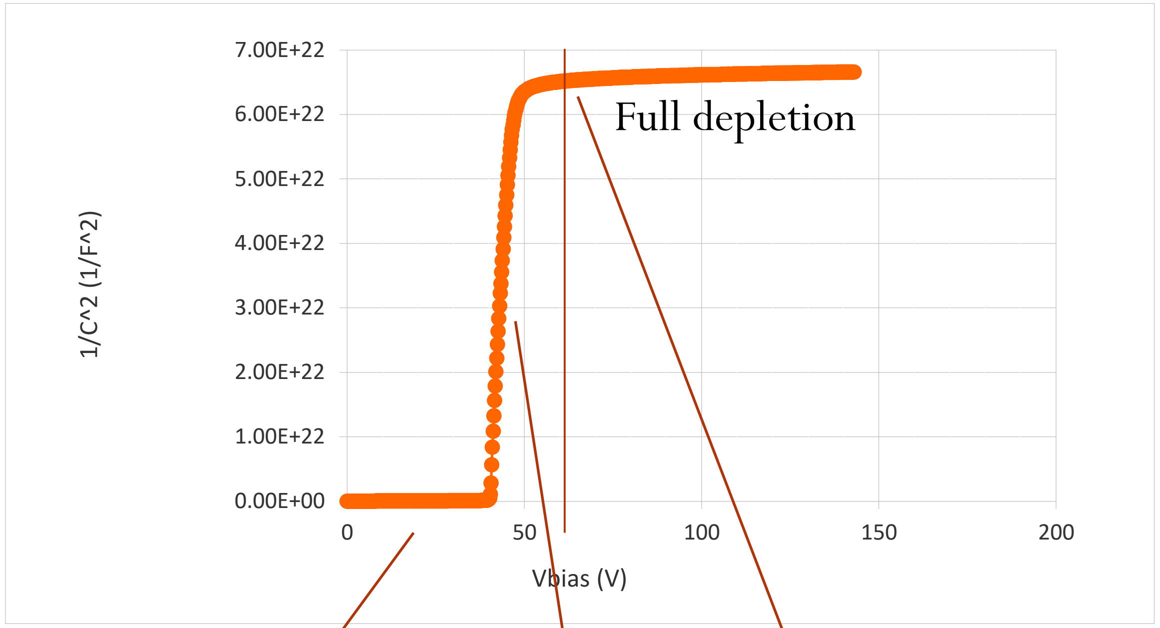




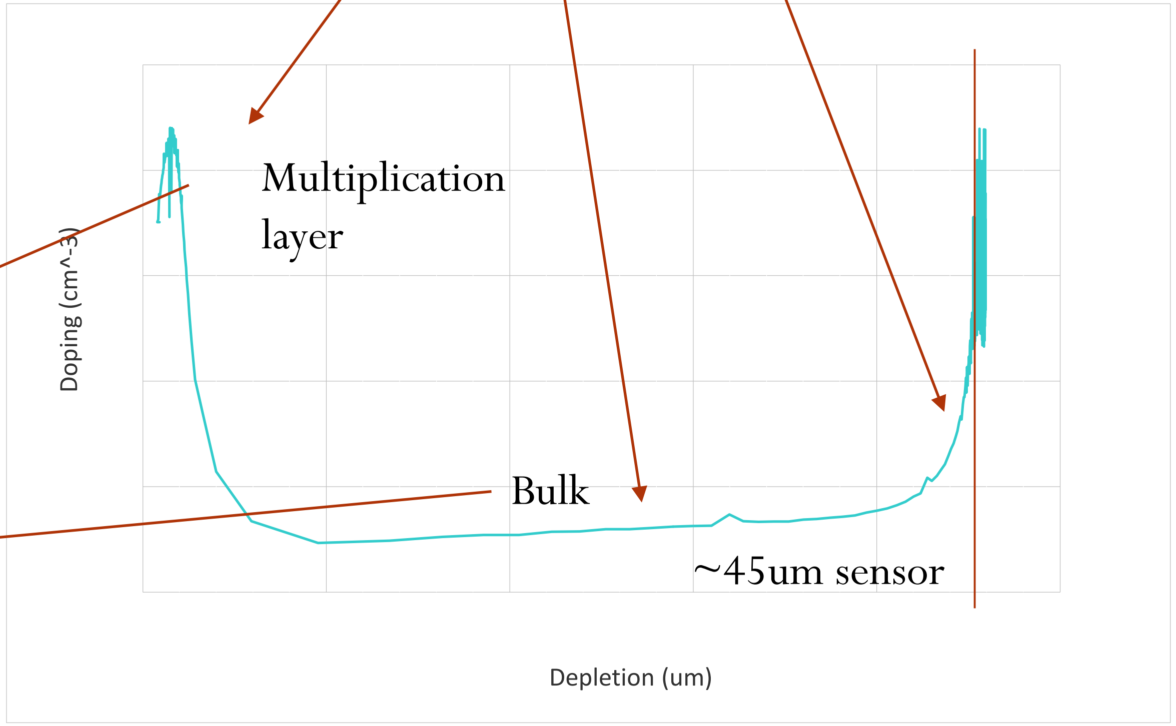


Sensor testing – IV/CV

- 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



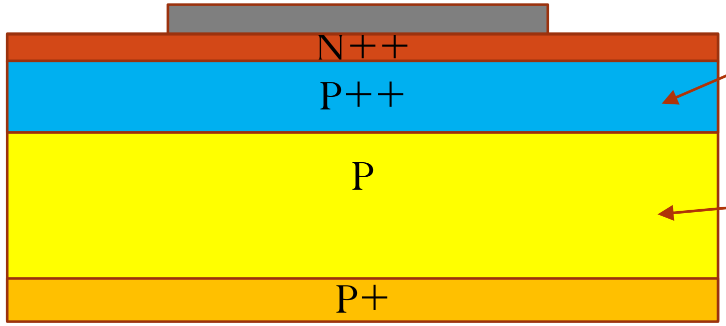
Full depletion



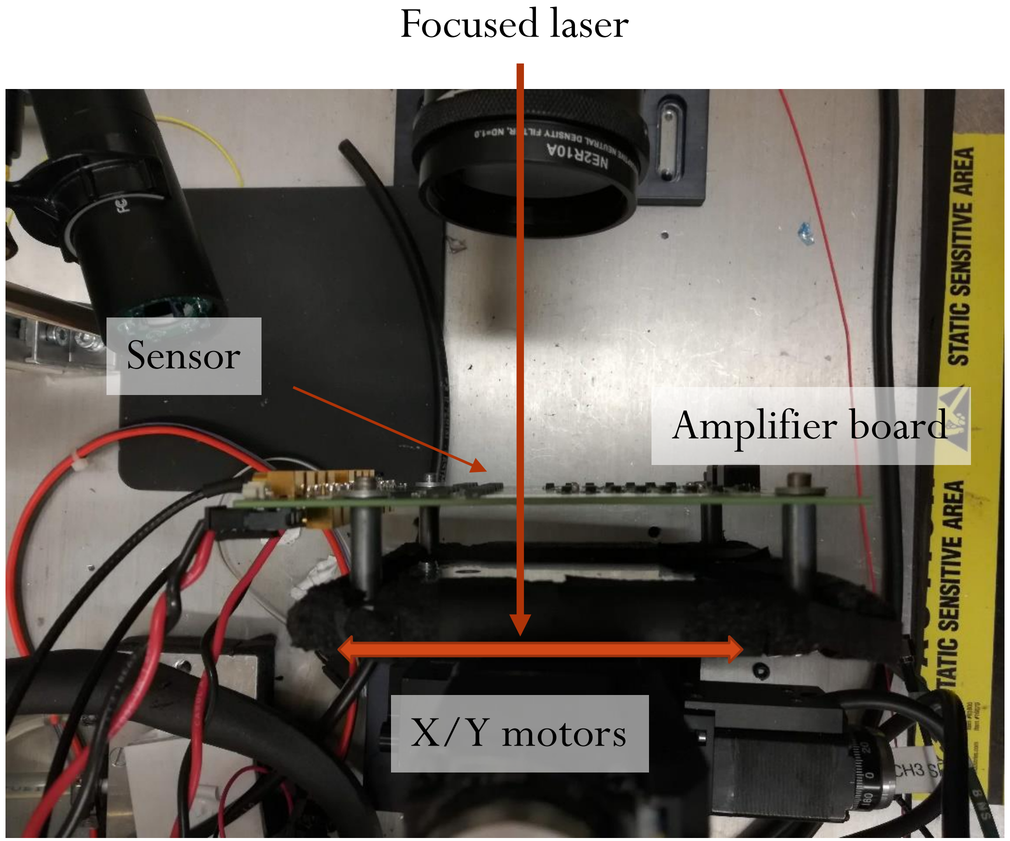
Multiplication layer

Bulk

~45um sensor



Sensor testing –Laser TCT setup

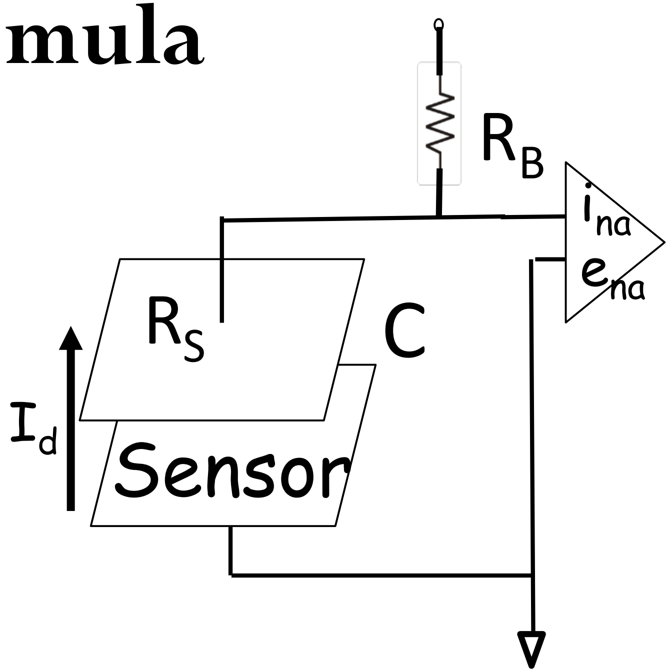


- Sensors are mounted on a multi-channel analog amplifier board with bandwidth ~1 GHz
  - Response is readout by 2 GHz/20 Gs oscilloscope
- **IR laser (1064 nm)** mimics charge deposit of a Minimum Ionizing Particle (MiP)
  - Focused laser beam with spot width ~20 um
- Amplifier board is mounted on X/Y 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

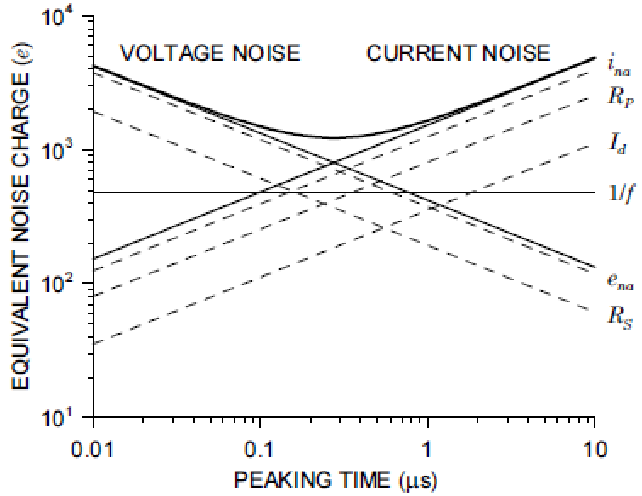
- Strictly speaking, applies to "lumped elements" (separate C, R_S)

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

Signal-shape parameters (of order 1)

$$Q^2 = \overbrace{\boxed{F_i\tau\left(2eI_d+\frac{4kT}{R_B}+i_{na}{}^2\right)}}^{\text{Noise current sources}} + \overbrace{\boxed{\frac{F_vC^2}{\tau}\left(4kTR_s+e_{na}{}^2\right)}}^{\text{Noise voltage sources}}$$

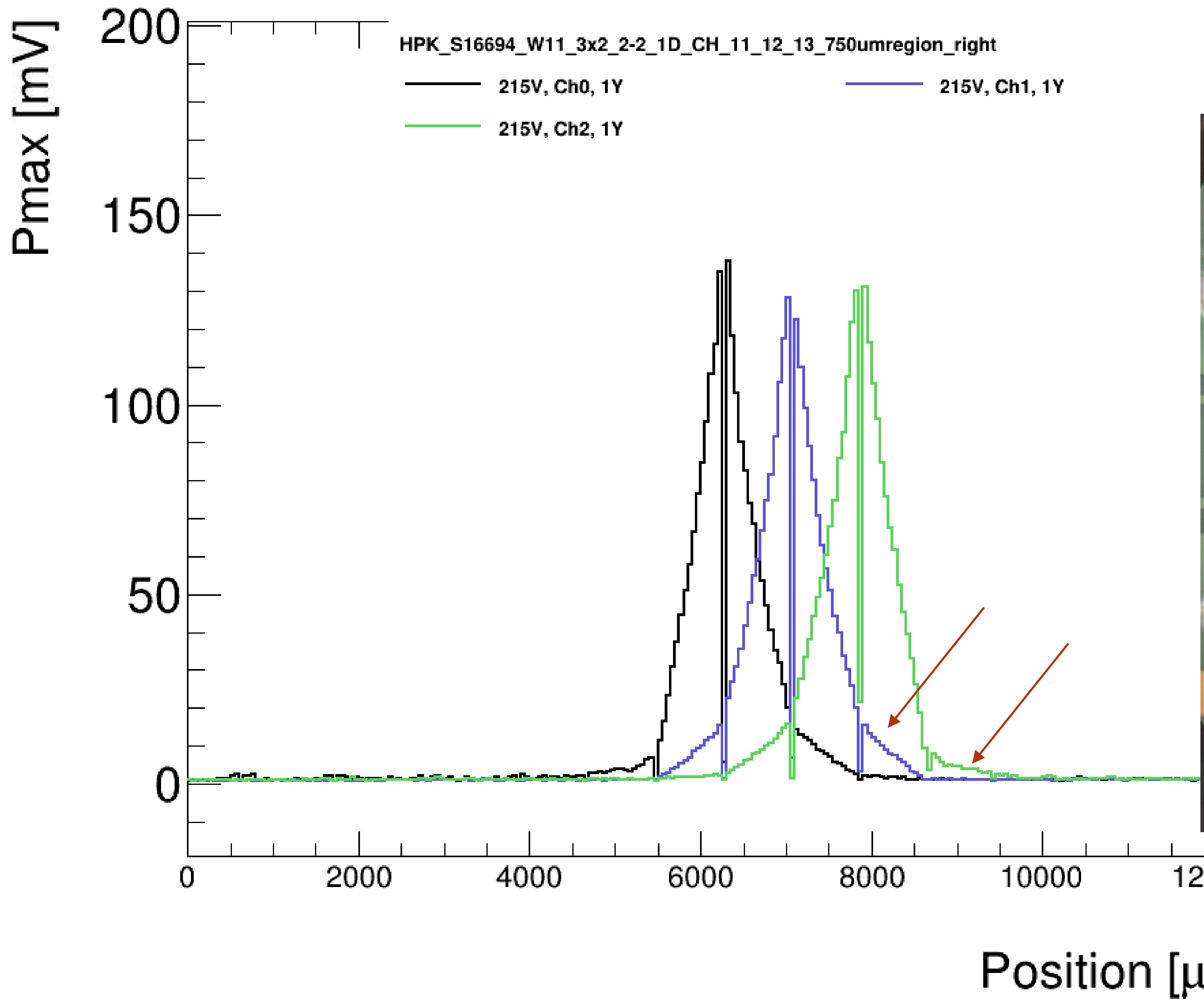
Amplifier shaping time (1/Bandwidth)

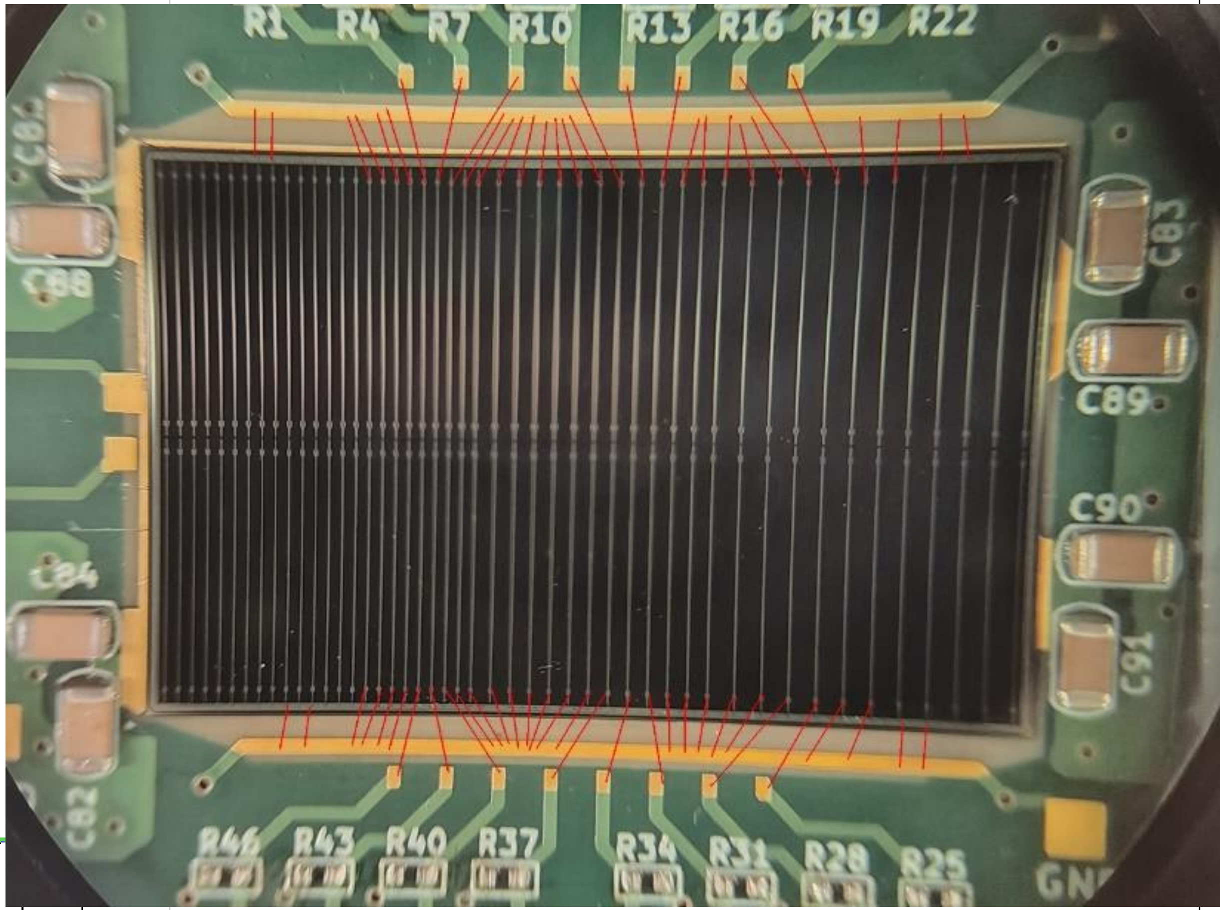


(For a particular set of parameters)

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

From "Semiconductor detector systems", H. Spieler


HPK_S16694_W11_3x2_2-2_1D_CH_11_12_13_750umregion_right
215V, Ch0, 1Y
215V, Ch1, 1Y
215V, Ch2, 1Y
Pmax [mV]
200
150
100
50
0
0
2000
4000
6000
8000
10000
12000
Position [µm]


R1
R4
R7
R10
R13
R16
R19
R22
C86
C88
C83
C89
C90
C84
C91
C82
R46
R43
R40
R37
R34
R31
R28
R25