

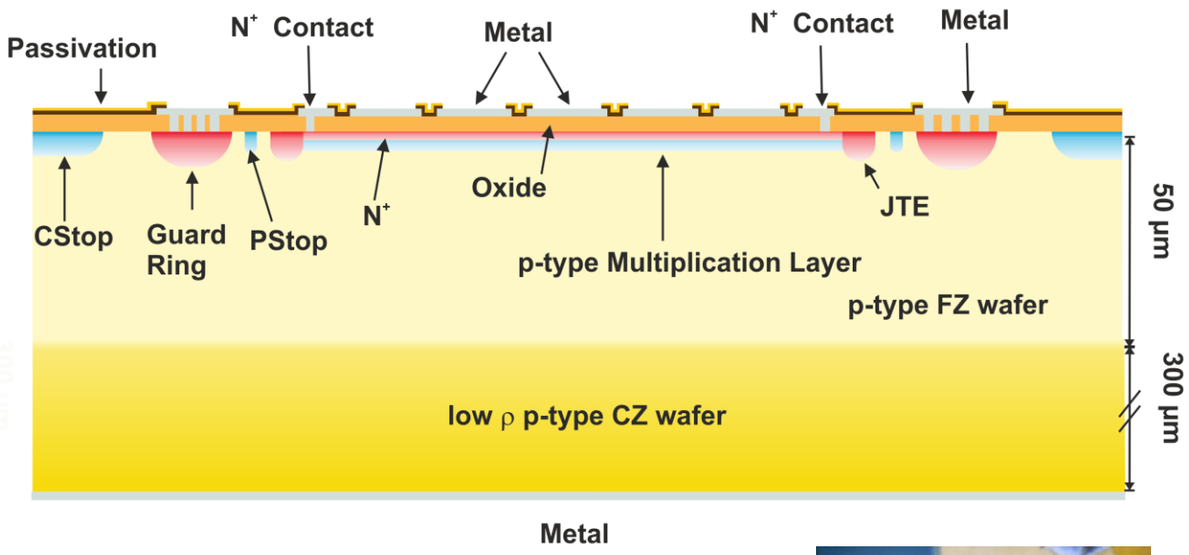
Performance of AC-LGADs for ePIC time of flight layers and beyond

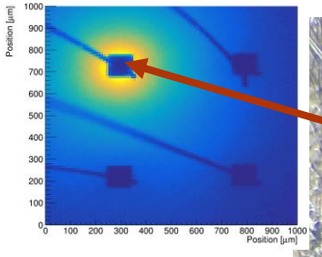
Dr. Simone M. Mazza, A. Tiernan, A. Gsponer, A. Molnar
(SCIPP, UC Santa Cruz)
G. Giacomini (BNL)
On behalf of SCIPP UFSD group and ePIC TOF

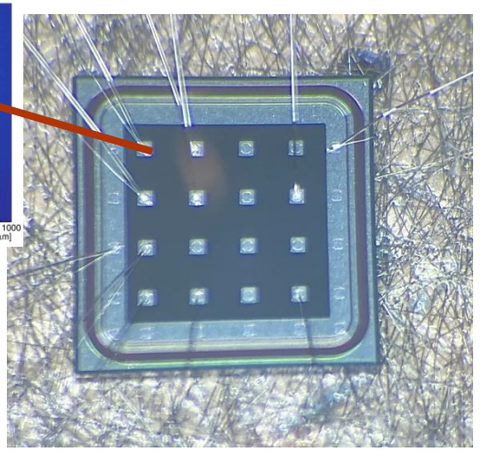
CPAD 2026, Oct 2026, UW

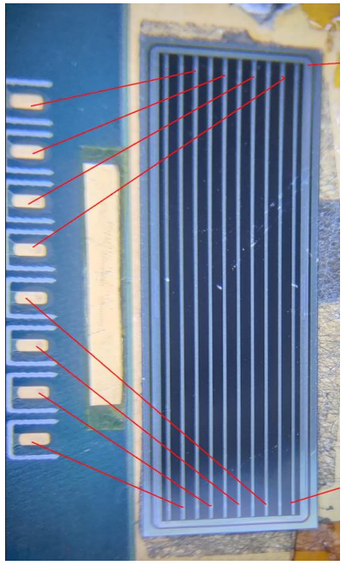
AC-LGADs

- ‘Standard’ LGADs has granularity limited to ~mm scale due to the high field on the surface
- High-granularity **AC-coupled LGAD**
  - Continuous multiplication layer coupled with resistive (low doping) N+ layer after the gain layer
  - Readout pads are AC-coupled with insulator layer
- AC-LGAD has intrinsic **charge sharing**
  - Gain increases allows for smaller metal pads
  - Using information from multiple pixels/strips for hit reconstruction
- Reduce channel density and power dissipation while maintaining good resolution



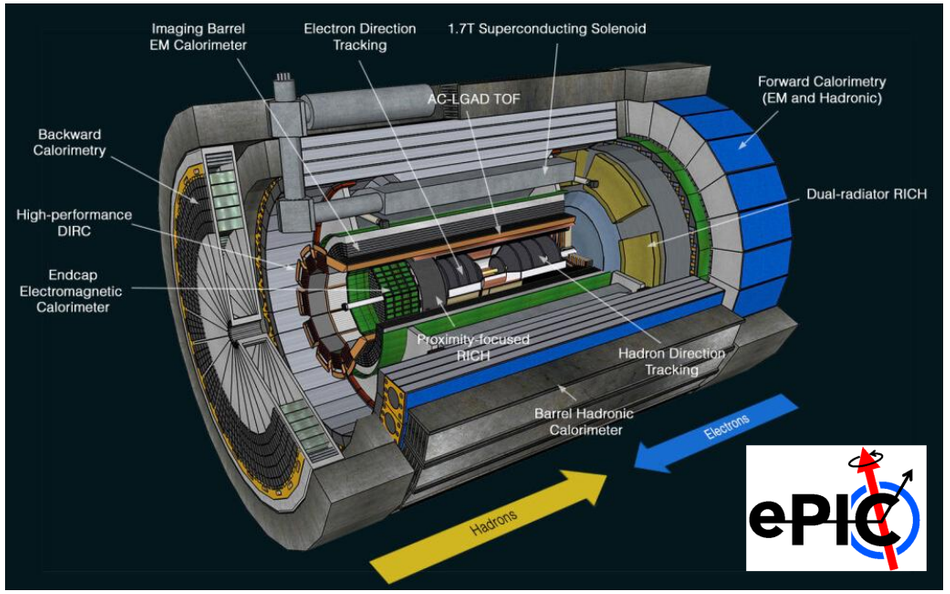






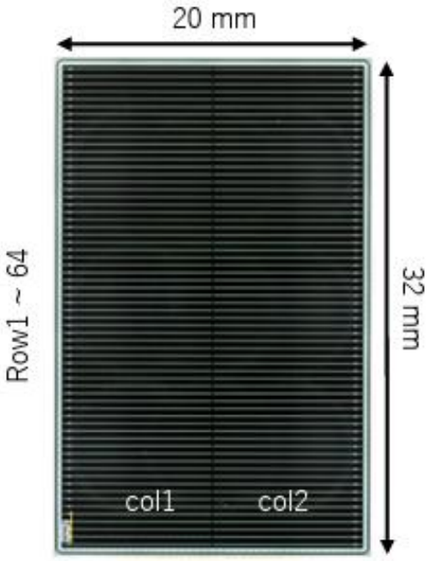
The ePIC detector

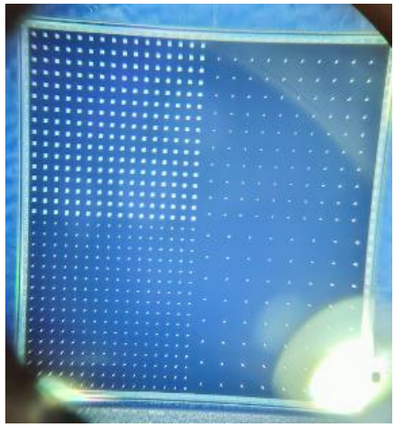
- **4D tracking** is a necessity to reach ePIC's physics goals
- **Particle identification with time of flight (TOF)**
  - For e/π/K/p at low/intermediate momentum
  - Require good time resolution and meaningful flight distance
- **A TOF layer** is foreseen for both barrel and end-cap in ePIC
  - Barrel (BTOF) with 1cm-long strip, 500um pitch
  - End-cap (FTOF) with 500 x 500 um pixels
  - Off-momentum detector (OMD) with same design as FTOF



- **TOF layers based on AC-LGAD technology**

outdated **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	40	30 ($r \cdot \phi$)	3%
Forward TOF	1.1	0.5*0.5	3.2M	25	30 (x, y)	5%
				Challenging		**Challenging**

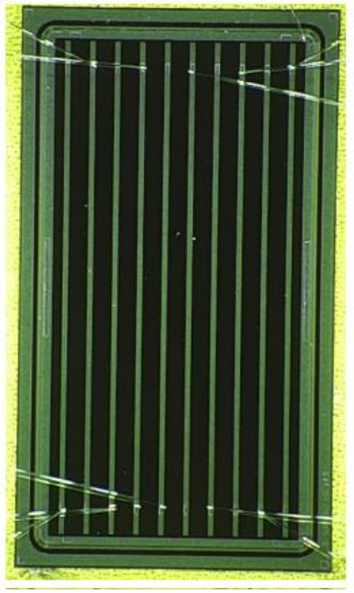




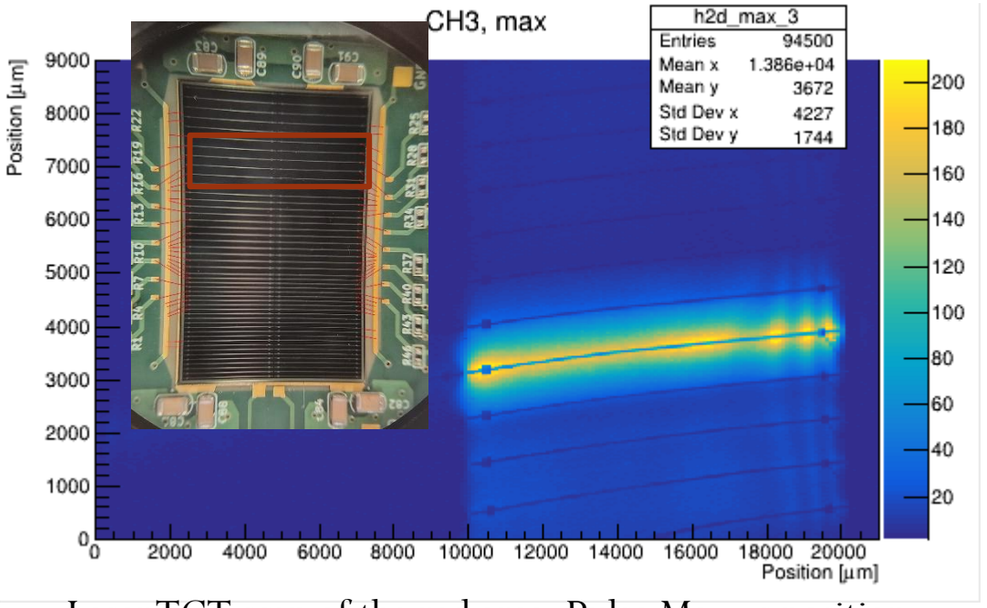
ePIC strip AC-LGADs prototype runs

- **2023:** Small-size AC-LGADs prototypes (1x0.5cm) at HPK, defined parameters of geometry, oxide and N+ resistivity (https://arxiv.org/abs/2407.09928 https://doi.org/10.1016/j.nima.2024.169478)
  - Time resolution 35ps , Position resolution 20um
- **2024:** ePIC full-size production of HPK strip AC-LGADs → biggest AC-LGAD ever!
  - Nominal size 3.2x2.2 cm with 1cm strip 'segments', strip width: 40-50um, strip pitch 500, 750, 1000 um
  - 50/30um thicknesses, using parameters identified in 2023.Yield issues with 50um thickness, but addressed in following production
  - Identified 500x50um with 50um thickness as the best geometry
  - 10.22323/1.513.0020
- **2025:** ePIC full-size (no pitch variation) production done at HPK in 2025,Yield >80%, similar performance as 2024 sensors
  - Variation in thickness (20-30-50um) and geometry (500x1cm, 1000x0.5cm)

2023

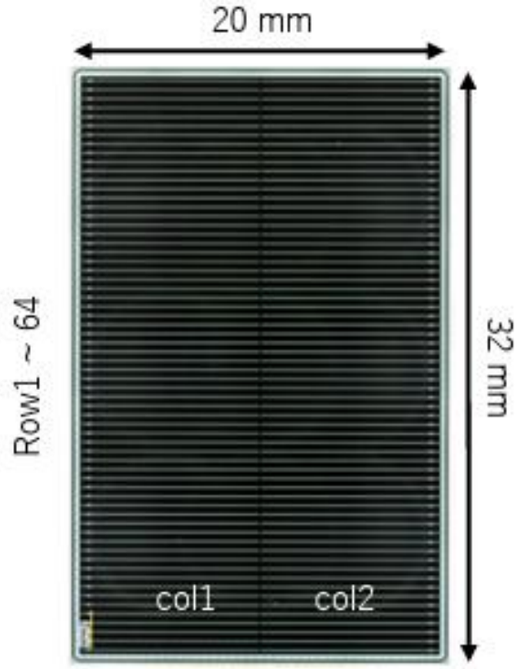


2024



Laser TCT scan of the red area, Pulse Max vs position
IR laser spot 20um, time width 30ps

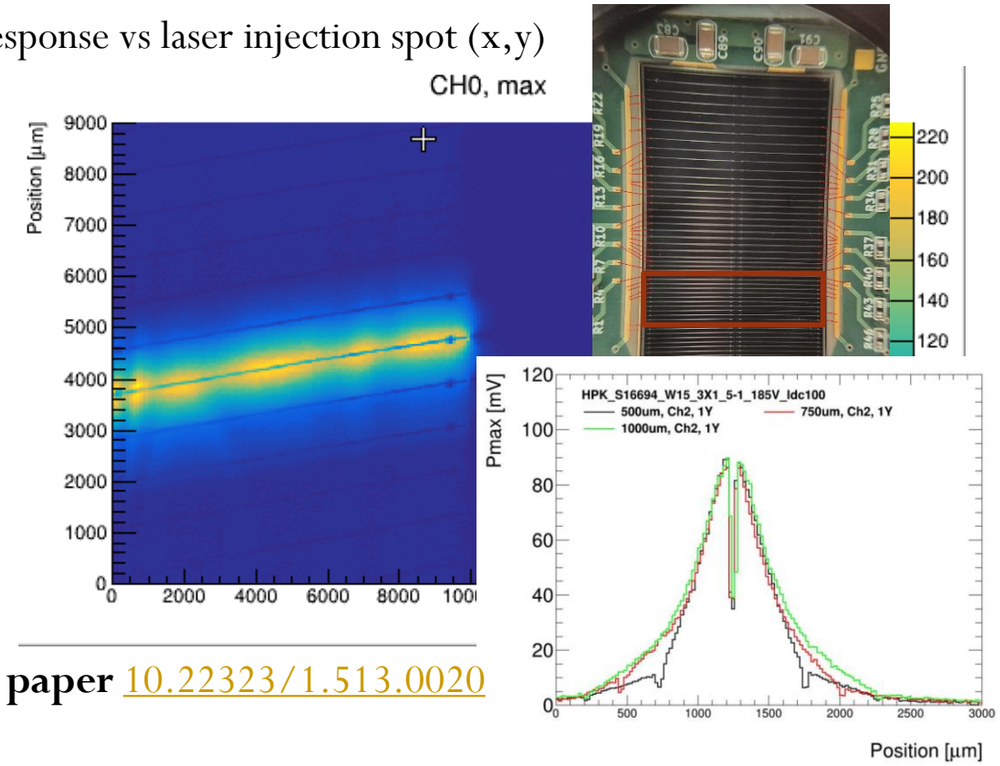
2025



HPK production results - TCT

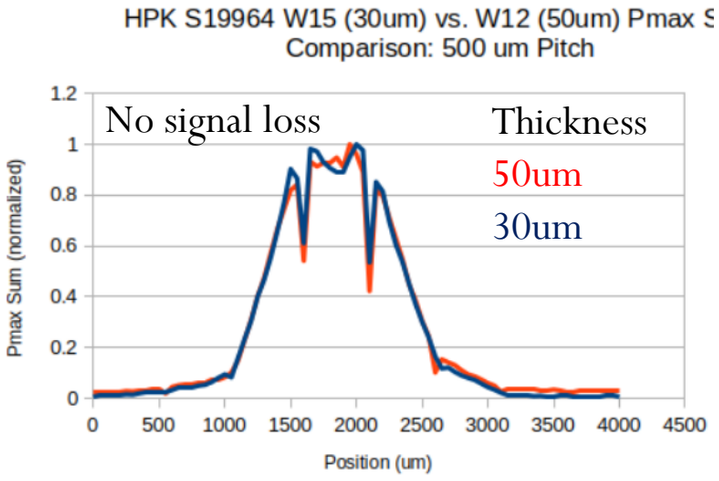
- Laser TCT (spot size 10-20um) scan of large prototypes
  - Injected charge comparable with MIP
- Strip pitch has a minor effect on the charge sharing profile
  - Loss of S/N in between strips for larger pitch
  - Depends on sensor thickness
- **Time of arrival delay** ~2ps/um perpendicular to the strip and ~0.01ps/um parallel to the strip
  - Need to be corrected for good time resolution

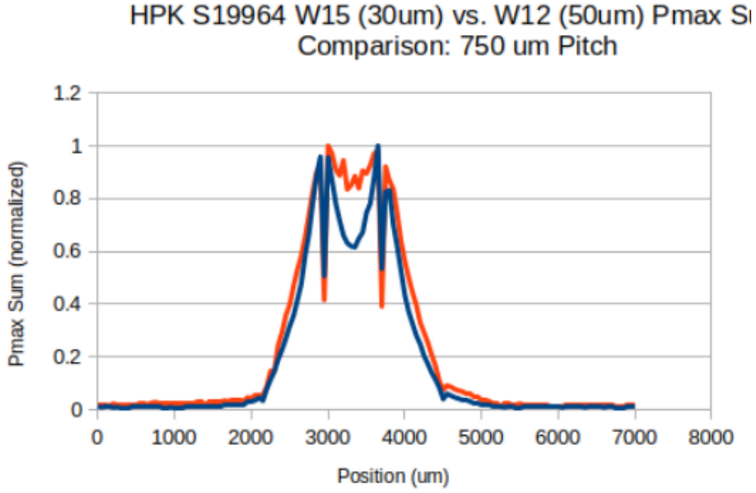
Strip response vs laser injection spot (x,y)

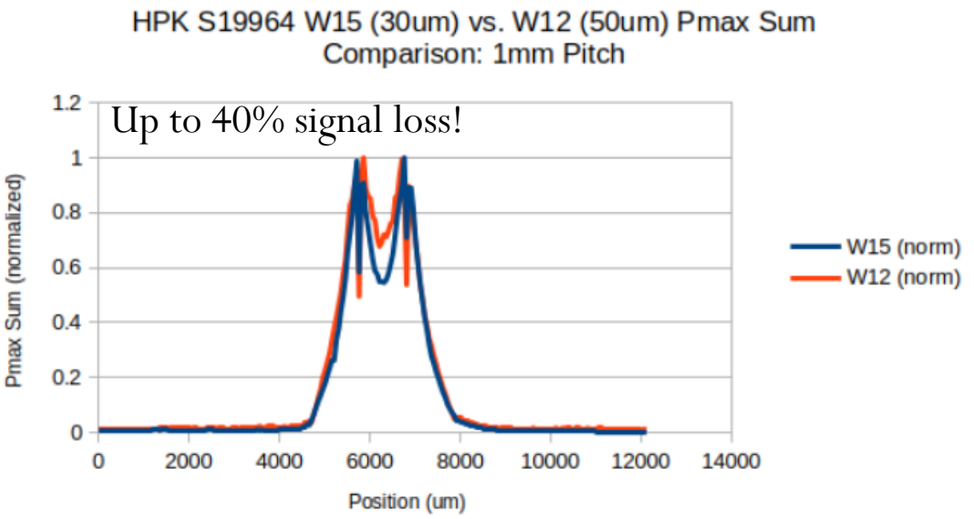


paper 10.22323/1.513.0020

Sum of two channels perpendicular to the strip for the three different pitches





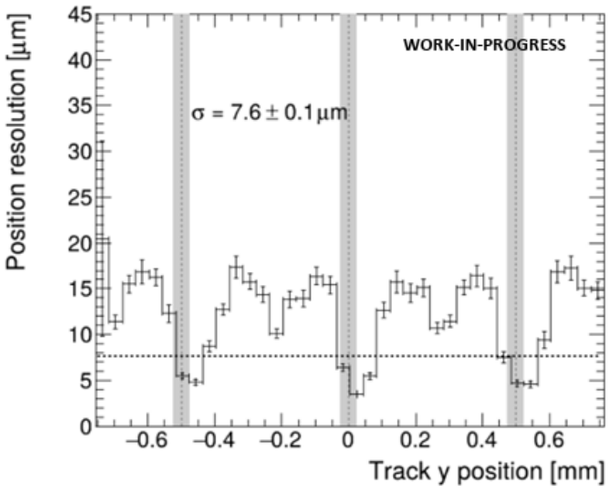


Student: M. Davis, G. Stage, A. Borgijin

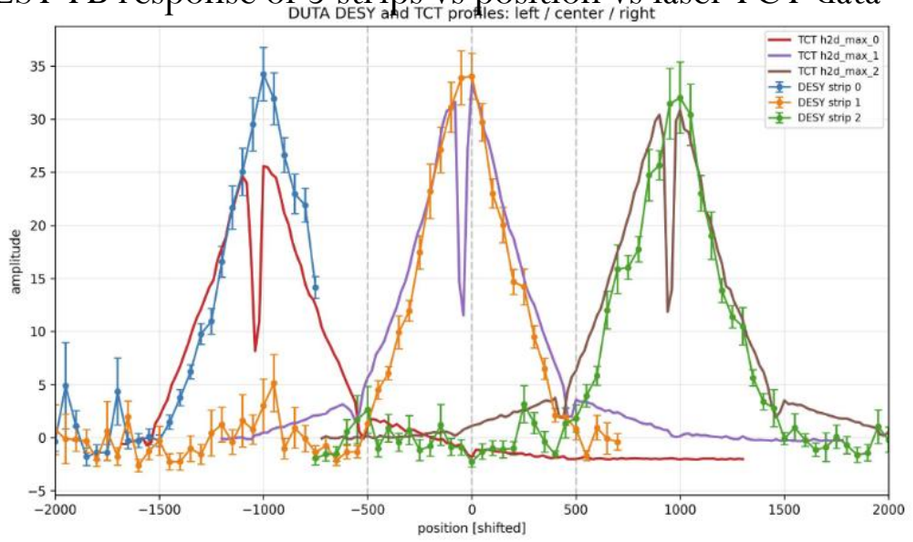
Performance of HPK devices - resolution

- 2024 strip sensor tested at DESY in Dec 2025
  - **Position resolution <15um**, but no time reference available for time resolution
  - Strip response vs position same as laser TCT data in the lab
- Time resolution of measured in the lab using beta source with coincidence trigger
  - Event reconstruction using TB data, time resolution as reconstructed DUT time minus trigger time
  - Corrections for arrival delay applied (~2um/ps)
  - **Around 40-50 ps of time resolution over the tested region of 3 strips**

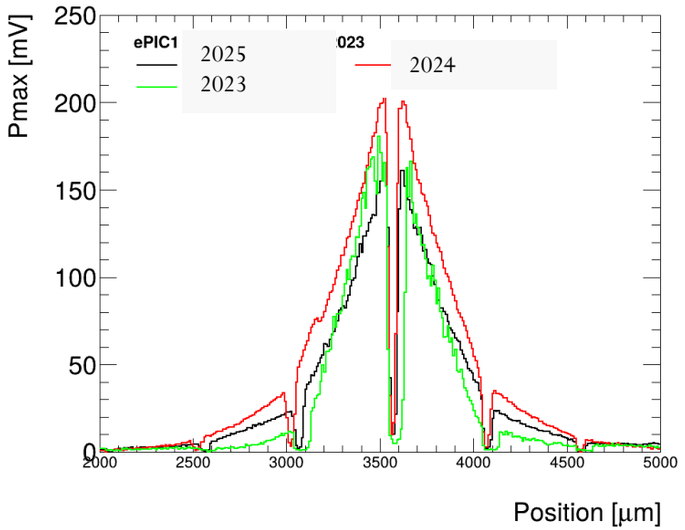
From S. Yano, Hiroshima U.

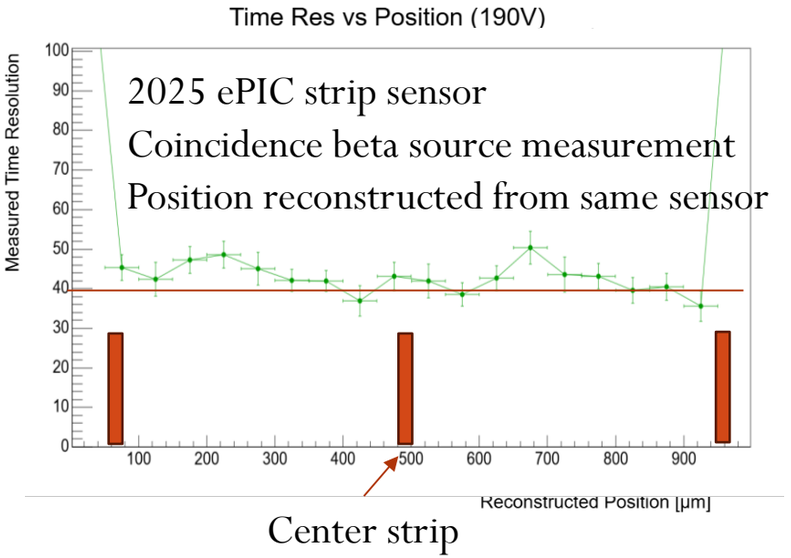


DESY TB response of 3 strips vs position vs laser TCT data



Laser TCT comparison of the three years





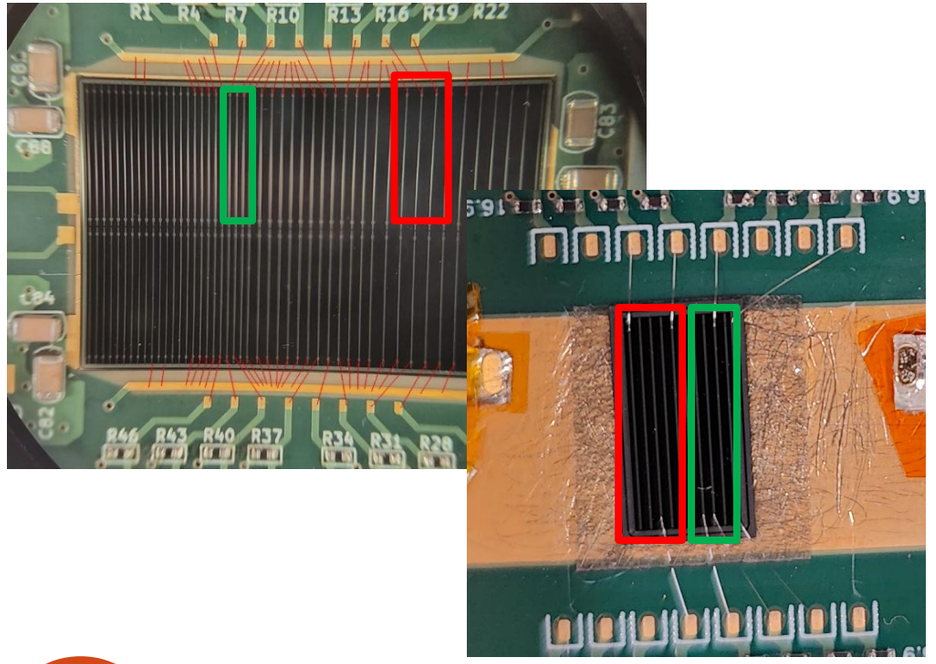
Center strip

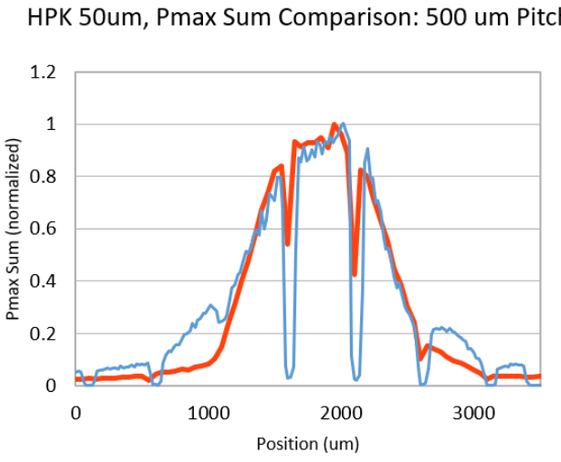
Dr. Simone M. Mazza - University of California Santa Cruz

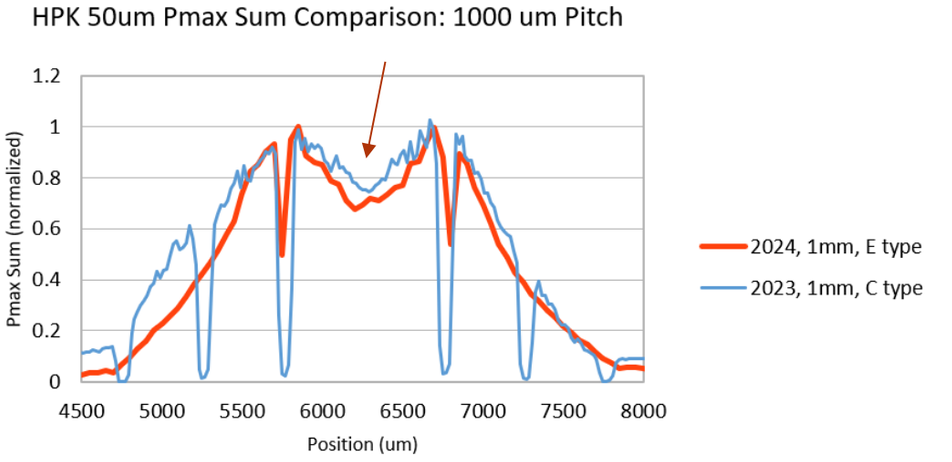
Students: L. Guccione-Jimenez, M. Davis

Resistivity effects at different pitches

- Plan to study larger pitch for lower resistivity devices to check effects on large pitch
  - HPK 2024 s16694, 50um, (n+ sheet resistance: 1600 Ω/□ (E-type)), 50um strip width
  - HPK 2023 W8, 50um, (n+ sheet resistance: 600 Ω/□ (C-type)), 100um strip width (1mm simulated by connecting every other strip)
- Sum of two nearby channels (normalized to 1) → not a large effect!
  - Not a lot of difference both for 500um and 1mm pitch, S/N loss for C-type slightly less for 1mm pitch

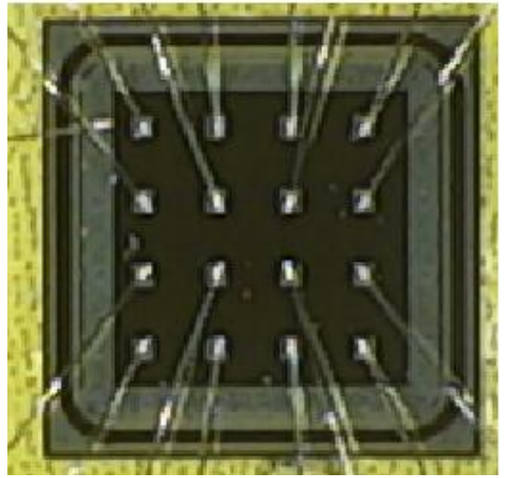


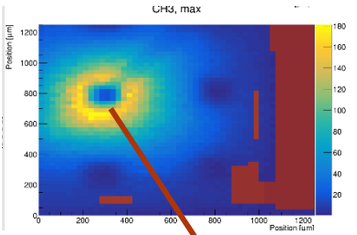


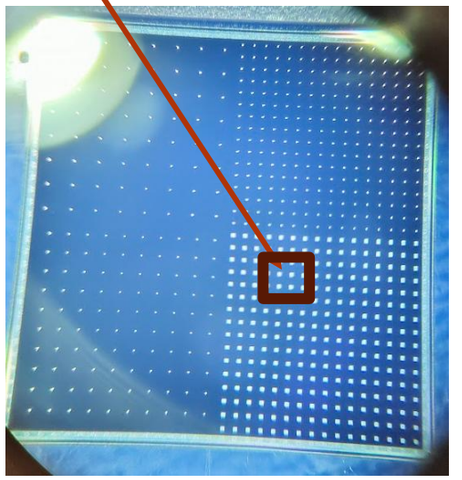


ePIC pixel prototypes

- **2023:** Small pixel prototypes with different parameters
  - Time resolution 20ps, position resolution 30um
  - https://arxiv.org/abs/2407.09928
- **2024:** ePIC full-size production of pixel AC-LGADs from HPK of 1.6x1.6 cm
  - Using parameters from 2023 production
  - Pixel pitch and width: 50,100,150um, pitch 500, 750, 1000 um. 30um and 20um thick
  - Yield >80% for all wafers
- KEK test beam (in 2026) for 2024 production data analysis ongoing,
  - Will steer next production
- See https://indico.phy.ornl.gov/event/677/contributions/2683/ for lab characterization





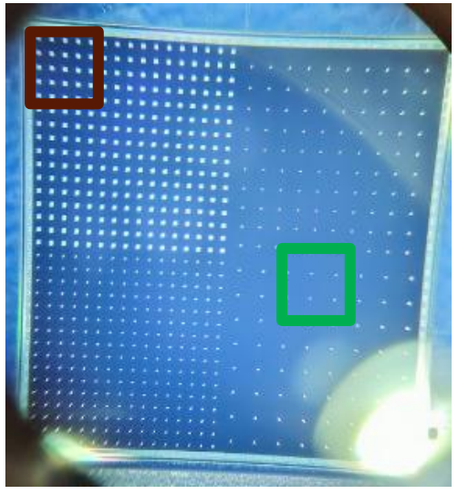


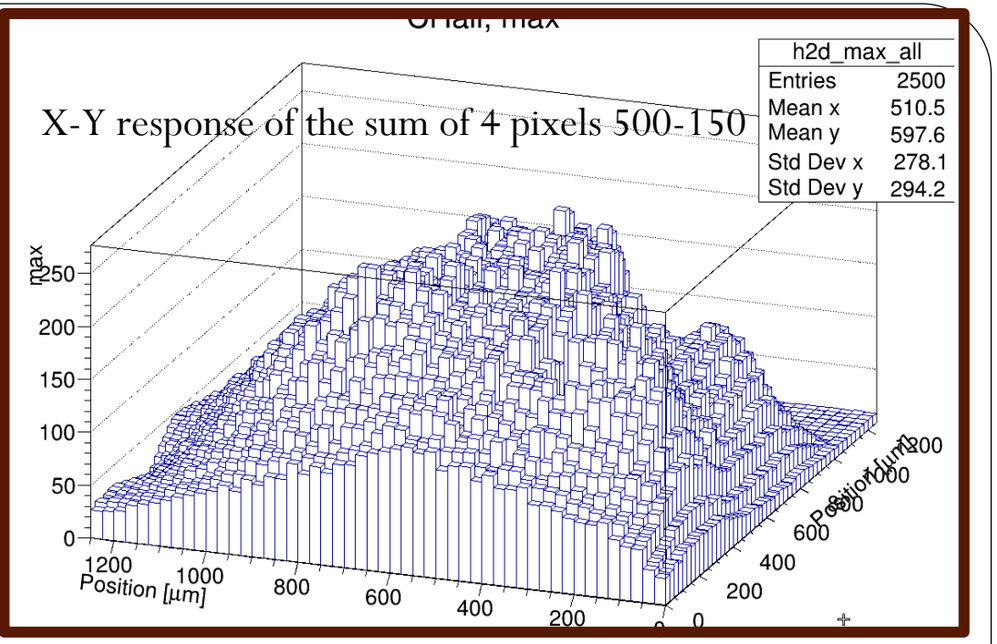
Detector type	Thickness	Pitch-width 1	Pitch-width 2	Pitch-width 3	Pitch-width 4
W3 pixBIG	20um	500-150	500-100	750-100	1000-100
W3 pixSmol	20um	500-150	500-50	750-50	1000-50
W7 pixBIG	30um	500-150	500-100	750-100	1000-100
W7 pixSmol	30um	500-150	500-50	750-50	1000-50

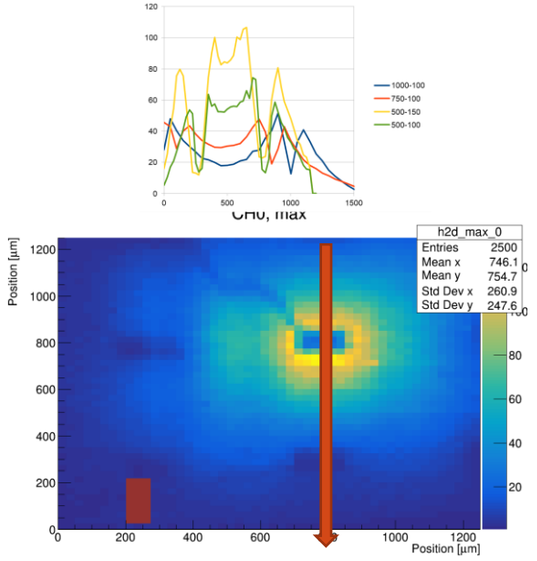
Students: N. Lynch, A. Drumm, Y. Spinos, O. Khandelwal

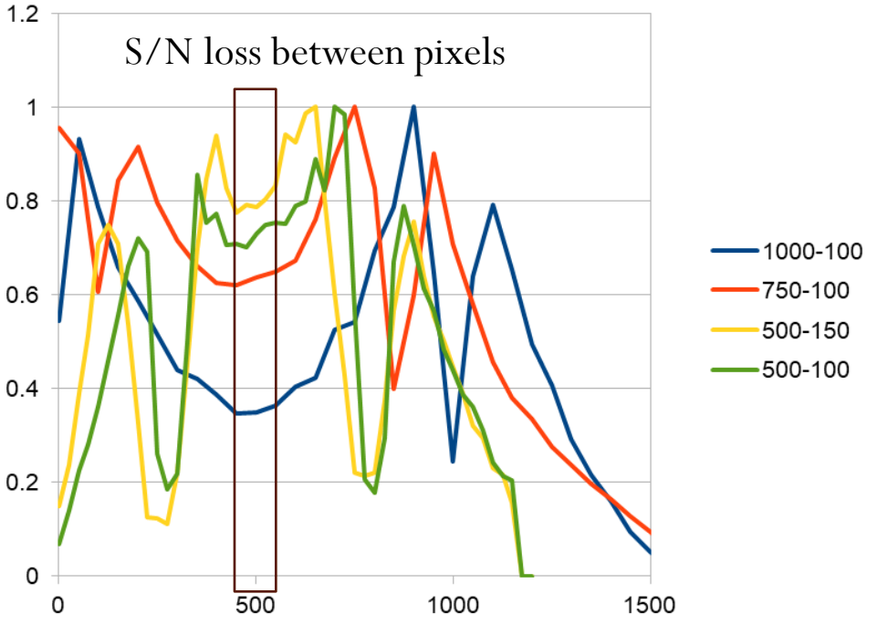
Pixel laser TCT testing

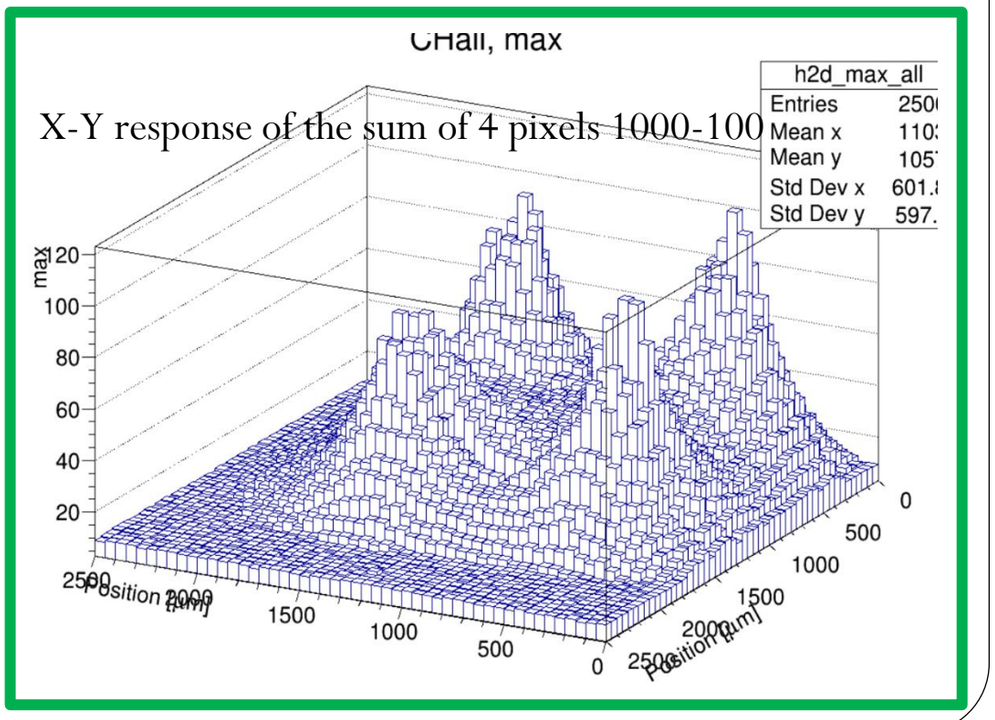
- Sensor: W7 (30um) – big pixels
  - 500-150um vs 1000-100um geometry
  - **Small S/N loss** if pixel size is decreased
  - **Large S/N loss** in between pixels if pitch in increased
- Signal propagation time is similar for all geometries









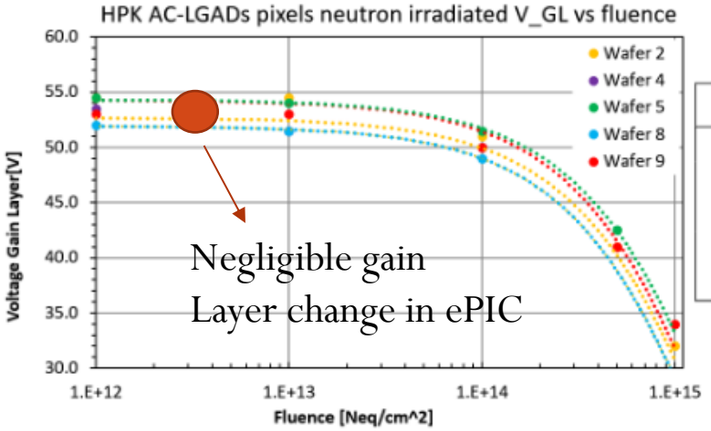


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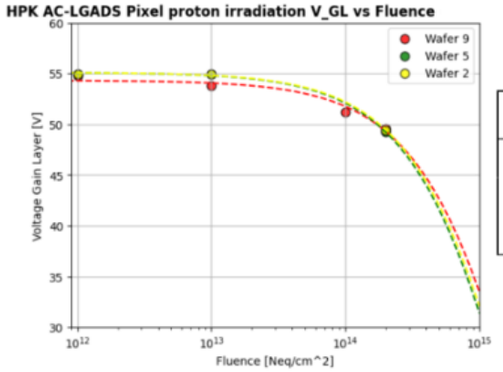
Students: M. Davis, N. Lynch, O. Khandelwal

Irradiation effects on AC-LGADs

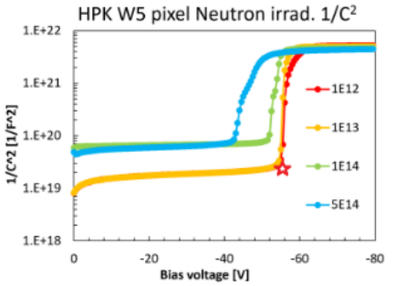
- Neutron (TRIGA – IJS group) and proton (FNAL – organized by UNM) irradiation on 2023 HPK production
- Up to 1e13 Neq, no significant change in sensor IV properties and gain layer doping
  - Gain layer doping proportional to Vgl (gain layer depletion voltage) or 'foot' (star in the plot)
  - C-factor (degradation) comparable for protons and neutrons, degradation similar to "standard" DC-LGADs
- **Response of AC-LGAD strips is unchanged**
  - Same signal propagation in N+
- Irradiated ePIC full-size sensors at FNAL recently (UNM group), studies ongoing



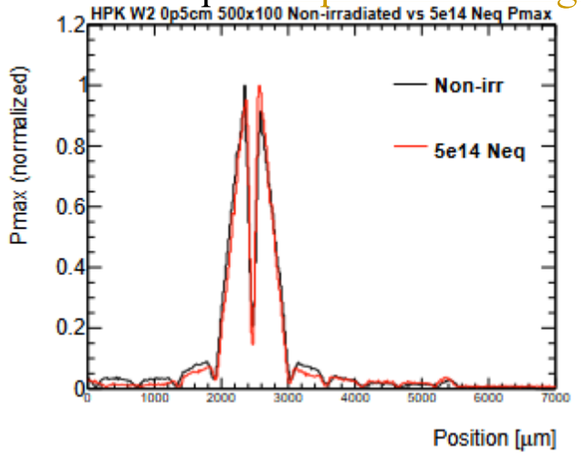
Wafer	C factor $\left[\frac{cm^2}{Neq}\right]$
W2	5.38×10^{-16}
W4	3.69×10^{-16}
W5	4.93×10^{-16}
W8	5.81×10^{-16}
W9	4.54×10^{-16}

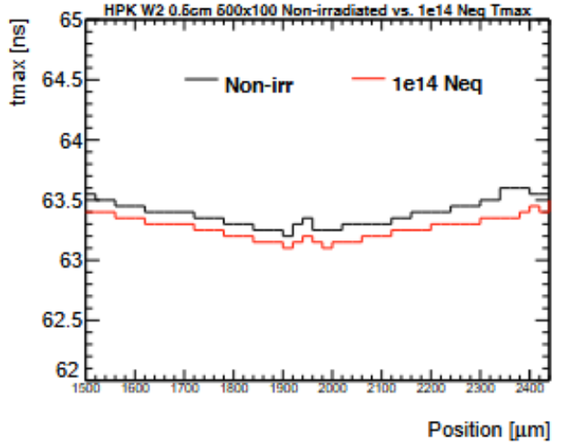


Wafer	C factor $\left[\frac{cm^2}{Neq}\right]$
W2	5.42×10^{-16}
W5	5.63×10^{-16}
W9	4.85×10^{-16}



Paper https://arxiv.org/abs/2503.16658

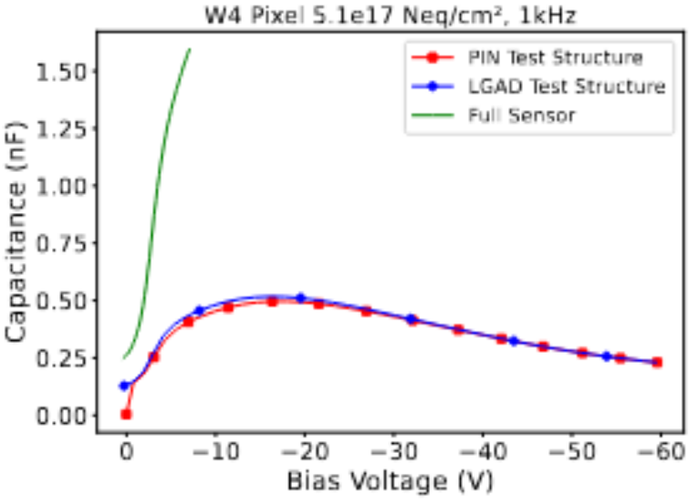




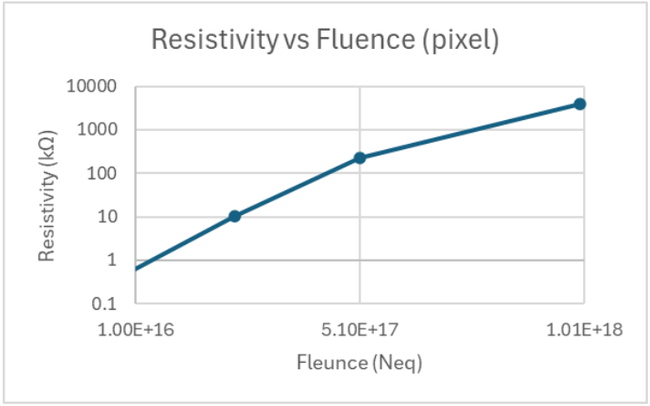
Student: G. Stage, J. Ding, M. Davis

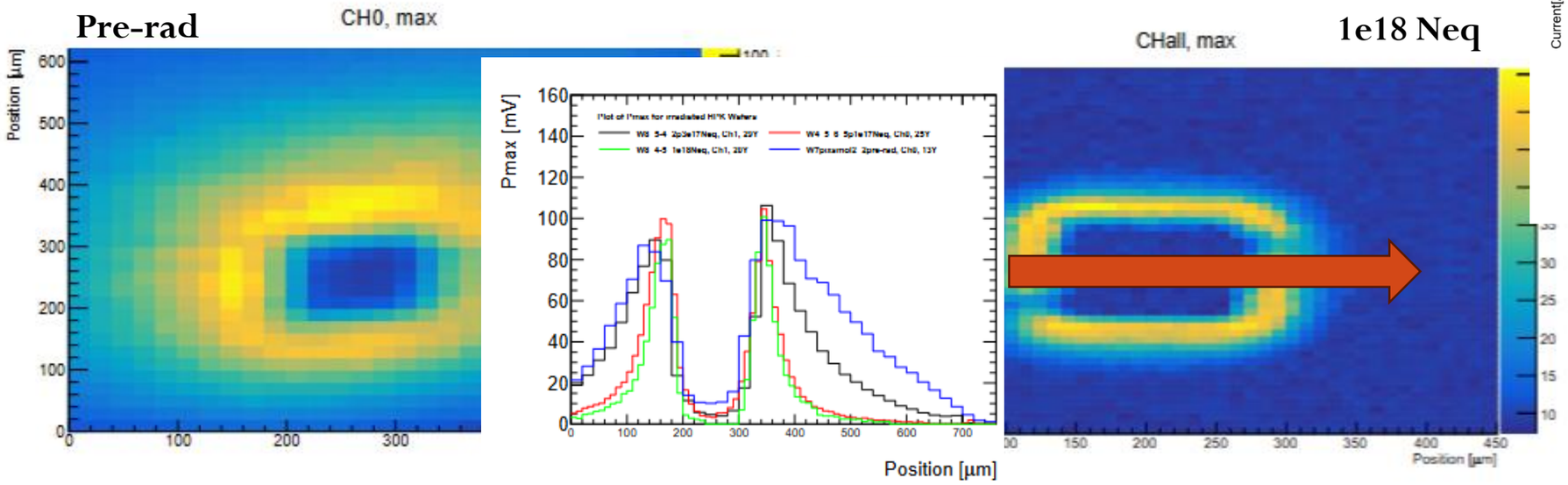
Extreme fluence effects

- Irradiated ePIC full-size pixel/strip AC-LGADs and test structure to 1E18Neq (Triga reactor – IJS group)
  - Gain layer completely disappears already at 2.3E17Neq
  - Difficult to reach full depletion
- N+ resistivity greatly increases
  - [1] show that N+ resistivity changes with irradiation already at 1E15 Neq
  - Going up to MΩ for 1E18Neq
- Scan of a pixel for laser TCT shows the effect of the increased resistance
  - Increased pixel isolation







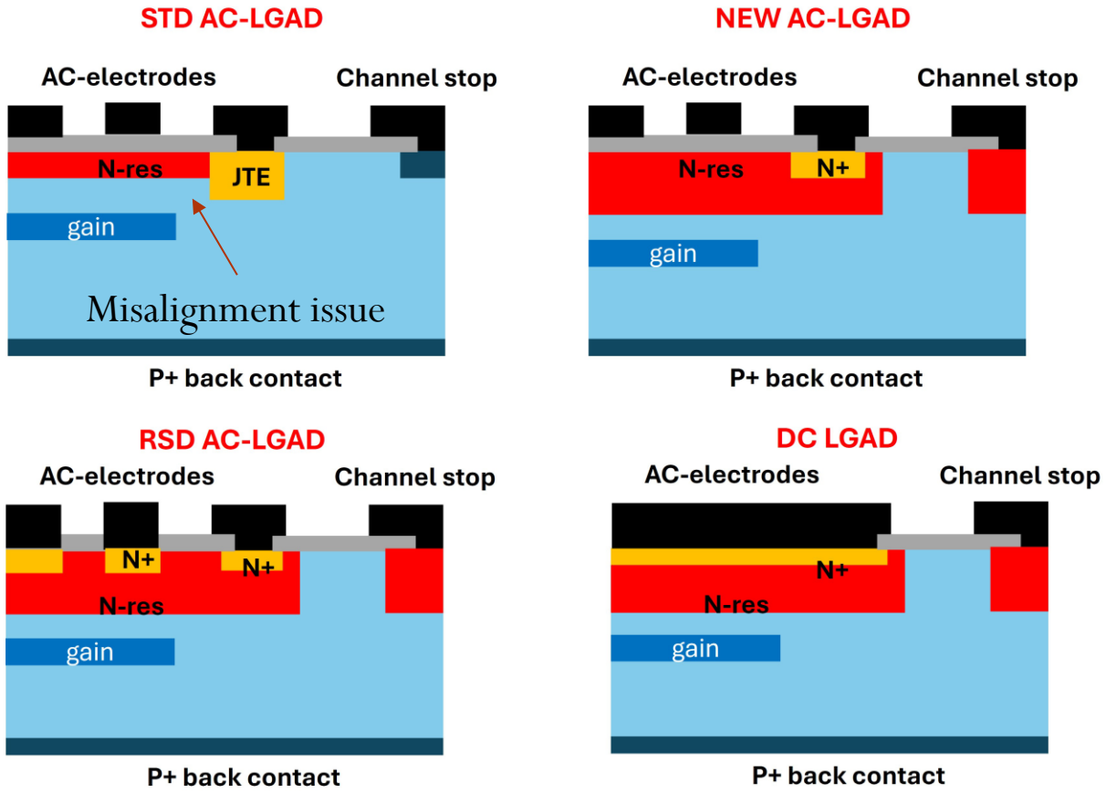


[1] https://indico.cern.ch/event/1386009/contributions/6279049

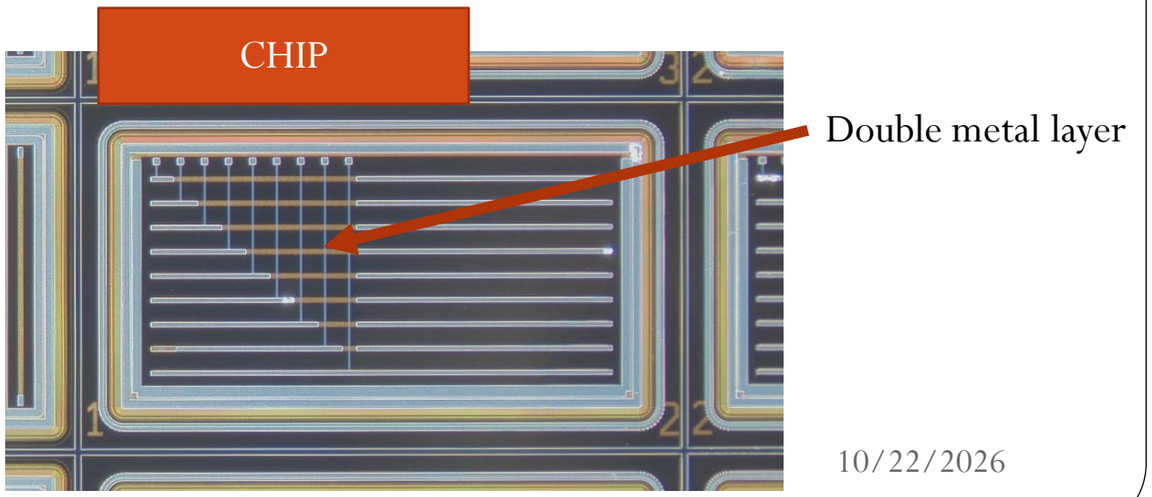
Student: Andrew Esparza

Improved AC-LGAD designs

- R&D can continue for EIC detector 2 or for a future ePIC upgrade
  - Collaboration of UCSC and BNL to push performance and better time resolution
- Type 1: update of AC-LGAD design to improve production yield
- Type 2: directly connect strips to reduce signal over multiple strips
  - Increase S/N (better charge collection), might allow for longer strips and pitch to reduce channel count
- Type 3: lateral readout for strips with double metal layer
  - Simplified assembly for 100% coverage

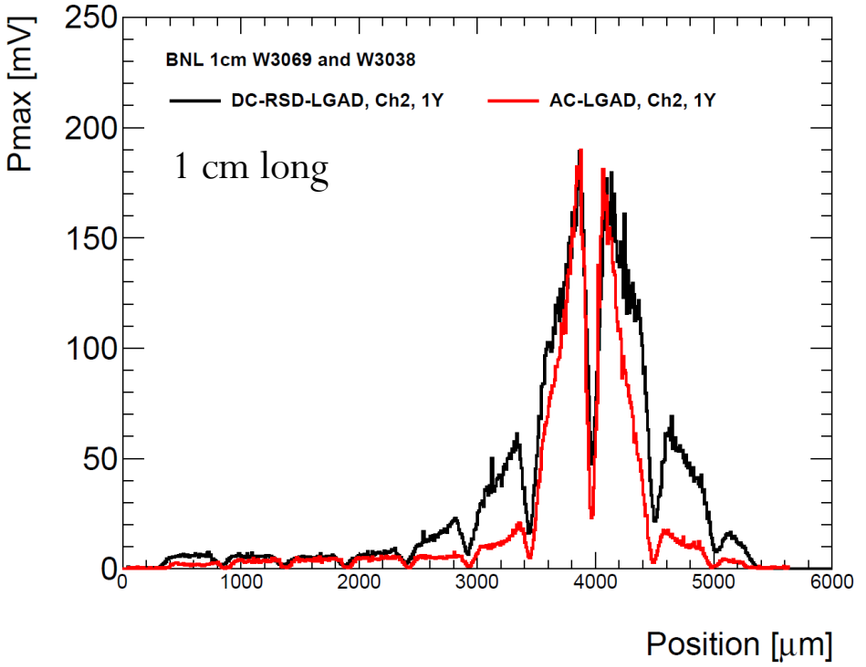


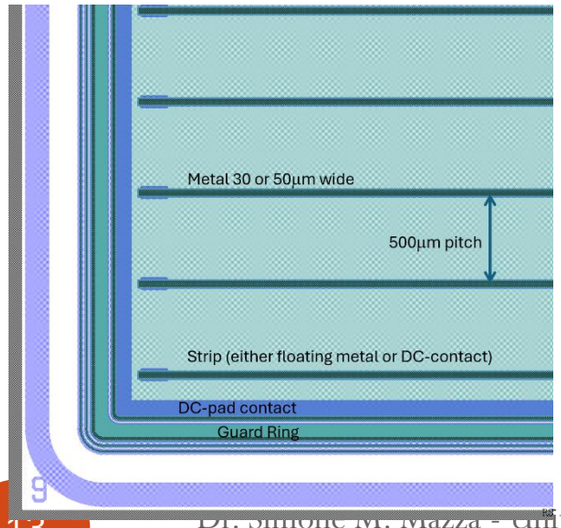
- BNL Production 1: done with erd112 remaining funds
  - Results in https://indico.global/event/14966/contributions/132618/
- BNL Production 2: updated design after testing production 1, ready for testing soon

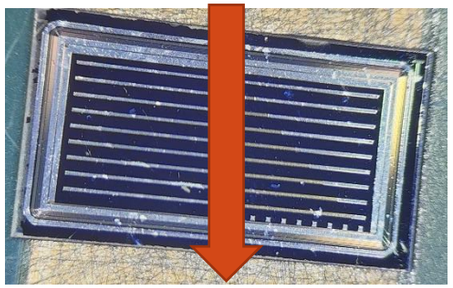


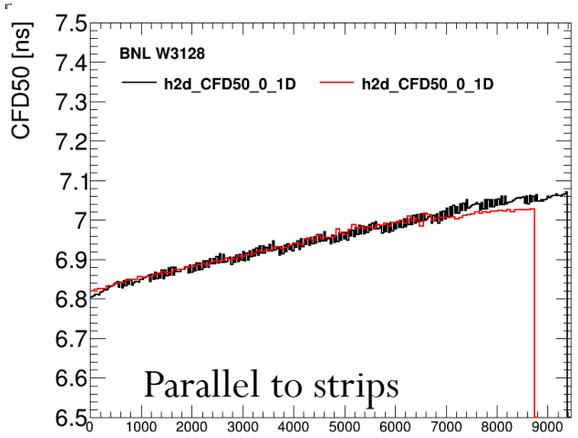
DC-RSD prototype vs AC-LGAD

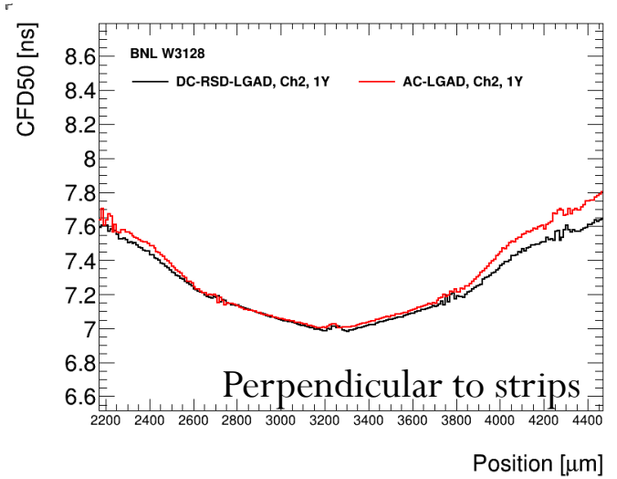
- Prototype of new type of AC-LGAD and DC-RSD produced at BNL
- Testing two sensors with same geometry; 1cm long, 500um pitch, 100um wide strips
  - Laser TCT scan across the sensor shows worse performance for DC-RSD in terms of charge sharing
  - But different behavior for different wafers?
  - Timing proprieties (rise time, time of arrival) are the same
- New production will feature smaller DC contact and strips: ready soon







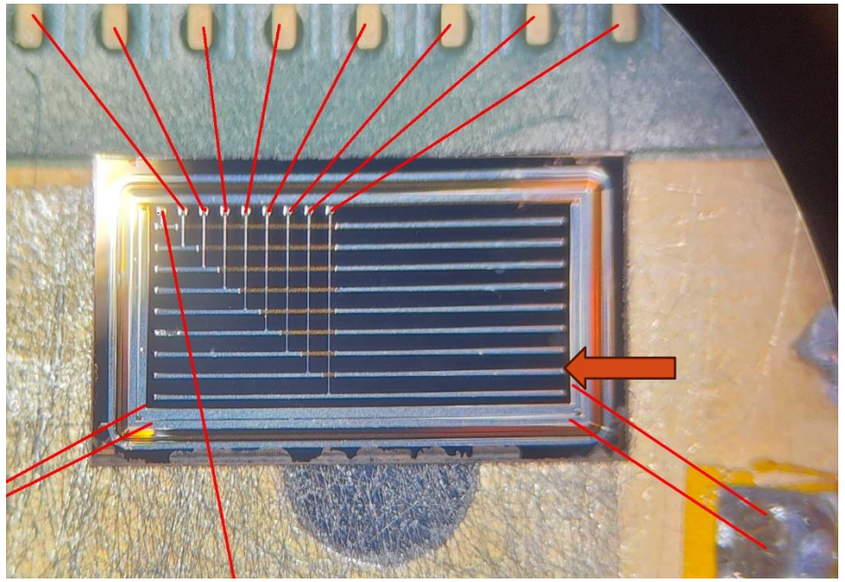


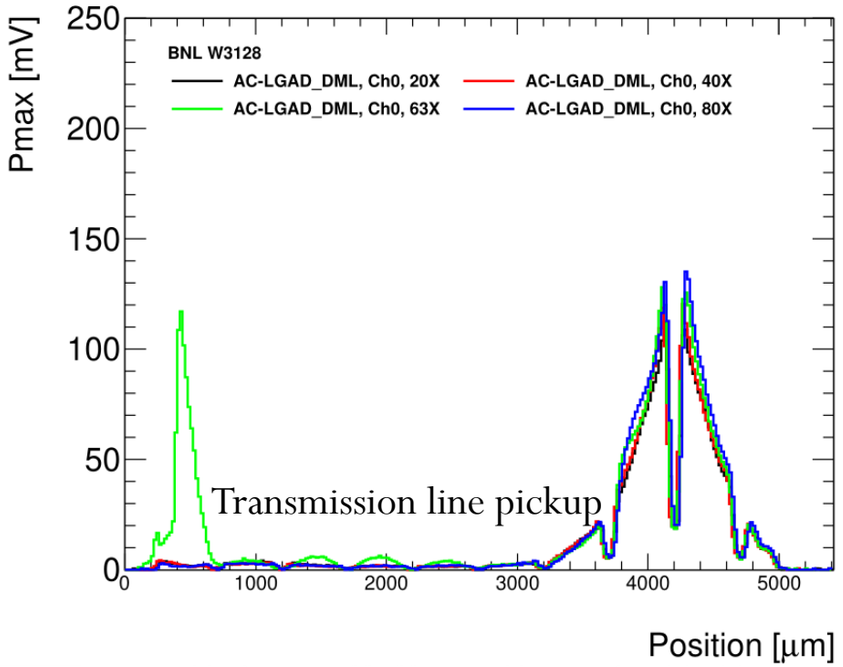


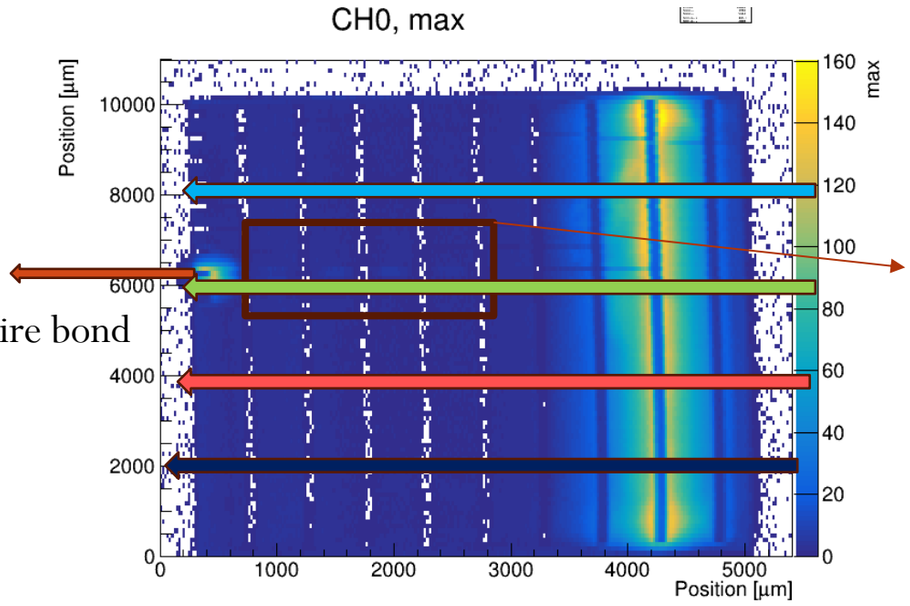
Student: A. Molnar, C. Altafulla

DML AC-LGADs

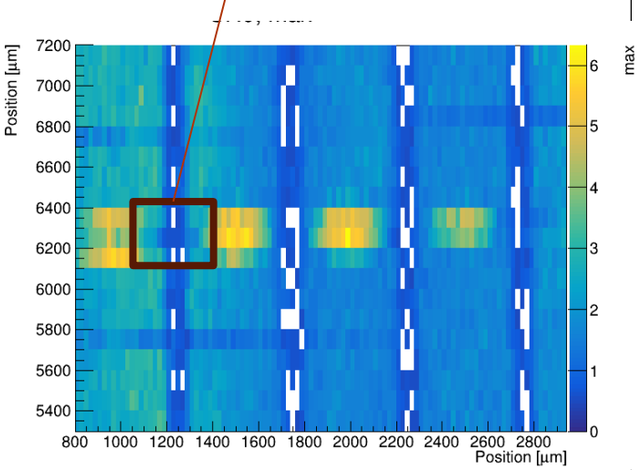
- Proof of principle works! Behaves as standard AC-LGAD
- Pickup of the cross strip is minimal, extra pickup at the bonding pad
  - Pickup on the line is ~4%
  - Cross talk with perpendicular strip hard to test with laser
- Behavior across the strip is homogeneous
  - Both Pmax and rise time are ok
- **Signal delays are complex to correct for**
  - Large delays due to transmission lines
  - Signal propagation in strip and transmission line is different





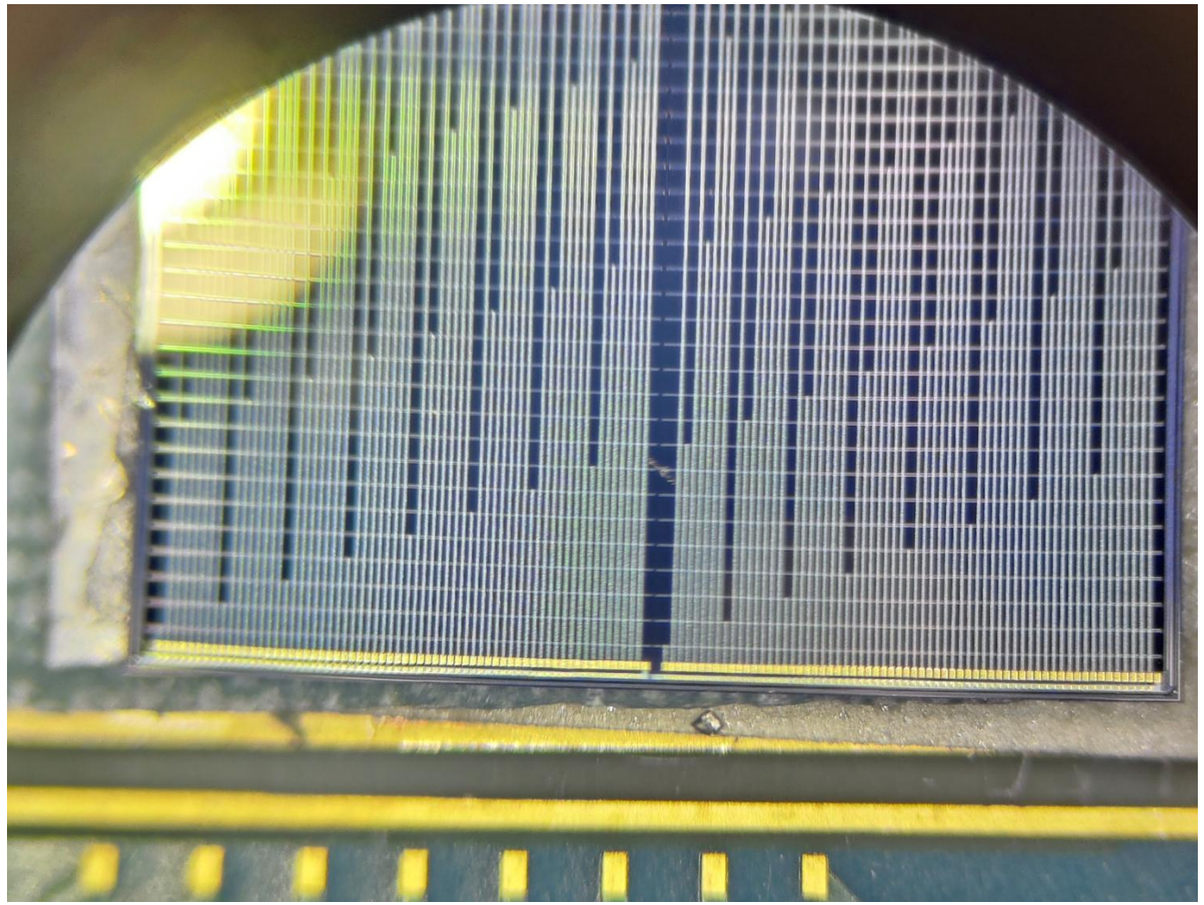


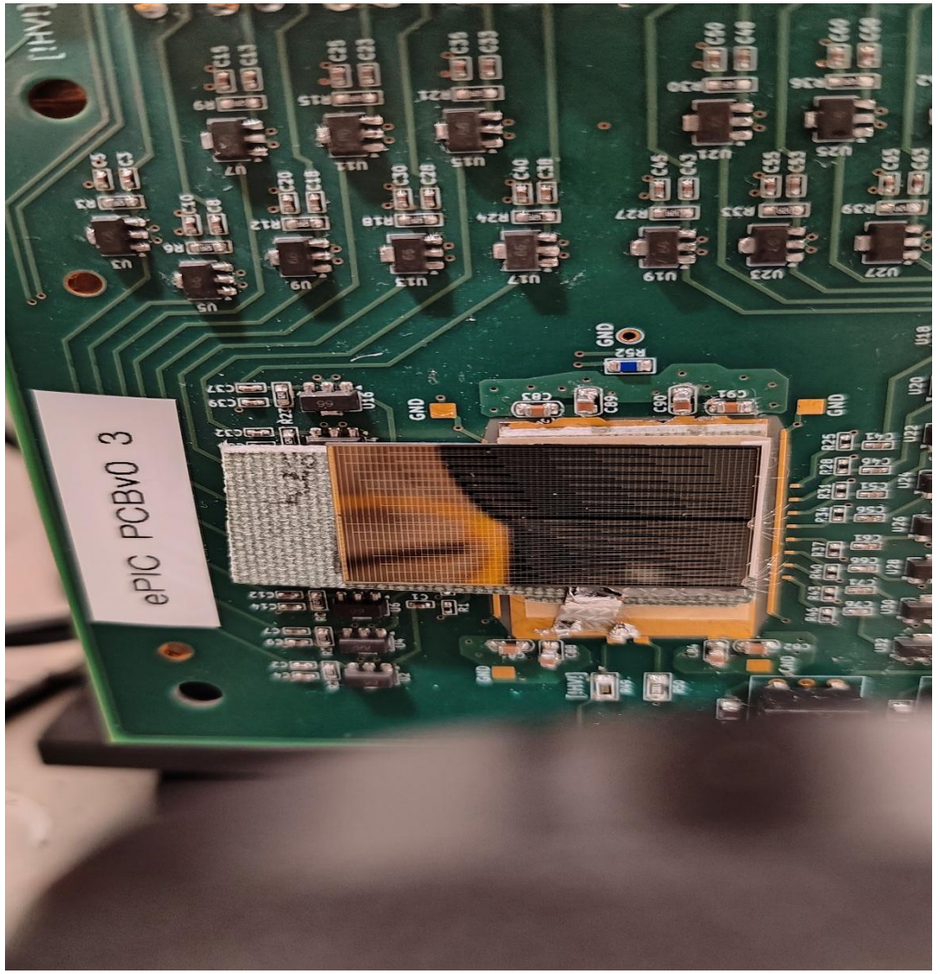
Can't test crosstalk under metal



Student: A. Molnar, C. Altafulla

Double metal sensor produced by HPK currently under testing



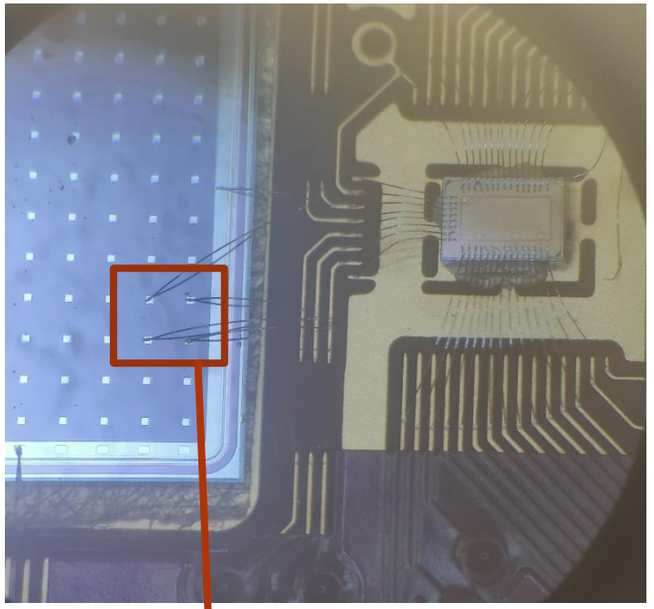


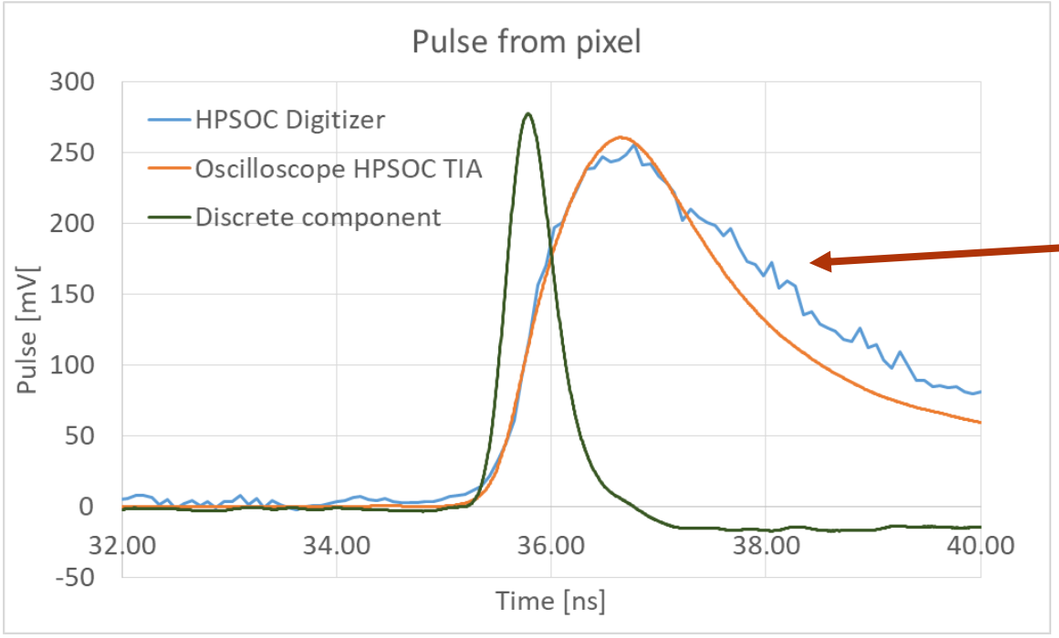
HP-SOC, a full readout chip

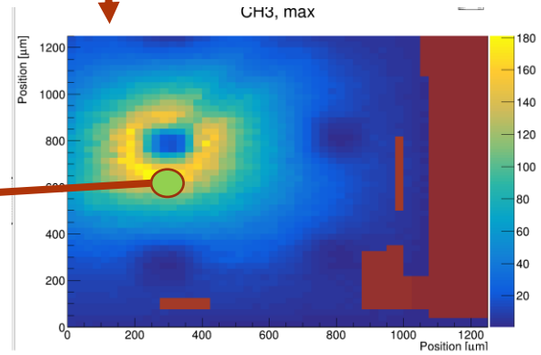
NALU SCIENTIFIC

- HP-SOC is a system on chip developed by NALU scientific in collaboration with UC Santa Cruz and U. Hawaii at Manoa
  - TIA amplifier, GHz bandwidth (pixel capacitance <1pF) and 13.5 Gs/s digitizer
  - Goal of 1mW/ch for front end
  - Full waveform → can use ML to reconstruct events precisely
- HP-SOC v2a (4ch) tested with ePIC 30um pixel sensor using laser TCT
  - Rise time of ~700 ps and S/N of ~50, Jitter ~14ps
- See previous CPAD: https://indico.global/event/14966/contributions/134102/

HP-SOC v2 connected to pixel





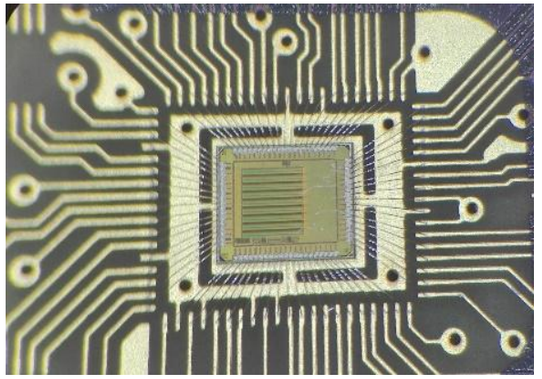


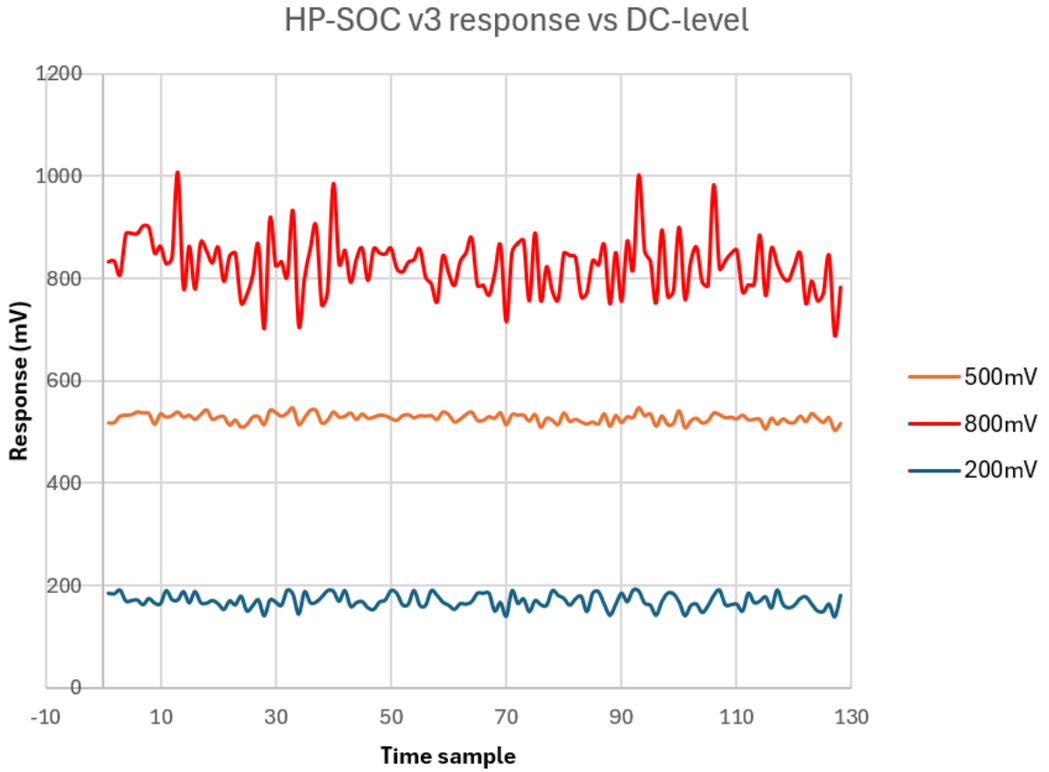
Laser scan with discrete component board

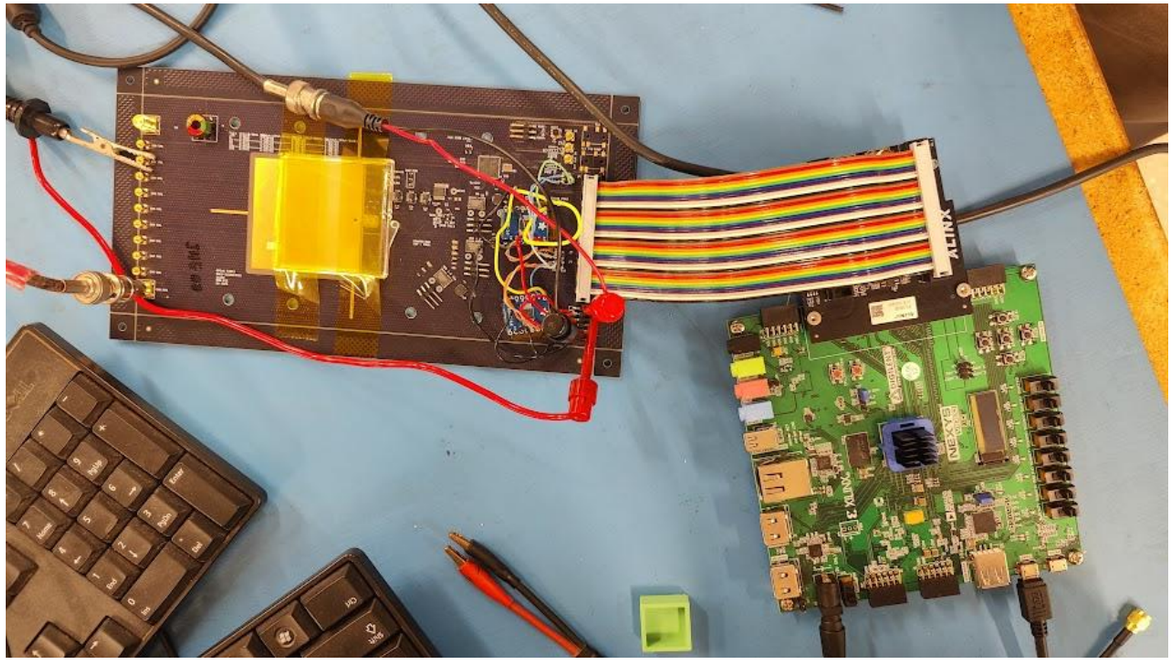
HP-SOC, a full readout chip

NALU SCIENTIFIC

- HP-SOC v3 setup in testing: 9 channel chip, front end plus digitizer
  - Lab testing at NALU, UCSC and UH. Will present first results at IEEE
- LID (LGAD Integrated Desing) in development targeting strip readout (~10pF input capacitance) (SBIR phase-I, waiting for SBIR phase-II)

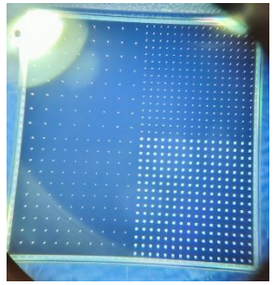


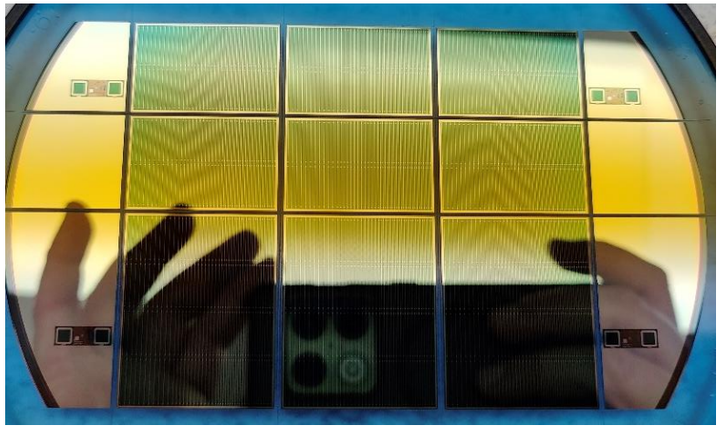


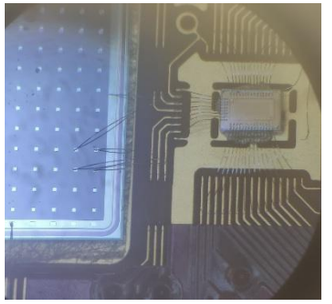


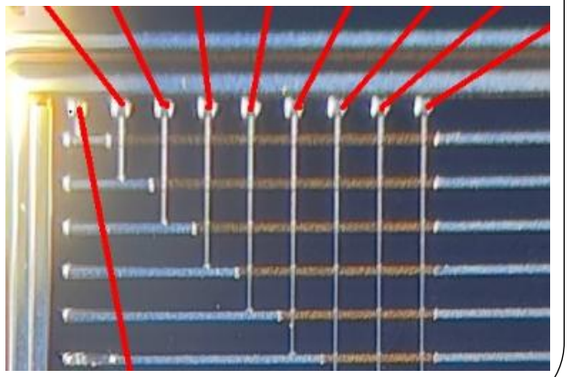
Conclusions

- Large AC-LGADs for the ePIC TOF layers are reaching maturity
  - First large-scale AC-LGAD productions for both strips and pixel from HPK
  - Planning multiple test beams next year (DESY, KEK, SLAC ESTB application submitted)
- Tested irradiation and extreme irradiation effects on test and full-size AC-LGADs
- Producing and testing innovative AC-LGAD designs
  - DC-RSD strip sensors
  - Double-metal strip sensors
- System-on-chip development (amplifier and digitizer) ongoing for the two geometries (HP-SOC, LID)









SCIPP

SANTA CRUZ INSTITUTE
FOR PARTICLE PHYSICS

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Thanks for the attention

Many thanks to the SCIPP group students and technicians!

In particular to students:
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N. Lynch, A. Drumm, Y. Spinos, O. Khandelwal, A. Esparza, L. Guccione-Jimenez

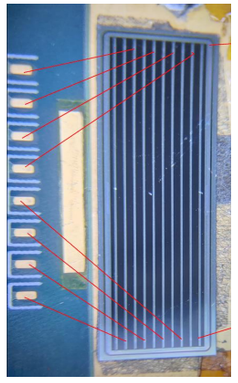
Thanks to HPK and BNL for fabricating sensors for this study

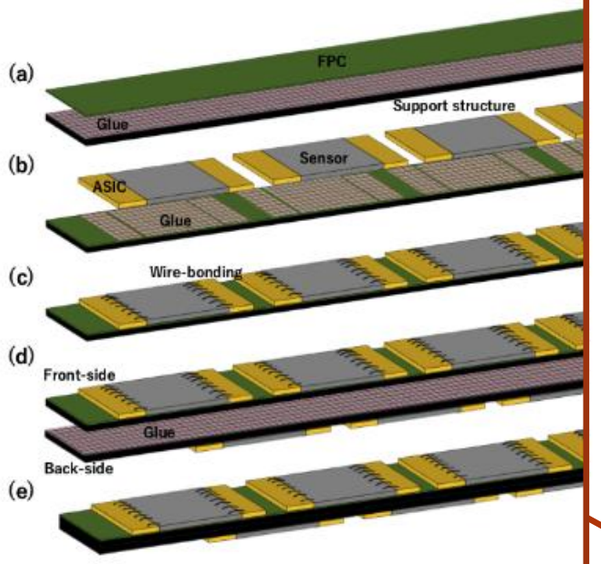
This work was supported by the United States Department of Energy,
grants DE-SC0010107 and DE-SC0020255.

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

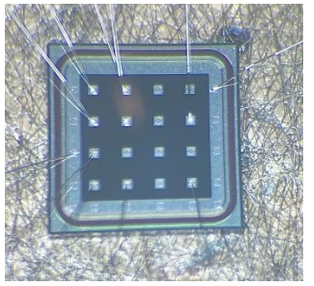
Backup

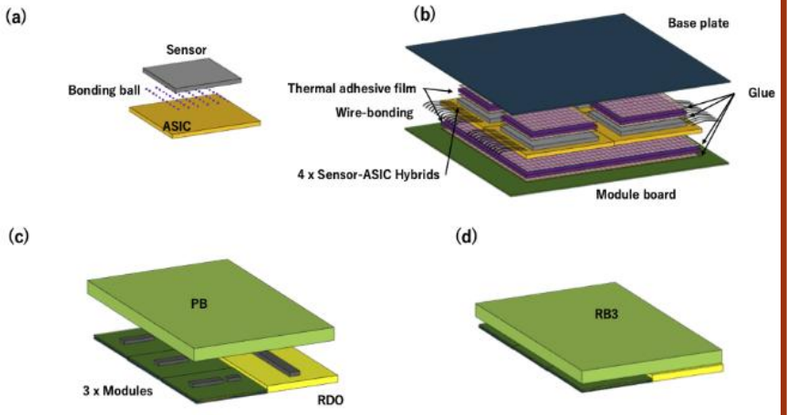
TOF layout in ePIC



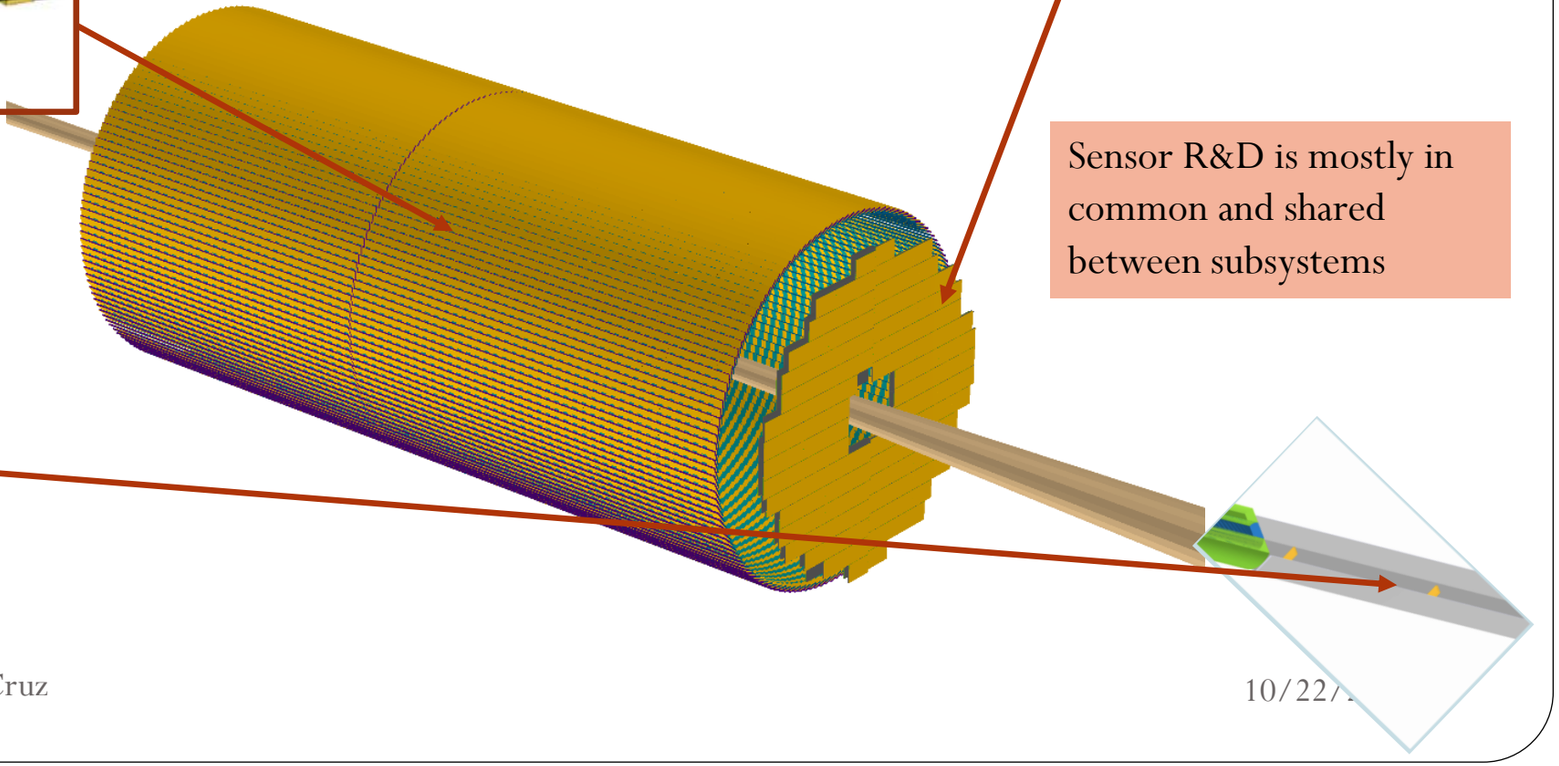


Sensors: strips
Readout: FCFD

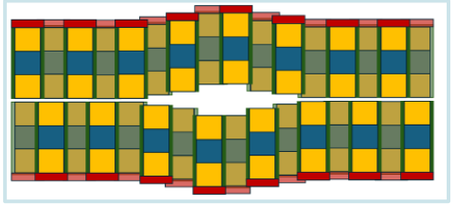




Sensors: pixels
Readout: EICROC



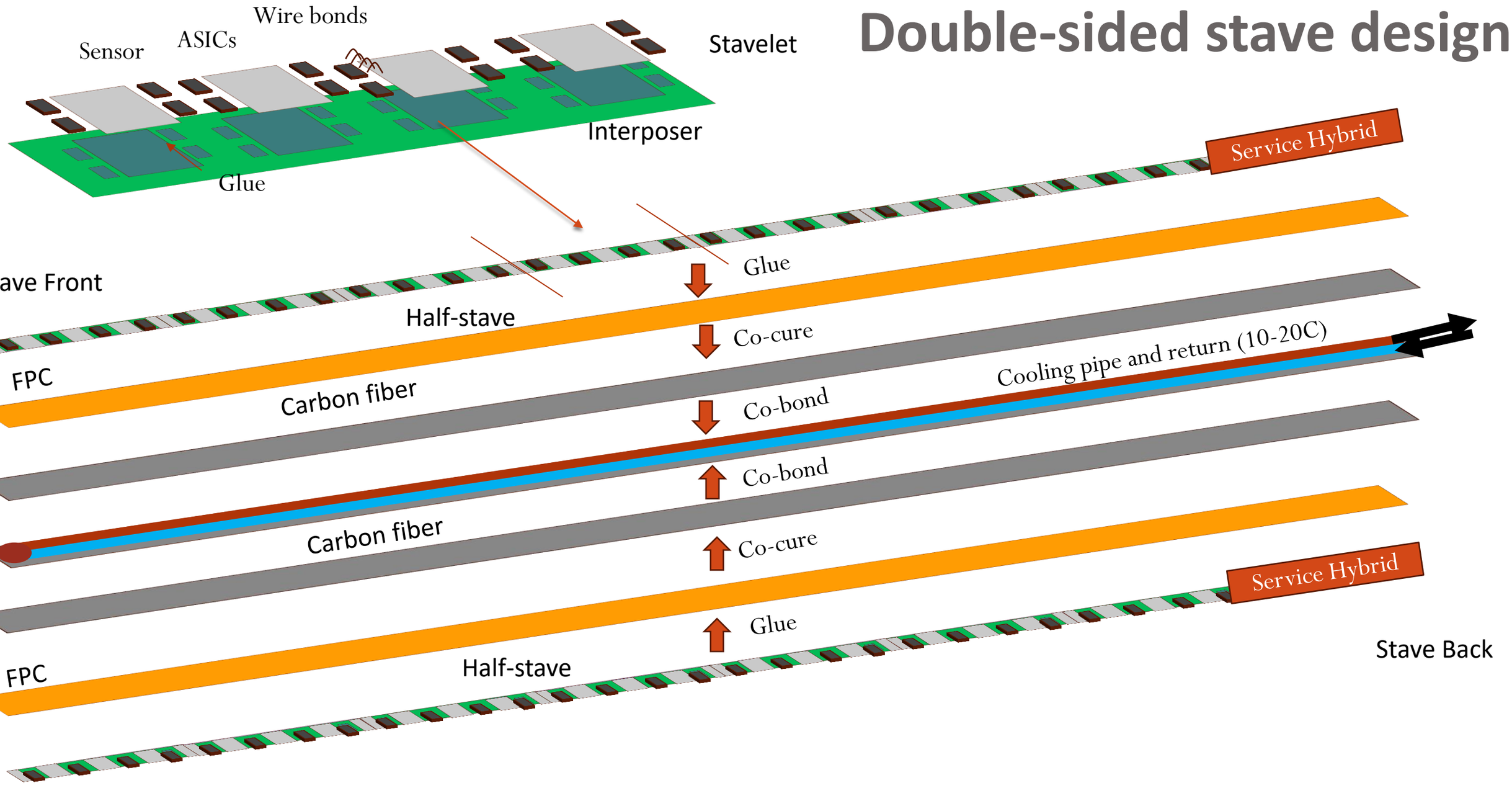
Sensor R&D is mostly in common and shared between subsystems



Sensors: pixels
Readout: EICROC

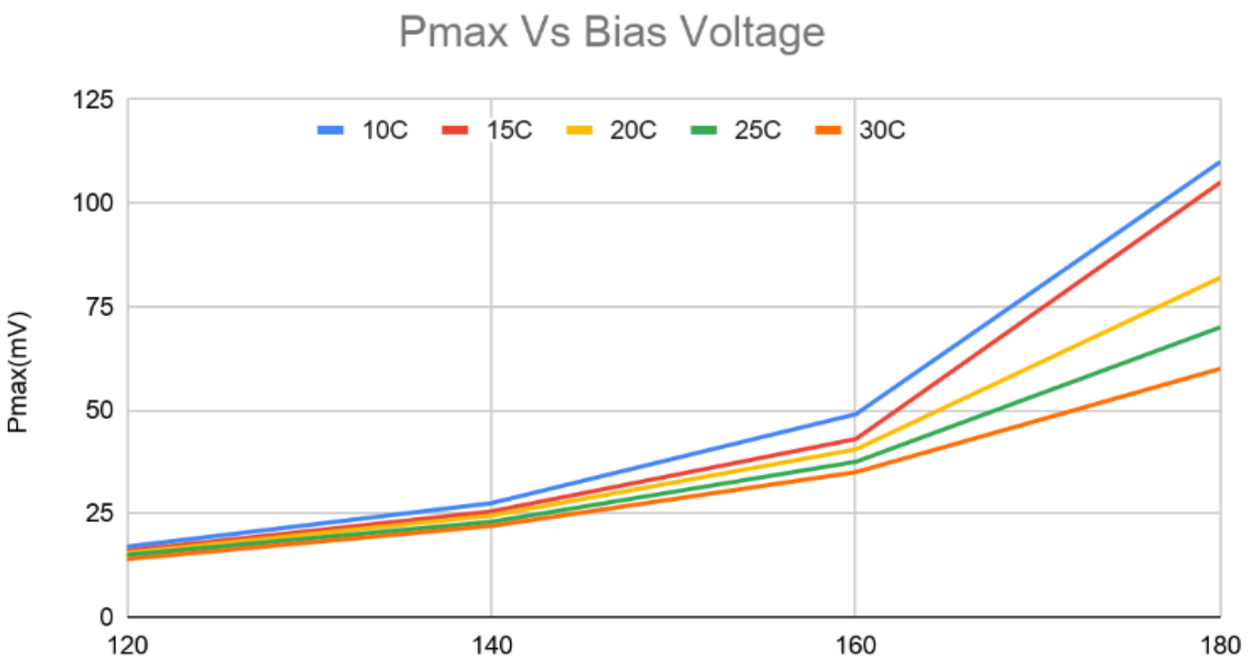
Off-Momentum Detectors (OMD)

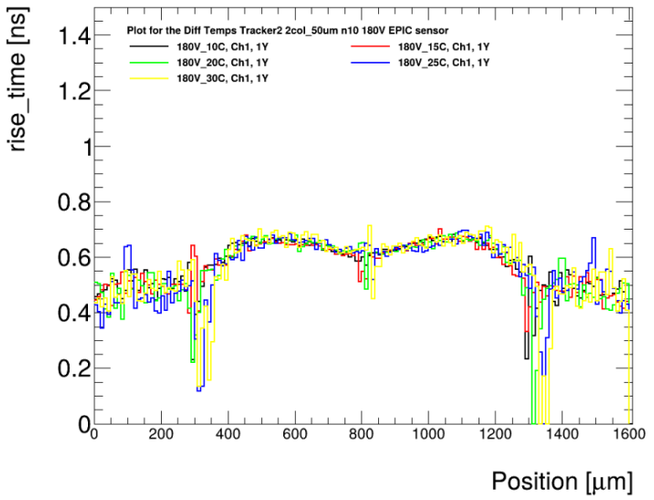
Double-sided stave design

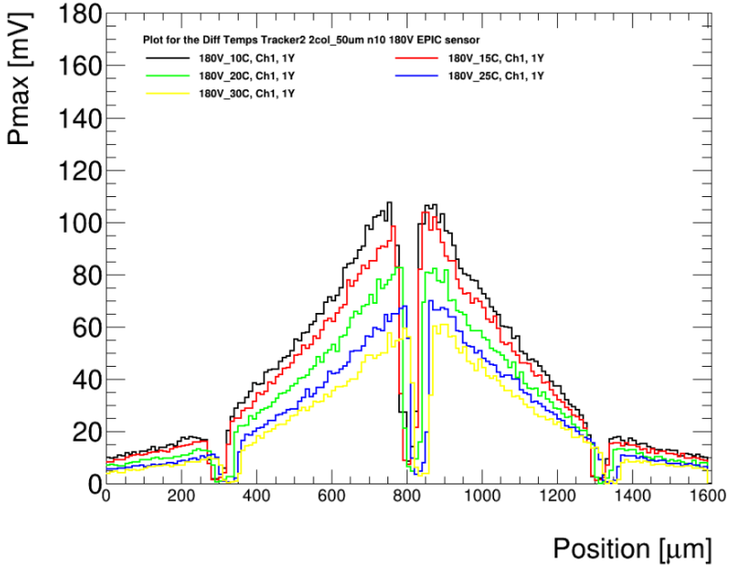


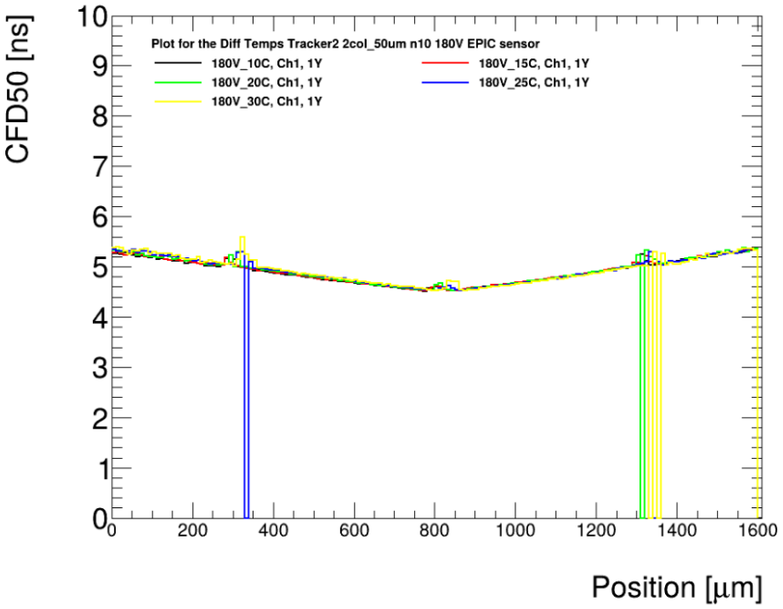
Temperature effects

- Temperature effects to the sensor response
- Measured signal amplitude with laser TCT
- Gain is affected by the temperature but rise time and signal propagation are not
  - (as expected)



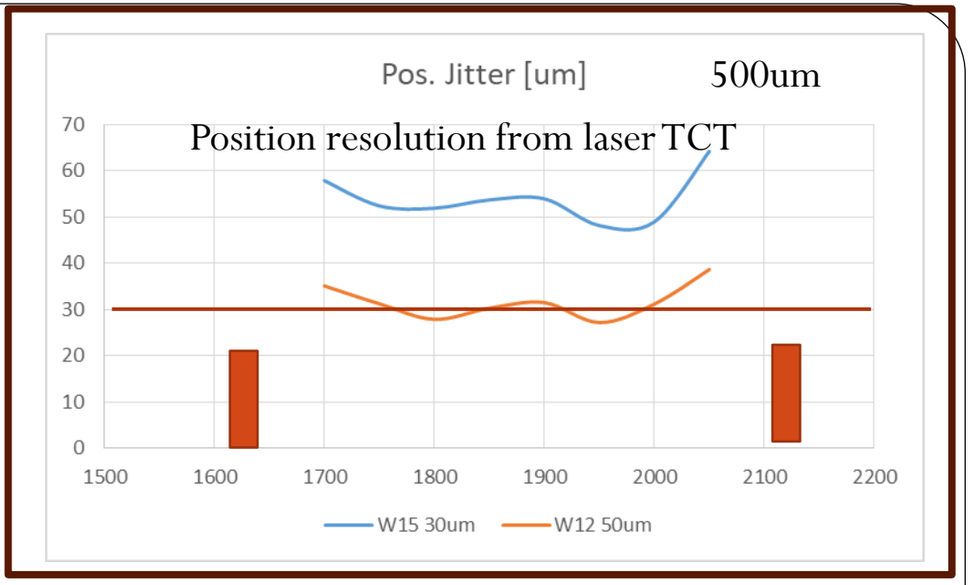


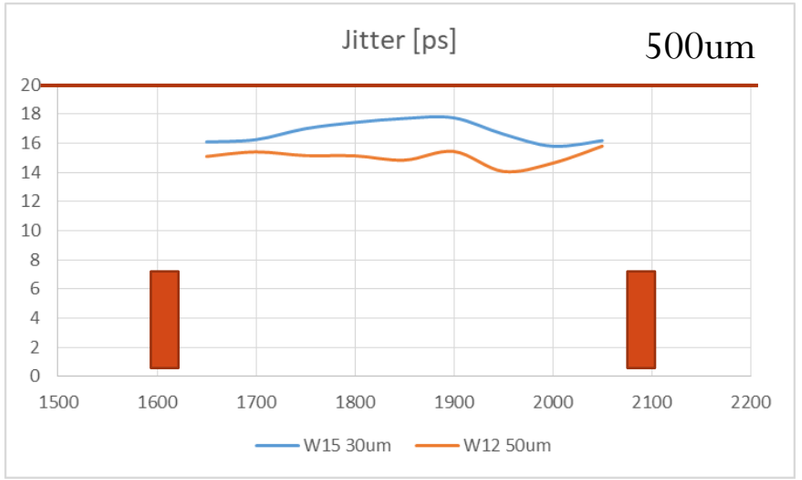


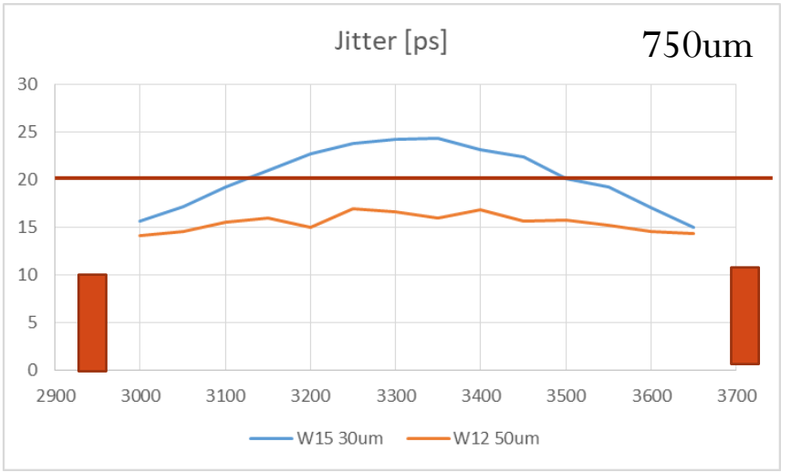


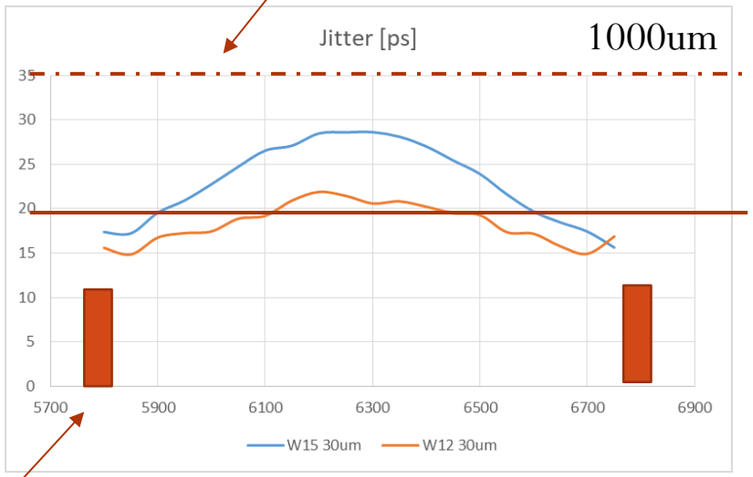
HPK production results - TCT

- Previous productions (small prototypes) met BTOF requirements
- Only laser TCT test available for new production
  - Measuring the Jitter as $\sigma_T = Rise_T/(\frac{S}{N})$
  - Position Jitter as in https://doi.org/10.1016/j.nima.2024.169478
- Increased strip distance reduces performance
  - Reduced thickness (30um vs 50um) doesn't seems beneficial
- Took data with beam at Jlab in Aug 2025, analysis ongoing





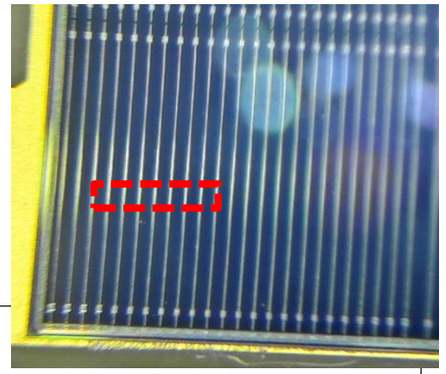


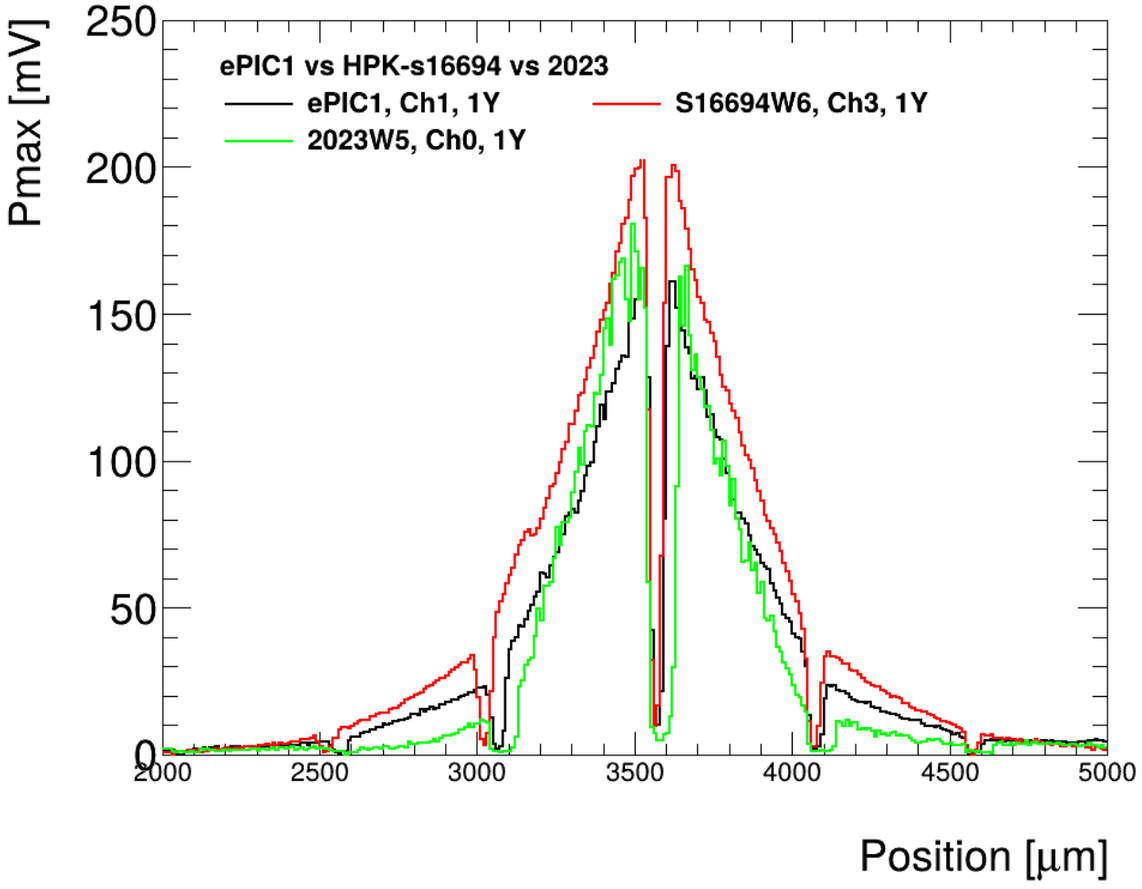


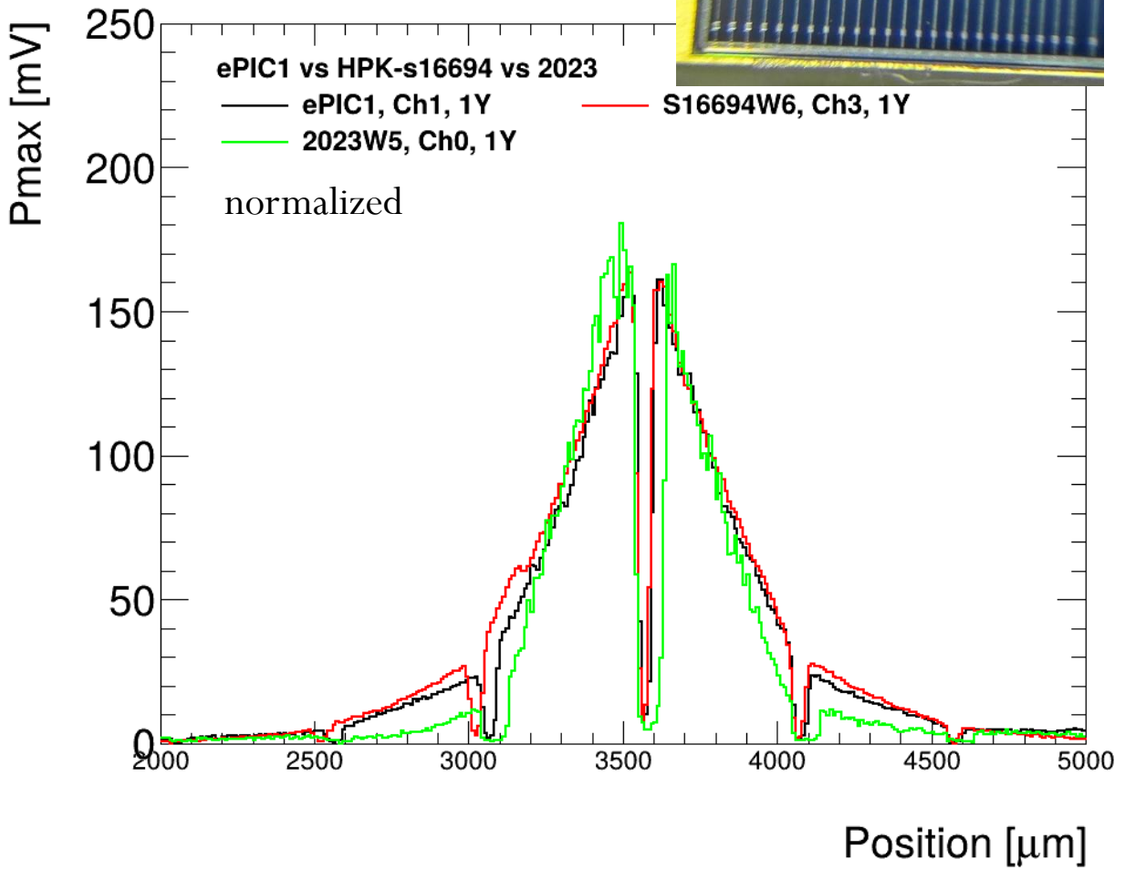
More details in: https://indico.phy.ornl.gov/event/677/contributions/2683/

Comparison of HPK devices from 2023, 2024 and 2025

- Laser TCT data comparison, using same laser power, maximum voltage
  - Note: same laser power is not same injected charge (variations occur)

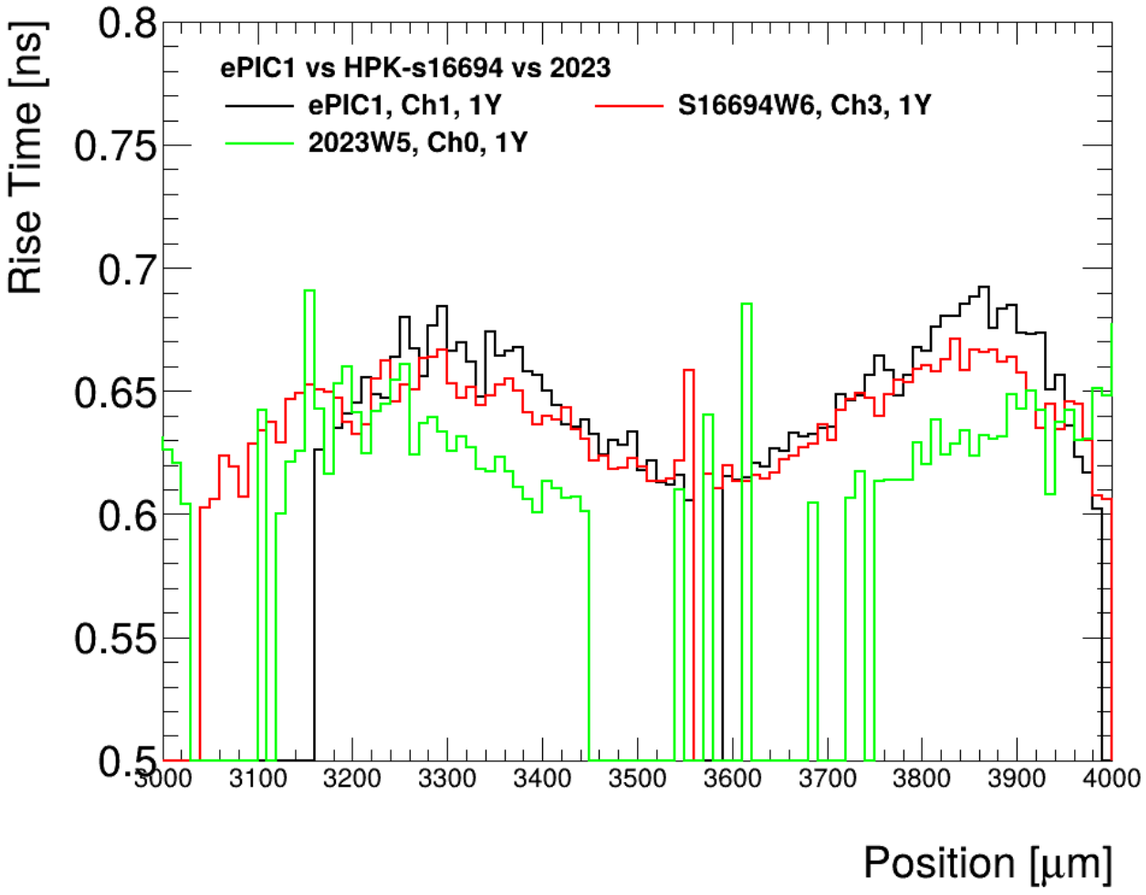


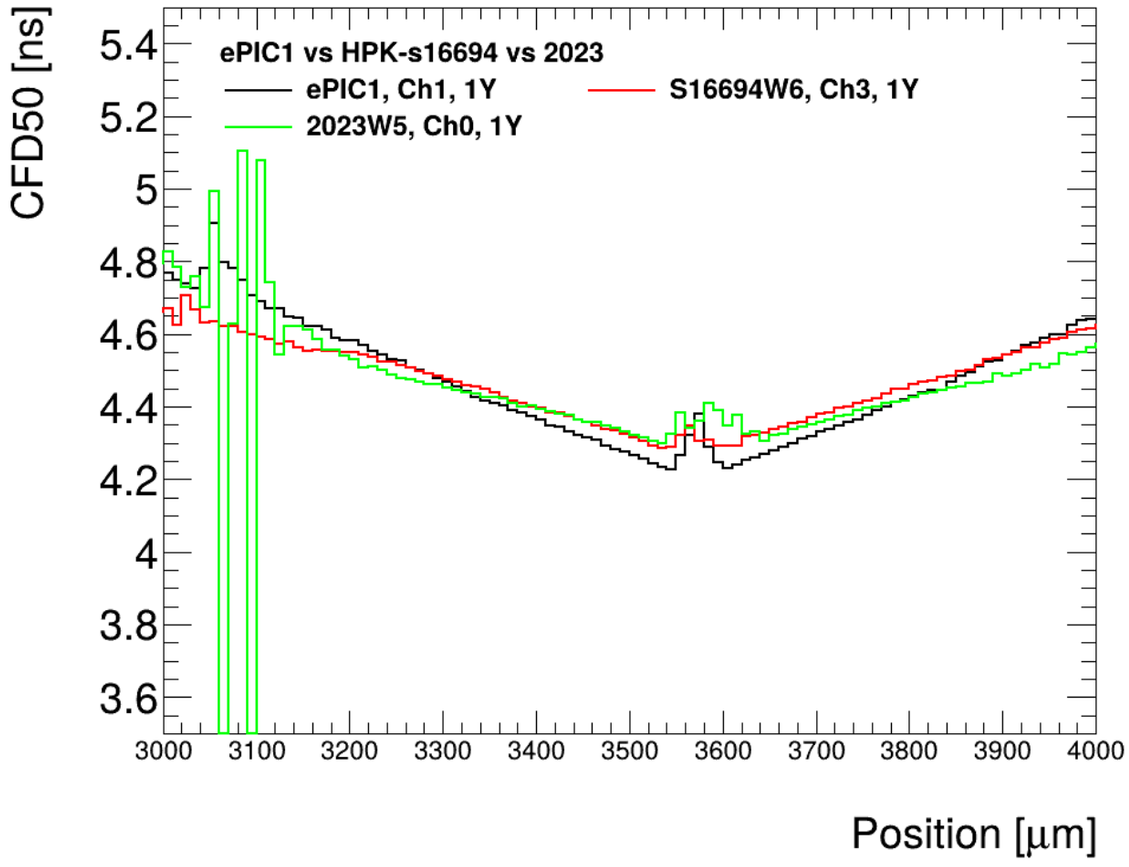




Comparison of HPK devices from 2023, 2024 and 2025

- Laser TCT data comparison, using same laser power, maximum voltage
  - Note: same laser power is not same injected charge (variations occur)





Comparison of HPK devices from 2023, 2024 and 2025

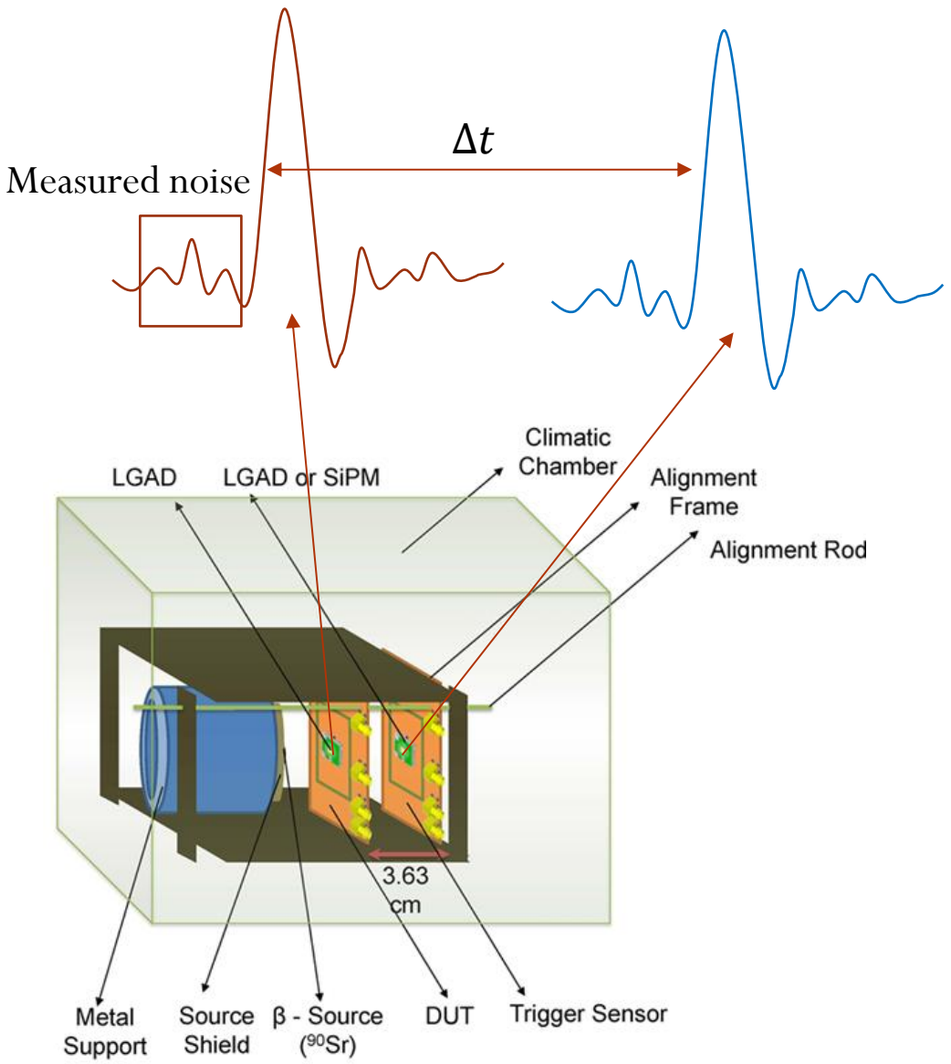
- Laser TCT data comparison, using same laser power, maximum voltage
  - Note: same laser power is not same injected charge (variations occur)

- Comments:
  - Using the same laser power we get roughly the same signal for the three devices
  - Rise time is comparable
  - Time of arrival correction is comparable

- Notes:
  - The 2023 sensor has the same thickness, N+ resistivity and oxide as S16694
  - The 2025 has a different oxide thickness (thicker)
  - The 2024 and 2025 sensors have the same geometry 500x50um
  - The 2023 is 500x100um, I can't find a 500x50um anymore
  - The 2023 is also very lightly irradiated, but that should not affect performance

Sensor testing – Sr90 telescope

Details: S.M. Mazza et al. arXiv:1804.05449



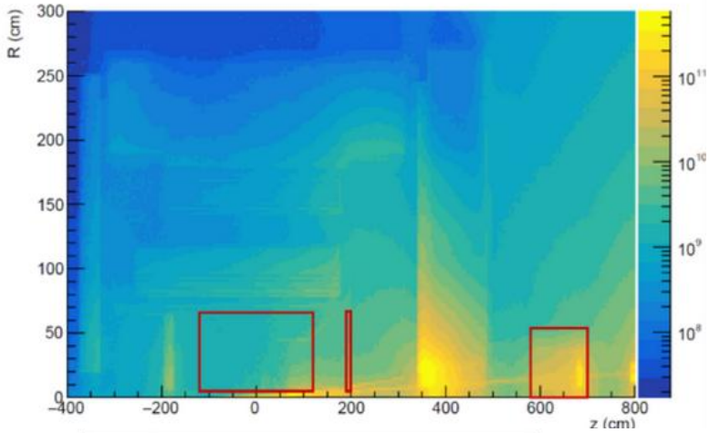
- **Same sensors tested with beta source with coincidence trigger**
- Two sensors are aligned with a beta source
  - DUT (Device Under Test) to characterize: **on 16ch board, readout 3 strips. Use to reconstruct event position**
  - Trigger with known performance, **1mm size**
- Sensors mounted on fast amplifier boards (~2Ghz) and read out by a fast oscilloscope (2Ghz, 20Gs)

- **Collected charge**
- **Time resolution**: sigma of time difference between trigger sensor (with known time resolution) and DUT,
- **Gain**: collected charge divided by collected charge in same thickness PiN

- **Data taking still ongoing**
- **See next talk!**

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



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

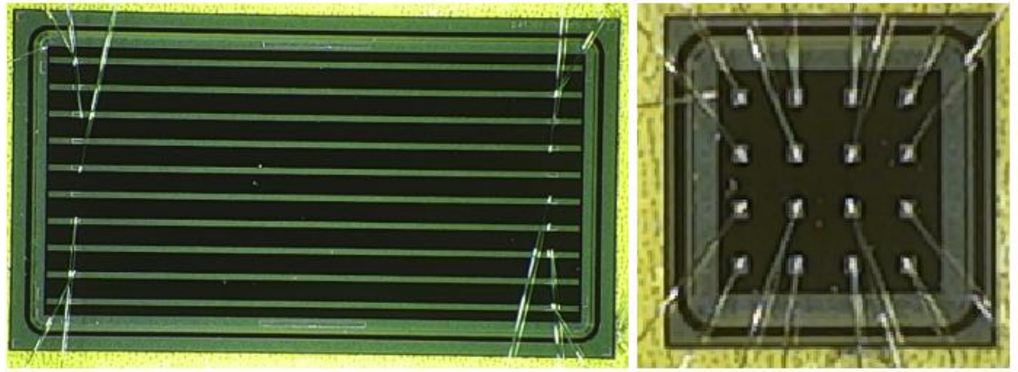
Strips W5

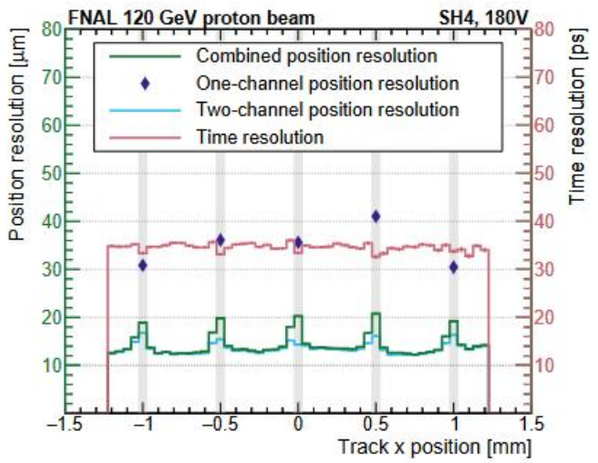
Fluence	0.5 cm	1 cm	2 cm
1.00E+12	54	54	
1.00E+13	42		54
1.00E+14		52	53

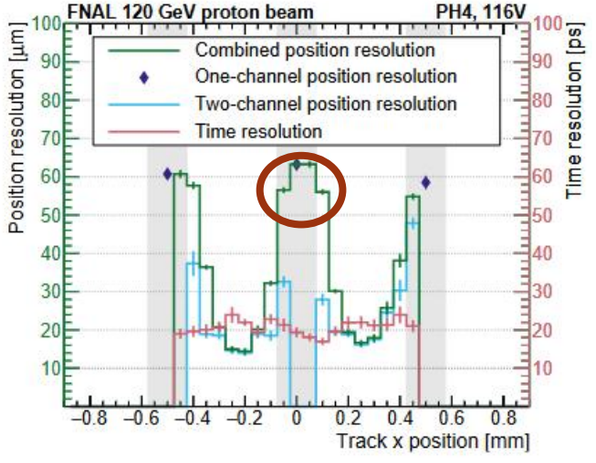
- Thanks to G. Kranberger and I. Mandic for the JSI irradiation
  - Funded by EUROLABS
- Thanks to S. Seidel and J. SI (UNM) for the proton irradiation

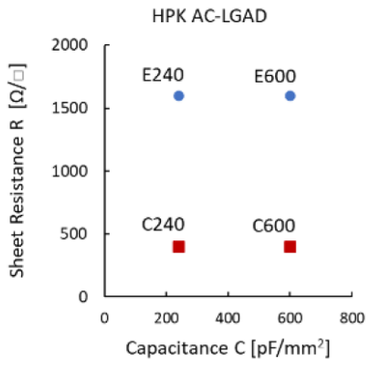
2023 HPK production

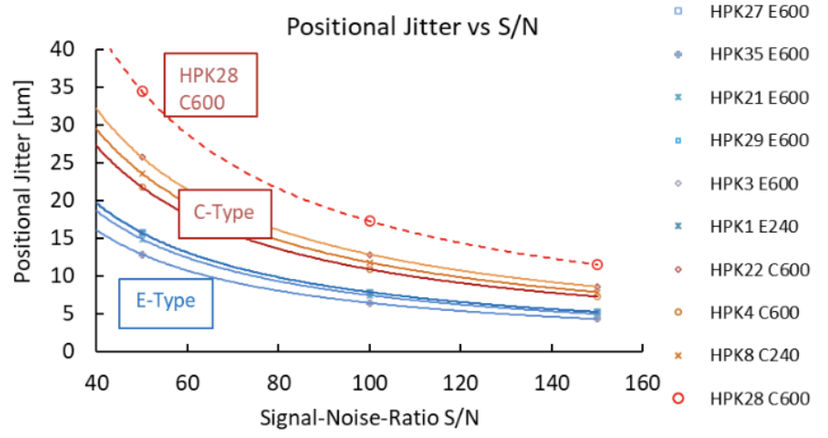
- Test beam and laboratory campaign to characterize HPK sample
  - Matrix of different pitch/size metal, different N+ resistivity and oxide thicknesses
- FNAL test beam results from HPK 2023 production, most ePIC requirements are met
  - Time resolution ~35ps for 1cm x 500um strips and ~20ps for 500um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







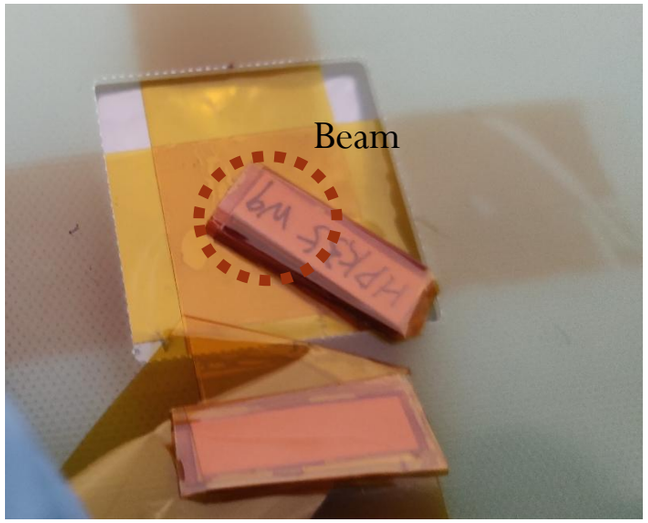


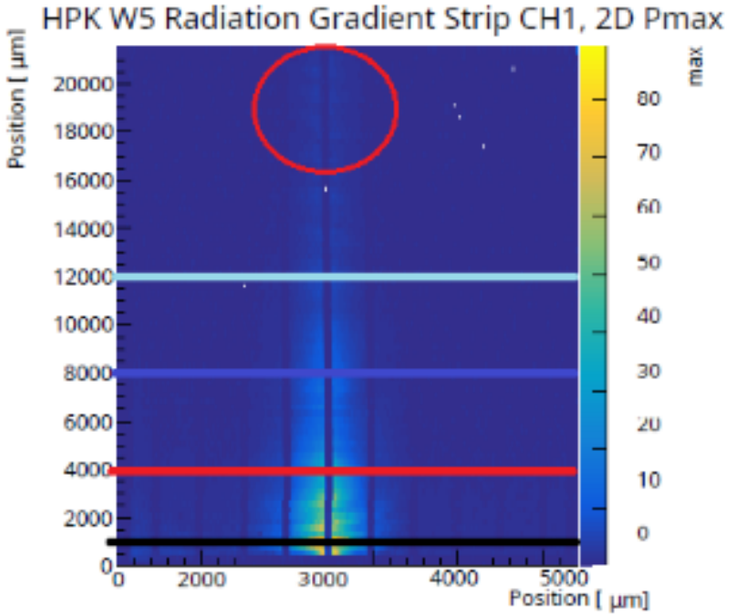


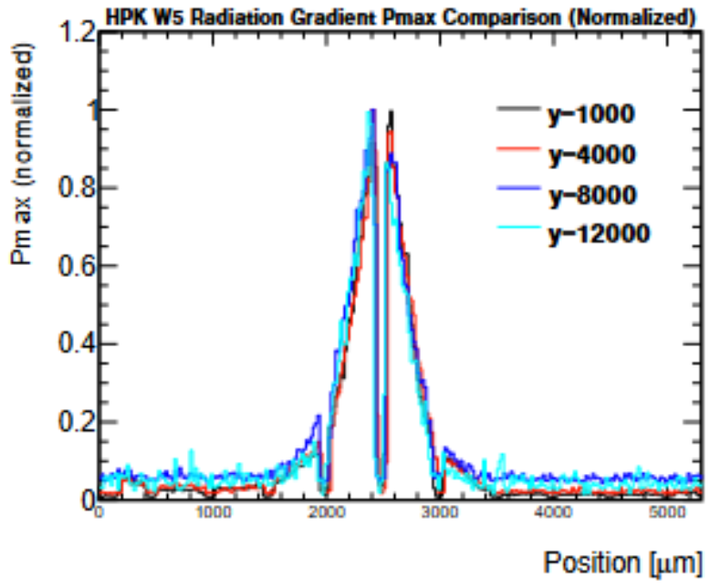
References: https://arxiv.org/abs/2407.09928 https://doi.org/10.1016/j.nima.2024.169478

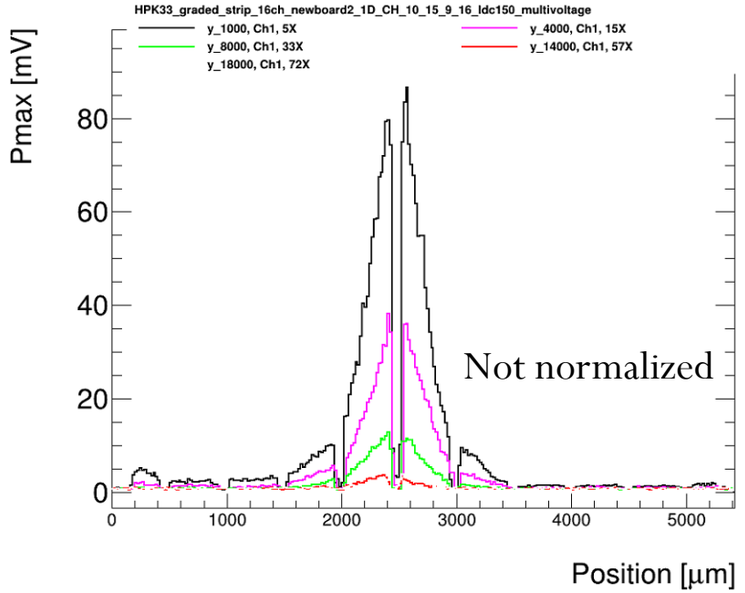
TCT laser studies - Protons

- 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!





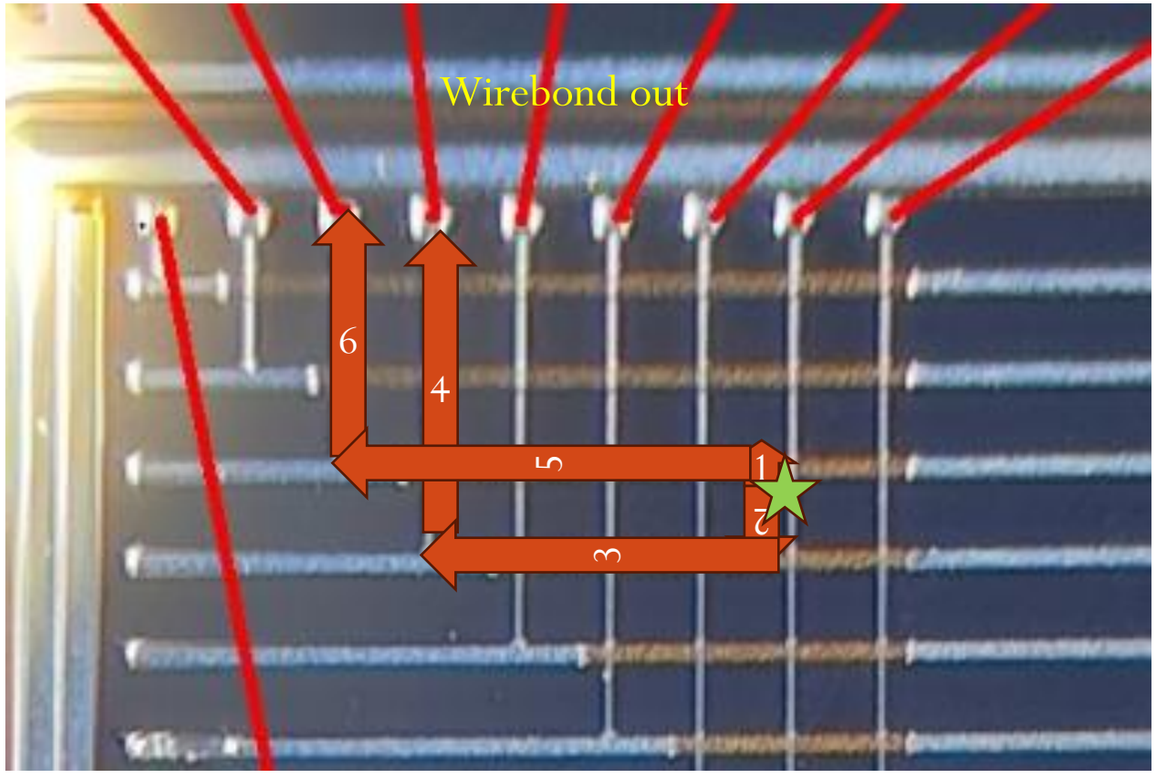




Student: G. Stage, A. Borgijin

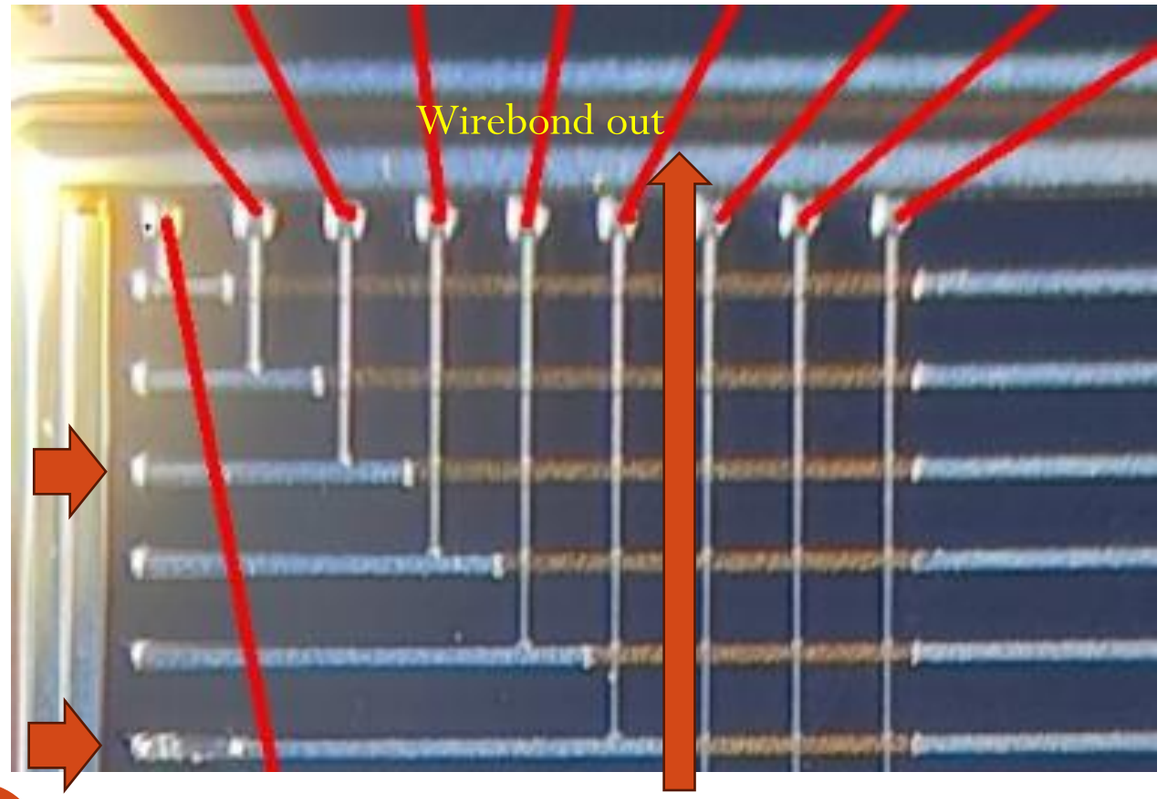
Delay correction in DM AC-LGAD

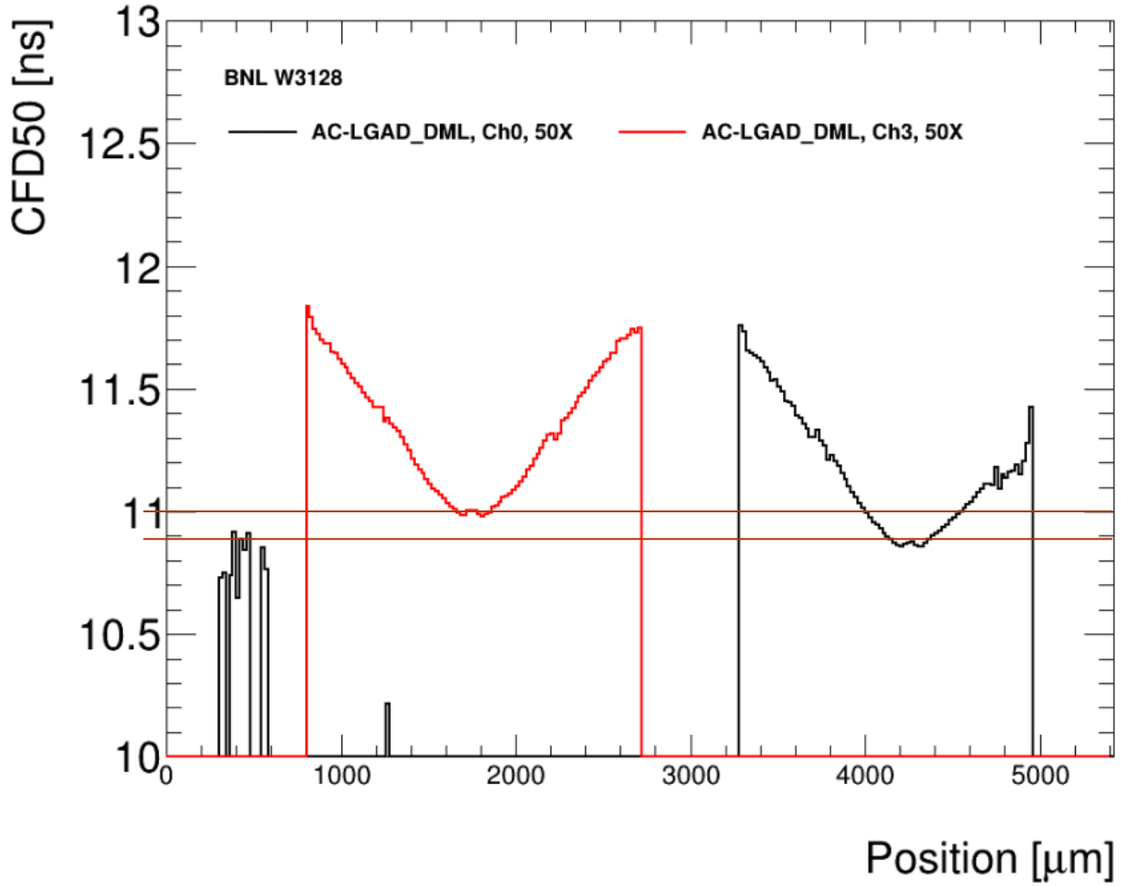
- Correction is much more complicated, different strips have different delays vs (x,y)
- Propagation in signal strip and transmission line could be different



Delay correction in DM AC-LGAD

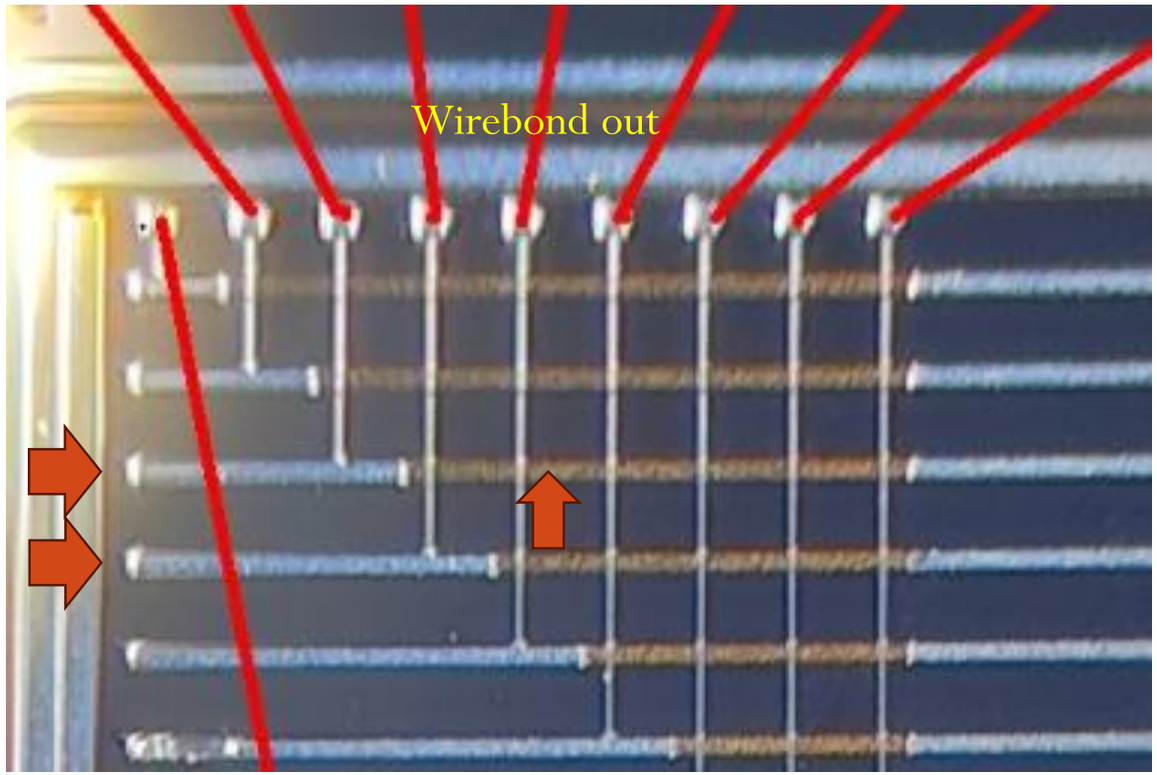
- Time of arrival vs position for two strips, same Y
- About ~100ps delay

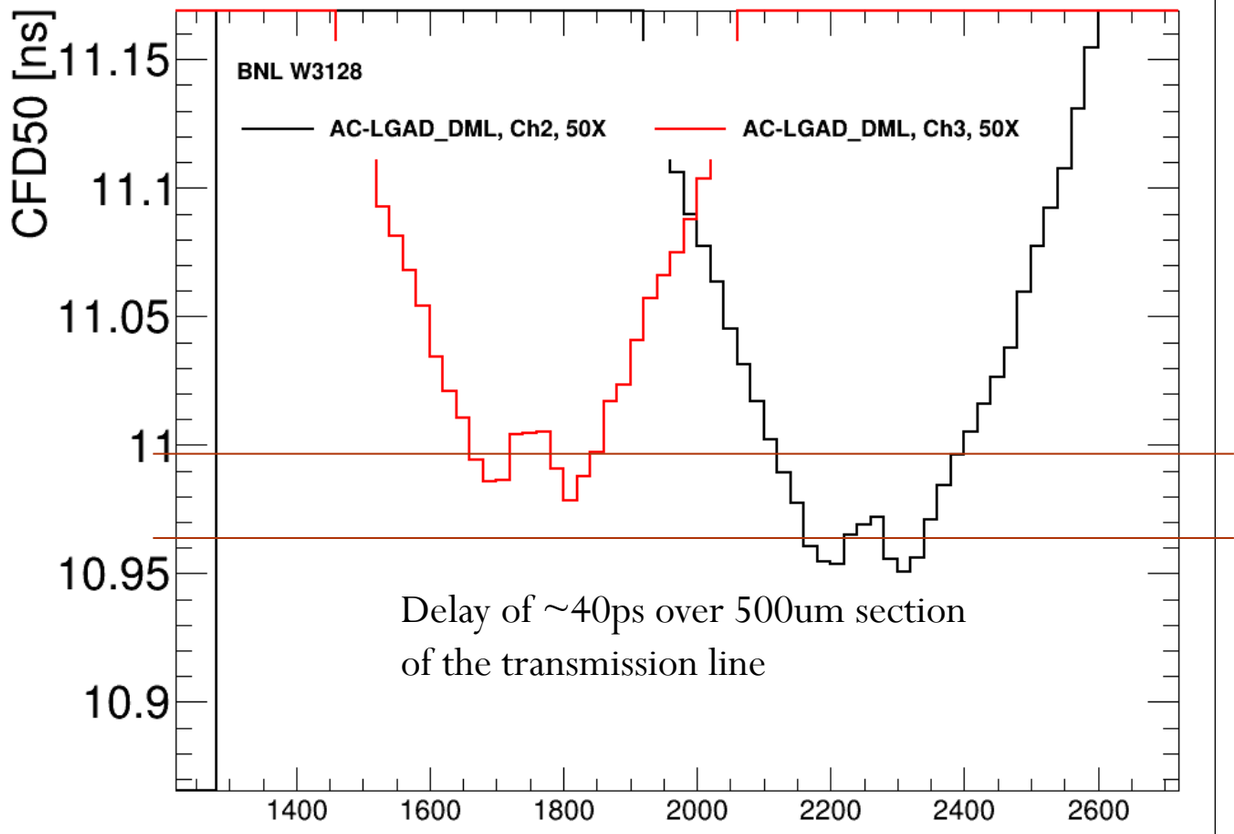




Delay correction in DM AC-LGAD

- Time of arrival vs position for two nearby strips, same Y





Delay correction in DM AC-LGAD

- Propagation across strip is faster
- Different impedance of the two, complicates things
- Might be produced to match

