Development of low-mass 4D tracking technology for the ePIC TOF PID layers

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

US FCC meeting, Sept 2026, SLAC

THE UNIVERSITY OF CALIFORNIA 1868 LET THERE BE LIGHT

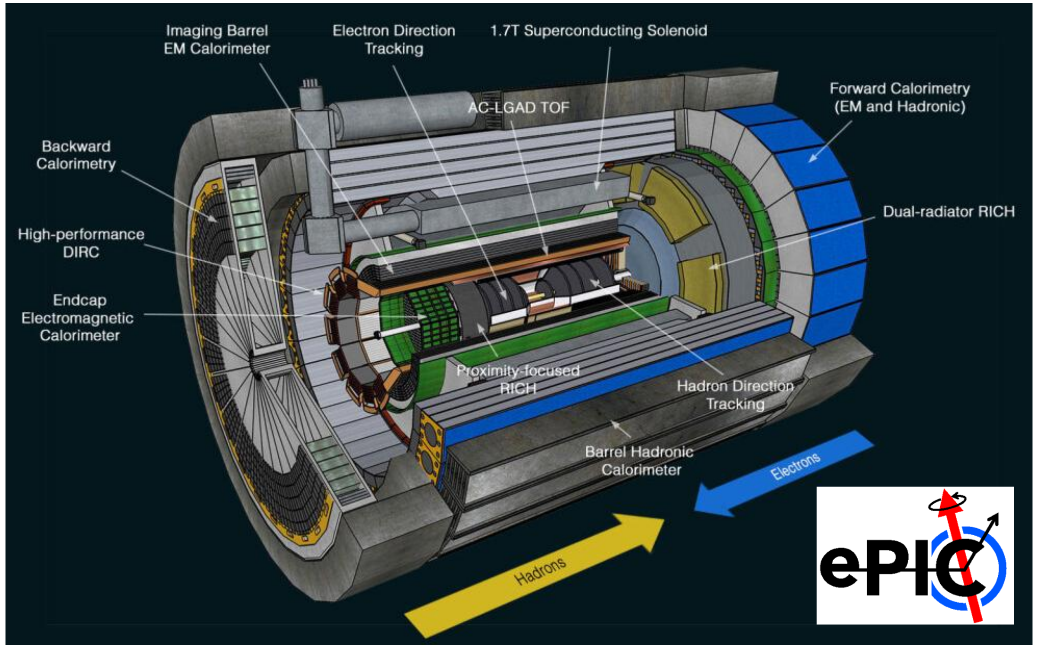
DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

SCIPP SANTA CRUZ INSTITUTE FOR PARTICLE PHYSICS UC SANTA CRUZ

ePIC

The ePIC detector

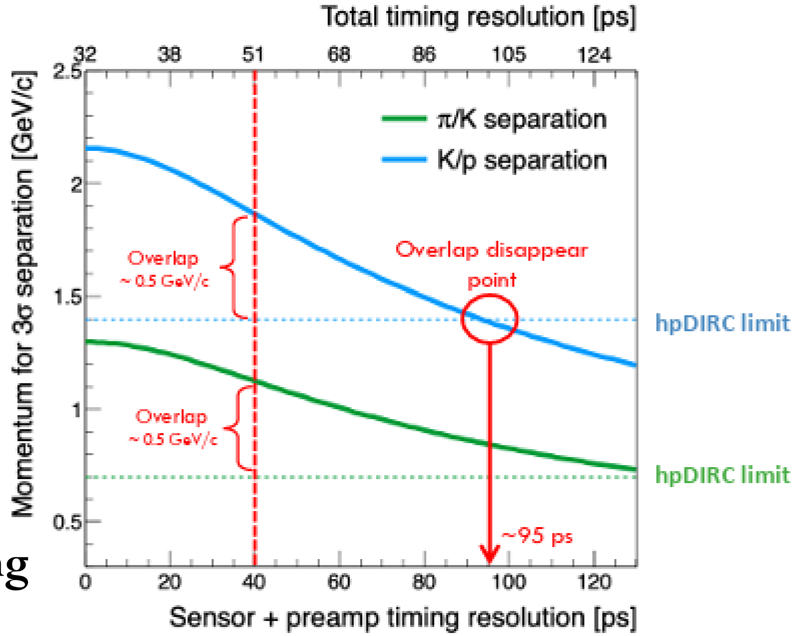
- **4D tracking** is a necessity to reach ePIC's physics goals
- **Particle identification with time of flight (TOF)**
  - For e/π/K/p at low/intermediate momentum
  - Require good time resolution and meaningful flight distance
- **A TOF layer** is foreseen for both barrel and end-cap in ePIC
  - Barrel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



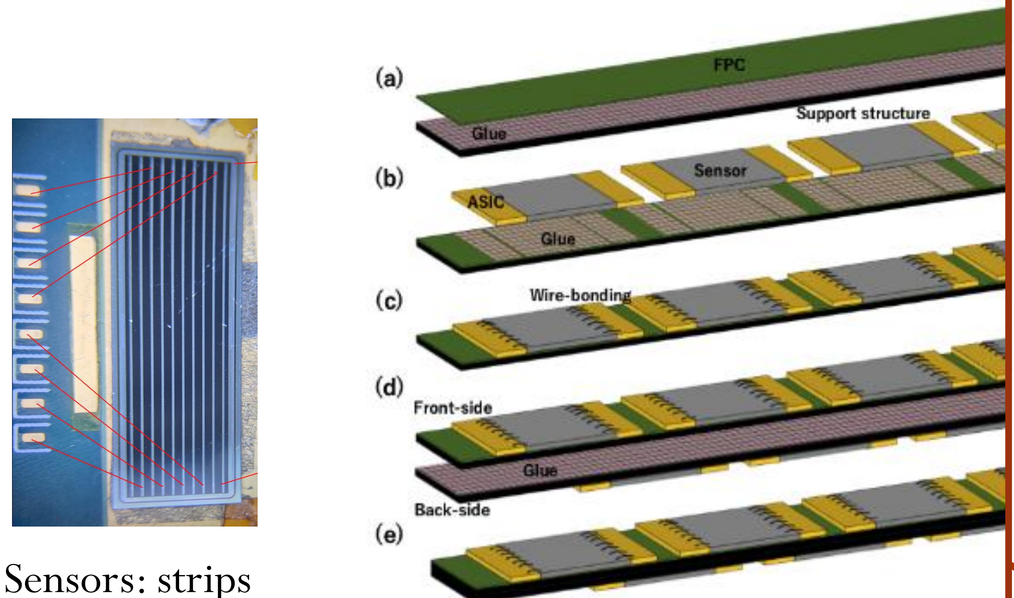
- **TOF layers based on AC-LGAD technology**

outdated **Subsystem**	Area (m^2)	dimension (mm^2)	channel count	timing σ_t (ps)	spatial σ_x (μm)	material budget (X/X_0)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

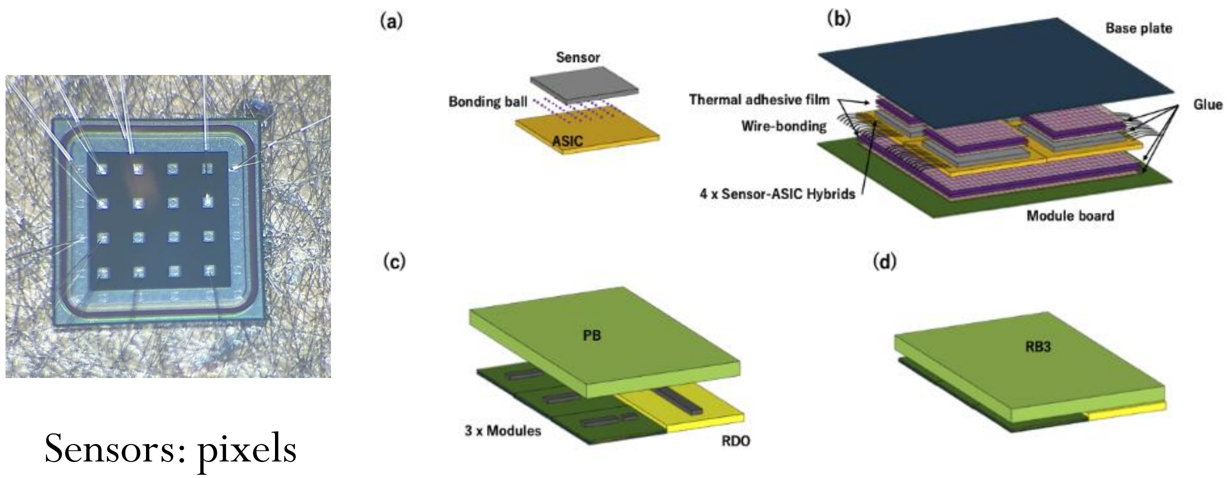
Challenging **Even more challenging**



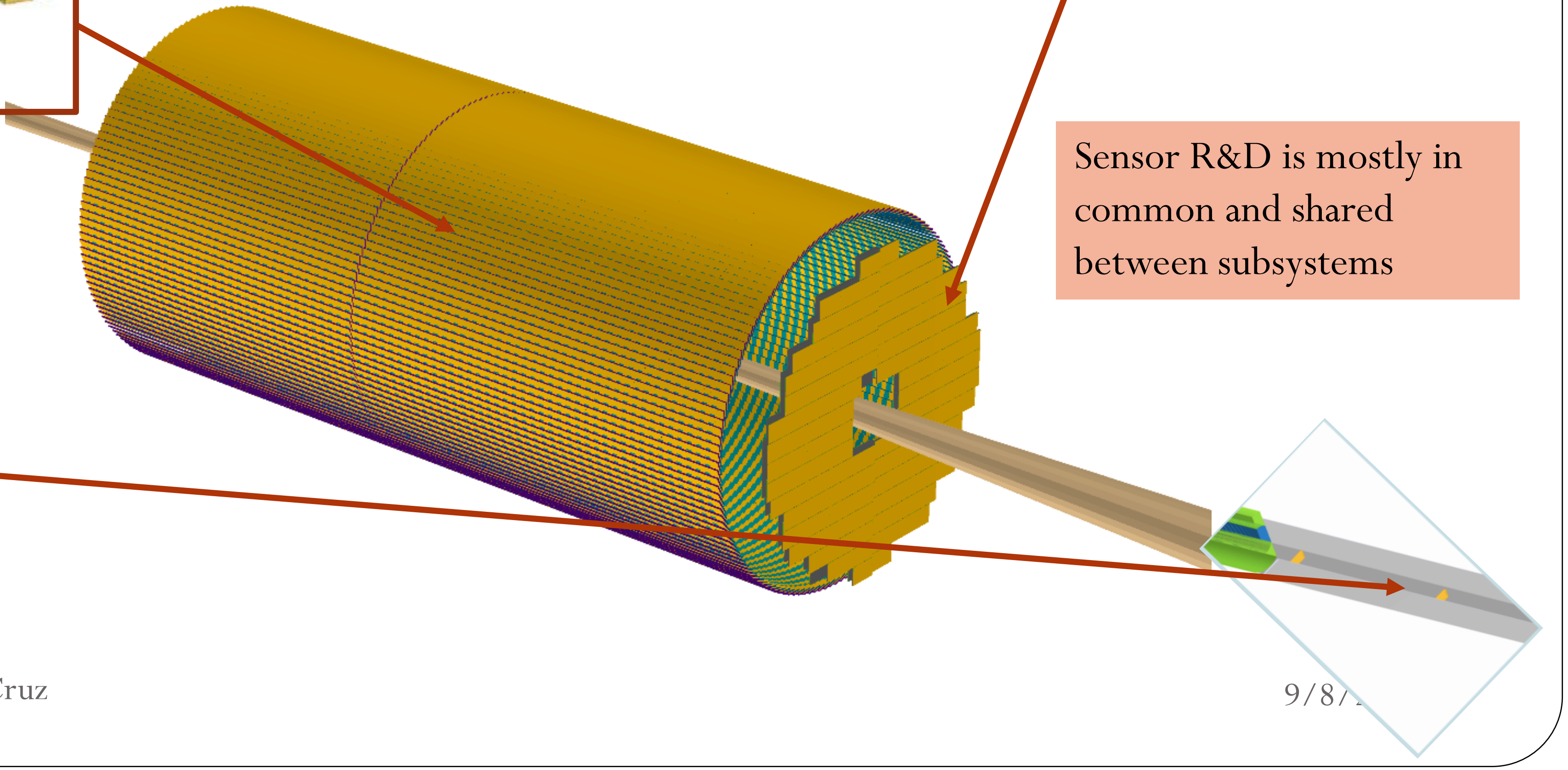
TOF layout in ePIC



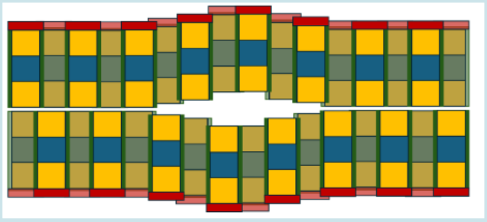
Sensors: strips
Readout: FCFD



Sensors: pixels
Readout: EICROC



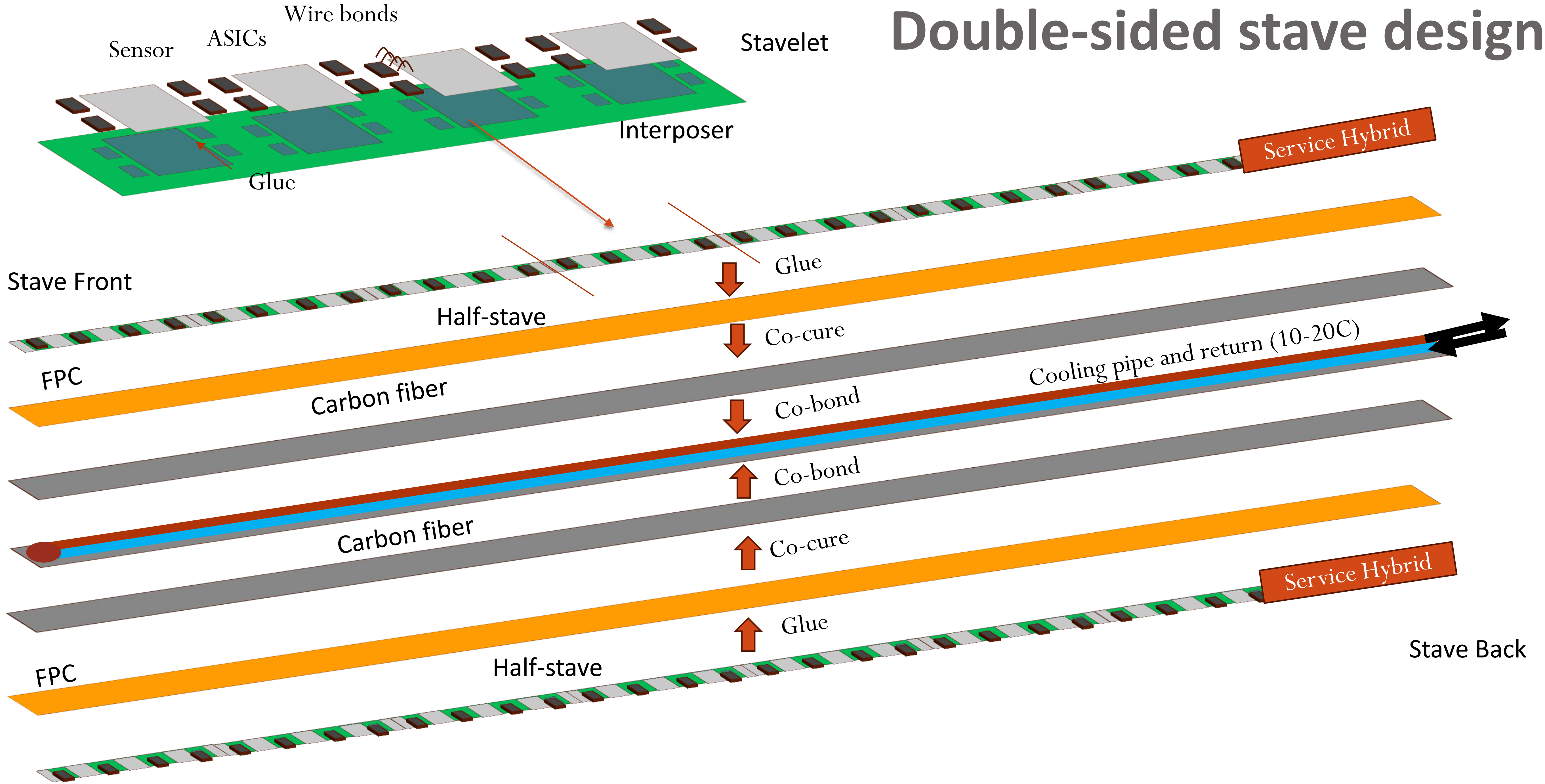
Sensor R&D is mostly in common and shared between subsystems



Sensors: pixels
Readout: EICROC

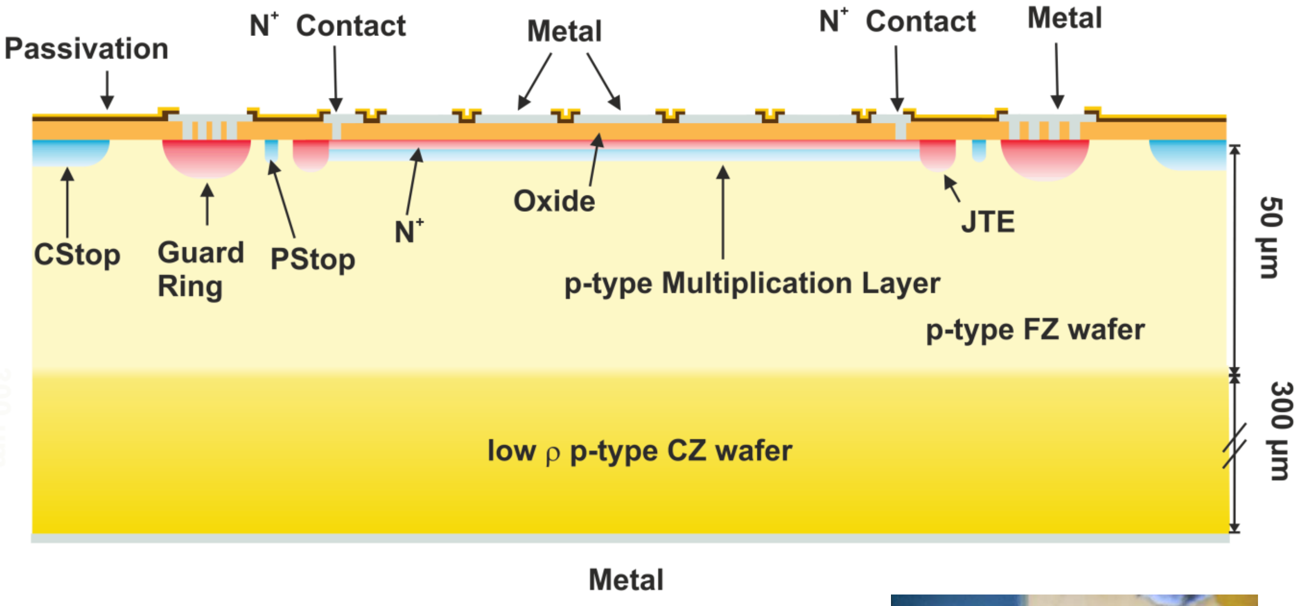
Off-Momentum Detectors (OMD)

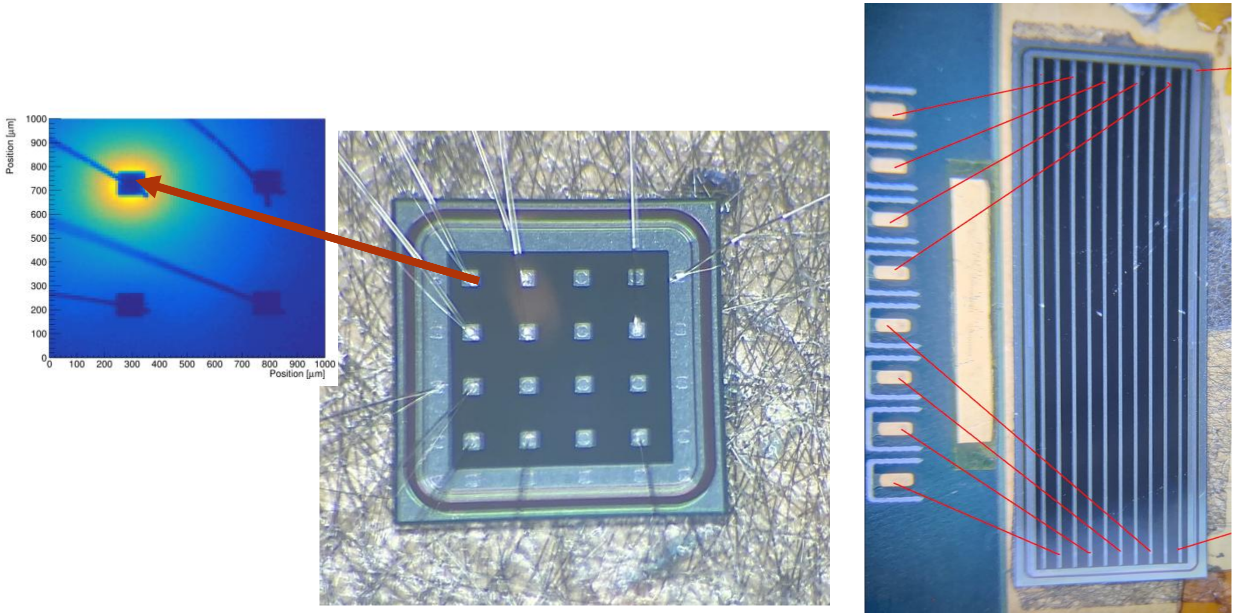
Double-sided stave design



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
- Readout for timing consume power, cannot use the same high-density readout as standard tracking
  - AC-LGADs reduce channel density and power dissipation while maintaining good resolution

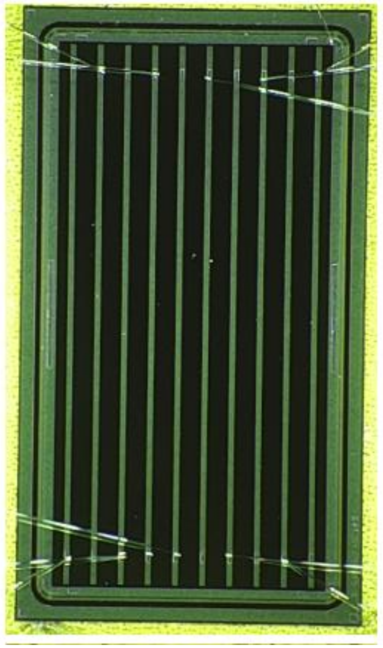




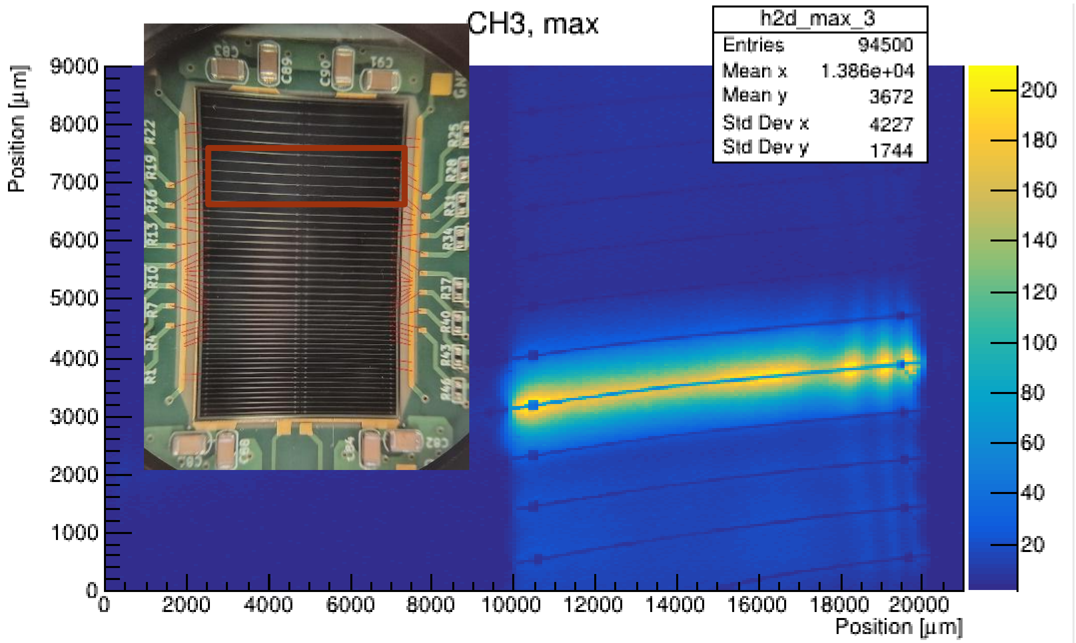
ePIC strip AC-LGADs prototype runs

- **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
  - https://arxiv.org/abs/2511.02939
- **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

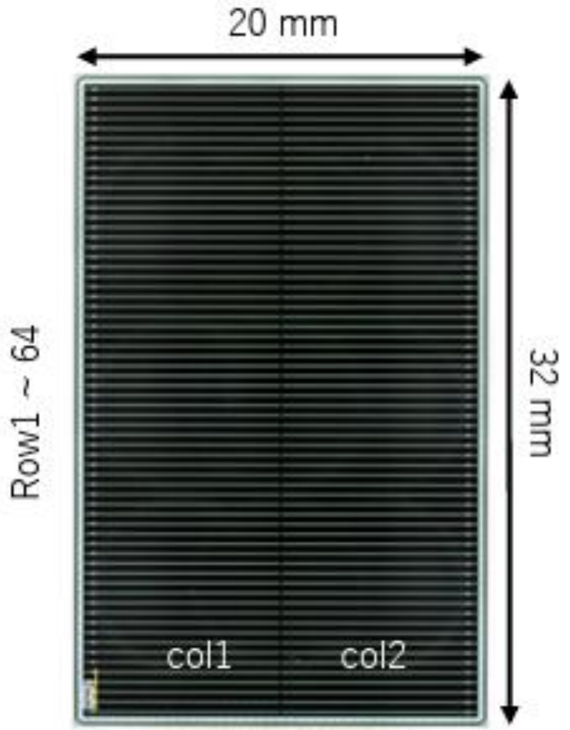


2024



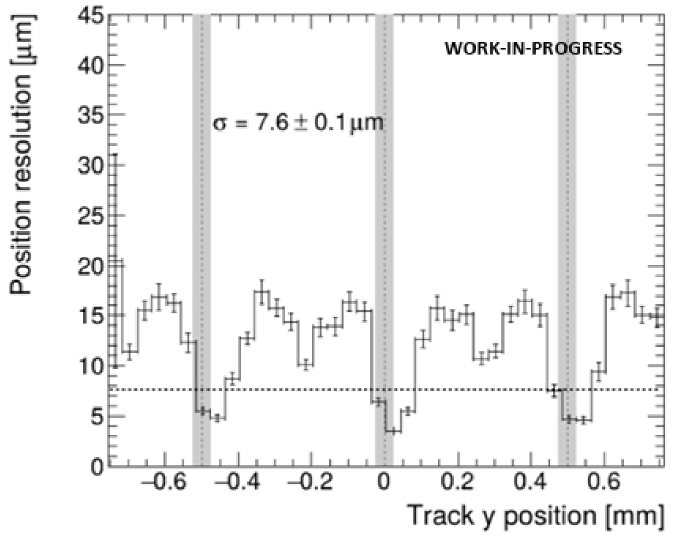
Laser TCT scan of the red area, Pulse Max vs position
IR laser spot 20um, time width 30ps

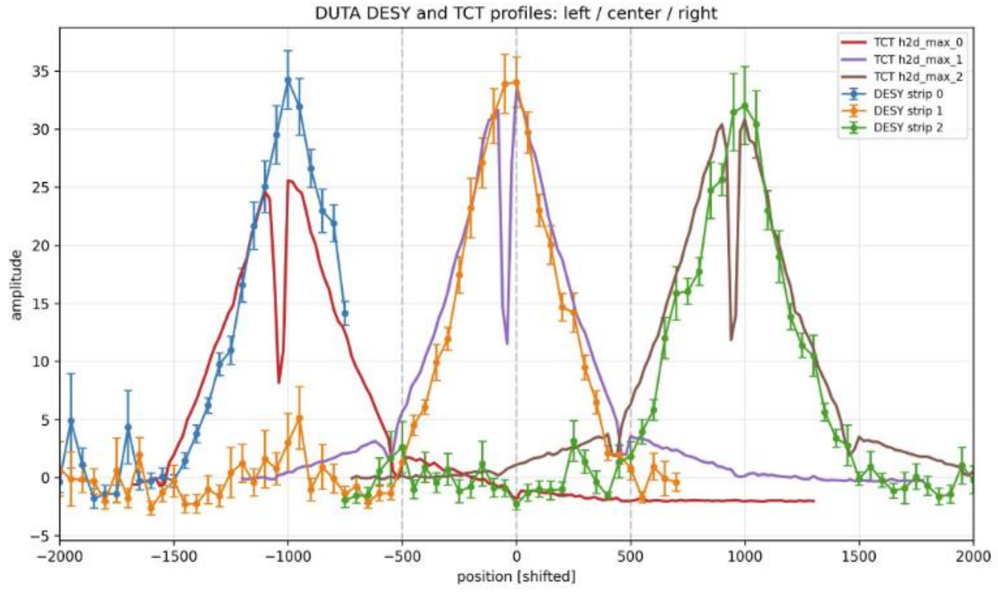
2025



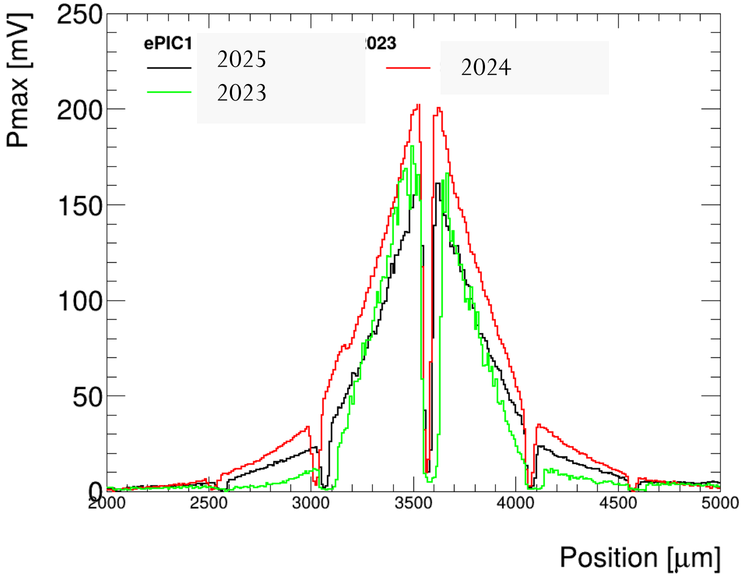
Comparison of HPK devices from 2023, 2024 and 2025

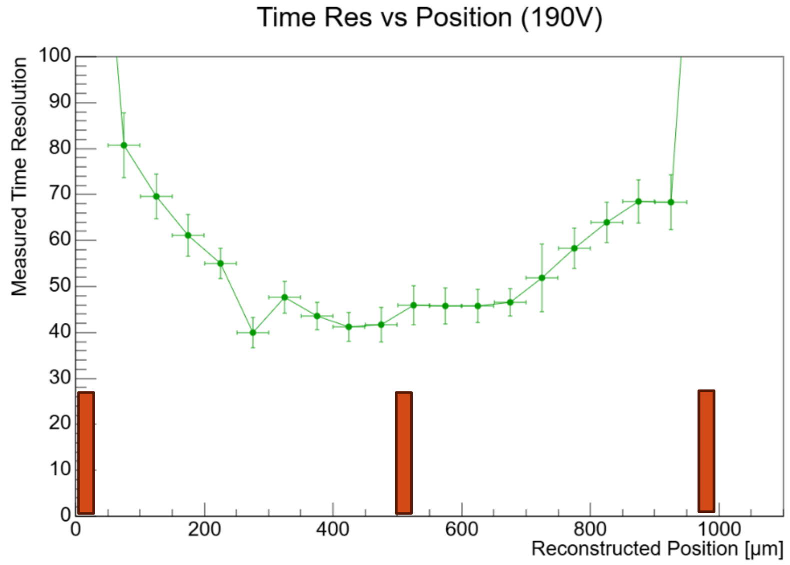
- 2024 strip sensor tested at DESY, strip response vs position same as laser TCT data in the lab
  - **Position resolution <10um**, but no time reference available for time resolution
  - Using information to get the 'true' response of strips for event reconstruction.
- Laser TCT data comparison of sensors from 2023, 2024, 2025: response is similar using same laser power, maximum voltage
- Time resolution of 2025 sensor measured in the lab using beta source with coincidence trigger
  - Reconstructing events using TB profile, time resolution as reconstructed DUT time minus trigger time
  - **Around 40-50 ps of time resolution near the central strip**
- Test beam done at KEK in summer, data analysis ongoing





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

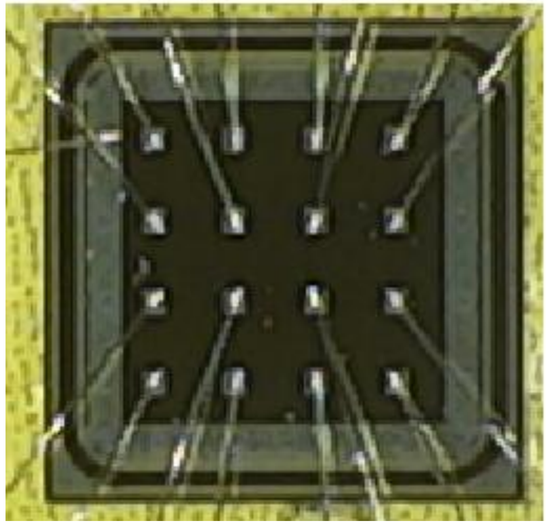




Center strip

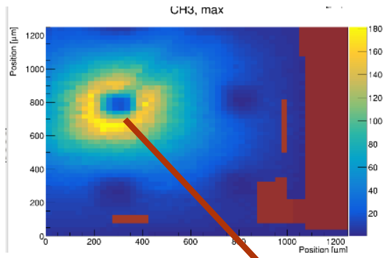
Students: L. Guccione-Jimenez

ePIC pixel prototype

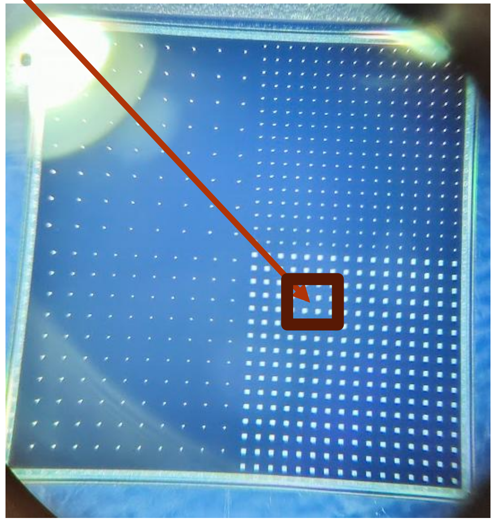


- **2023:** Small pixel prototypes with different parameters
  - Time resolution 20ps, position resolution 30um
  - https://arxiv.org/abs/2407.09928
- **2024:** ePIC full-size production of pixel AC-LGADs from HPK of 1.6x1.6 cm
  - Using parameters from 2023 production
  - Pixel pitch and width: 50,100,150um, pitch 500, 750, 1000 um. 30um and 20um thick
  - Yield >80% for all wafers
- KEK test beam for 2024 production data analysis ongoing, will steer 2026/2027 production
  - Already identified 500um as maximum pitch before S/N loss

- See https://indico.phy.ornl.gov/event/677/contributions/2683/ for lab characterization



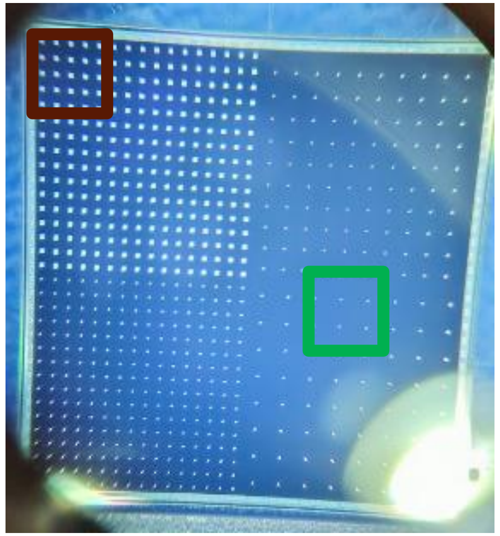
Detector type	Thickness	Pitch-width 1	Pitch-width 2	Pitch-width 3	Pitch-width 4
W3 pixBIG	20um	500-150	500-100	750-100	1000-100
W3 pixSmol	20um	500-150	500-50	750-50	1000-50
W7 pixBIG	30um	500-150	500-100	750-100	1000-100
W7 pixSmol	30um	500-150	500-50	750-50	1000-50

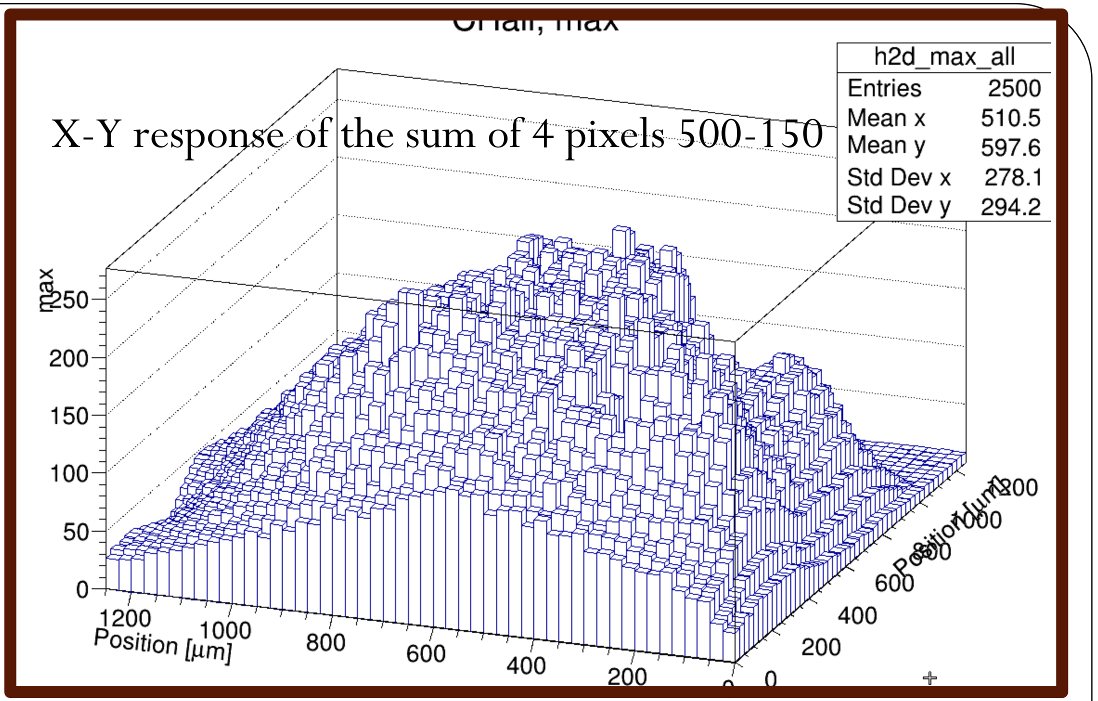


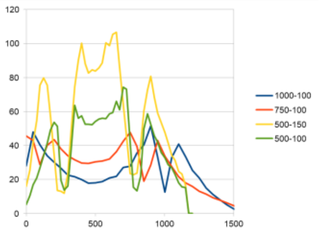
Students: N. Lynch, A. Drumm, Y. Spinos, O. Khandelwal

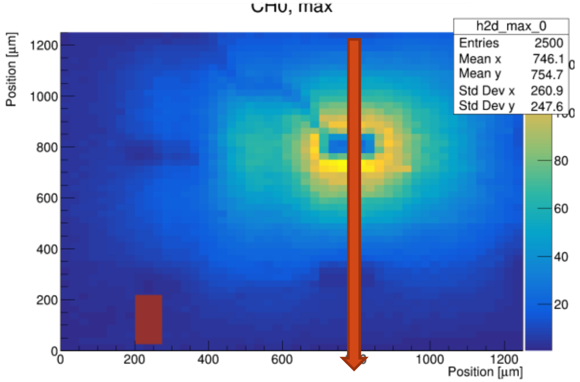
Pixel laser TCT testing

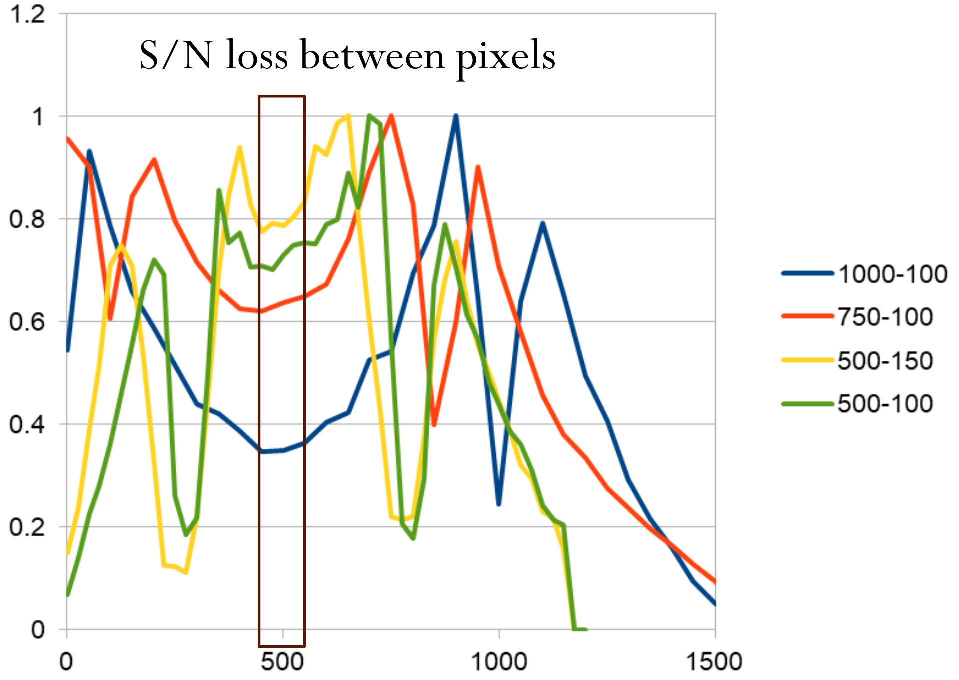
- Sensor: W7 (30um) – big pixels
  - 500-150um vs 1000-100um geometry
  - S/N loss if pixel size is decreased
  - S/N loss in between pixels if pitch in increased
- Signal propagation time is similar for all geometries

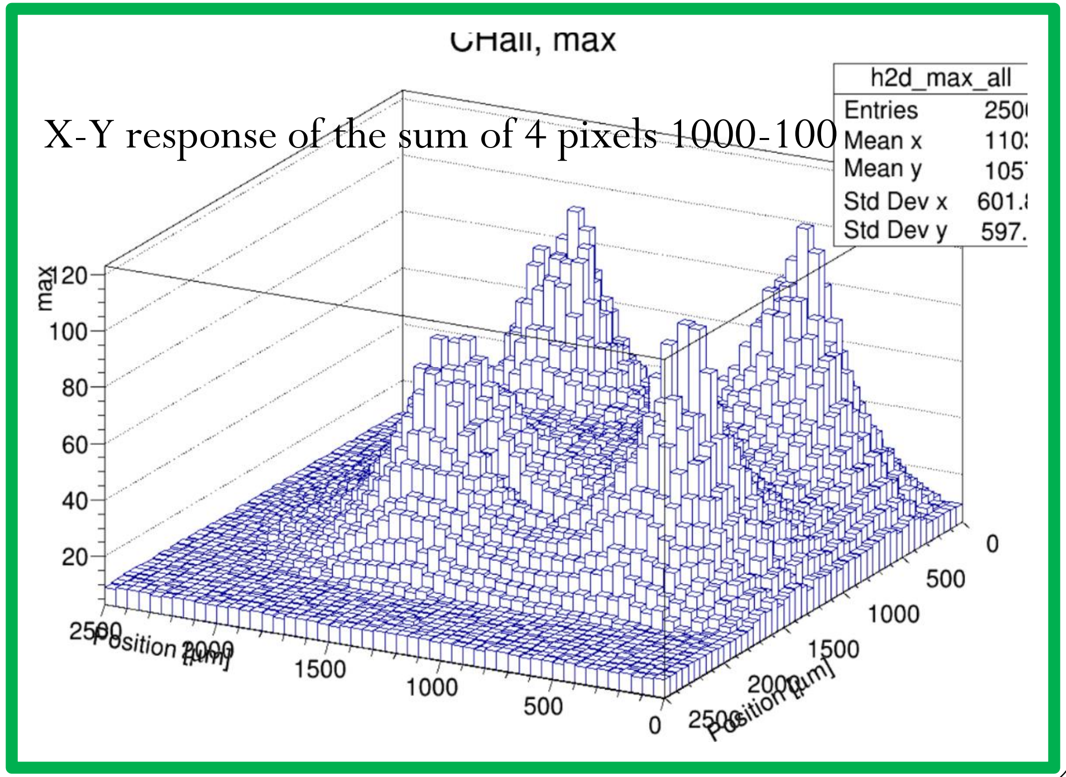










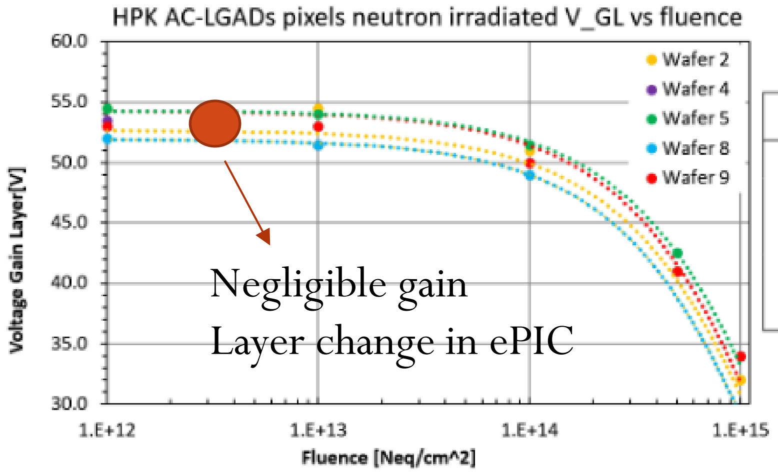


Dr. Simone M. Mazza - University of California Santa Cruz

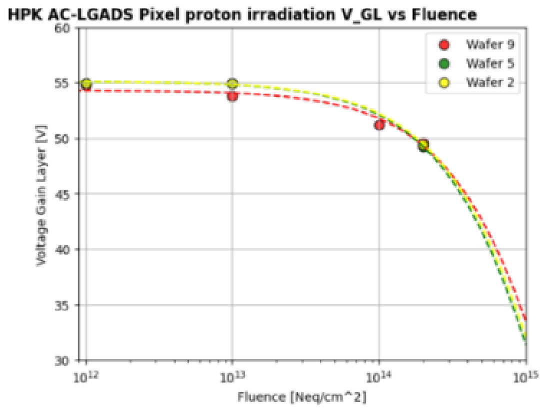
Students: M. Davis, N. Lynch, O. Khandelwal

Irradiation effects on AC-LGADs

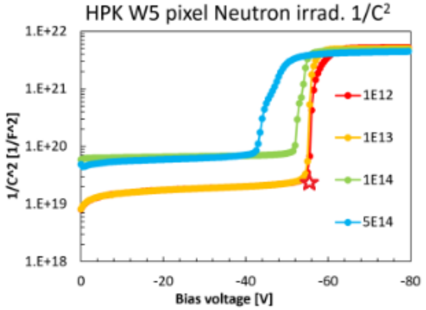
- Neutron (IJS) and proton (FNAL) irradiation on 2023 HPK production
- Up to 1e13 Neq, no significant change in sensor IV properties and gain layer doping
  - Leakage current scales with bulk volume
  - Current and breakdown voltage increases with fluence (as expected)
- Gain layer doping proportional to Vgl (gain layer depletion voltage) or 'foot' (star in the plot)
  - Degradation parameter 'c' from fit on the Vgl vs fluence
  - Behavior across wafers is consistent
- C-factor comparable for protons and neutrons, degradation similar to "standard" DC-LGADs
- **Response of AC-LGAD strips is unchanged**
  - Same signal propagation in N+
- Full-size ePIC prototypes neutron/proton irradiated as well, studies ongoing

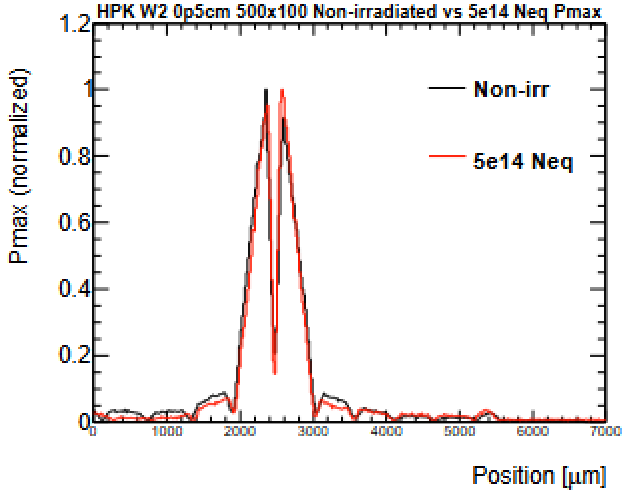


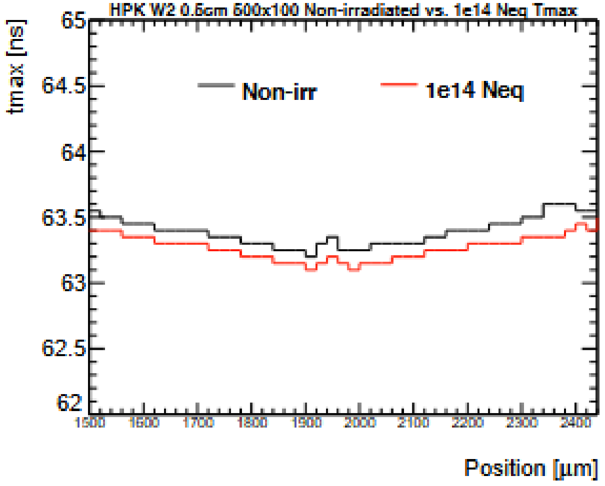
Wafer	C factor $\frac{cm^2}{Neq}$
W2	5.38×10^{-16}
W4	3.69×10^{-16}
W5	4.93×10^{-16}
W8	5.81×10^{-16}
W9	4.54×10^{-16}



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







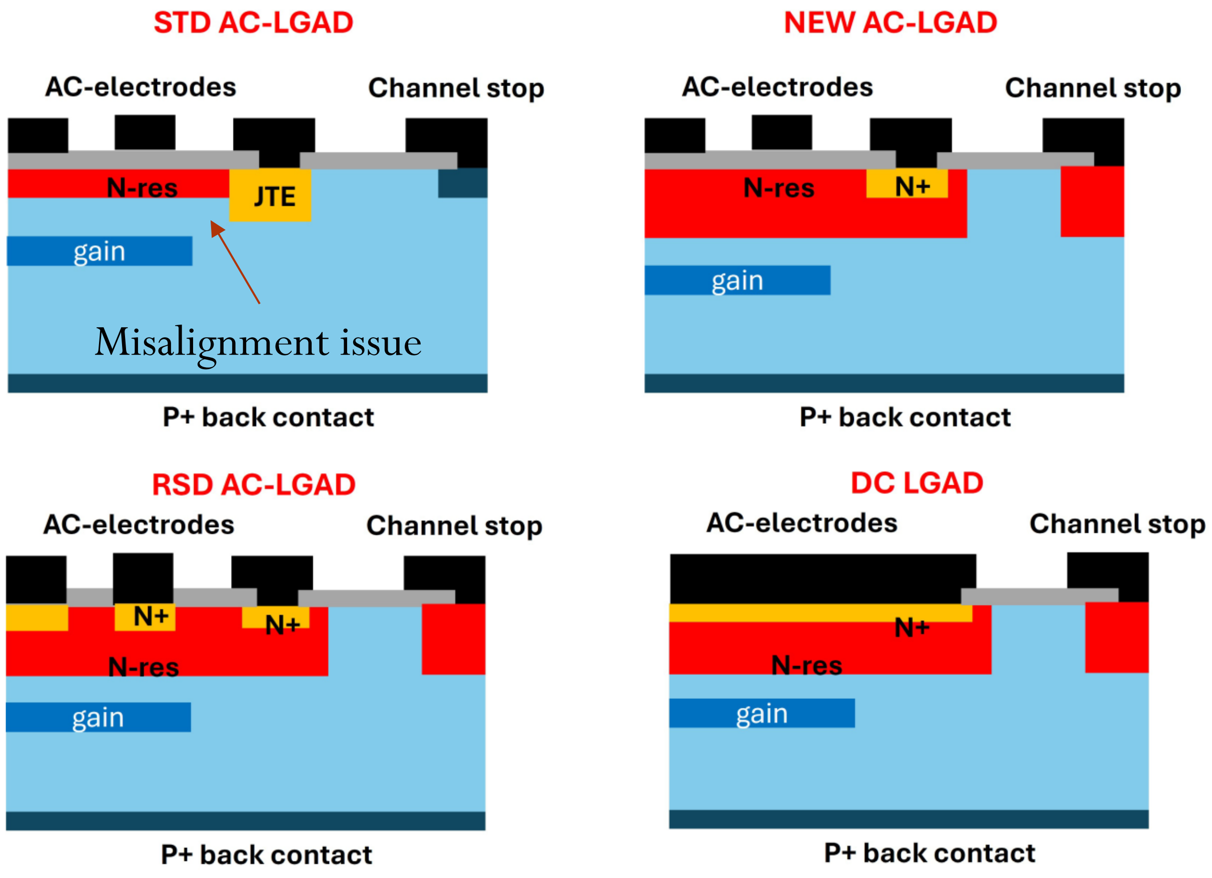
Student: J. Ding, M. Davis

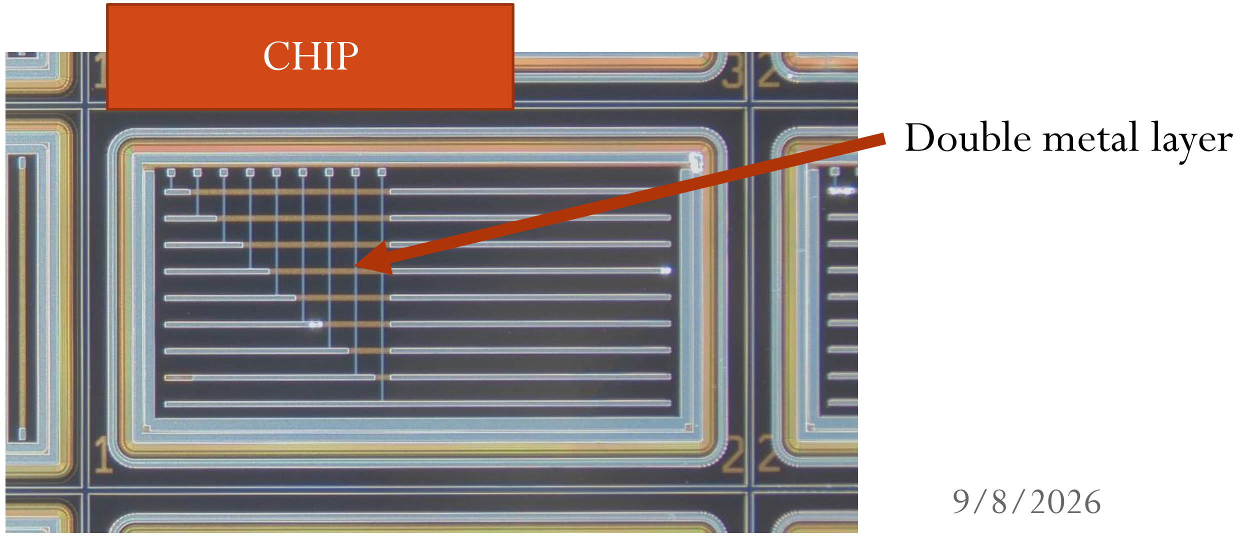
https://arxiv.org/abs/2503.16658

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
  - Development of new type of devices from HPK as well
- 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
  - First test not good, but new productions ongoing
- Type 3: lateral readout for strips with double metal layer
  - Simplified assembly for 100% coverage

- Production 1: done with erd112 remaining funds
  - Results in https://indico.global/event/14966/contributions/132618/
- Production 1 ½: a few test strip sensors on another sensor production, will start soon
- Production 2: design ongoing, funded by EIC R&D funds





EICROC - IOMEGA and collaborators

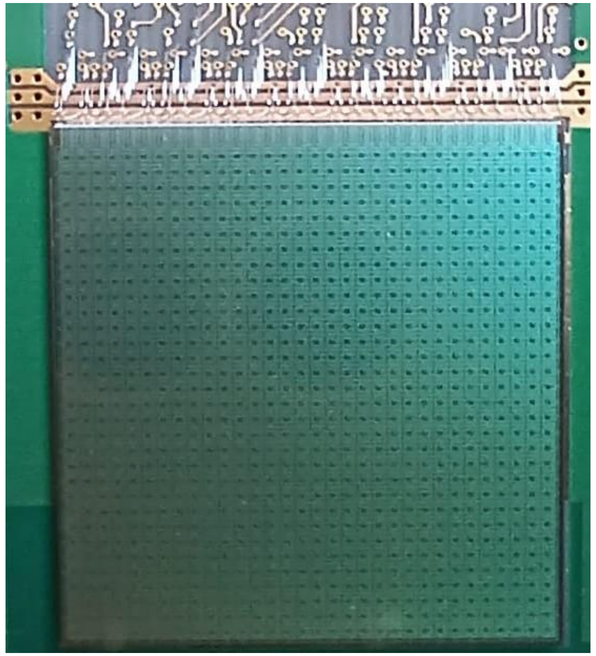
- Readout for pixel AC-LGADs, target input capacitance ~1 pF
  - ADC for charge measurement : 8bit 40 MHz from AGH Krakow
  - EICROC0A (4x4) designed FY24-FY25, EICROC1 (32x32) FY25
  - EICROC2 will be fabricated Q1 2027
- Laboratory testing, time jitter ~30ps and position resolution ~30um
- Power ~1.5mW/ch

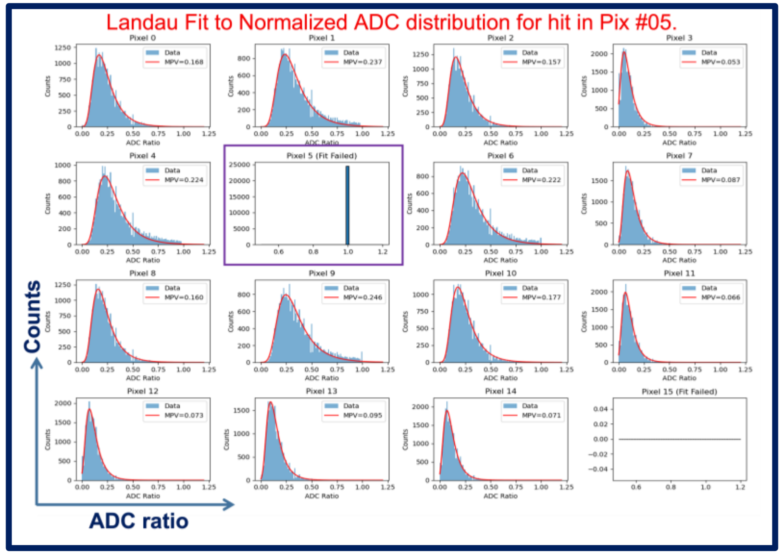
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

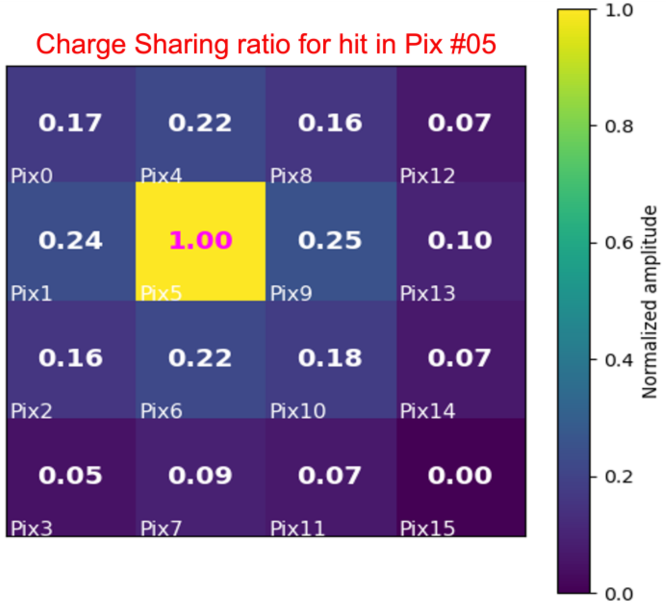
cea irfu

ΩMEGA Microelectronics

LPC Particules pLasmas Univers applications Laboratoire de Physique de Clermont





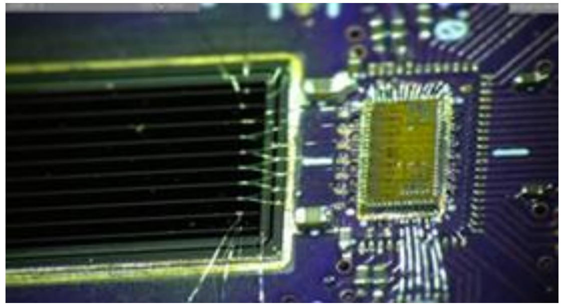


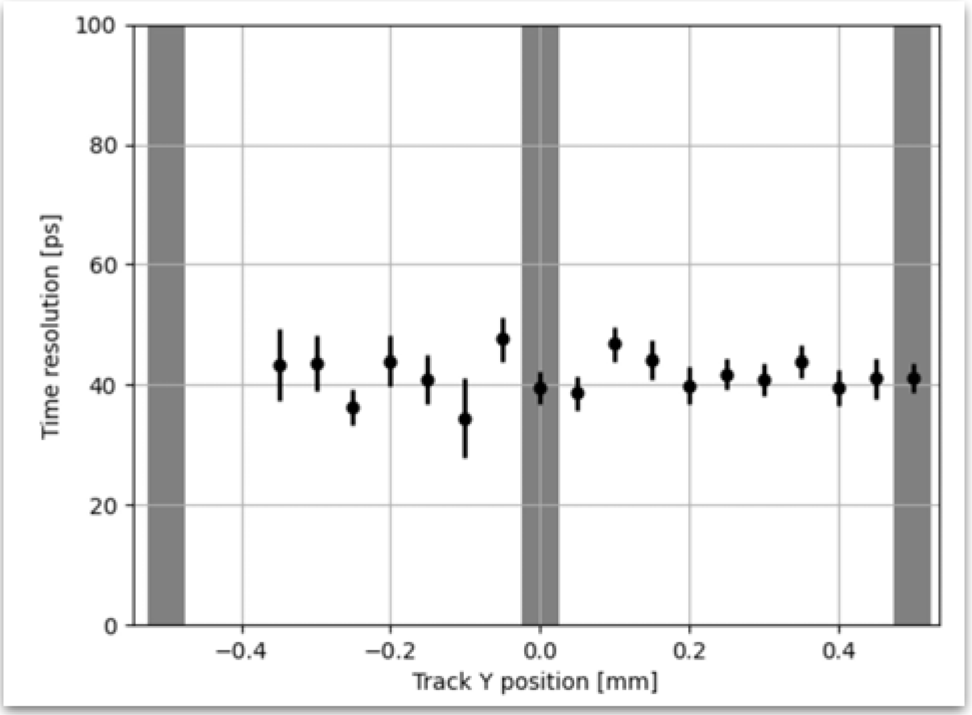
https://iopscience.iop.org/article/10.1088/1748-0221/20/04/C04014

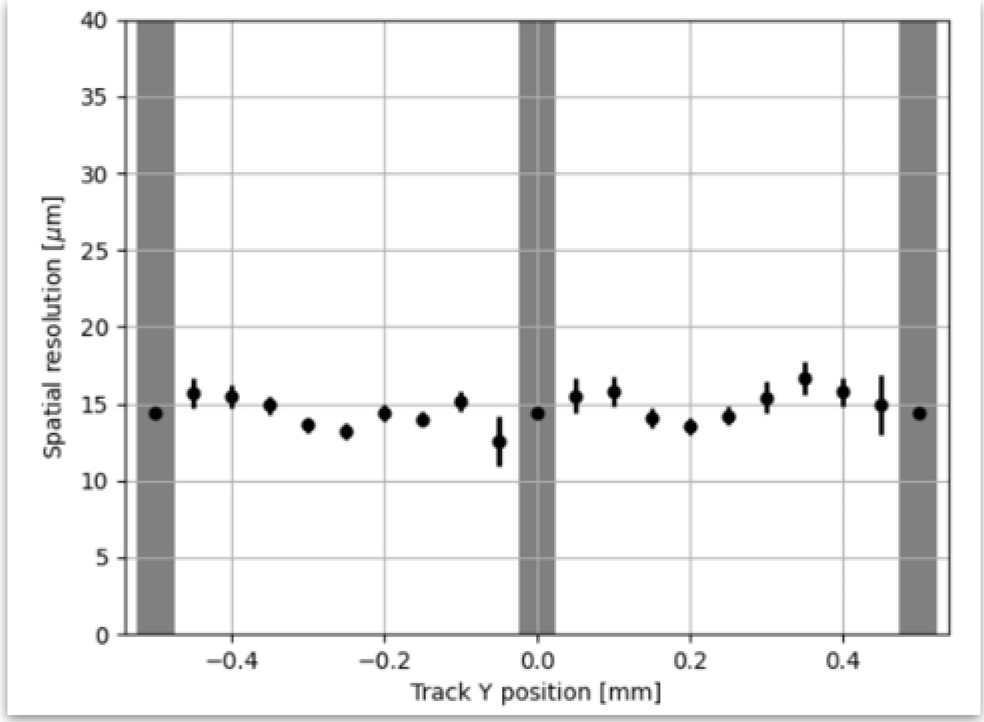
Close collaboration with Brookhaven National Laboratory

FCFD – FNAL group

- Readout for strips AC-LGADs, target input capacitance ~10pF
- Ongoing development for AC-LGAD readout for EIC with TSMC 65 nm
  1. V0 (2021-2022): first prototype to implement the Constant Fraction Discriminant
  2. V1 (2024): optimized for strip AC-LGAD sensors, plus position reconstruction
  3. V1.1 (2025): optimized for 1-cm long AC-LGAD strip sensors, with tunable thresholds
- Latest version (V1.1) tested at DESY, shows 40ps and 15um of resolution
- Power ~8 mW/ch





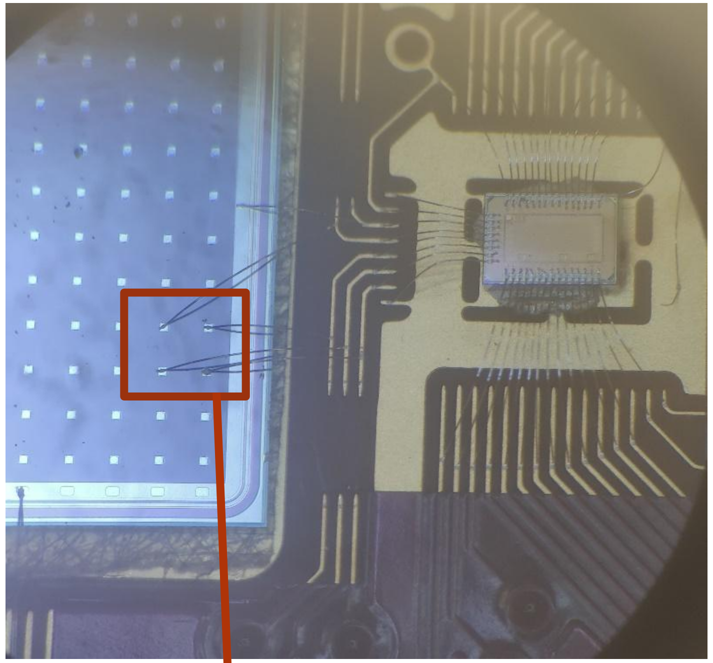


https://arxiv.org/abs/2512.19930 A. Apresyan

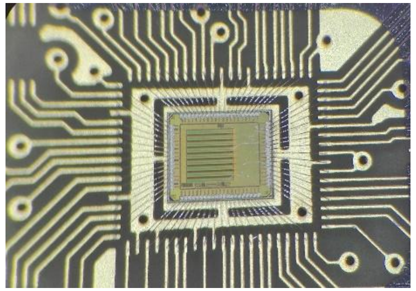
HP-SOC, a full readout chip

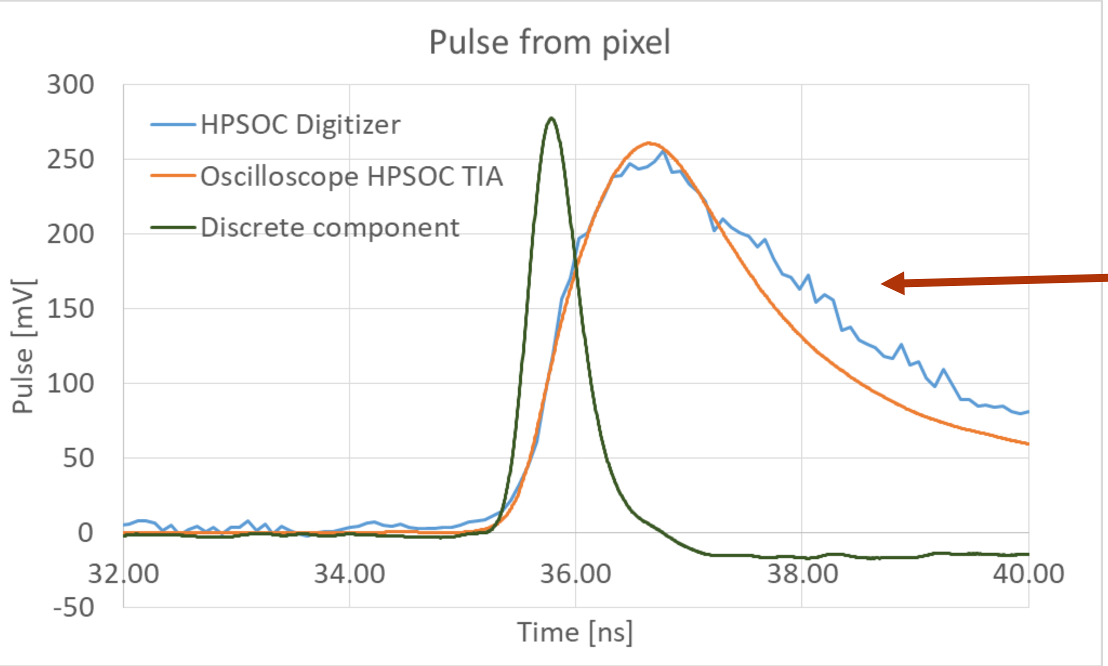
- Readout chip are decided for ePIC (EICROC, FCFD), but R&D continues
- HP-SOC is a system on chip developed by NALU scientific in collaboration with UC Santa Cruz and U. Hawaii at Manoa
  - TIA amplifier with GHz bandwidth and 13.5 Gs/s digitizer
  - Goal of 1mW/ch for front end
  - Full waveform → can use ML to reconstruct events precisely
- HP-SOC v2a tested with ePIC 30um pixel sensor using laser TCT
  - Rise time of ~700 ps and S/N of ~50, Jitter ~14ps
- Loss of bandwidth might be from connection through wire bonds and trace

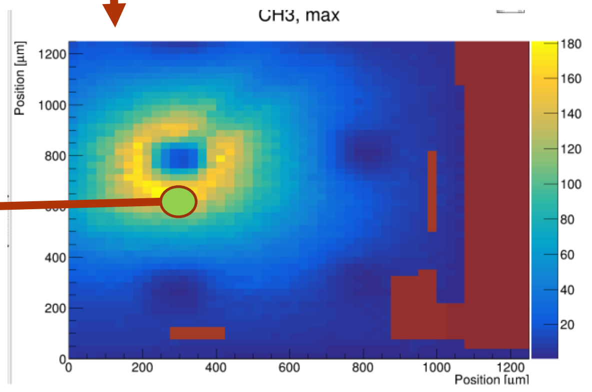
HP-SOC v2 connected to pixel



HP-SOC v3 mounted on a board, testing ongoing



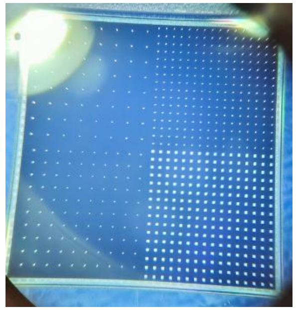


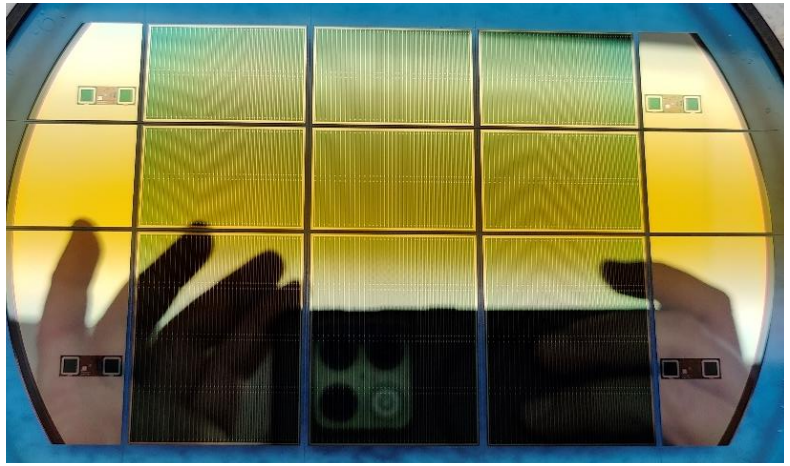


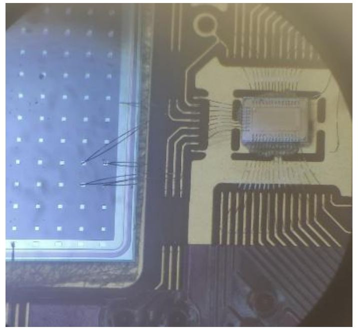
Laser scan with discrete component board

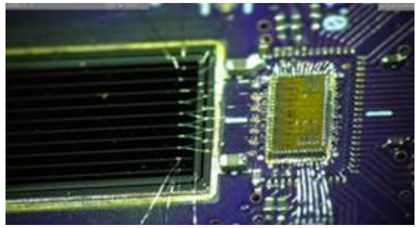
Conclusions

- Sensors for the ePIC TOF layers are reaching maturity
  - First large-scale AC-LGAD production from HPK lab tested
  - Test beam just completed at DESY and KEK
  - Planning multiple test beams next year (DESY, KEK, SLAC ESTB application submitted)
- New AC-LGAD sensors productions from HPK and FBK ready soon
- Tested irradiation effects on AC-LGADs, characterization of irradiated full-size sensors ongoing
- Readout chip development and testing ongoing for the two geometries
- Mechanical development of the BTOF and FTOF crucial as well to satisfy material budget requirements









Thanks for the attention

Many thanks to the SCIPP group students and technicians!

In particular to students:
<u>A. Molnar</u>, J. Ding, G. Stage, A. Borjigin, C. Altafulla, M. Davis, S. Beringer
N. Lynch, A. Drumm, Y. Spinos, O. Khandelwal, A. Esparza, L. Guccione-Jimenez

Thanks to HPK and BNL for fabricating sensors for this study

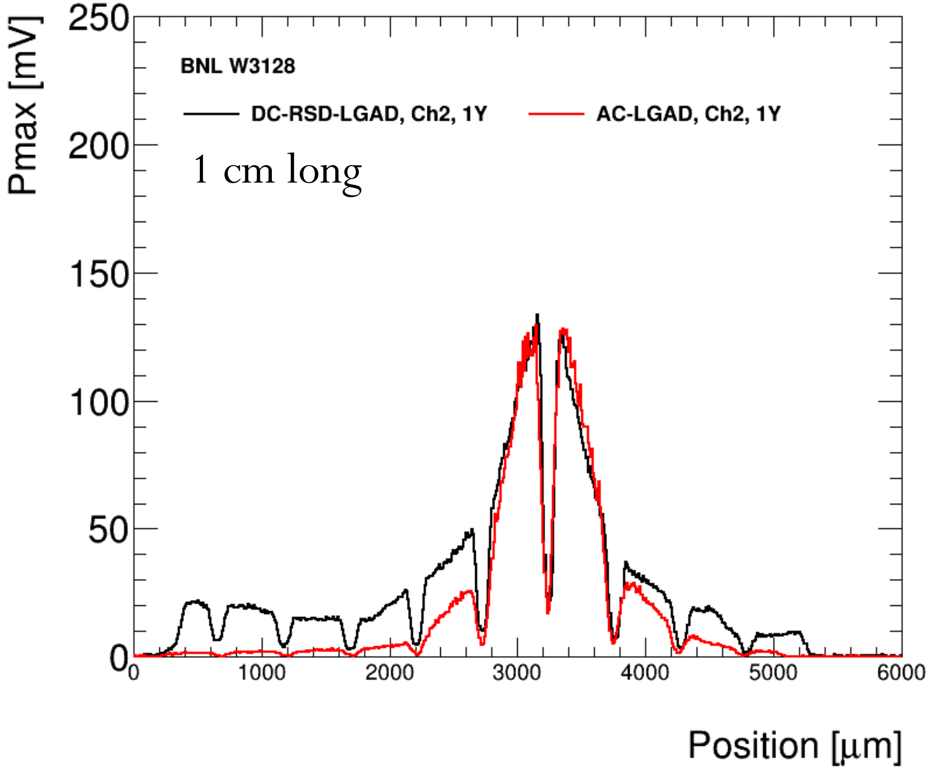
This work was supported by the United States Department of Energy,
grants DE-SC0010107 and DE-SC0020255.

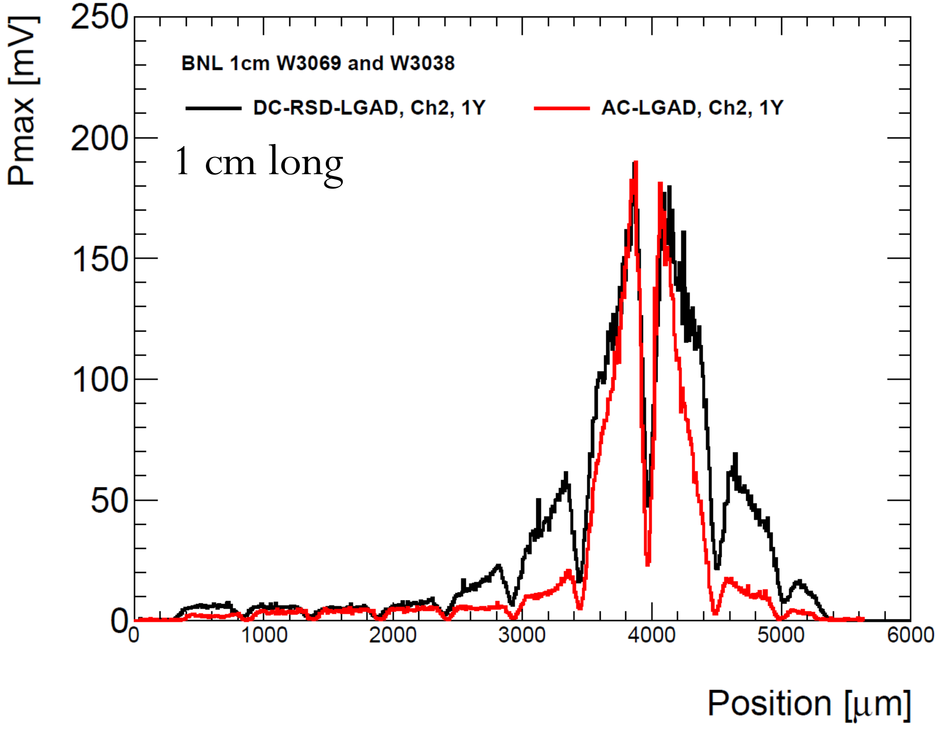
This work was supported by eRD112 funds from EIC and PED program

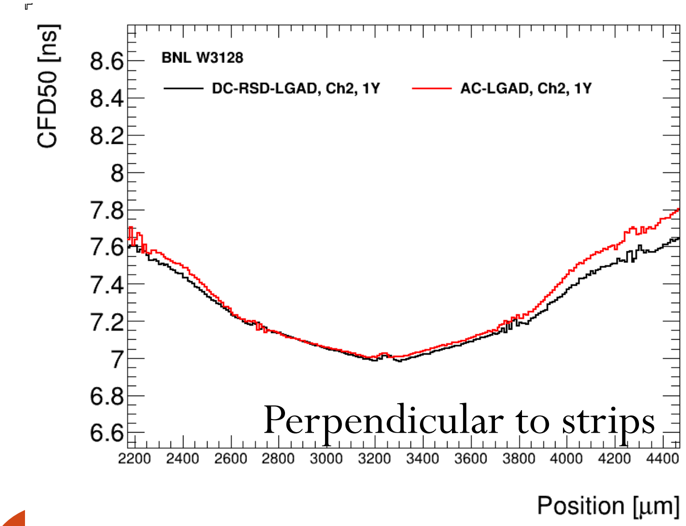
Backup

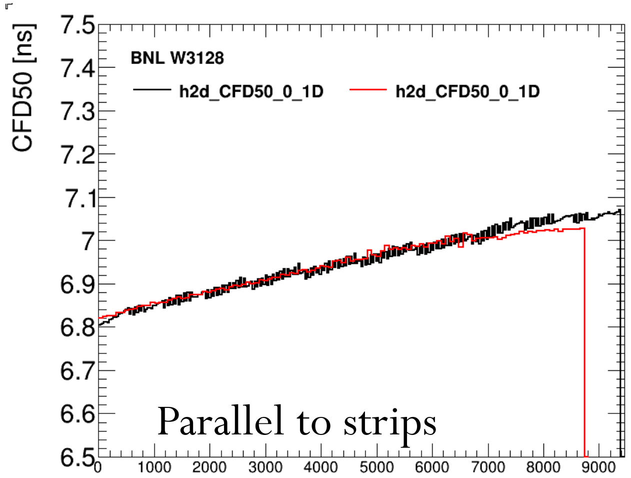
DC-RSD prototype vs AC-LGAD

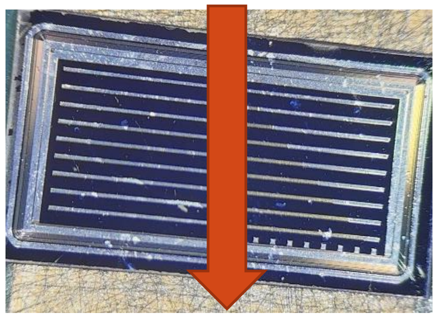
- First prototype of new type of AC-LGAD and DC-RSD produced at BNL
- Testing two sensors with same geometry; 1cm long, 500um pitch, 100um wide strips
  - Laser TCT scan across the sensor shows worse performance for DCRSD in terms of charge sharing (Ideal behavior is signal close to zero at first neighbor)
  - But different behavior for different wafers?
  - Timing proprieties (rise time, time of arrival) are the same







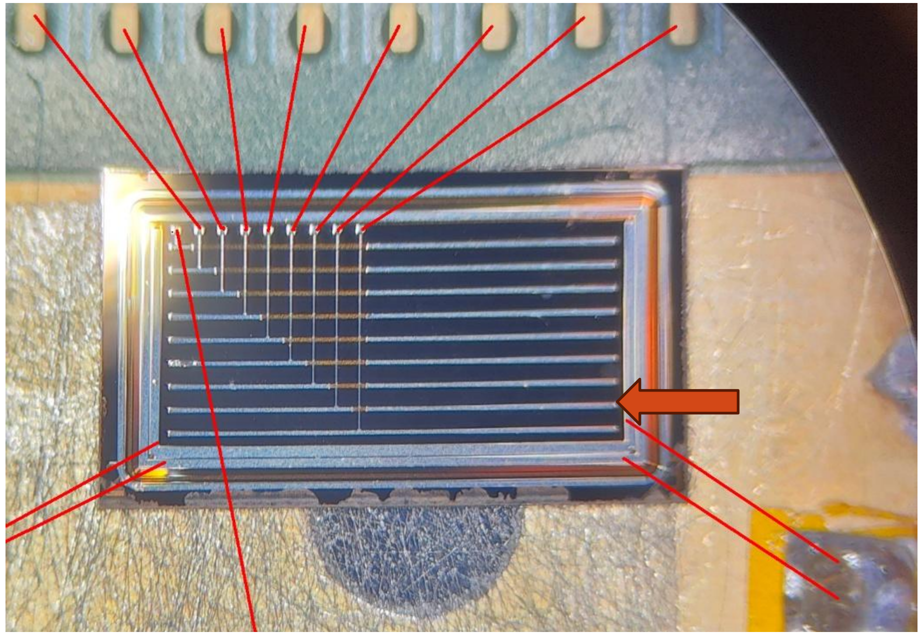




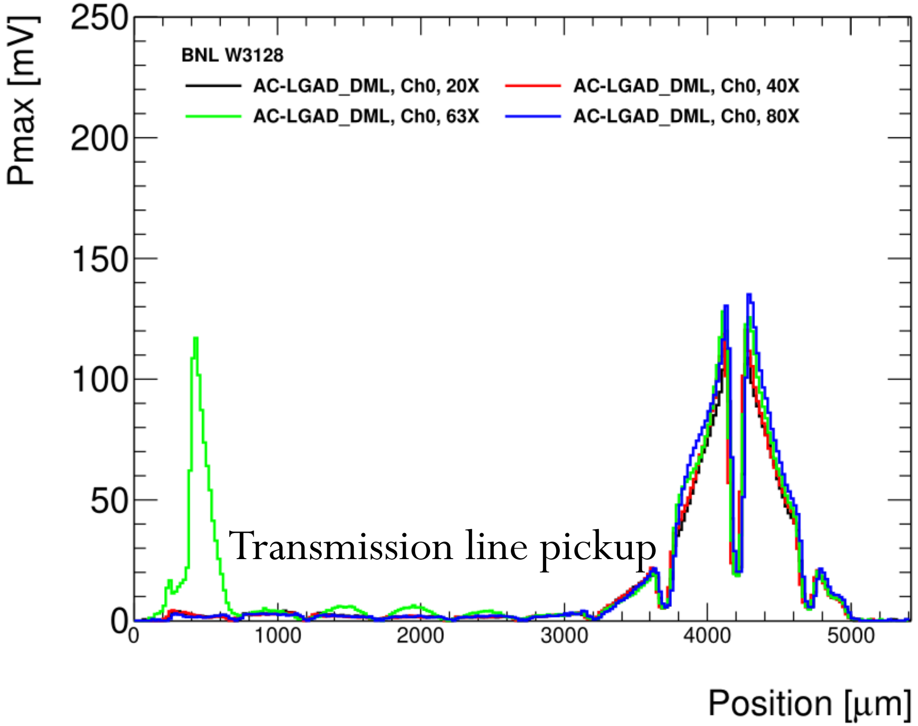
Student: A. Molnar, C. Altafulla

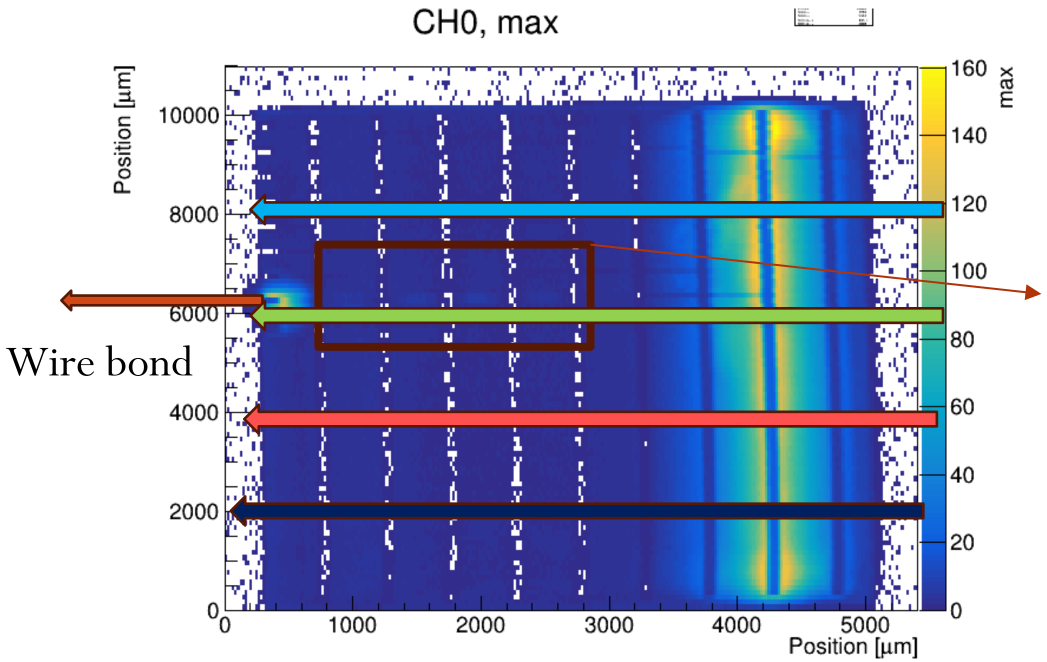
DML AC-LGADs

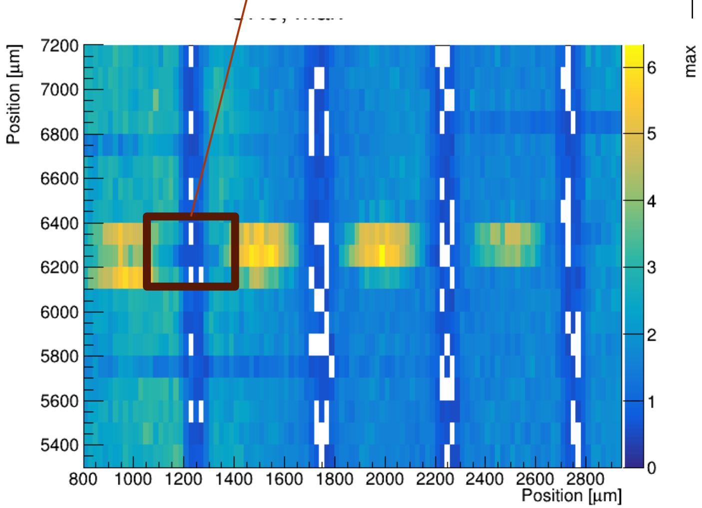
- Proof of principle works! Behaves as standard AC-LGAD
- Pickup of the cross strip is minimal, extra pickup at the bonding pad
  - Pickup on the line is ~4%
  - Cross talk with perpendicular strip hard to test with laser
- Behavior across the strip is homogeneous
  - Both Pmax and rise time are ok
- **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



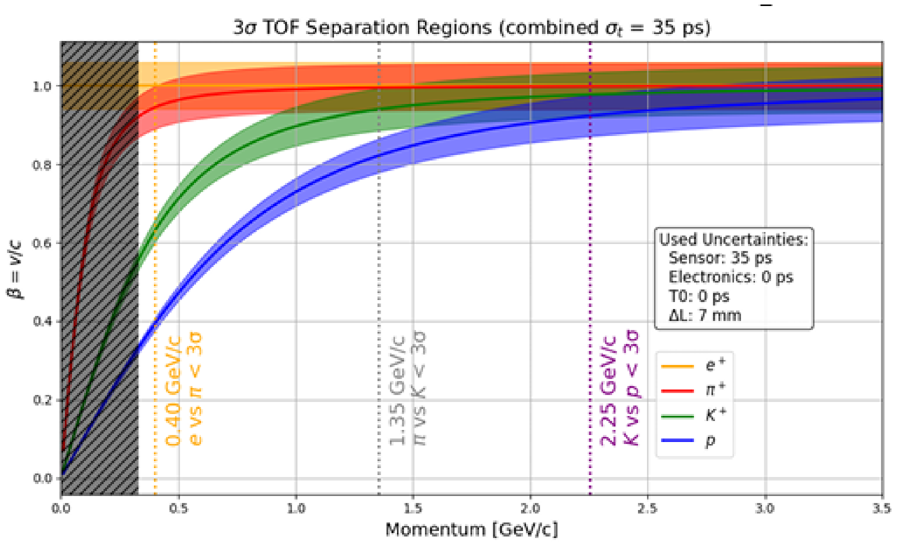


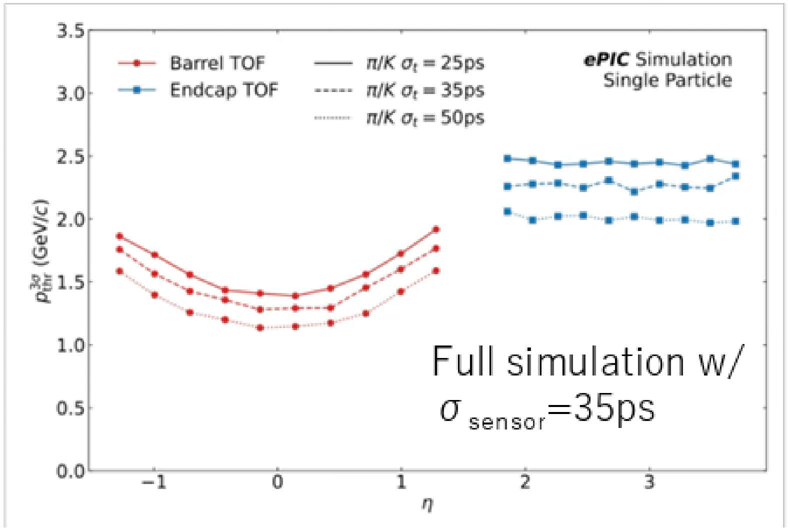


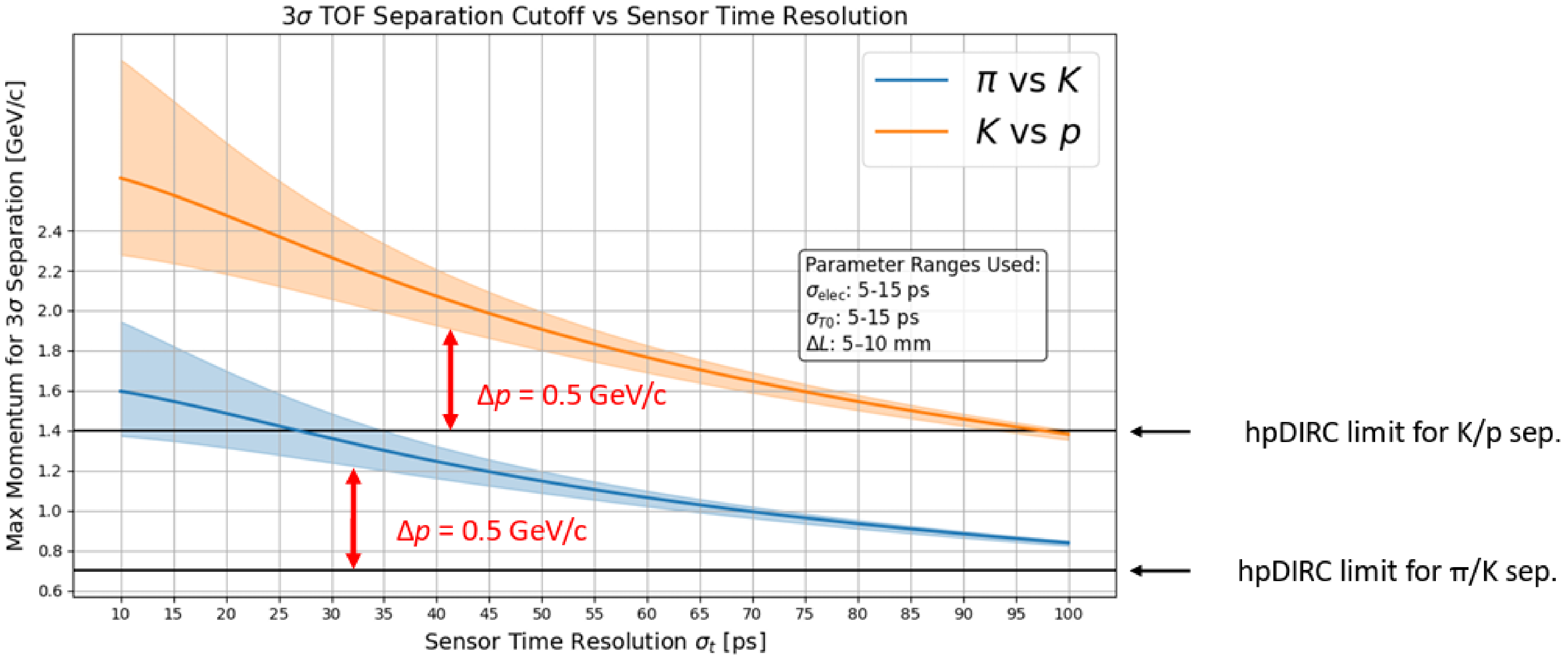
Student: A. Molnar, C. Altafulla

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

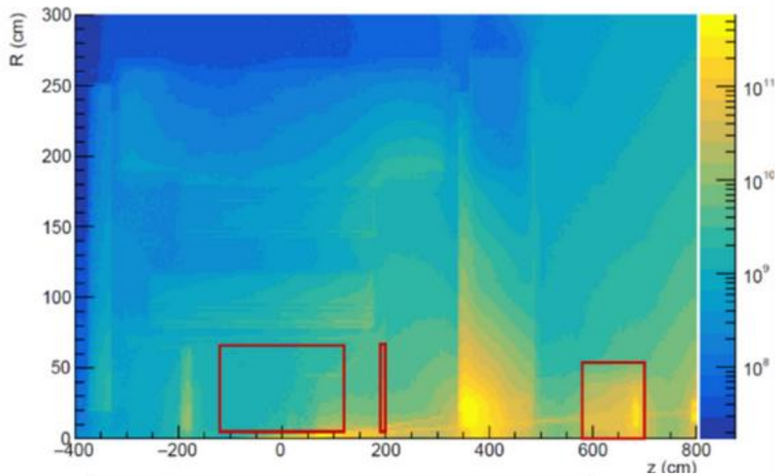






Radiation levels at ePIC

- 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

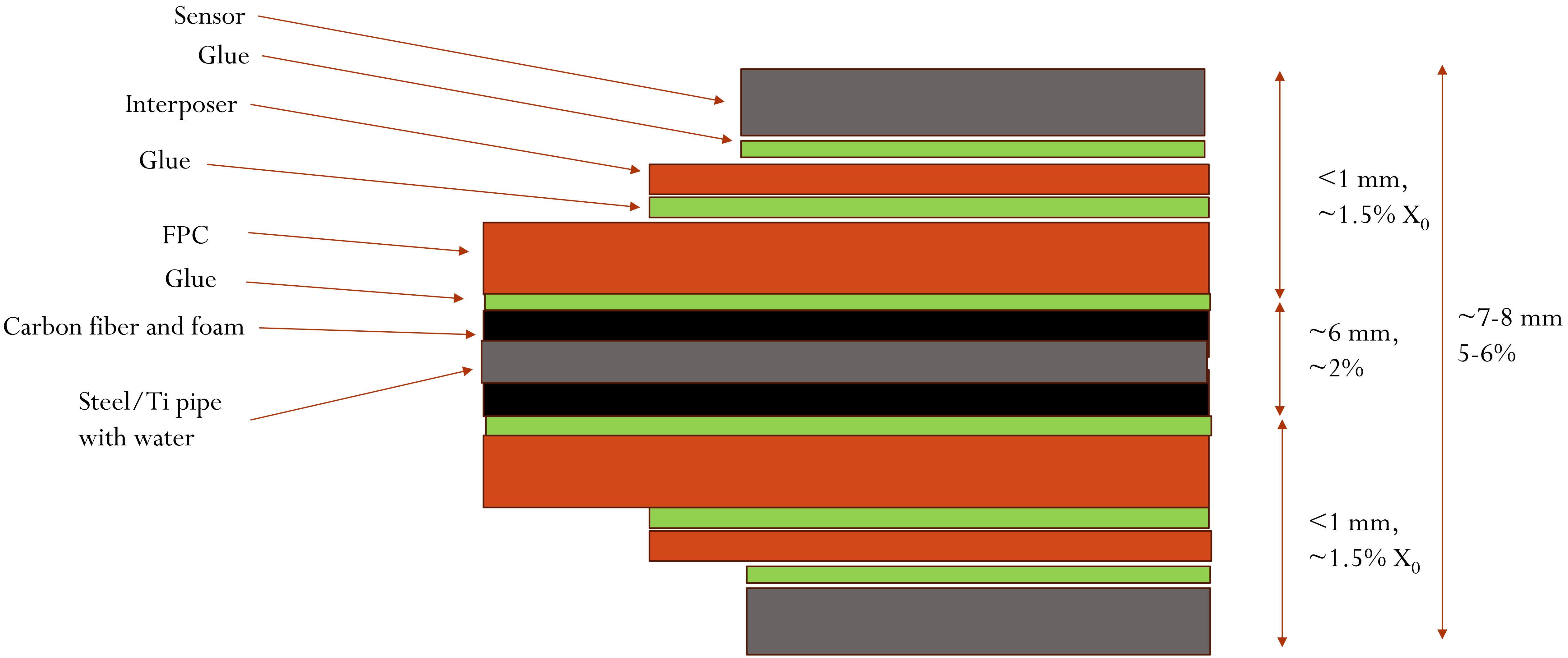
Fluence	0.5 cm	1 cm	2 cm
1.00E+14	52	52	
5.00E+14	44		48
1.00E+15		38	42

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

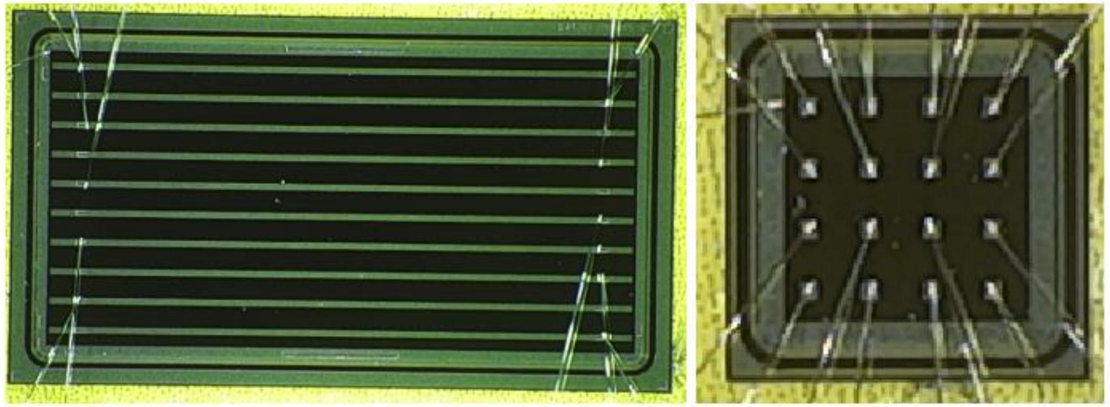
Cross section of assembled stave

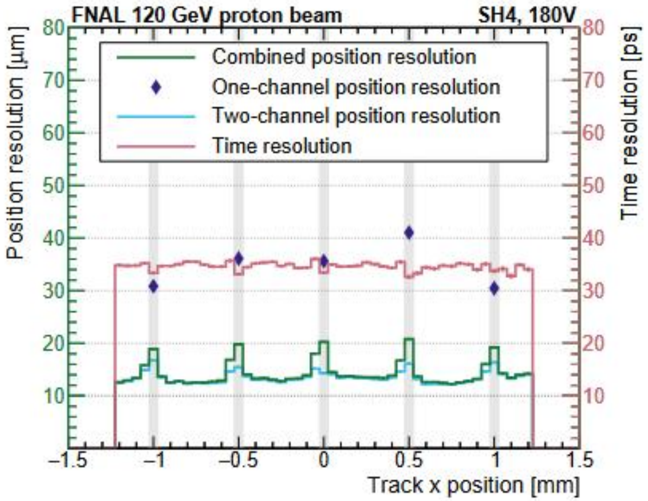
- Thickness: 2*[(200um Si (sensor) + 50um glue) + (25um copper, 50um Kapton) + 50um glue + (72um copper, 225um Kapton) + 50um glue + (1500um Carbon fiber)] + 2000um pipe plus water = ~7-8 mm → averaging ~5-6% X_0
- Simulation results indicates ~6% X_0 for material budget is ok

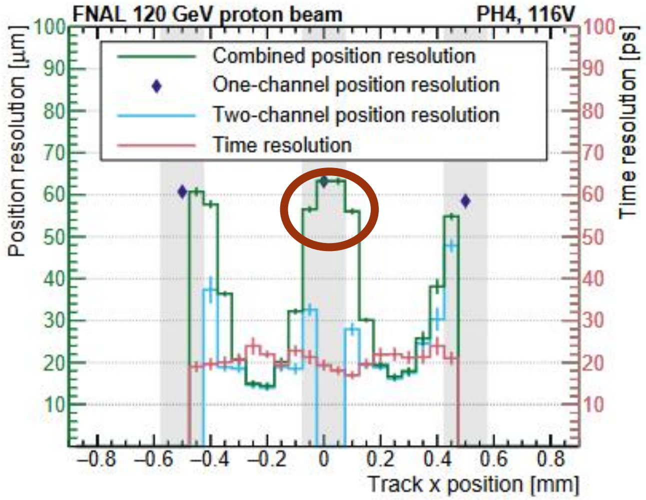


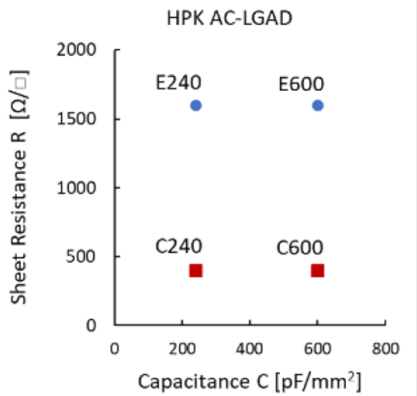
2023 HPK production

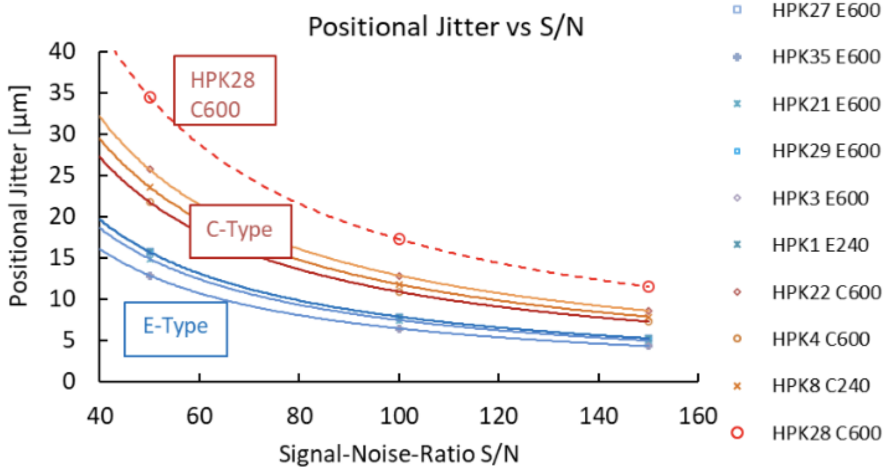
- Test beam and laboratory campaign to characterize HPK sample
  - Matrix of different pitch/size metal, different N+ resistivity and oxide thicknesses
- FNAL test beam results from HPK 2023 production, most ePIC requirements are met
  - Time resolution ~35ps for 1cm x 500um strips and ~20ps for 500um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





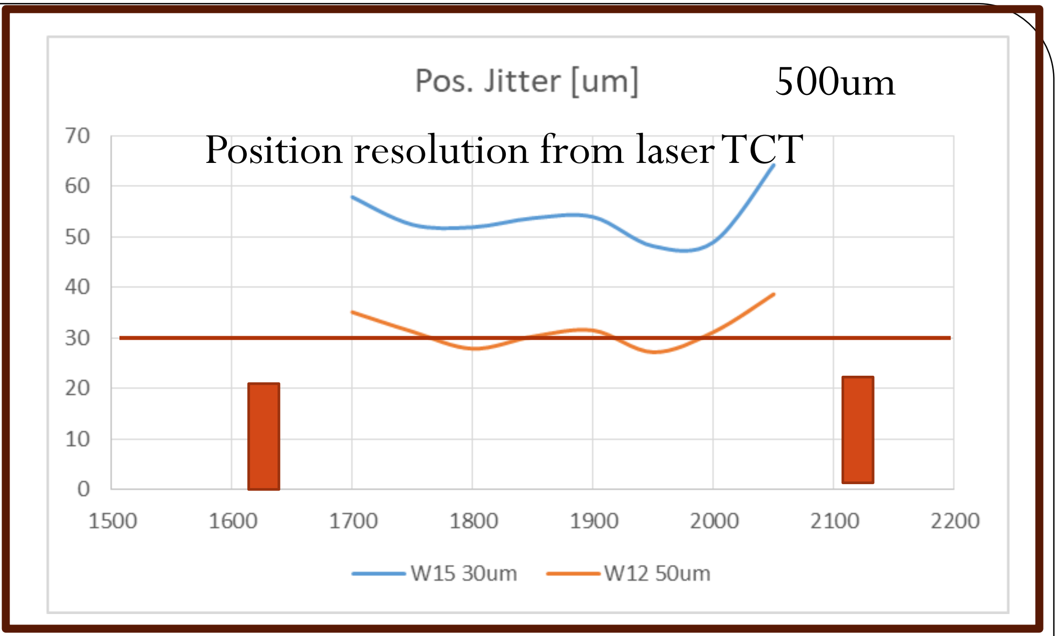




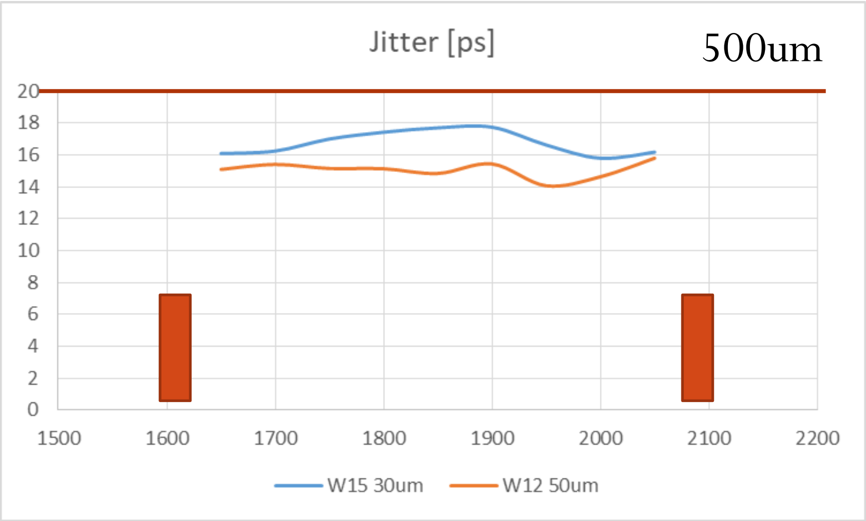


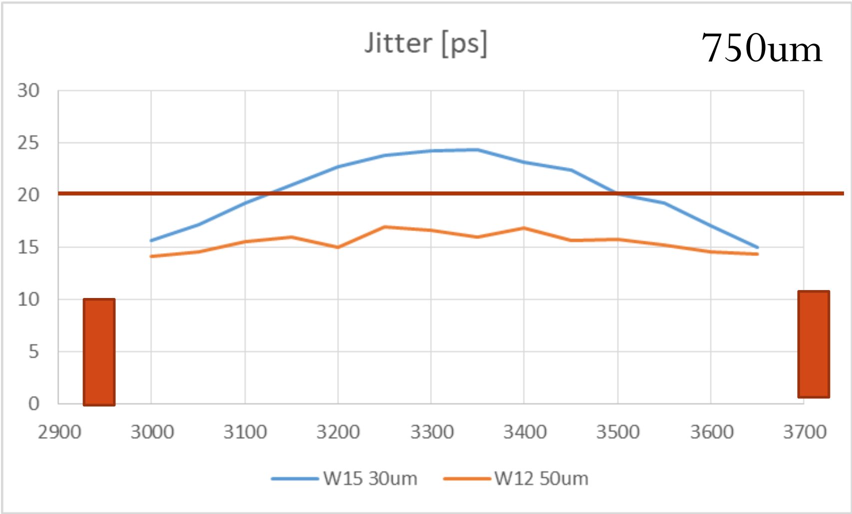
References: https://arxiv.org/abs/2407.09928 https://doi.org/10.1016/j.nima.2024.169478

Strips laser TCT testing

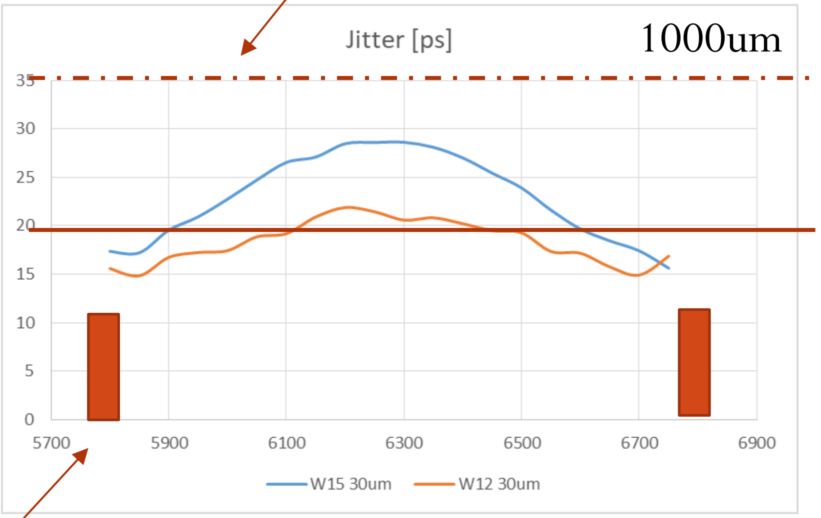


- Can estimate sensor behavior with laser TCT (test beam is more accurate)
  - Measuring the Jitter as $\sigma_{\mathrm{T}} = Rise_T/(\frac{S}{N})$
  - Position Jitter as in [1]
- Increased strip distance reduces performance
- Assumed signal from strips 60mV (from TB input)
- Reduced thickness (30um vs 50um) doesn't seem beneficial due to S/N loss (not counting Landau terms)





TOF requirement

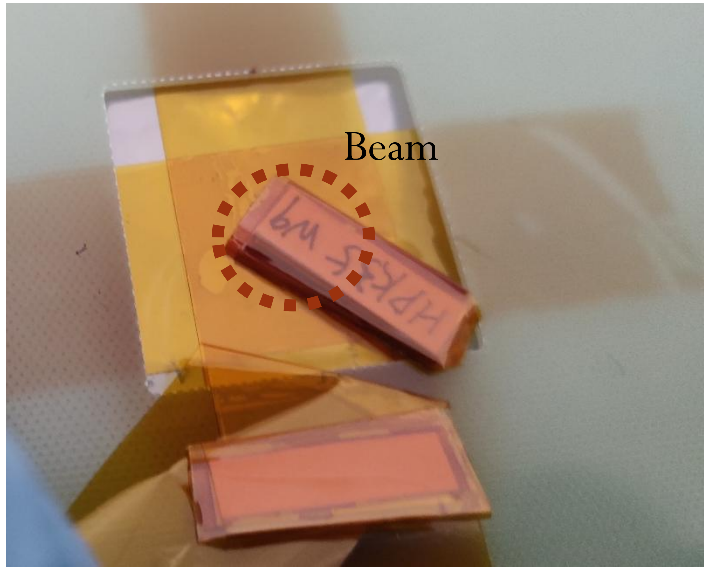


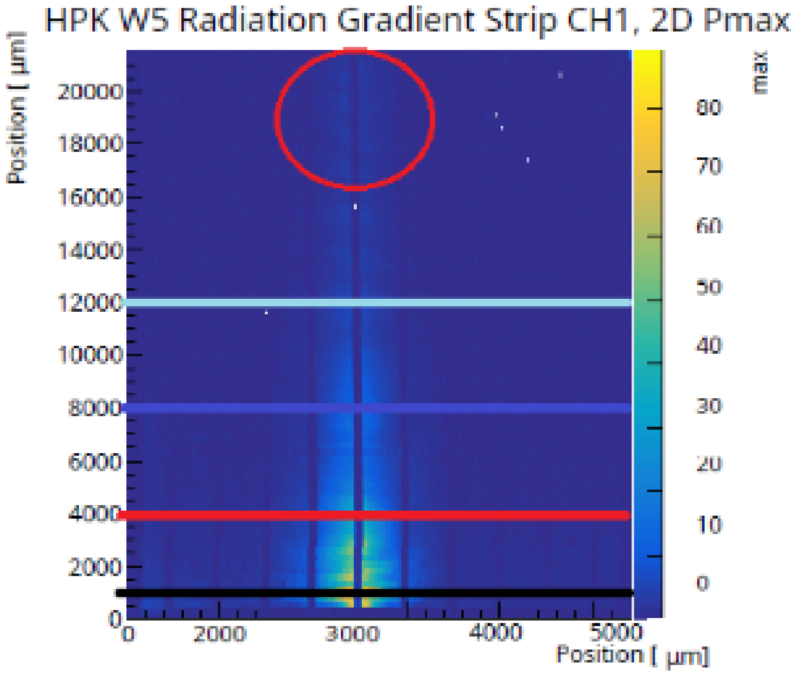
Strips

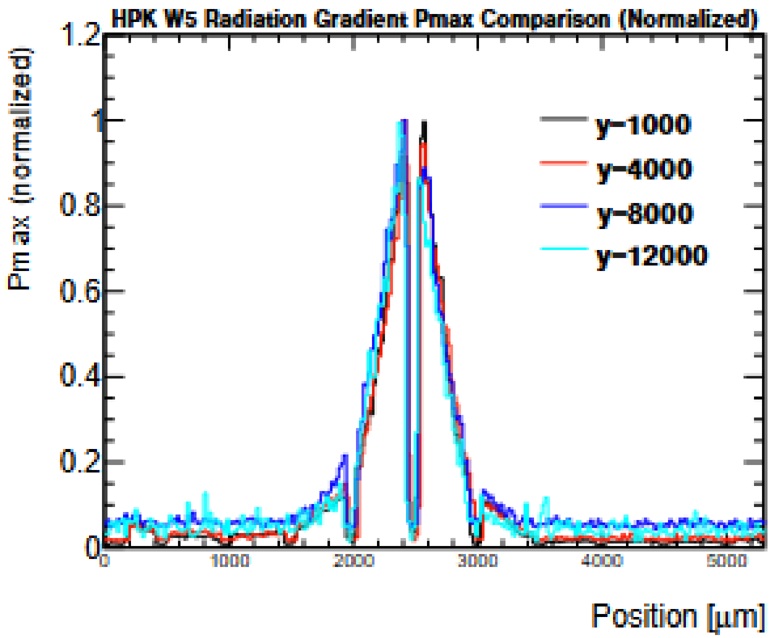
[1] https://doi.org/10.1016/j.nima.2024.169478 More results in: https://arxiv.org/abs/2511.02939

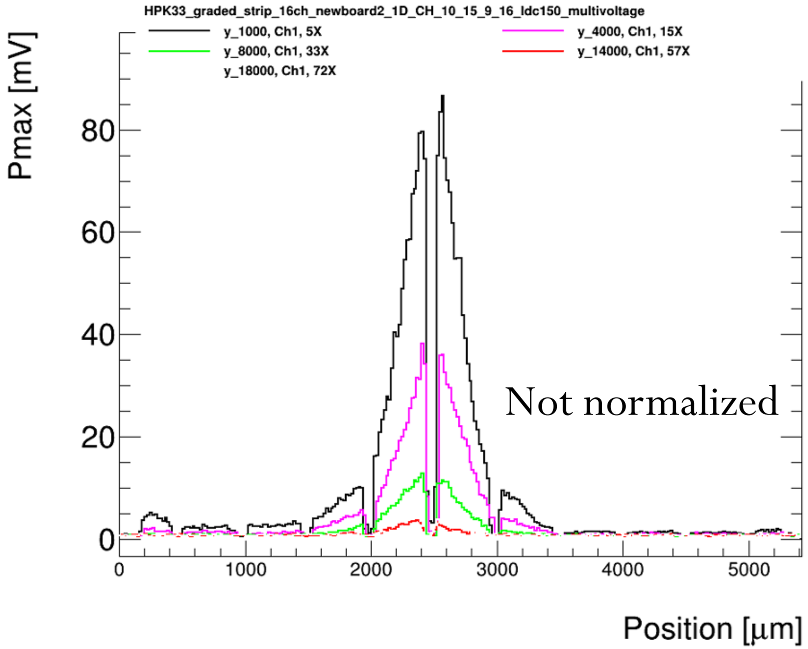
TCT laser studies - Protons

- 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!







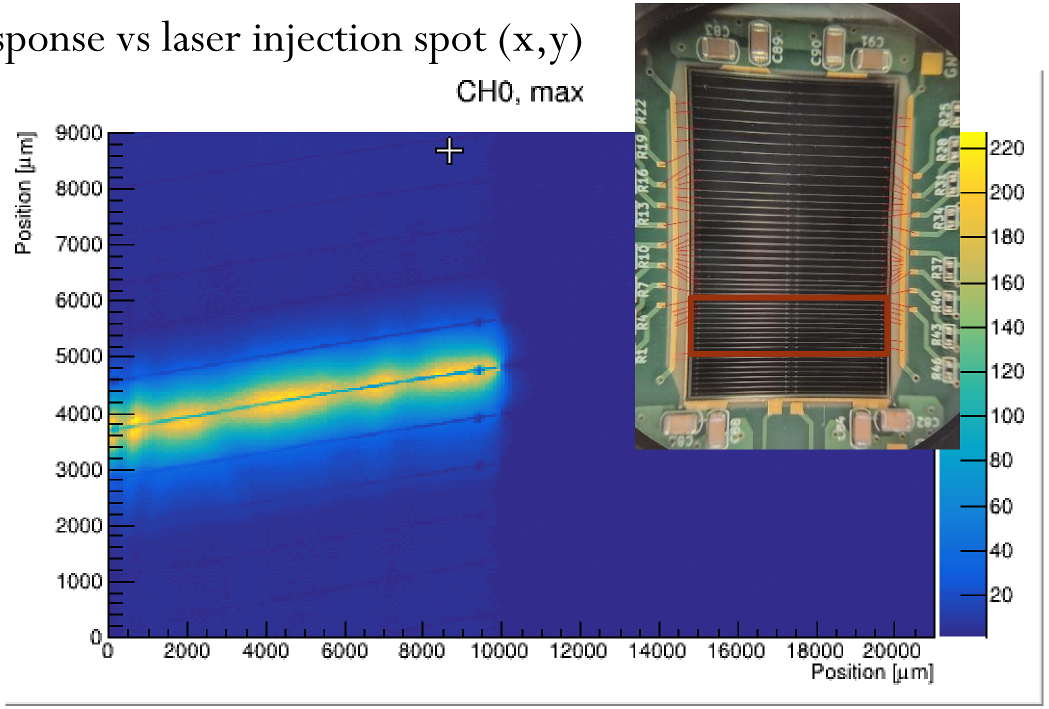


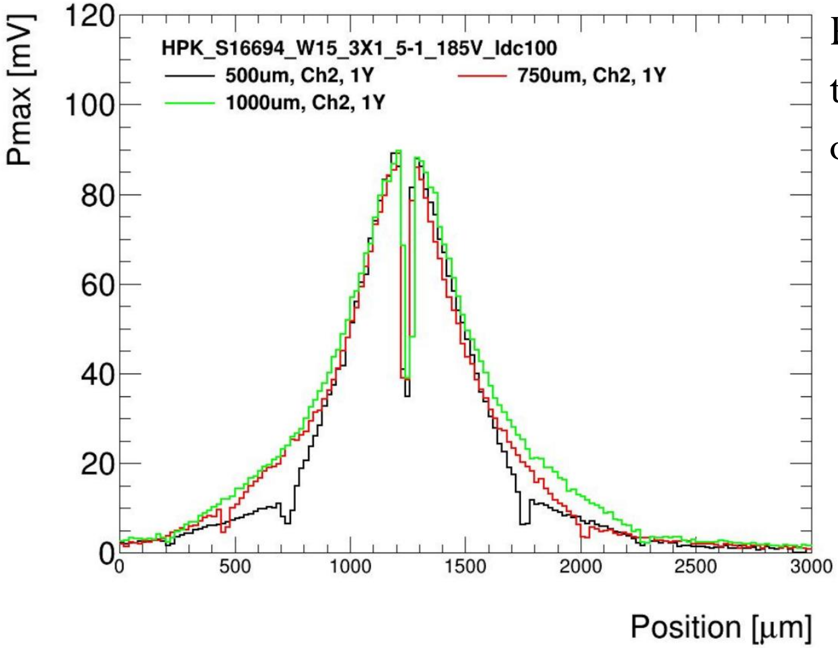
Student: G. Stage, A. Borgijin

HPK production results - TCT

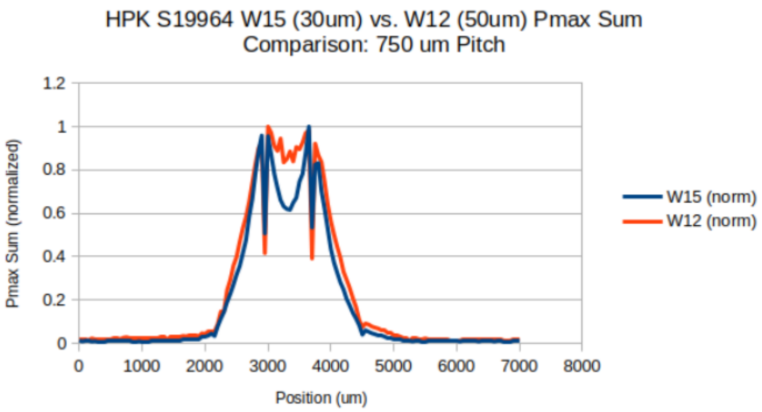
- Full size sensors tested on a 16ch board with laser TCT
  - Both 50um and 30um thicknesses, show similar performance
- Pulse as expected with rise-time 600-700 ps for 50um and 400ps for 30um
- Time of arrival variation delay ~2ps/um (250ps for 500um) perpendicular to the strip and ~0.01ps/um (<100ps for 1cm) parallel to the strip (metal propagation)

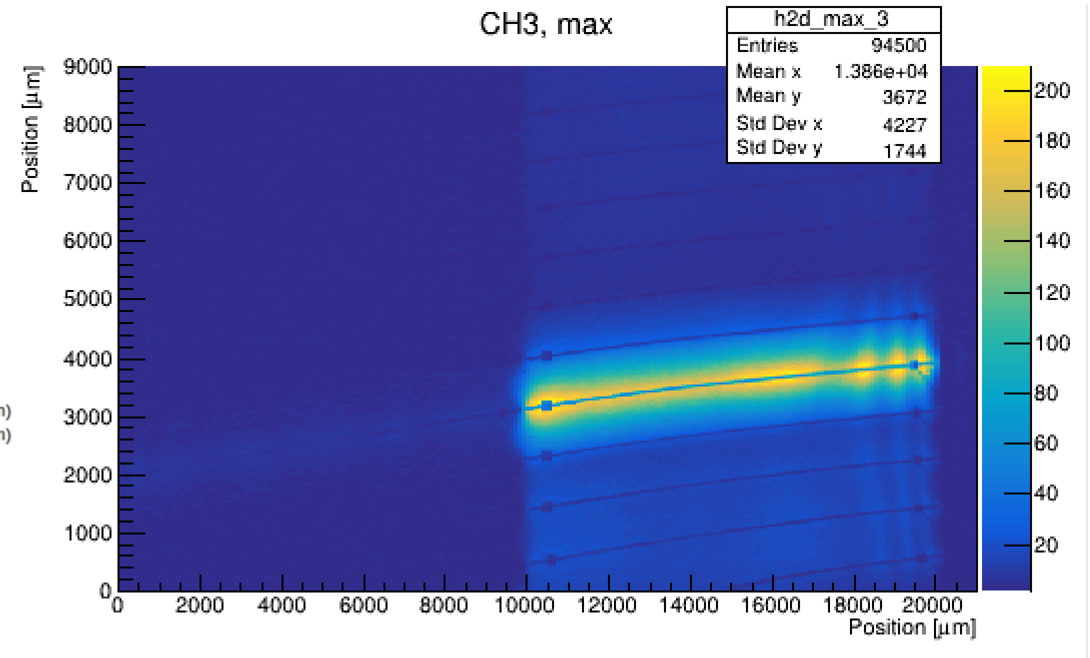
Strip response vs laser injection spot (x,y)





Profile response perpendicular to the strip for the three different pitches

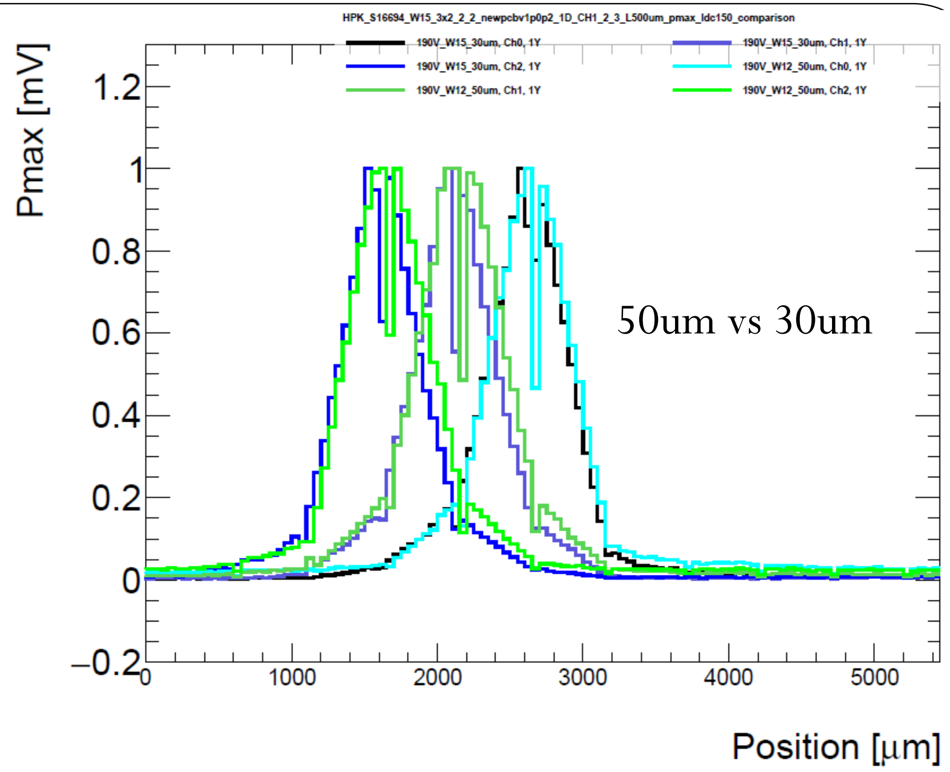


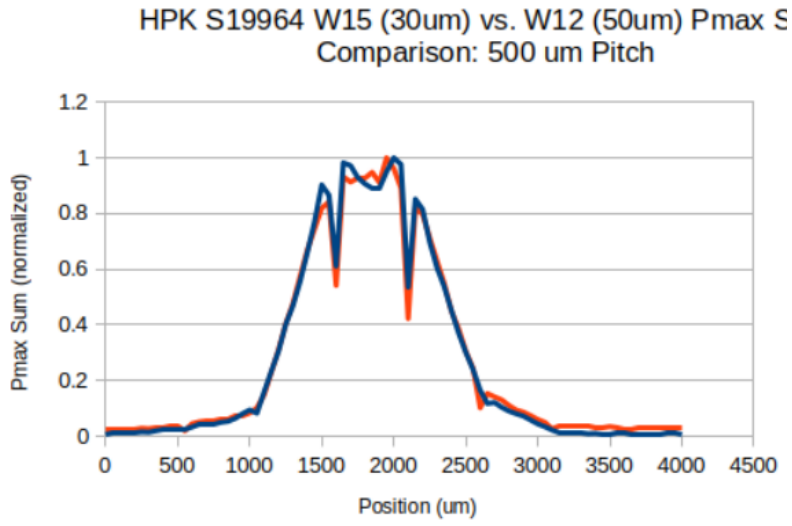


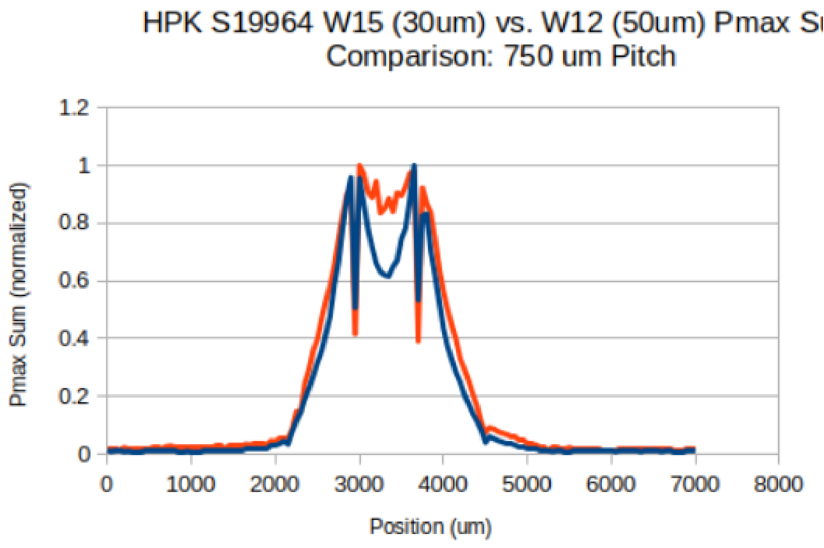
Student: M. Davis, G. Stage, A. Borgijin

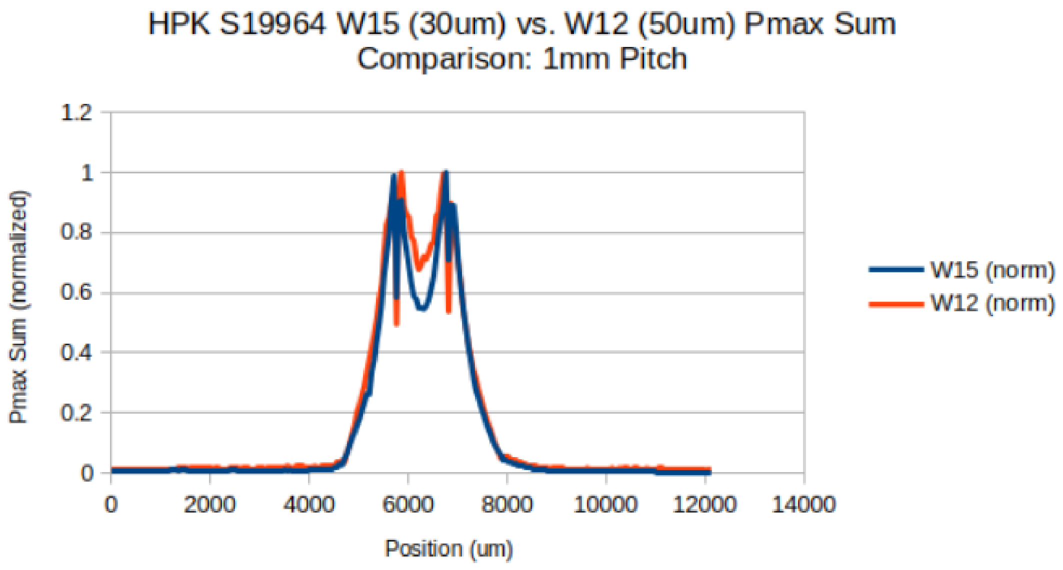
HPK production results - TCT

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









Student: G. Stage, A. Borgijin