Barrel TOF technical status

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June 11th - 13th, 2025, 10th EIC DAC Review

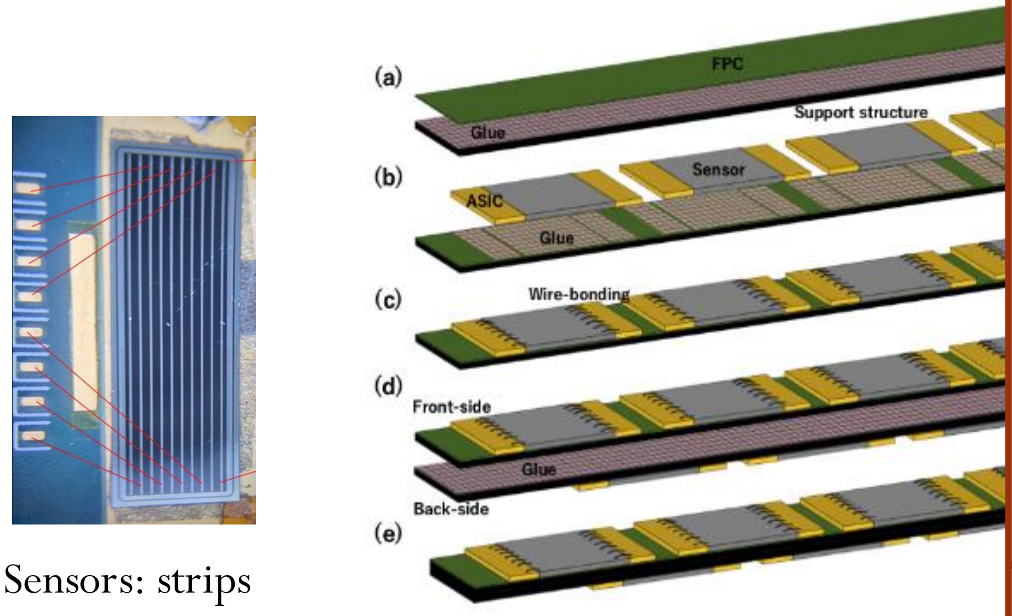
Charge questions

- Q1: Is the design of the ePIC detector and its sub-systems appropriate and progressing well?
- Q2: Are the remaining work and technical, cost and schedule risks adequately understood? Are there opportunities?
- Q3: Will the detector be technically ready for baselining by late 2025?
- Q4: Are the detector integration and planning for installation and maintenance progressing well? Are there areas where further ideas should be pursued?
- Q5: Will the detector be ready for start of construction by late 2026?

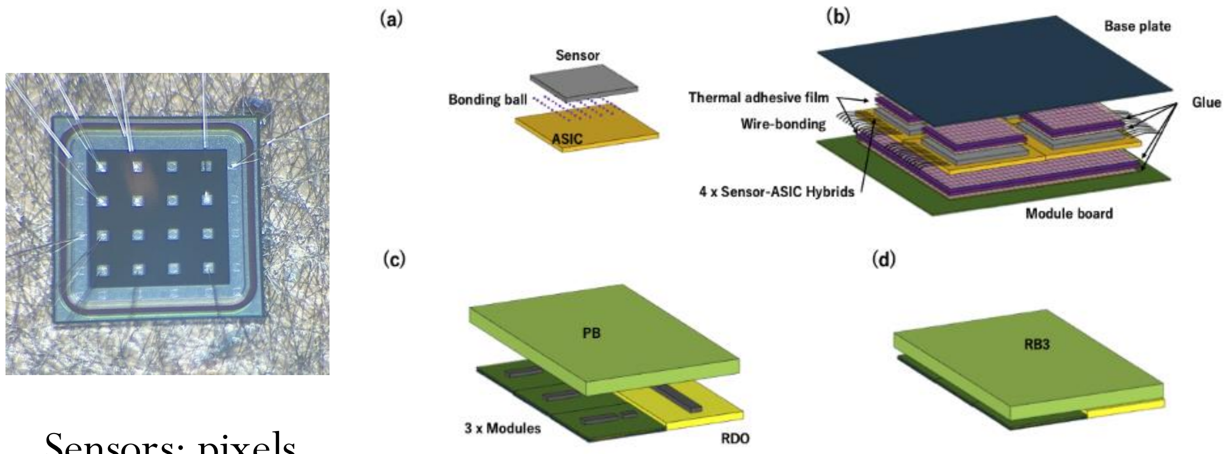
TOF layout in ePIC

Q1, Q2

This talk



Sensors: strips
Readout: FCFD

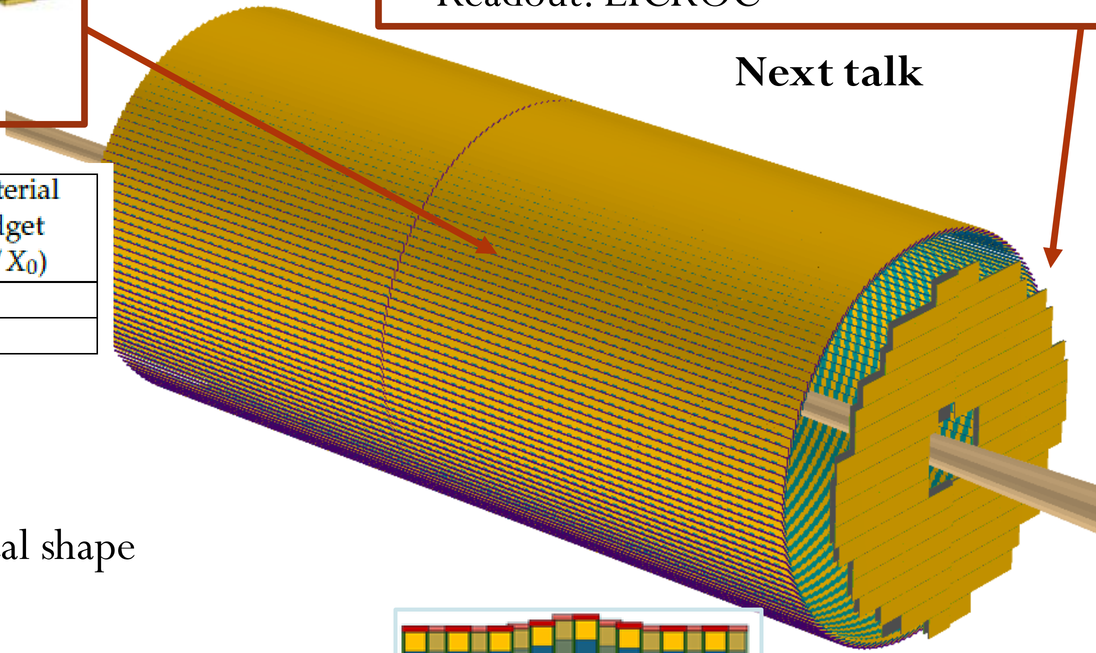


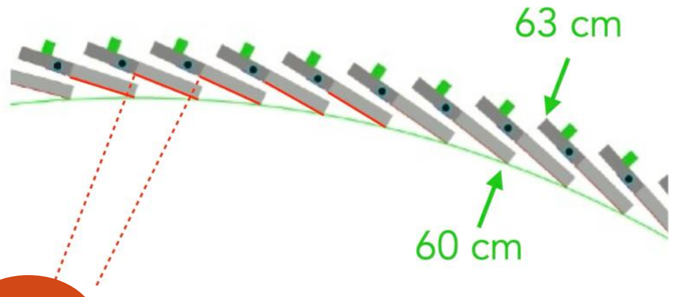
Sensors: pixels
Readout: EICROC

Next talk

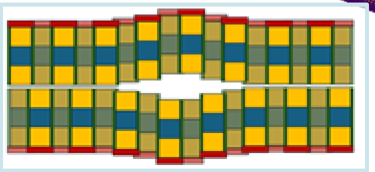
Sensor R&D is mostly in common and shared between subsystems

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%

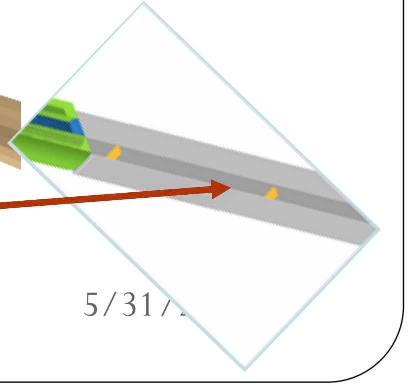




Make cylindrical shape by tilted staves



Off-Momentum Detectors (OMD)



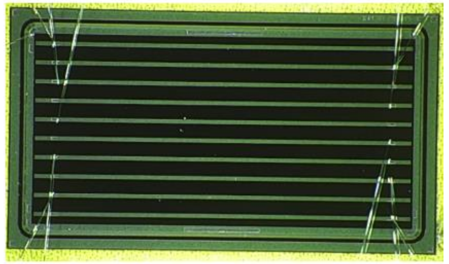
Sensors: pixels
Readout: EICROC

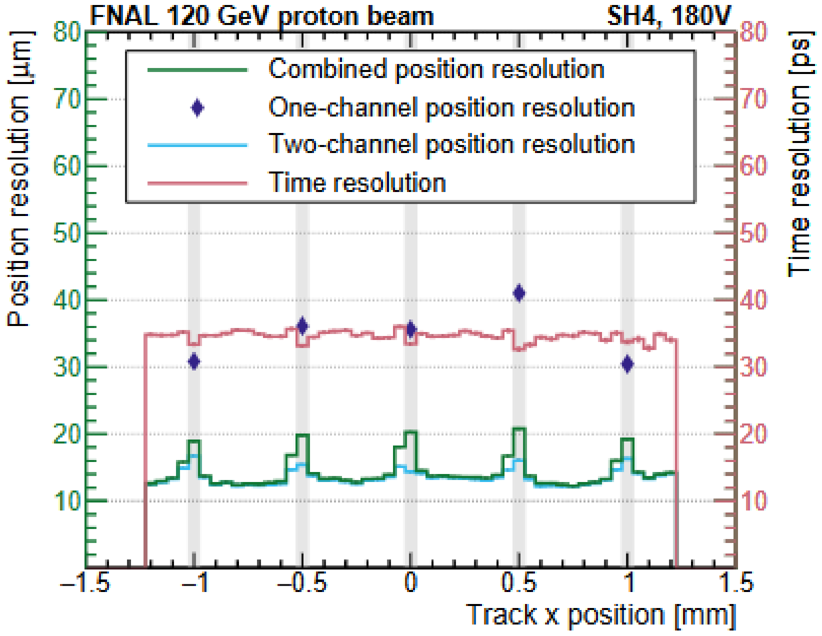
Sensors for the ePIC BTOF

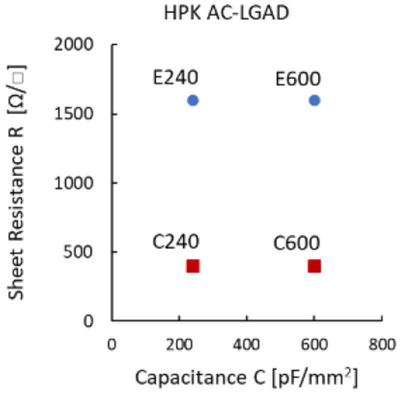
2023 HPK production

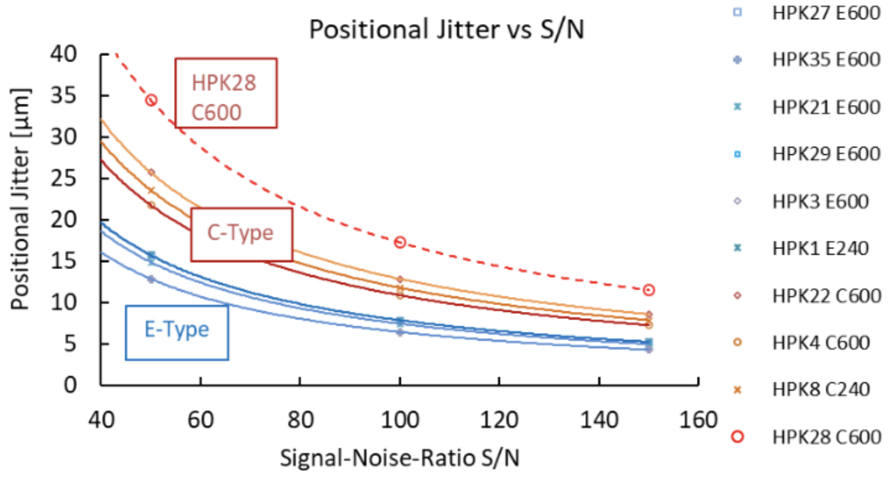
Q1, Q2

- 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, and positioning resolution ~15um for 1cm x 500um strips
- Laboratory studies done with TCT laser
  - Type E strips (more resistive) have better performance
  - 1cm strip length is the best compromise









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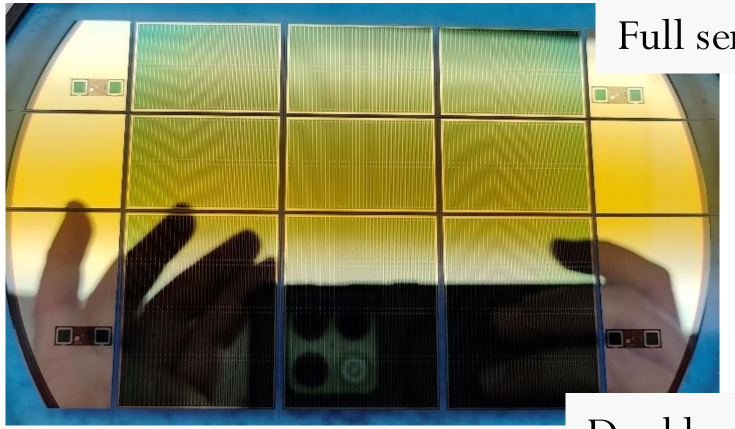
References: https://arxiv.org/abs/2407.09928 https://doi.org/10.1016/j.nima.2024.169478

2024 HPK production

Q1, Q2

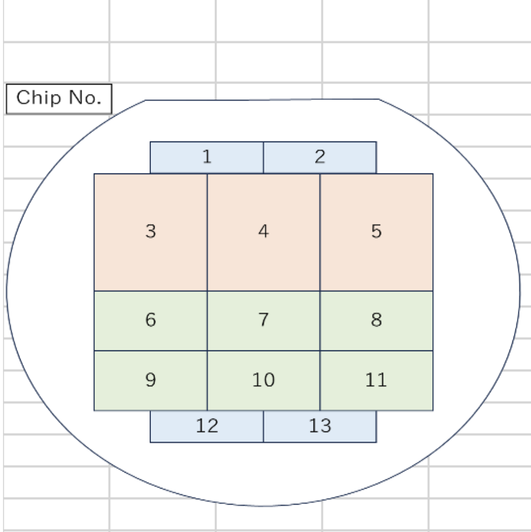
- ePIC full-size production of strip AC-LGADs from HPK with devices up to **3.2x4 cm**
  - Nominal size **3.2x2.2 cm** with 1cm strip 'segments'
  - Strip width: 50um, strip pitch 500, 750, 1000 um
- **First ever large prototype production of AC-LGAD**
- 8 wafers in hand, four 50um thick and four 30um thick
  - Low yield of 50 um has been solved
- Produced a new 16ch discrete component board that can house larger sensors

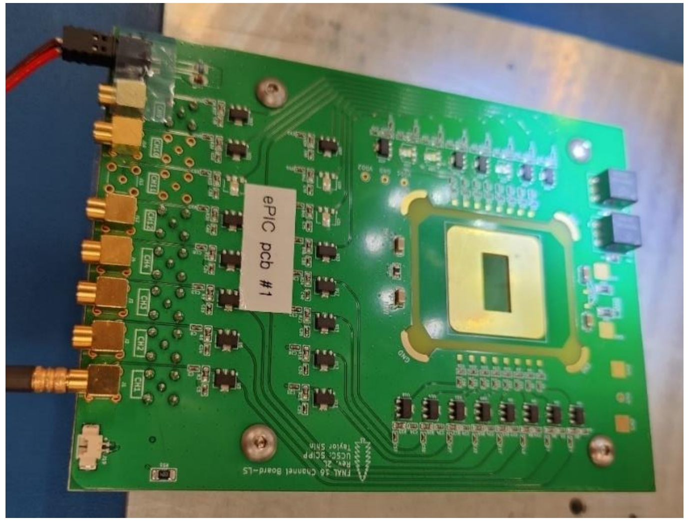
Half sensors

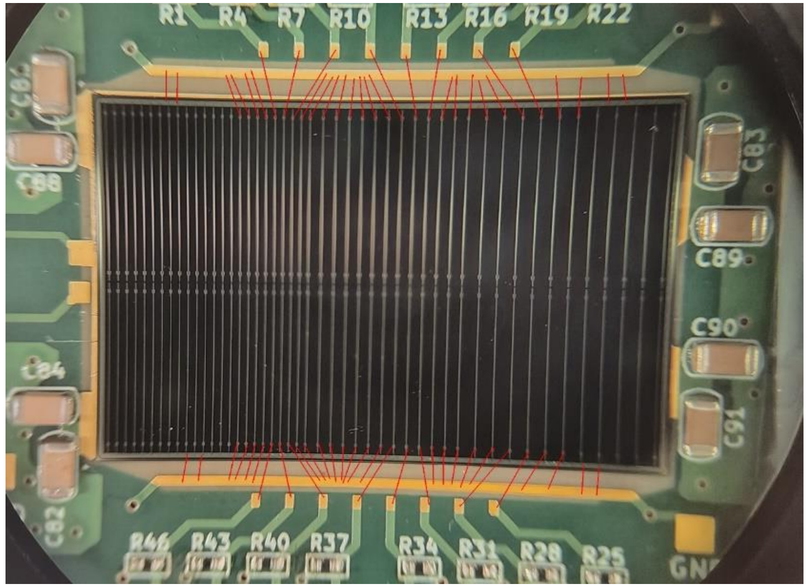


Full sensors

Double sensors







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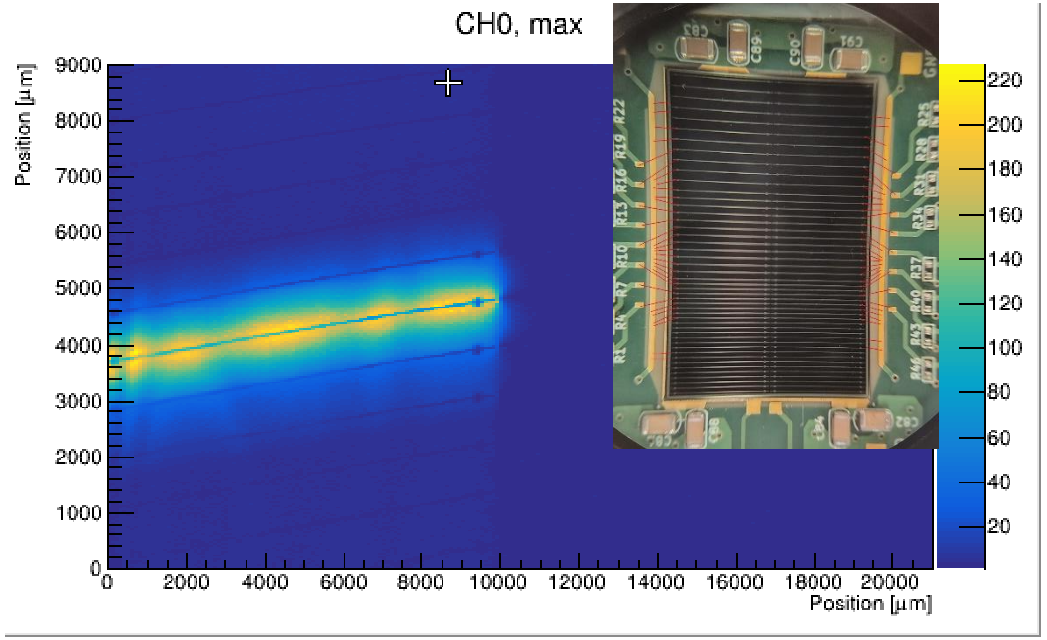
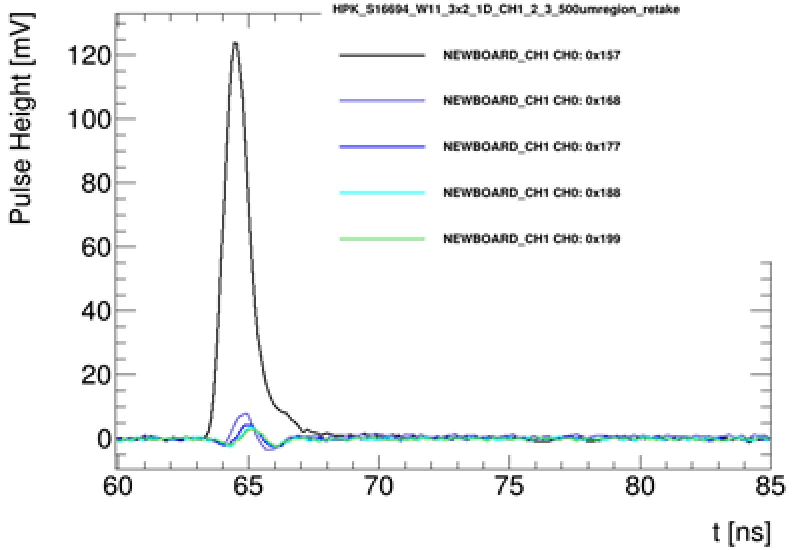
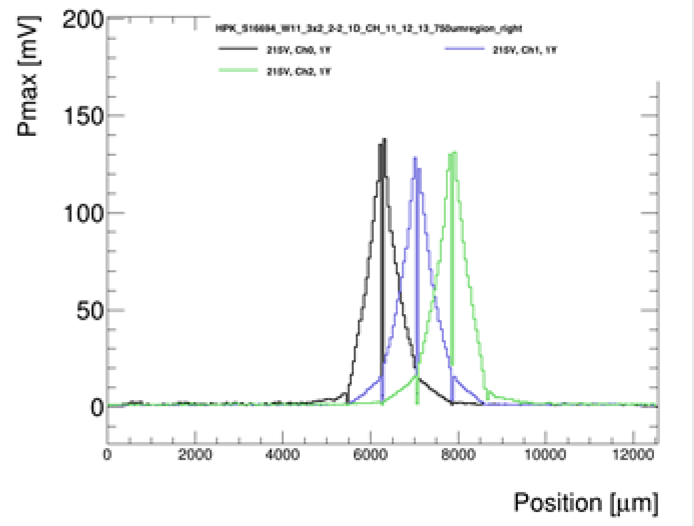
HPK production results - TCT

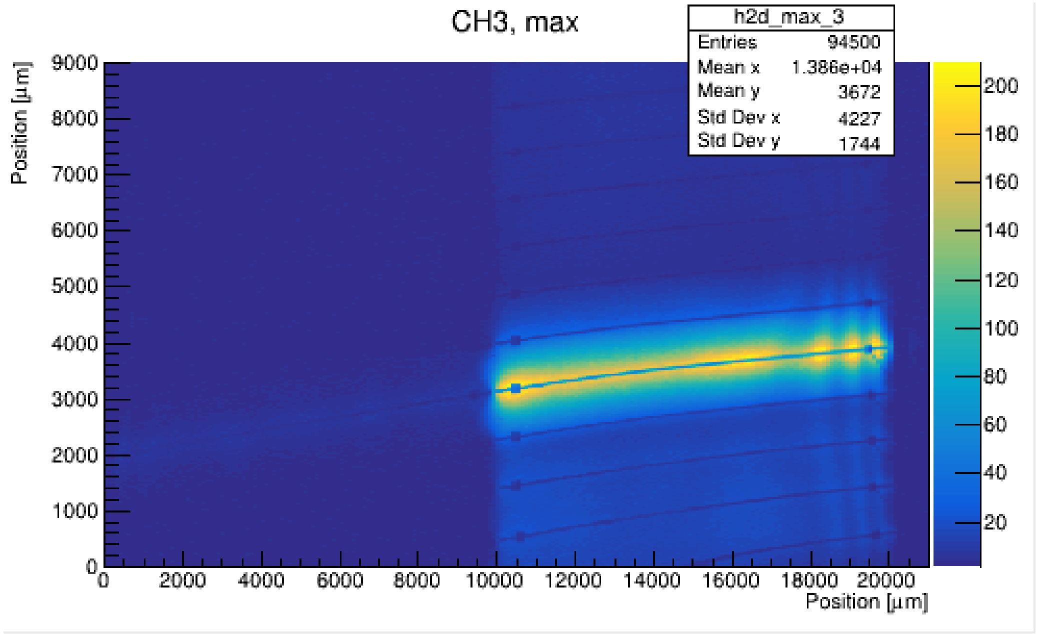
Q1, Q2

- Full size sensors tested on a large board with laser TCT
  - Both 50um and 30um thicknesses, show similar performance
- Sensor works well, some gain variation across strip but it's unclear if due to laser reflections, will verify at test beam
- Pulse as expected with rise-time 600-700 ps
- Signal for 1000um, 750um and 500um pitch is similar
  - Higher S/N loss between strips for 1000um





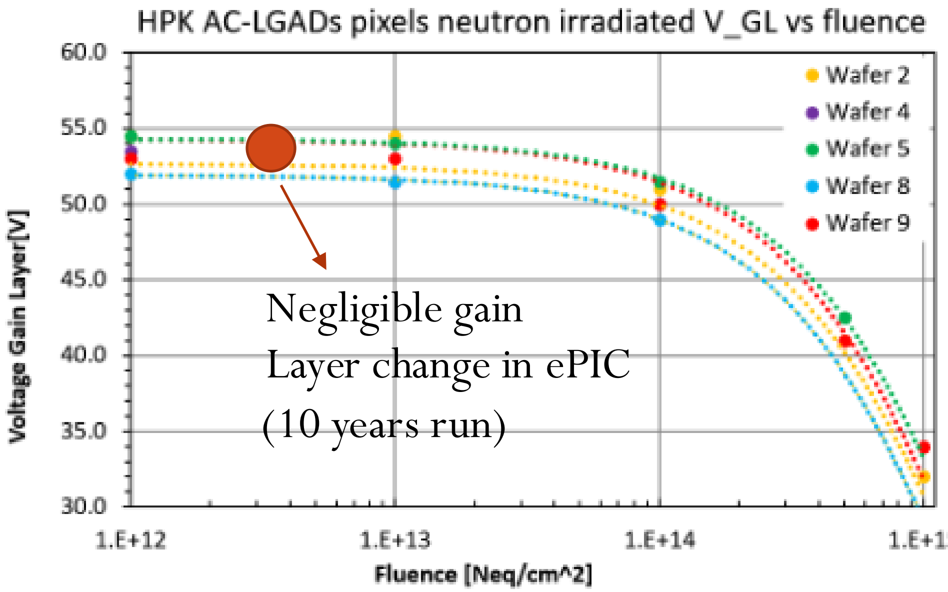




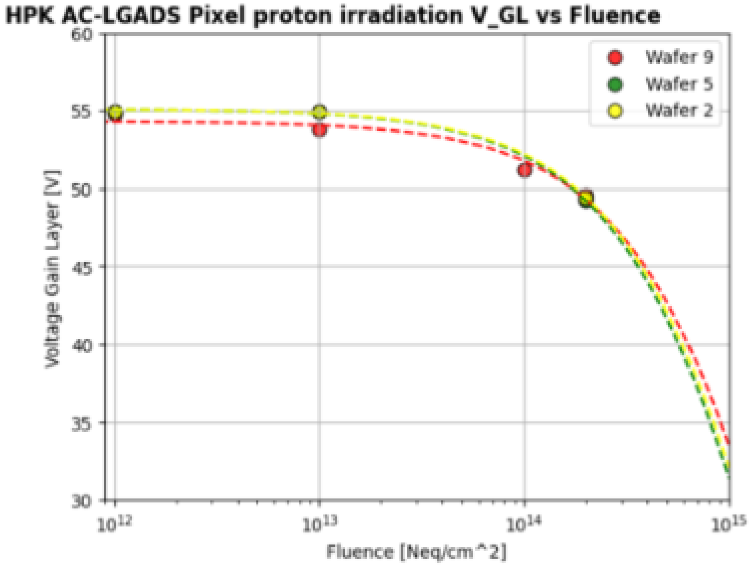
Irradiation effects on AC-LGADs

Q1, Q2

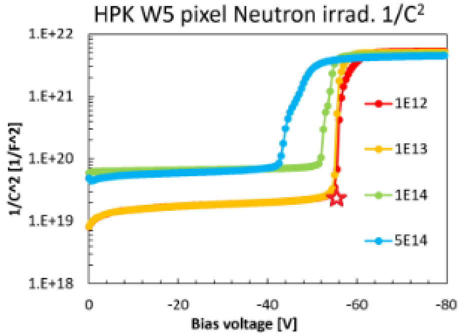
- Up to 1e13 Neq, no significant change in sensor IV properties and gain layer doping
  - Leakage current scales with bulk volume
  - Current and breakdown voltage increases with fluence (as expected)
- Gain layer doping proportional to Vgl (gain layer depletion voltage) or 'foot' (star in the plot)
  - Degradation parameter, 'c' factor, from fit on the distribution vs fluence
- Behavior across wafers is consistent
- Comparable results for protons and neutrons



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



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

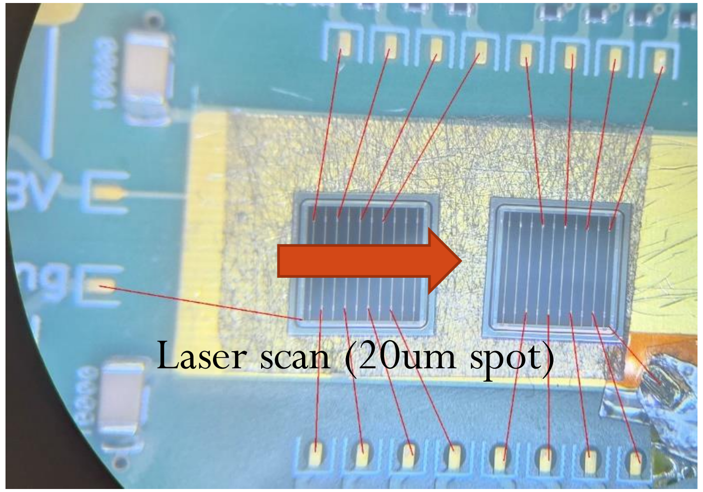


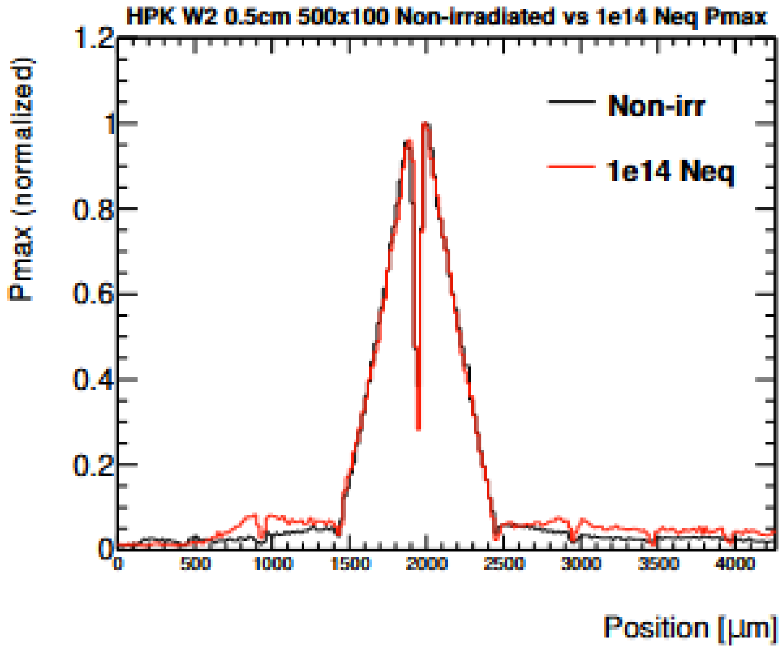
Student: J. Ding, M. Davis

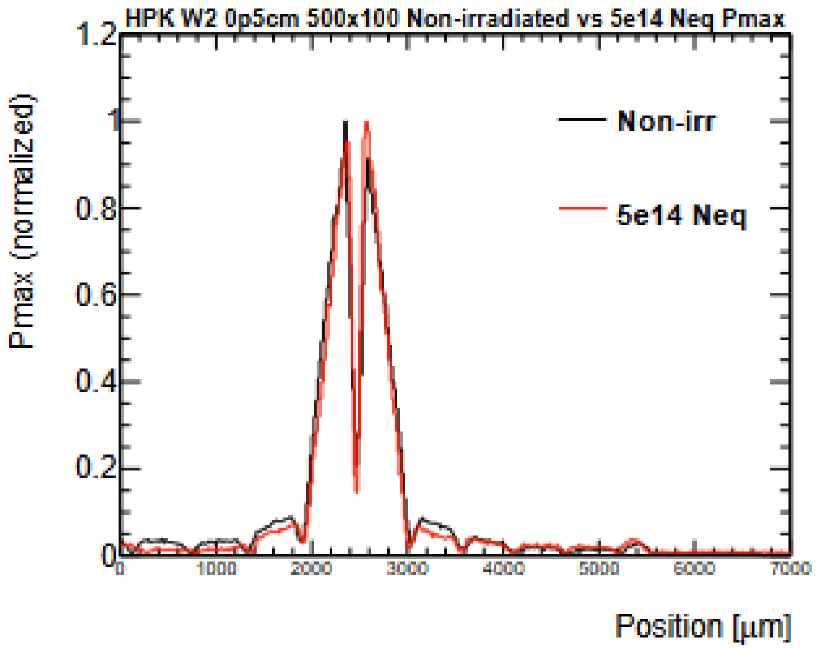
TCT laser studies - Neutrons

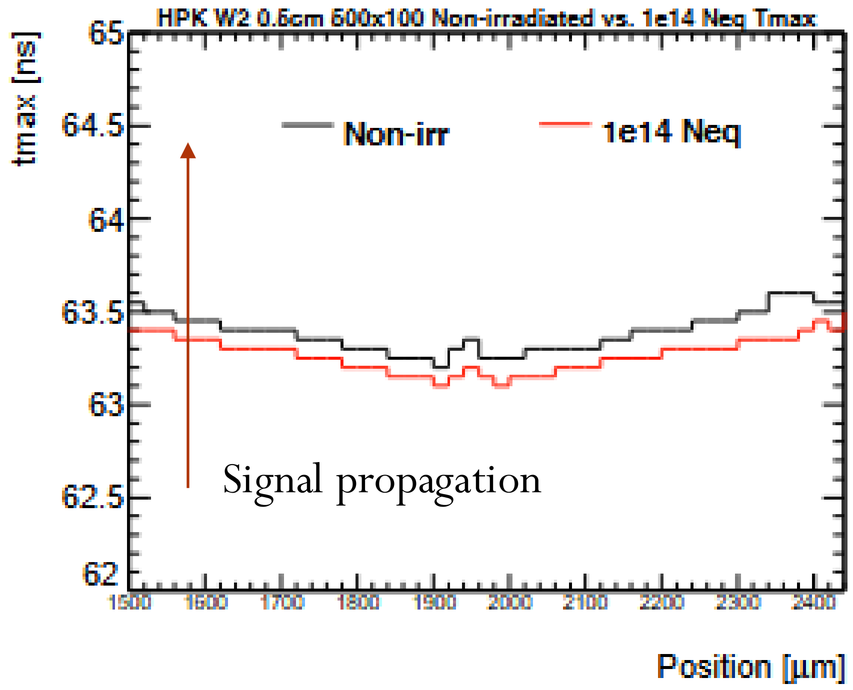
Q1, Q2

- Using laser TCT setup with cooling plate and FNAL 16ch board
- Direct AC-LGAD strips comparison non-irradiated and irradiated sensors
  - Two sensors types at two neutron fluence points 1e14Neq and 5e14Neq
  - Irradiated sensor was biased to higher voltages
- **At first order, the charge sharing distribution is unchanged**
- **Signal propagation in resistive N+ is the same**









Student: G. Stage, A. Borgijin

Sensors plans

Q1, Q2, Q3

- An additional HPK production with improved yield and optimize design is being organize with Japanese funds

- Organizing a fraction of an FBK production (multi-institution, common RD50 funds)
  - Strips and pixels
  - Plan to have a 'large' 1x1cm strip sensor

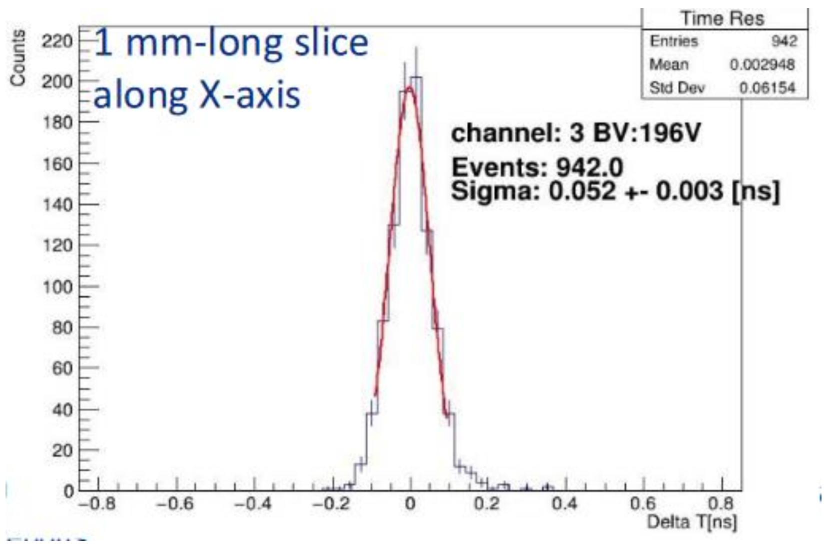
- Test beam plans this summer/fall at JLAB and KEK to characterize sensors

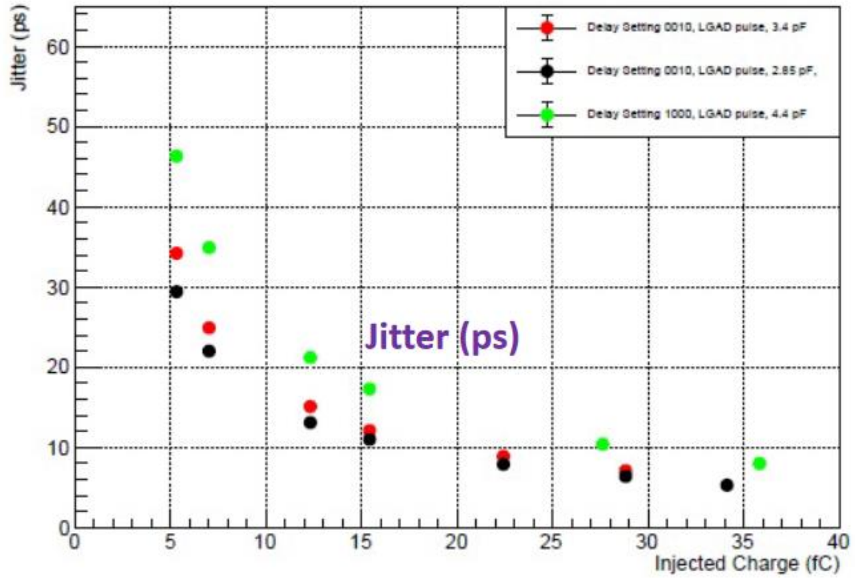
Electronics for the ePIC BTOF (frontend/backend)

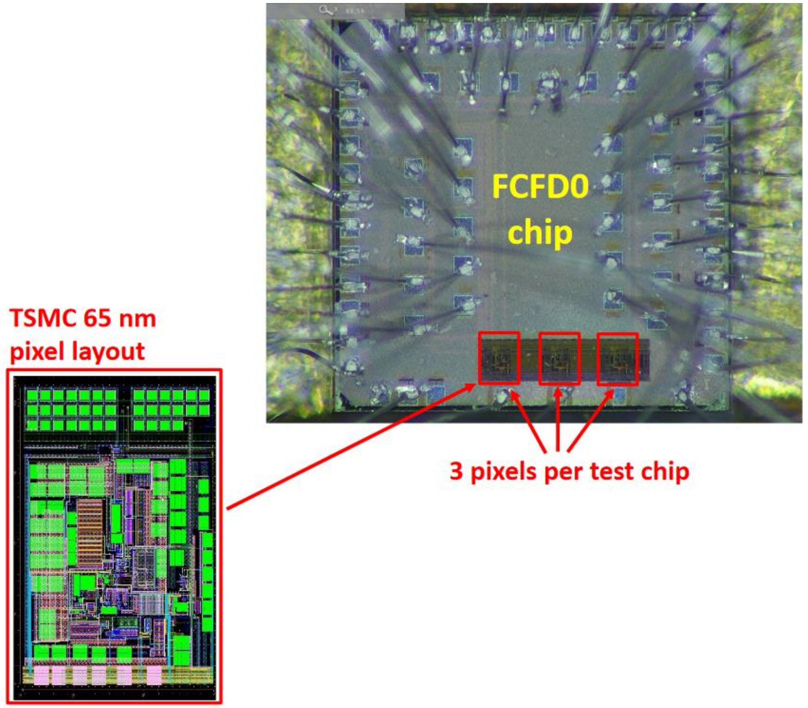
AC-LGAD strip readout – FCFD (FNAL)

Q1, Q2, Q3

- EICROC being developed for pixel AC-LGADs: target capacitance few hundred fF
  - But EICROC is not suitable for strips where capacitance can be o(10pF)
- AC-LGAD strip readout developed at Fermilab: variation of FCFD (calo readout)
  - Can accept higher input capacitance with target Jitter <10ps
- FCFDv1 – 6 channel received Jan 2024: Tested at FNAL in May/June 2024, AC & DC-LGAD (1 mm)
  - DC-LGAD @ 50 ps; AC-LGAD @ 52 ps
  - AC-LGAD should get <35 ps with improved comparator
- FCFDv1.1 with full-size sensor– TSMC May 2025; DESY tests in July 2025.
  - FCFDv2 with digital block will be available in Summar 2026
  - FCFDv3 (final design) will be available in 2027





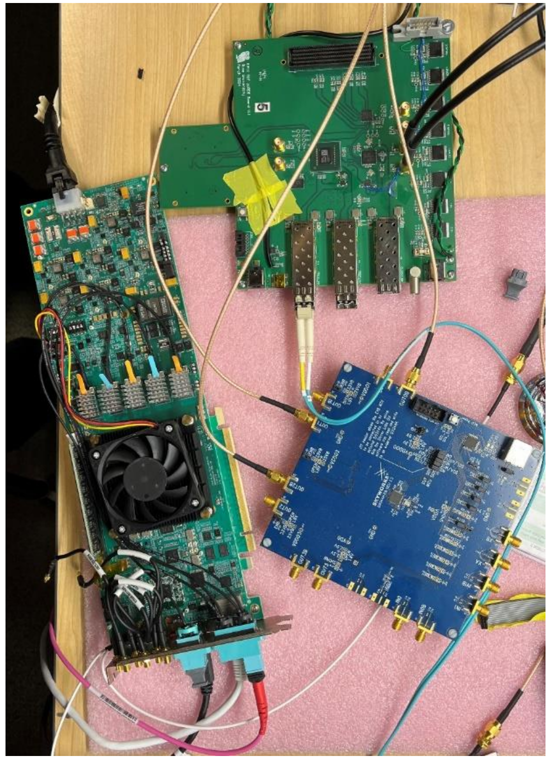


High Precision Clock Distribution

Q1, Q2, Q3

- ppRDO – pre-prototype Readout Board:
  - Generalized to allow readout from various ASICs – FMC connector
  - Xilinx Artix+ FPGA (low cost, CERN TCLink compatible
  - Clock Jitter cleaner – 5 ps
  - Clock recovery on Rx of SFP or direct clock on dedicated fiber
  - Establish procedures to readout ePIC's ASICs prototype PCBs
  - Develop common streaming readout scheme with DAQ's protocols
  - Platform for radiation tests (SEU measurement and handling)

- Produced and tested 6 PCBs.
  - Jitter measured at 3 ps (Ref clock – FLX182 Tx serializer – ppRDO)



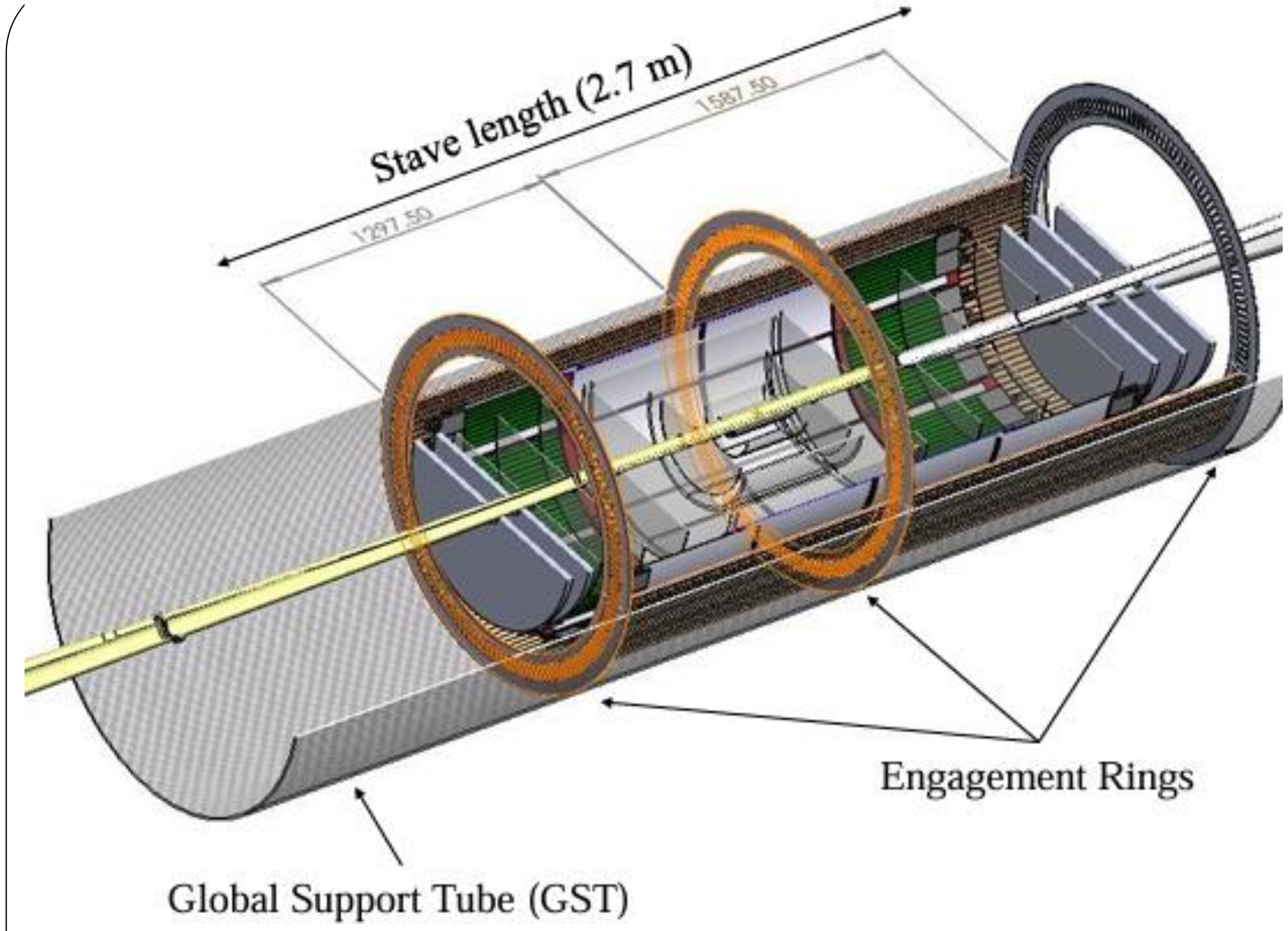
ppRDO
(ADCLK944)

Si5344H
(ref Clock)

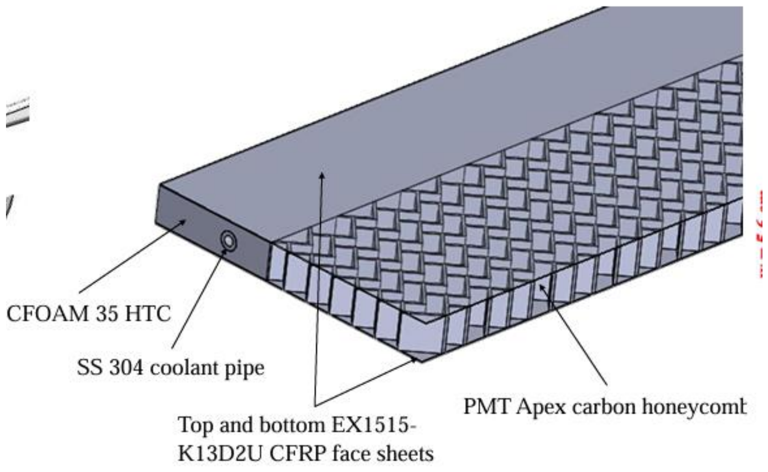
FLX182

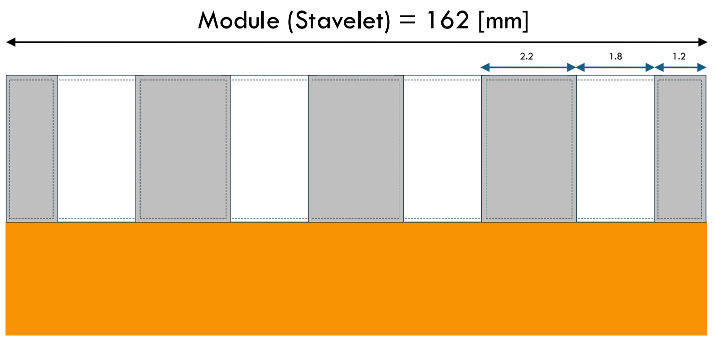
Mechanics and assembly

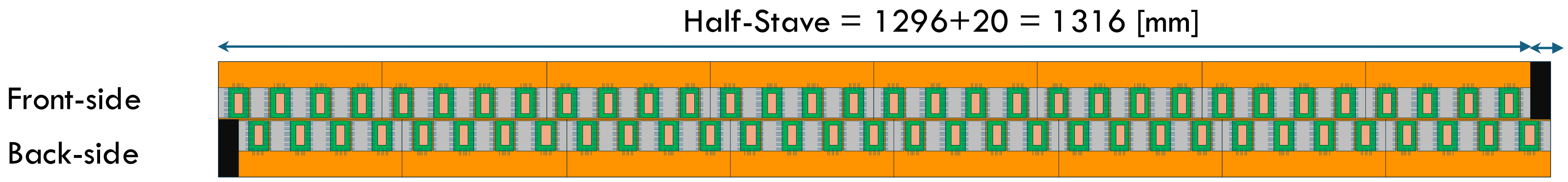
Q1, Q4

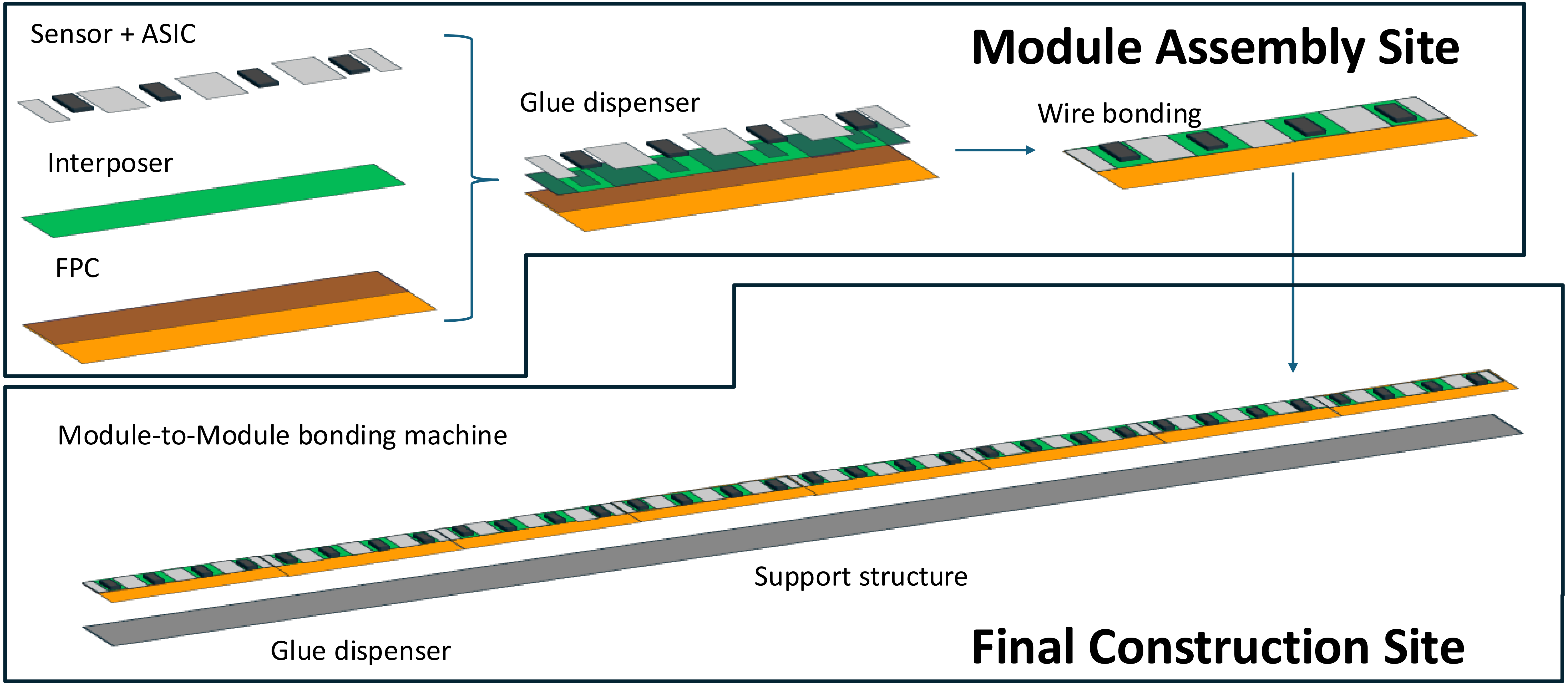


- "Pinwheel" structure of the barrel, divided in two symmetric stave section
- Support in carbon honeycomb with active pipe cooling
- Modular 'stavelets' assembled separately and mounted
- Peripheral board at the edge of the staves



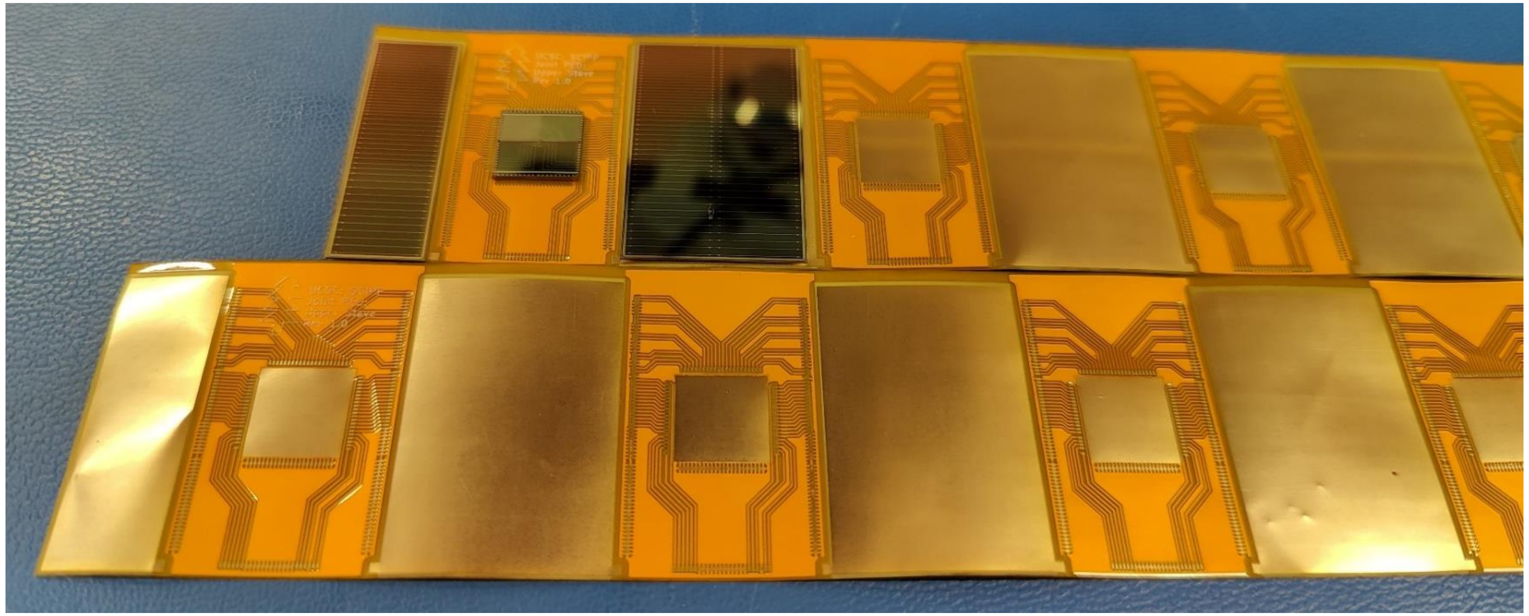




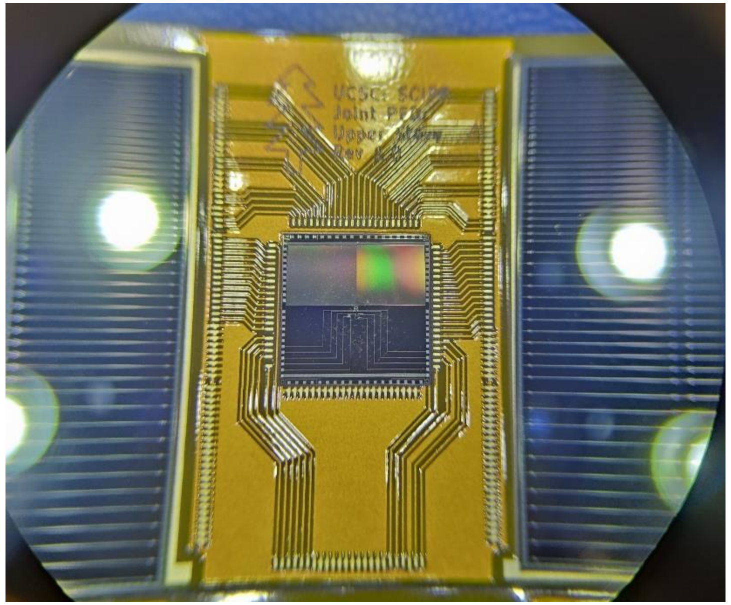

Sensor + ASIC
Module Assembly Site
Glue dispenser
Wire bonding
Interposer
FPC
Module-to-Module bonding machine
Support structure
Glue dispenser
Final Construction Site

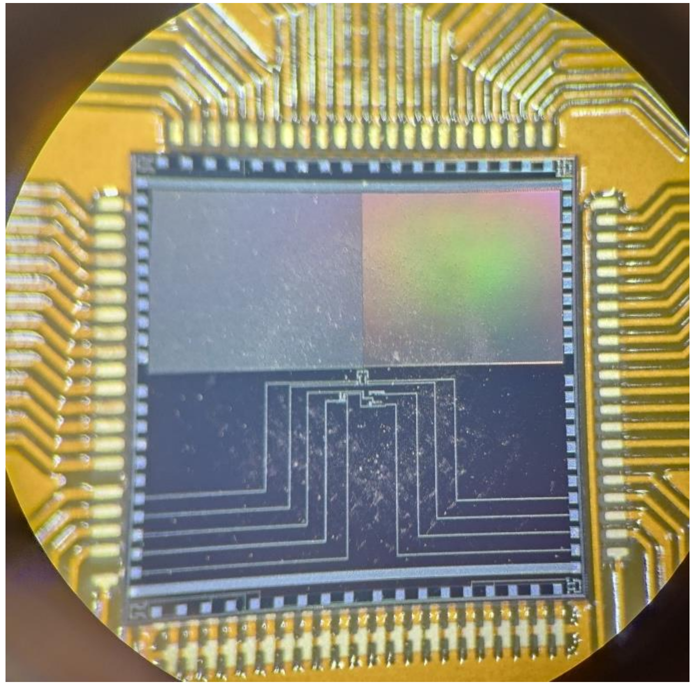
Demonstrator project

Q1, Q2, Q3, Q4

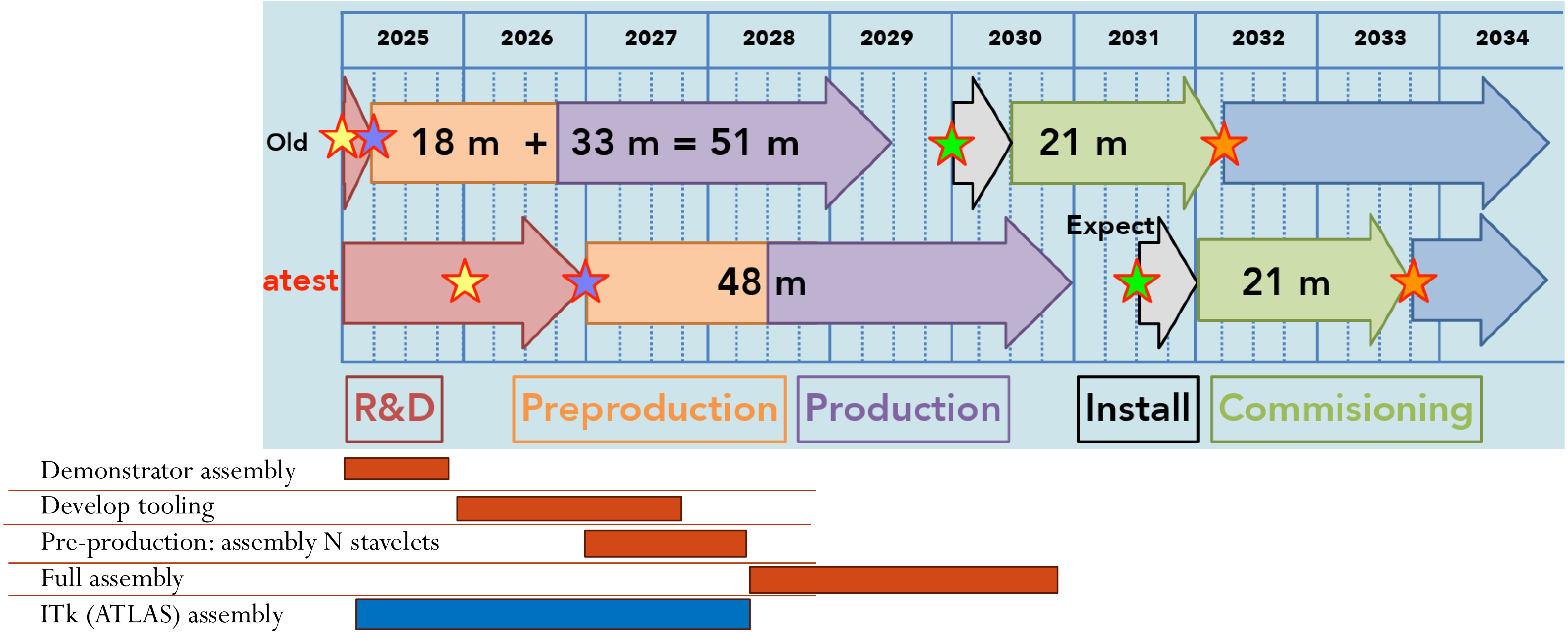


- Plan to demonstrate the assembly procedure and study the thermal characteristic of a stavelet
- First prototype of interposer board produced
- Using non working full size detectors from the HPK production
- Since no full-size ASIC available yet, using Si heaters
- Fully load a double-sided stavelet with active pipe cooling and check thermal dissipation in prototype



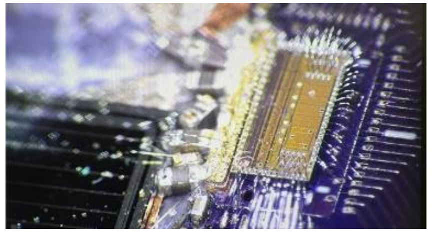


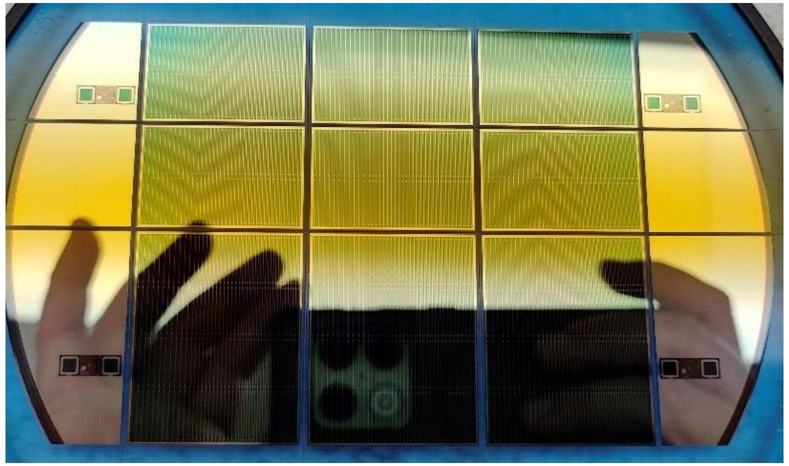
BTOF road-to-assembly

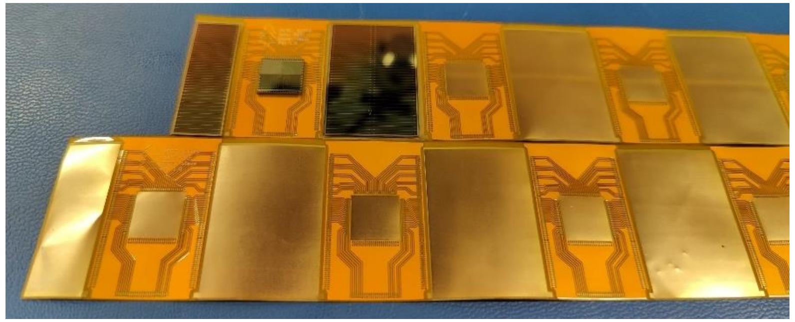


Conclusions

- Components and design of the ePIC BTOF layer is reaching maturity: TDR expected by the end of the year
- Ongoing development of AC-LGAD strips for the ePIC TOF layers
  - Received first large-scale AC-LGAD production from HPK, first results are optimistic
  - A FBK production is ongoing, an additional HPK production will start soon as well
- Readout chips currently being designed and tested: FCFD for BTOF
  - First test with full-size sensor and FCFD in July this year
  - Test beam planned for full-size sensor testing and readout electronic testing this Autumn
- Assembly procedure is being developed and organized
  - "Stavelet" is baseline design to facilitate the assembly and more serviceable
  - A thermo-mechanical demonstrator is expected by the end of summer







Charge questions

- Is the design of the ePIC detector and its sub-systems appropriate and progressing well?
  - **Yes, the design of its subsystems is progressing well, with the main bottlenecks being the availability of ASICs. The results of the first full-size sensor test conducted in the lab showed no problems. First full-size sensor + FCFD (ASIC for BTOF) will be tested this year. Assembling procedure and several properties related to thermal and electrical will be tested by using demonstrator this year.**
- Are the remaining work and technical, cost and schedule risks adequately understood? Are there opportunities?
  - **Remaining work is well understood. Main schedule risks are related to availability of ASIC. FBK sensors will also be tested to reduce the risk of manufacturing the sensors that form the core of this detector.**
- Will the detector be technically ready for baselining by late 2025?
  - **The detector baseline is well established, and we aim to resolve the remaining open questions**
- Are the detector integration and planning for installation and maintenance progressing well? Are there areas where further ideas should be pursued?
  - **We have a plan for a set of demonstrator staves that will lead us to higher level integration steps. It is crucial that ASIC, Sensor production and mechanical design progress on schedule.**
- Will the detector be ready for start of construction by late 2026?
  - **YES, but correlated with ASIC availability**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Thanks for the attention
THE UNIVERSITY OF CALIFORNIA
LET THERE BE LIGHT
1868

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In particular to students:
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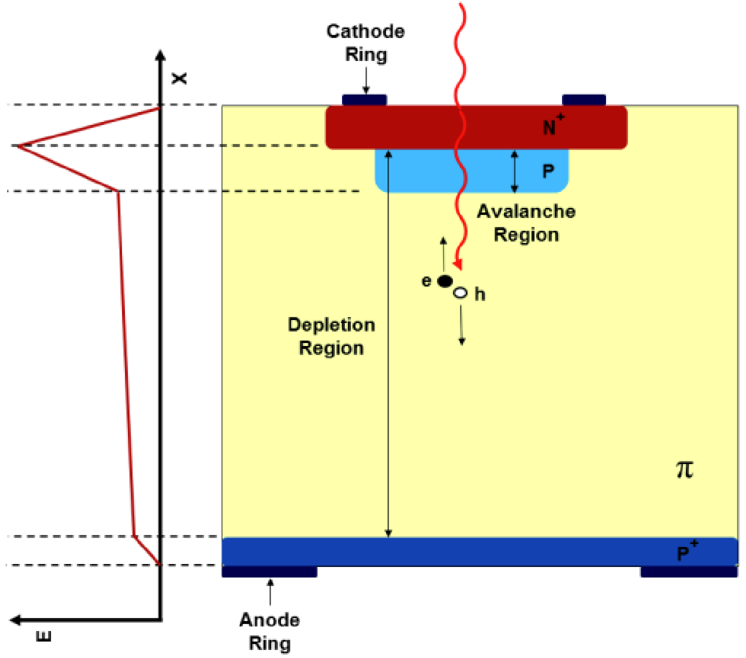
Backup

Low Gain Avalanche Detectors, LGADs

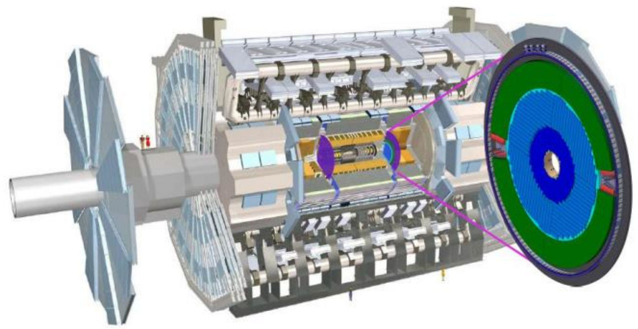
- LGAD: silicon detector with a thin (<5 μm) and highly doped (~10^{16}) multiplication layer
  - High electric field in the multiplication layer
  - Field is high enough for electron multiplication but not hole multiplication
- LGADs have intrinsic modest internal gain (10-50)
  - Gain $= \frac{Q_{LGAD}}{Q_{PiN}}$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



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

First application HL-LHC timing layers for ATLAS and CMS

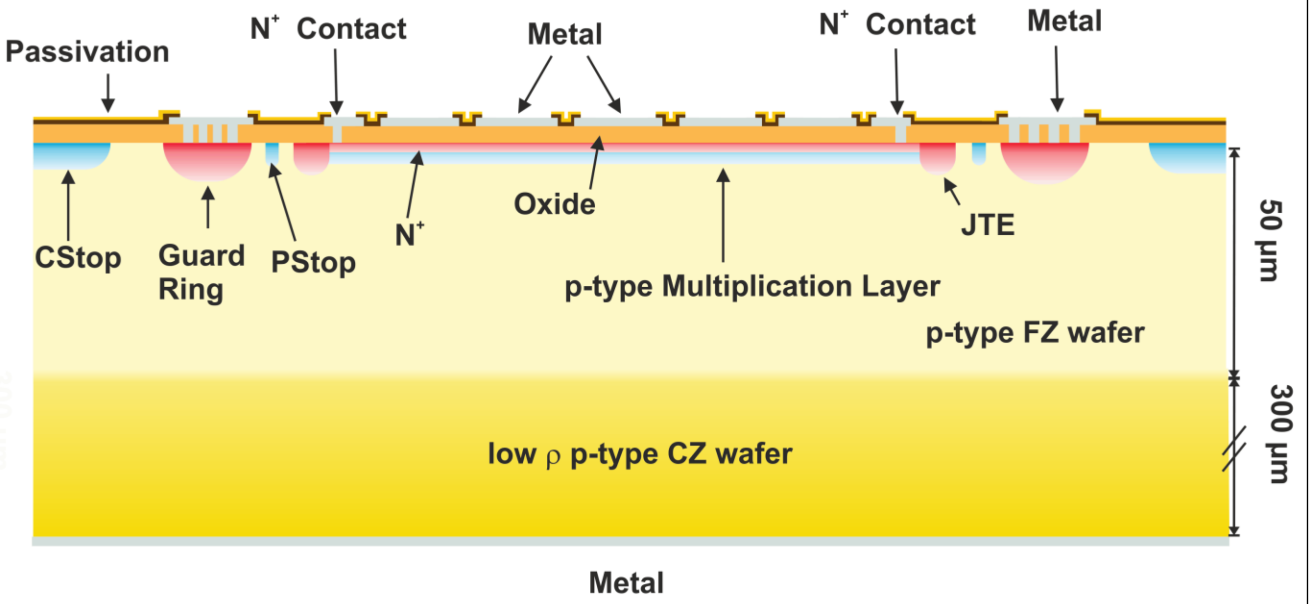
- Several producers of experimental LGADs around the world
  - CNM (Spain), HPK (Japan), FBK (Italy), BNL (USA), NDL (China)

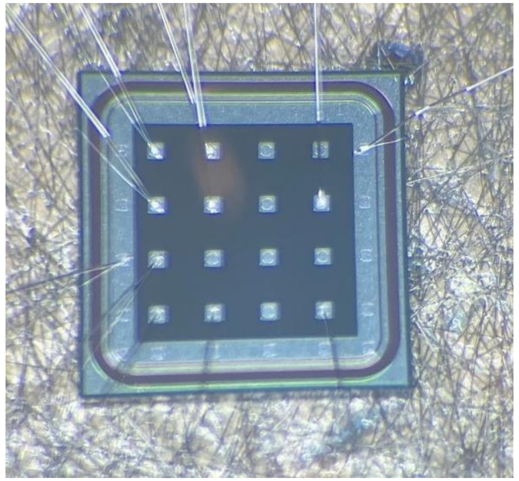


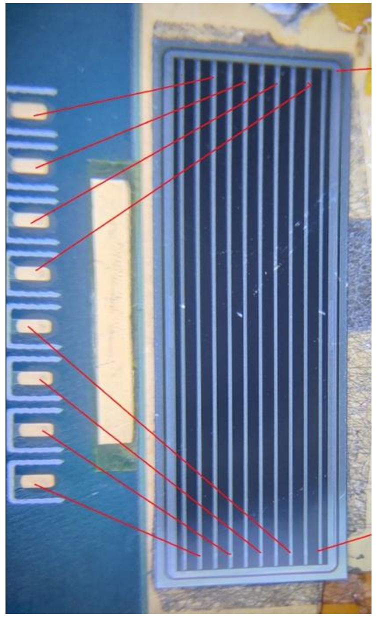
https://cds.cern.ch/record/2719855
https://cds.cern.ch/record/2667167

AC-LGADs

- 'Standard' LGADs has granularity limited to ~mm scale due to the high field on the surface
- Most advanced high-granularity prototype is the **AC-coupled LGAD**
  - Finer segmentation and easier implantation process
- Continuous multiplication layer coupled with resistive (low doping) N+ layer
- **Readout pads are AC-coupled**, insulator layer between N+ and pads
  - Any surface metal geometry is possible

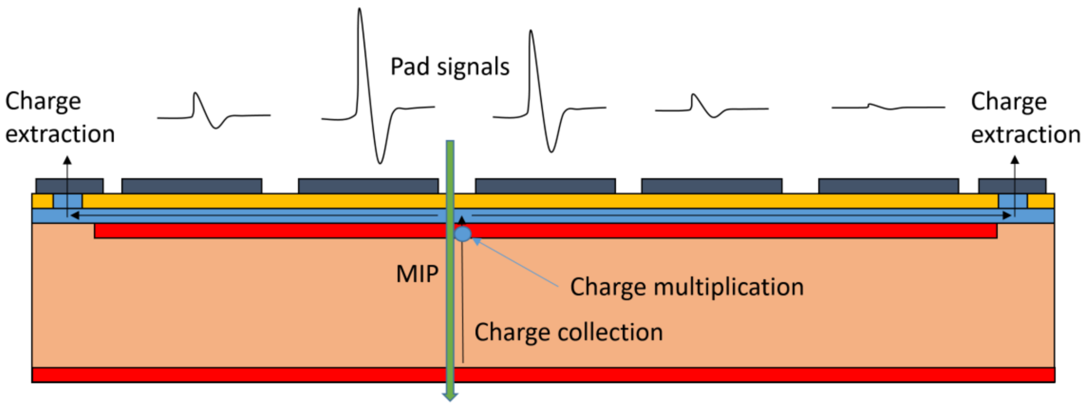


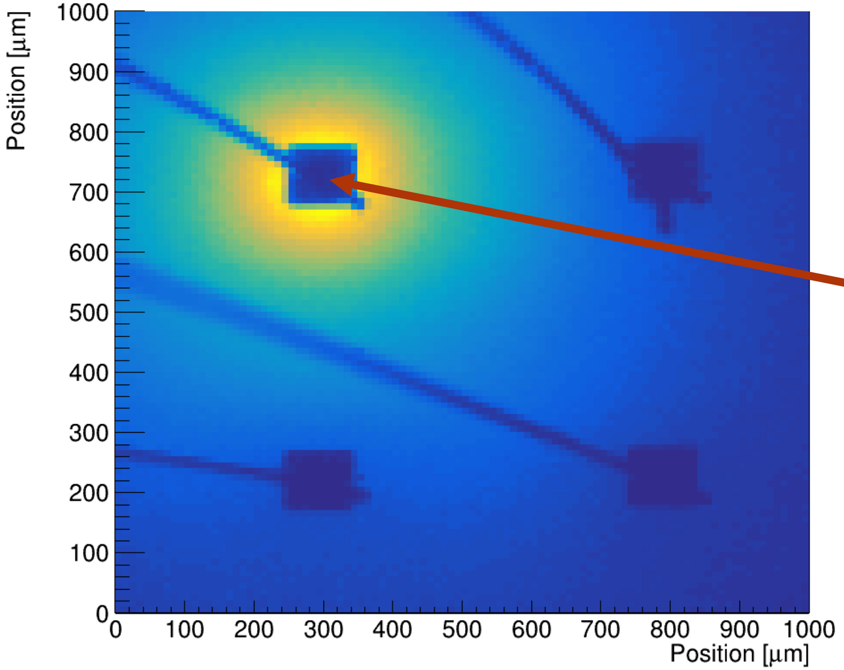


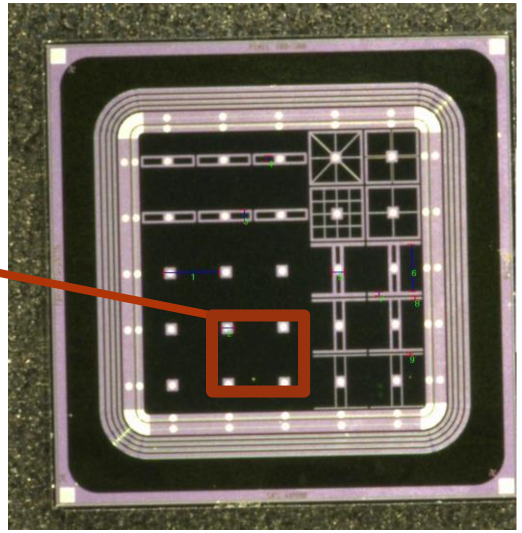


AC-LGAD hit reconstruction

- 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/strips for hit reconstruction
- Sparse readout is extremely useful to reduce channel density and power dissipation (issue for fast timing) while maintaining good resolution





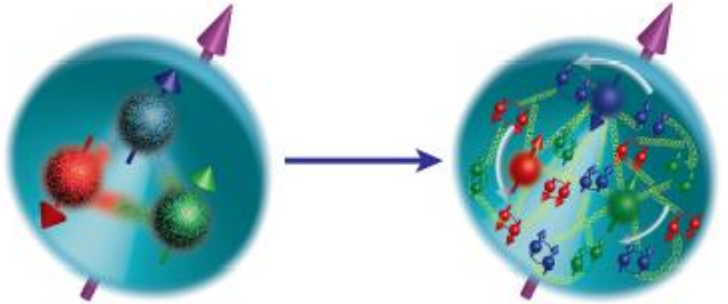


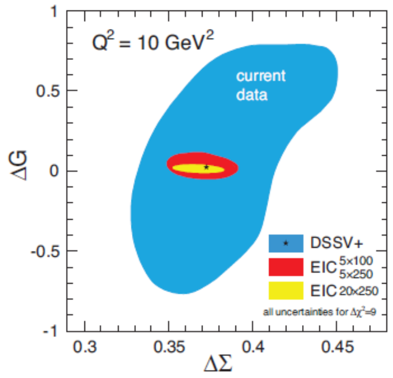
Electron-Ion collider

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

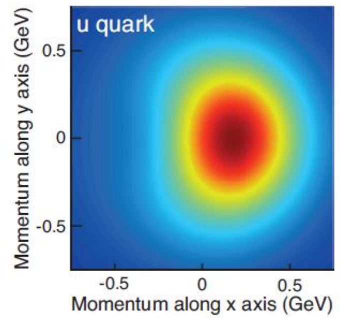
ePIC will provide key measurements:

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



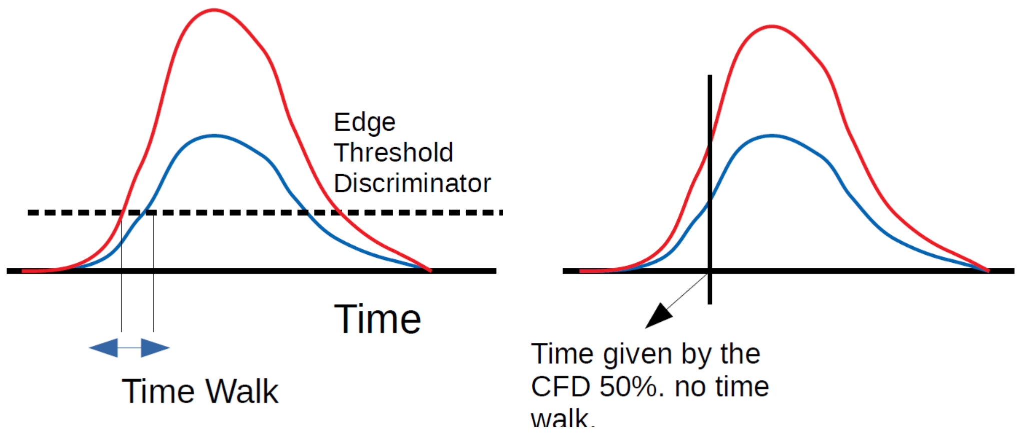


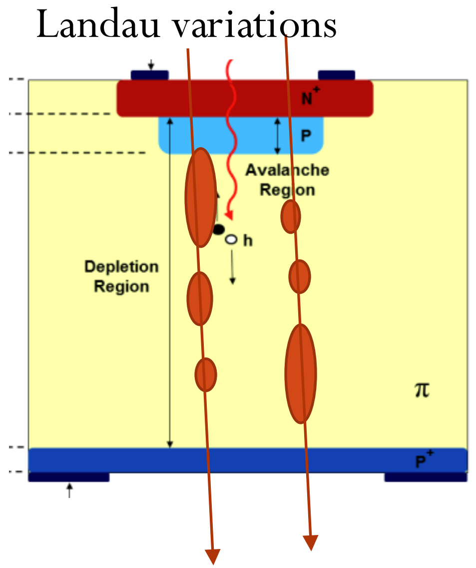
Gluon helicity contribution vs quark helicity contribution

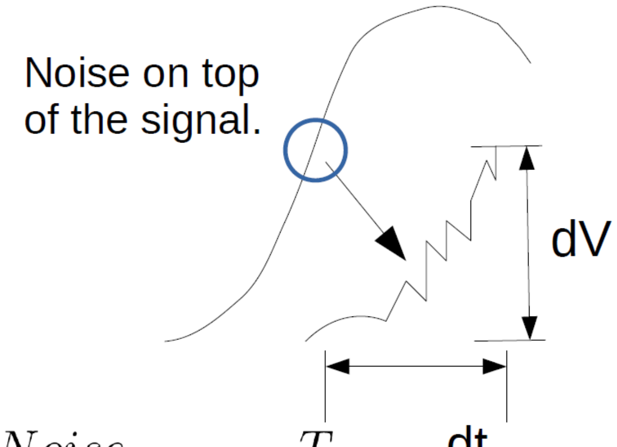


X-Y u quark motion
For proton traveling in Z

Time resolution







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

Sensor time resolution main terms

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

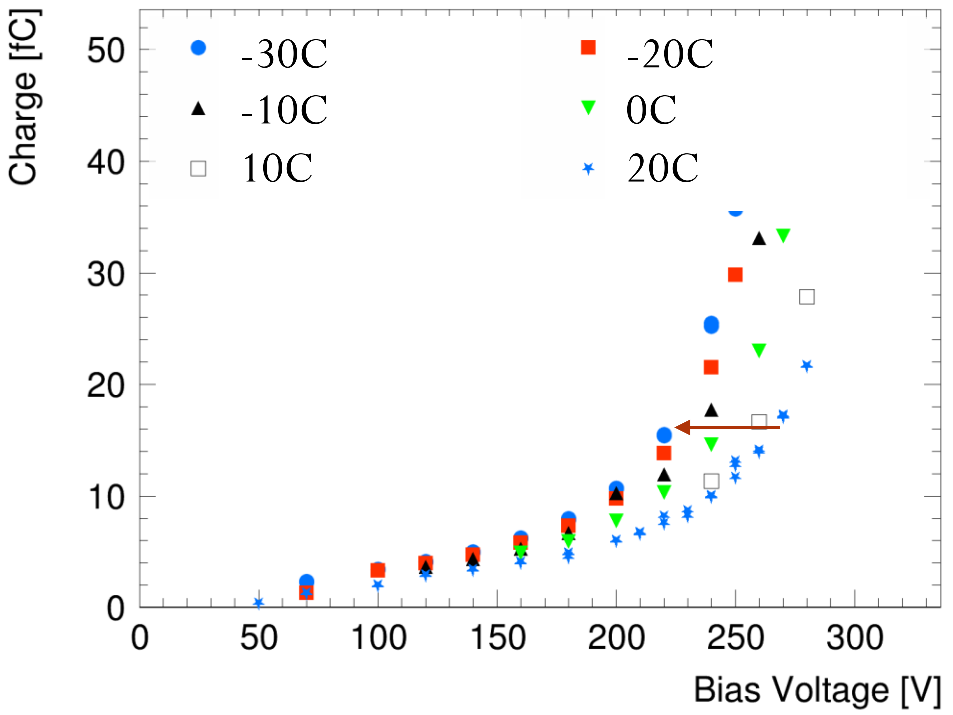
- **Time walk**:
  - Minimized by correcting the time of arrival using pulse width or pulse height (e.g., use 50% of the pulse as ToF)
- **Jitter**: from electronics
  - Proportional to $^1/_{\frac{dV}{dt}}$
  - Reduced by increasing S/N ratio with gain
- **TDC term**: from digitization clock (electronics)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

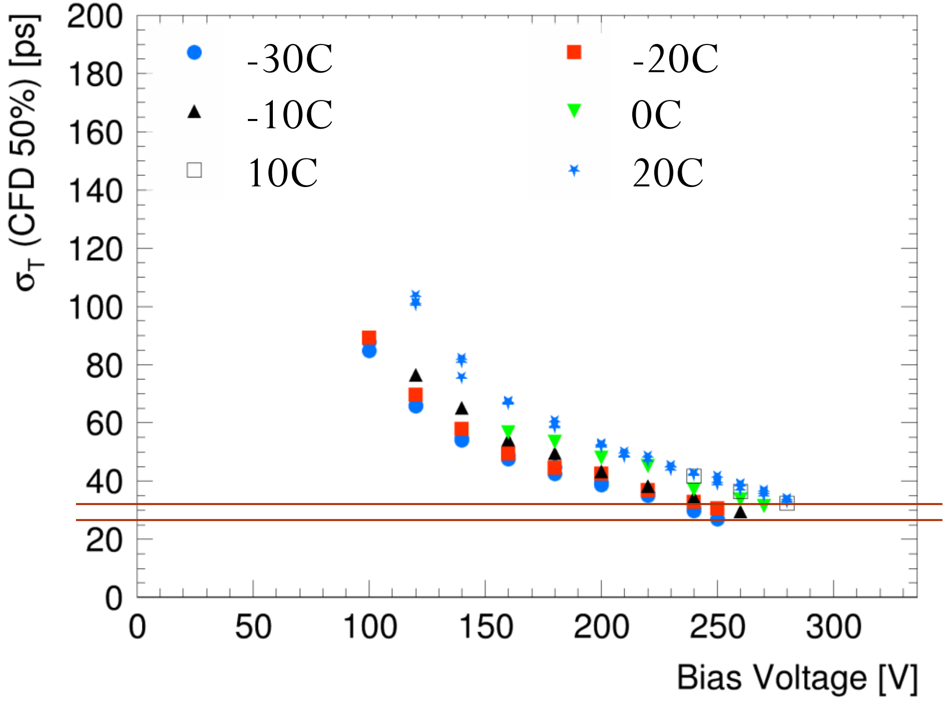
- **Bottom line: thin detectors with high S/N**

LGAD temperature dependence

- LGAD gain depends on temperature due to impact ionization dependence on e/h drift speed
- On a large temperature range the effect is significant
  - The same sensor has a ~50V breakdown variation over a 50C temperature change
  - Data from ATLAS/CMS prototype UFSD3.2 (FBK)
  - Similar study foreseen for ePIC AC-LGADs (laser station almost ready)
- The time resolution suffers slightly from the non-saturated drift velocity if the breakdown is too early (5ps worse for -30C)
  - Electric field in the bulk is too low between Gain layer depletion and breakdown

- In the case of ePIC the running temperature and temperature variation should not as extreme
  - However the breakdown voltage is <150V for most ePIC prototypes, (fairly low)
  - **Once the running temperature is set we should start testing devices at that temperature to measure realistic performance**
  - Then adjust the sensor design accordingly, a similar study happened for ATLAS with HPK (4 gain layer doping tunes)

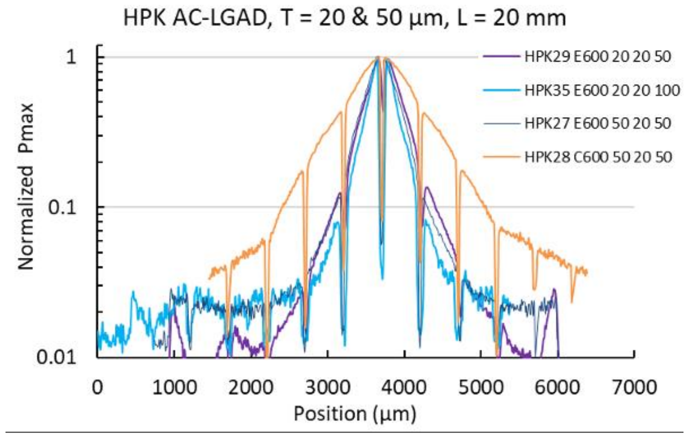


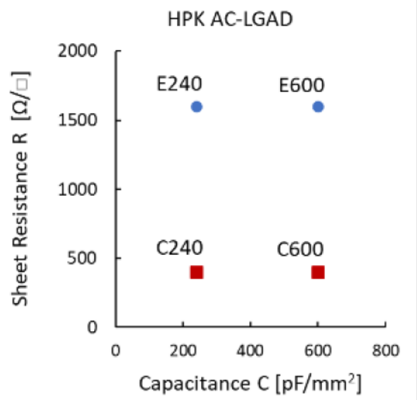


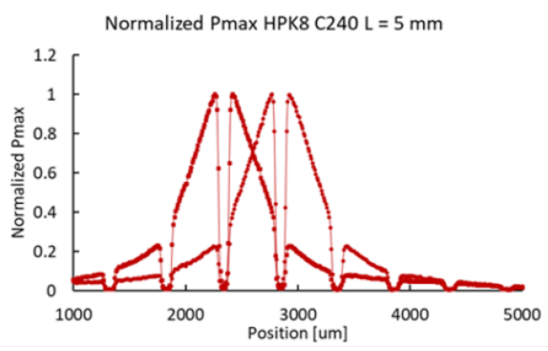
Student: J. Ding

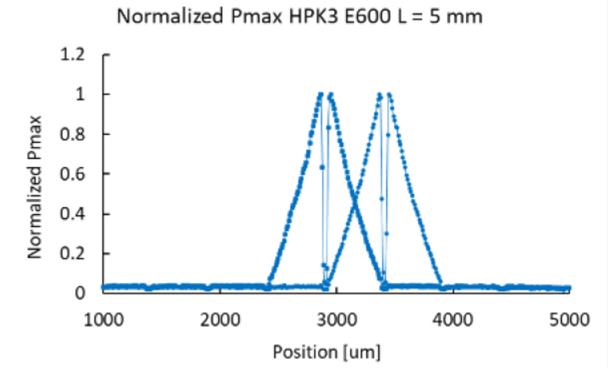
HPK 2023 lab studies

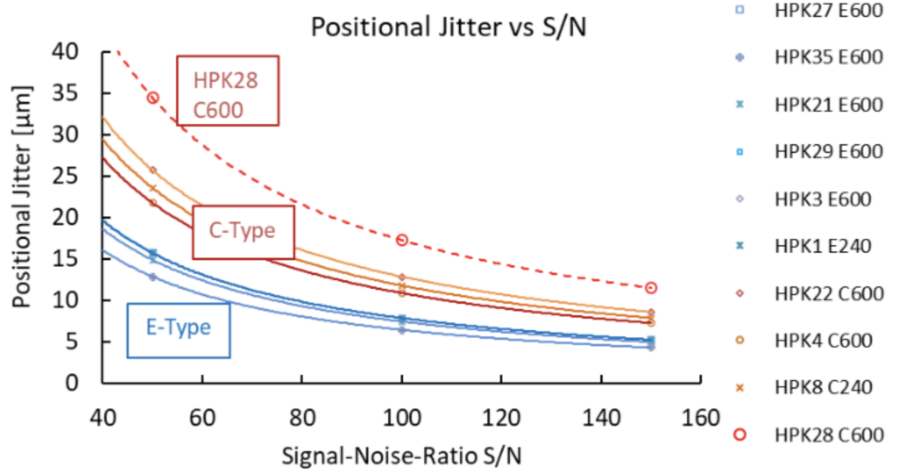
- Previous lab results from 2023 HPK production
  - https://doi.org/10.1016/j.nima.2024.169478
  - Based on laser TCT studies
- Conclusions:
  - Type E strips (more resistive) perform much better, oxide thickness has less impact but thinner is better.
  - Long strip length degrades both signal (rise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





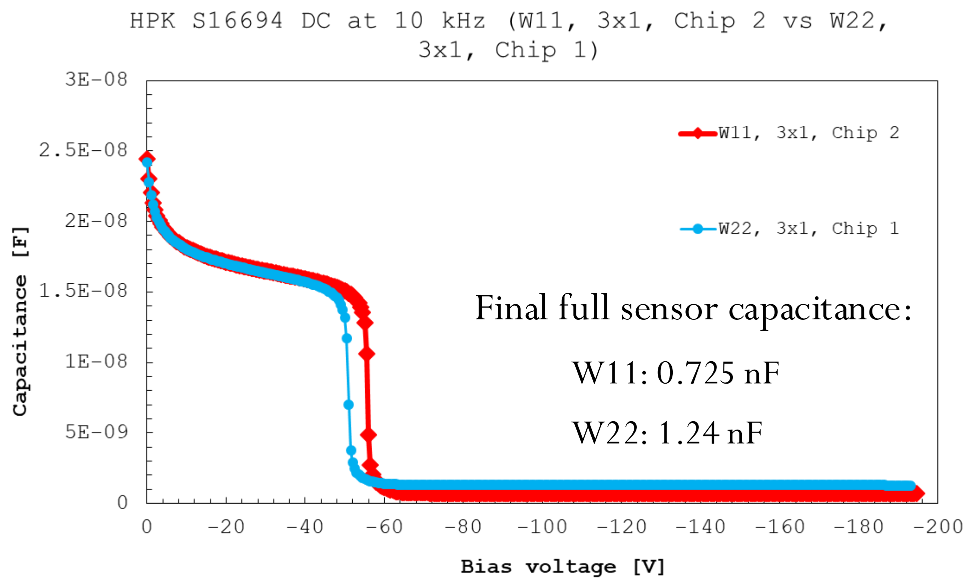


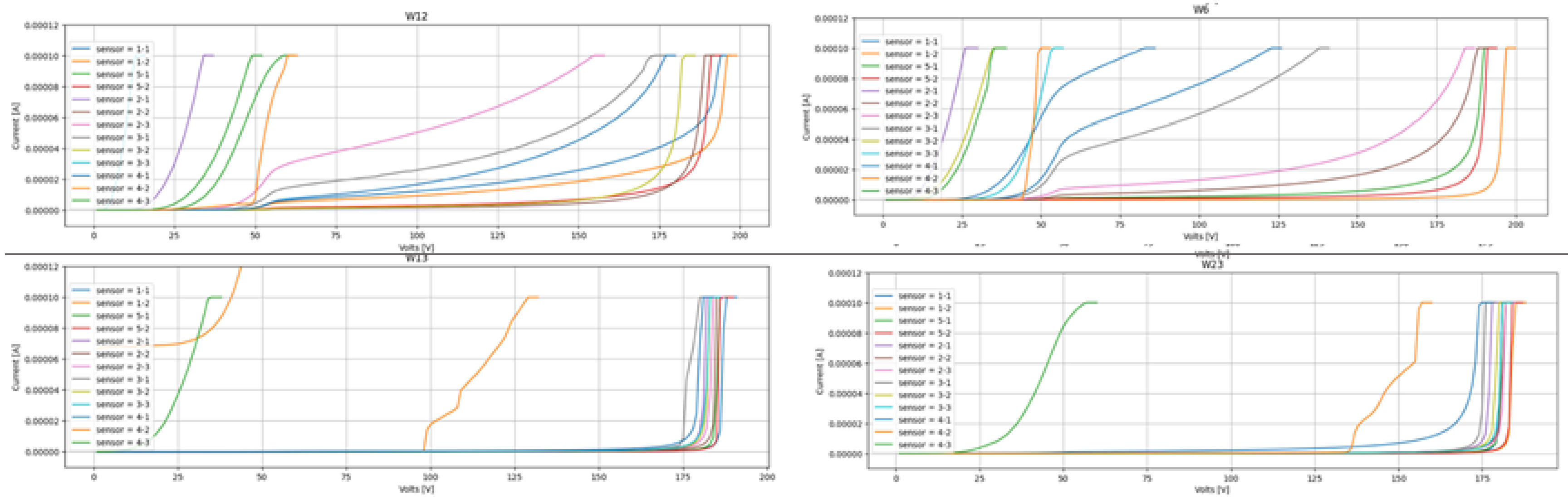




HPK production results – IV/CV

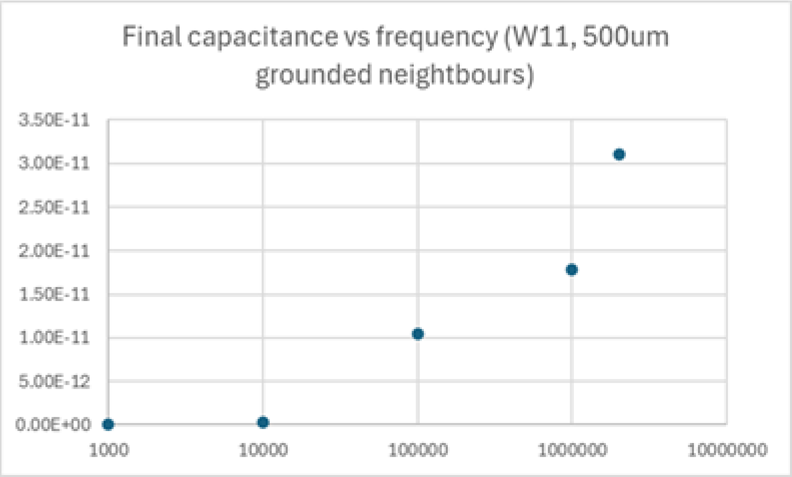
- Yield is not optimal, somehow better for 30um wafer
- Capacitance of full detector scales with thickness
- Measurement of strip capacitance (input capacitance to the amplifier) is not an easy task
  - Significantly changing with probing frequency
  - Several measurements ongoing with TCAD simulation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





50um

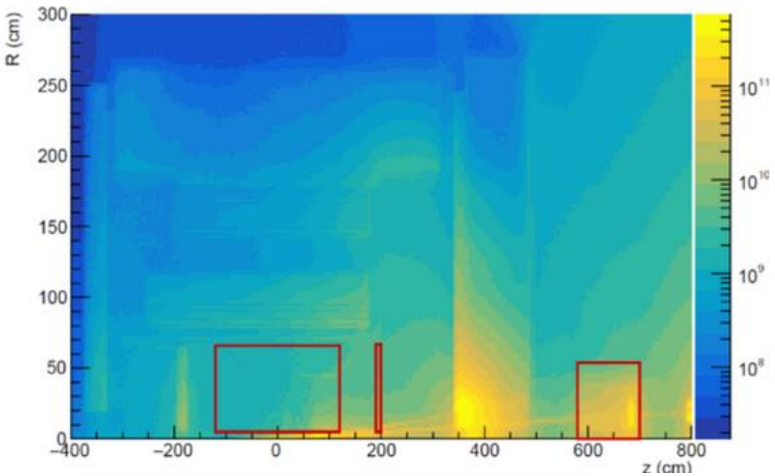
30um



Student: G. Stage, A. Borgijin

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

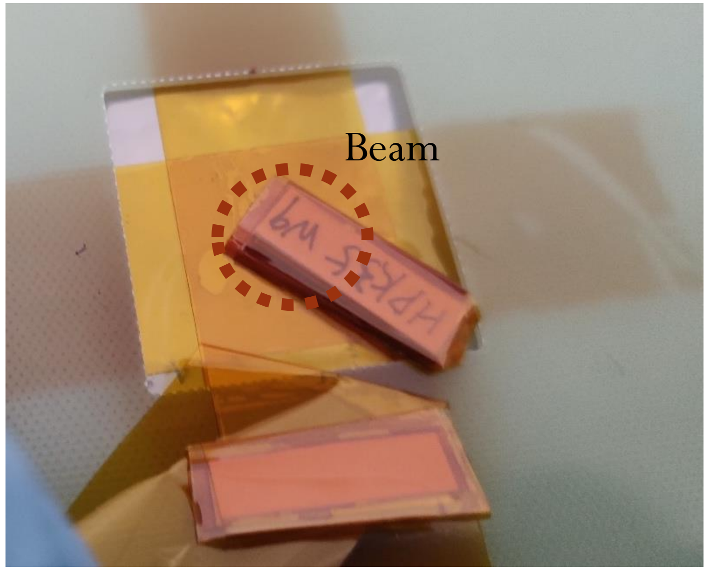
Fluence	0.5 cm	1 cm	2 cm
1.00E+14	52	52	
5.00E+14	44		48
1.00E+15		38	42

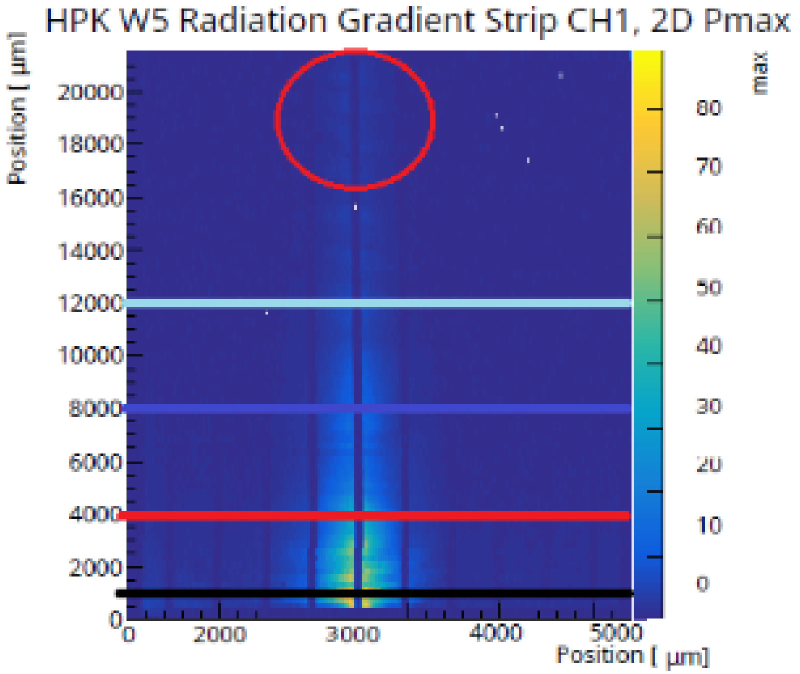
Strips W5

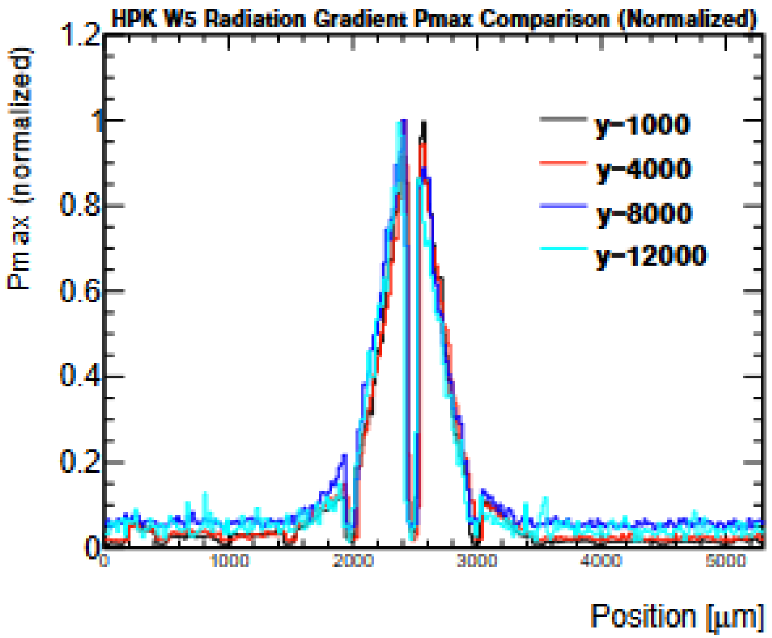
Fluence	0.5 cm	1 cm	2 cm
1.00E+12	54	54	
1.00E+13	42		54
1.00E+14		52	53

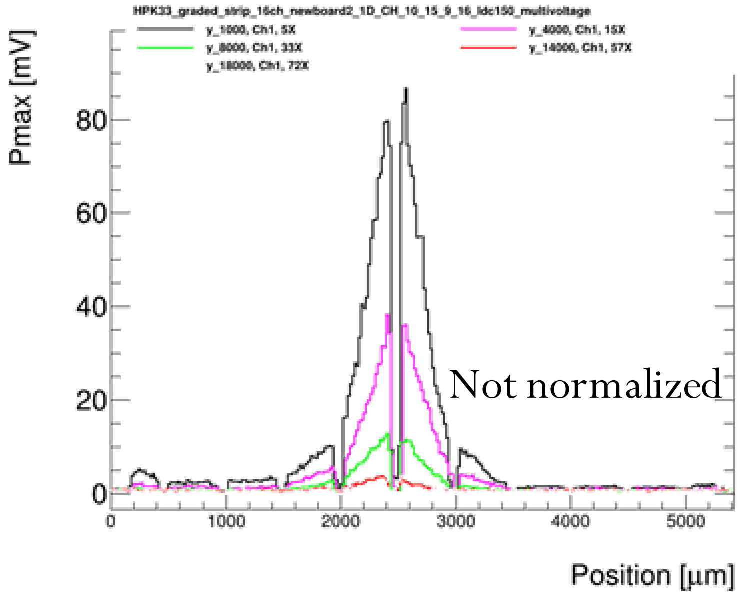
TCT laser studies - Protons

- 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!





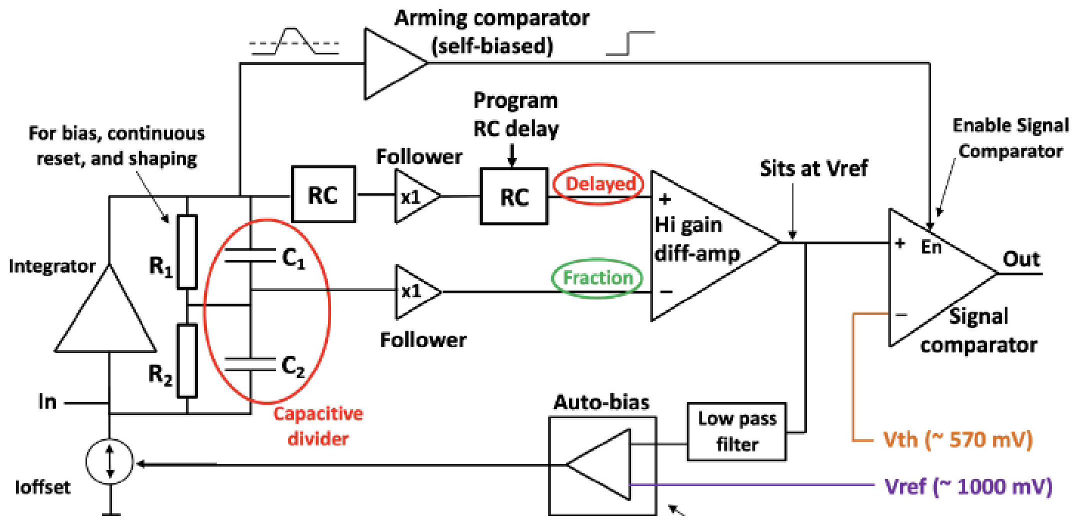




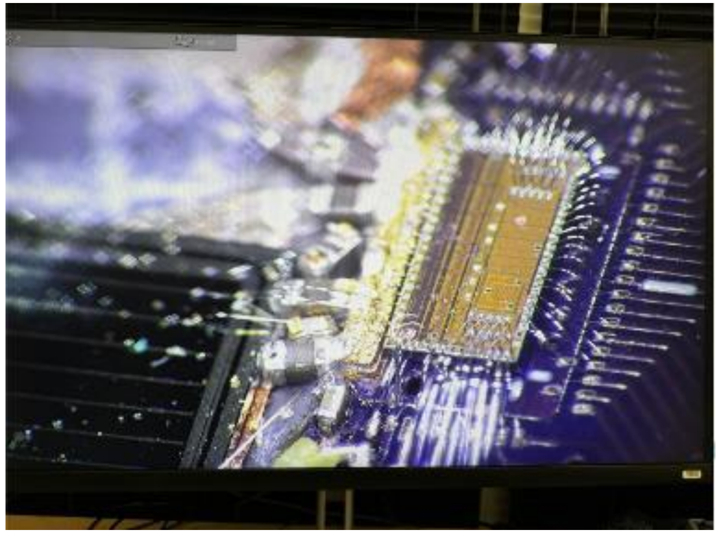
Student: G. Stage, A. Borgijin

FCFD

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



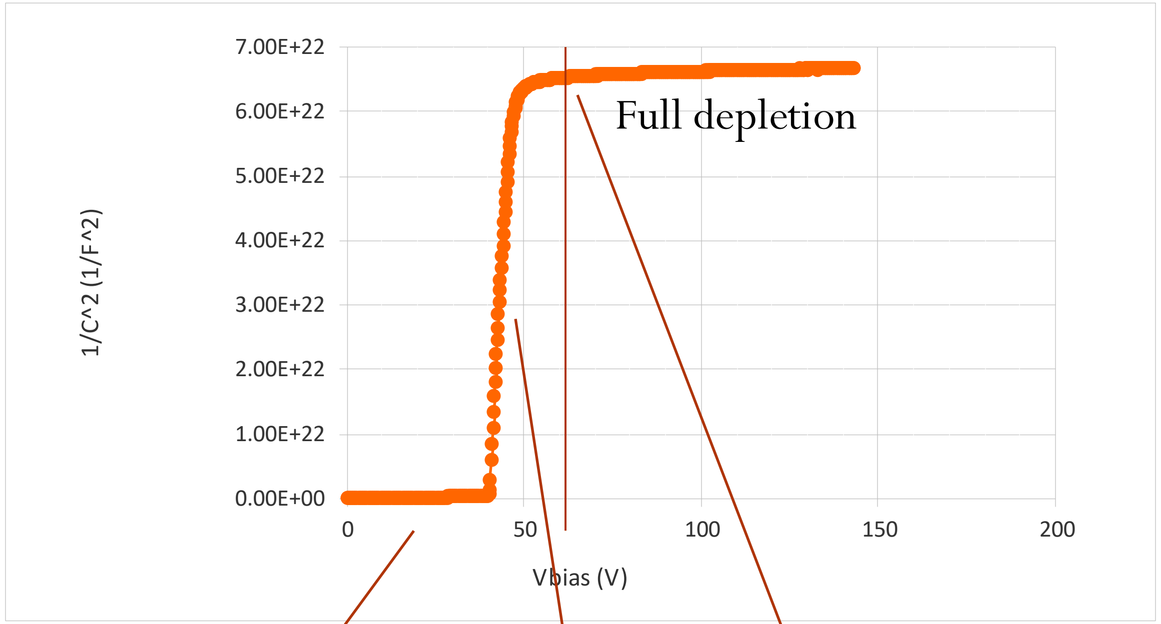
- 128 ch strip readout
- 65 nm CMOS
- Constant Fraction Discriminator
- Plus TDC, ADC, interfaces
- Cdin: <15 pF
- Dynamic Range: 5-40 fC
- Timing: 10-30 ps
- Links: ~Gbps, multiple
- Radiation tolerant.

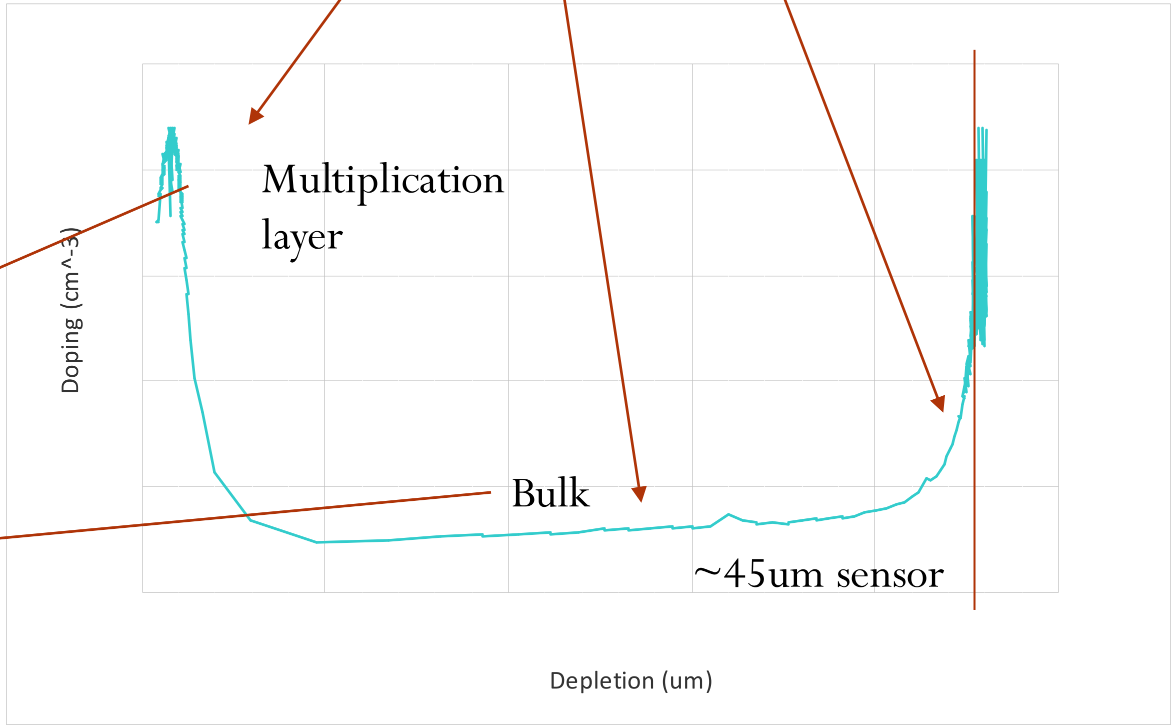


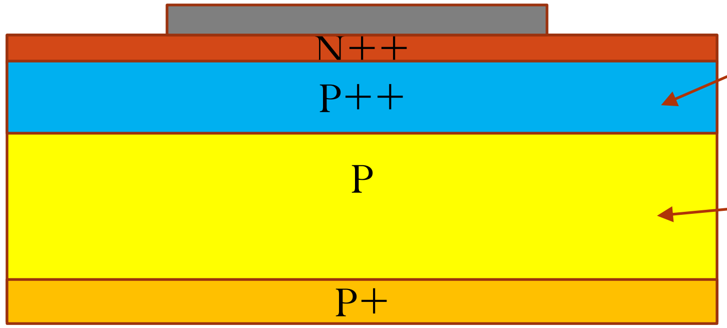
- FCFDv1 (6 ch): FY23 – FY24
- FCFDv1.1 (6ch): May 2025
- FCFDv2: FY25 – FY26
- FCFDv3: FY27 Production

Sensor testing – IV/CV

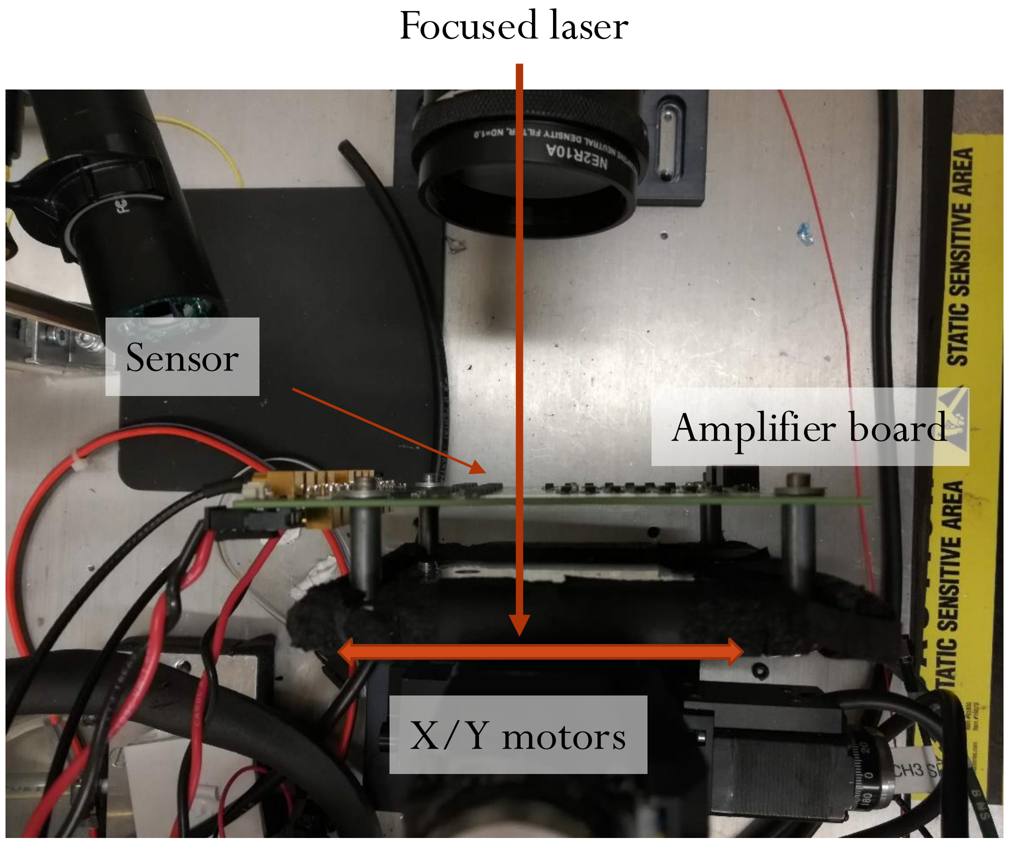
- Capacitance over voltage (CV)
  - Study doping concentration profile and full depletion of the sensor
  - Doping profile can be extracted from the $1/C^2$ derivative
- Study of the “foot” for LGADs on $1/C^2$
  - $1/C^2$ is flat until depletion of multiplication layer because of the high doping concentration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







Sensor testing –Laser TCT setup

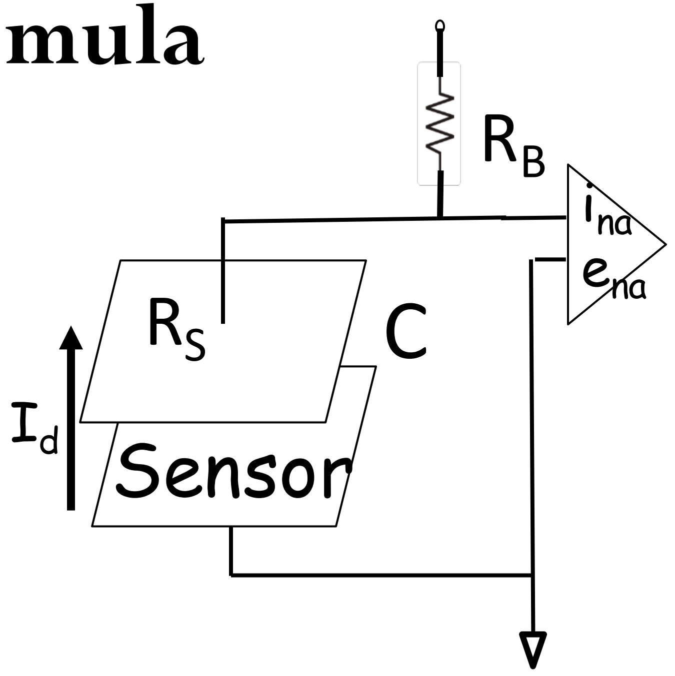


- Sensors are mounted on a multi-channel analog amplifier board with bandwidth ~1 GHz
  - Response is readout by 2 GHz/20 Gs oscilloscope
- **IR laser (1064 nm)** mimics charge deposit of a Minimum Ionizing Particle (MiP)
  - Focused laser beam with spot width ~20 um
- Amplifier board is mounted on X/Y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

Readout noise master formula

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

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



Noise level in equivalent electrons

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

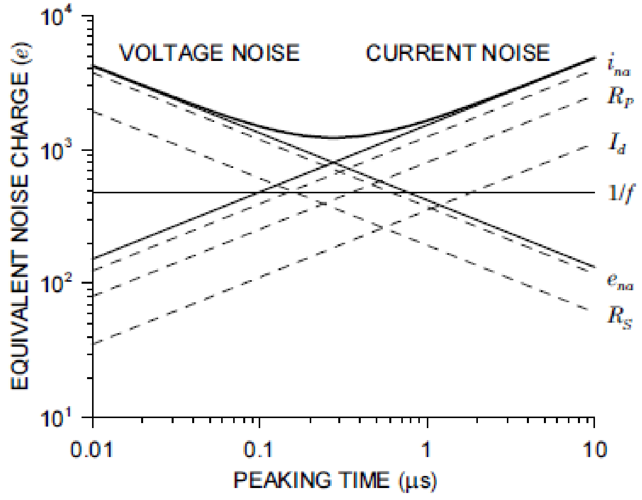
General rule of thumb: signal-to-noise of 12:1 for efficient operation

Signal-shape parameters (of order 1)

Noise current sources — Noise voltage sources

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

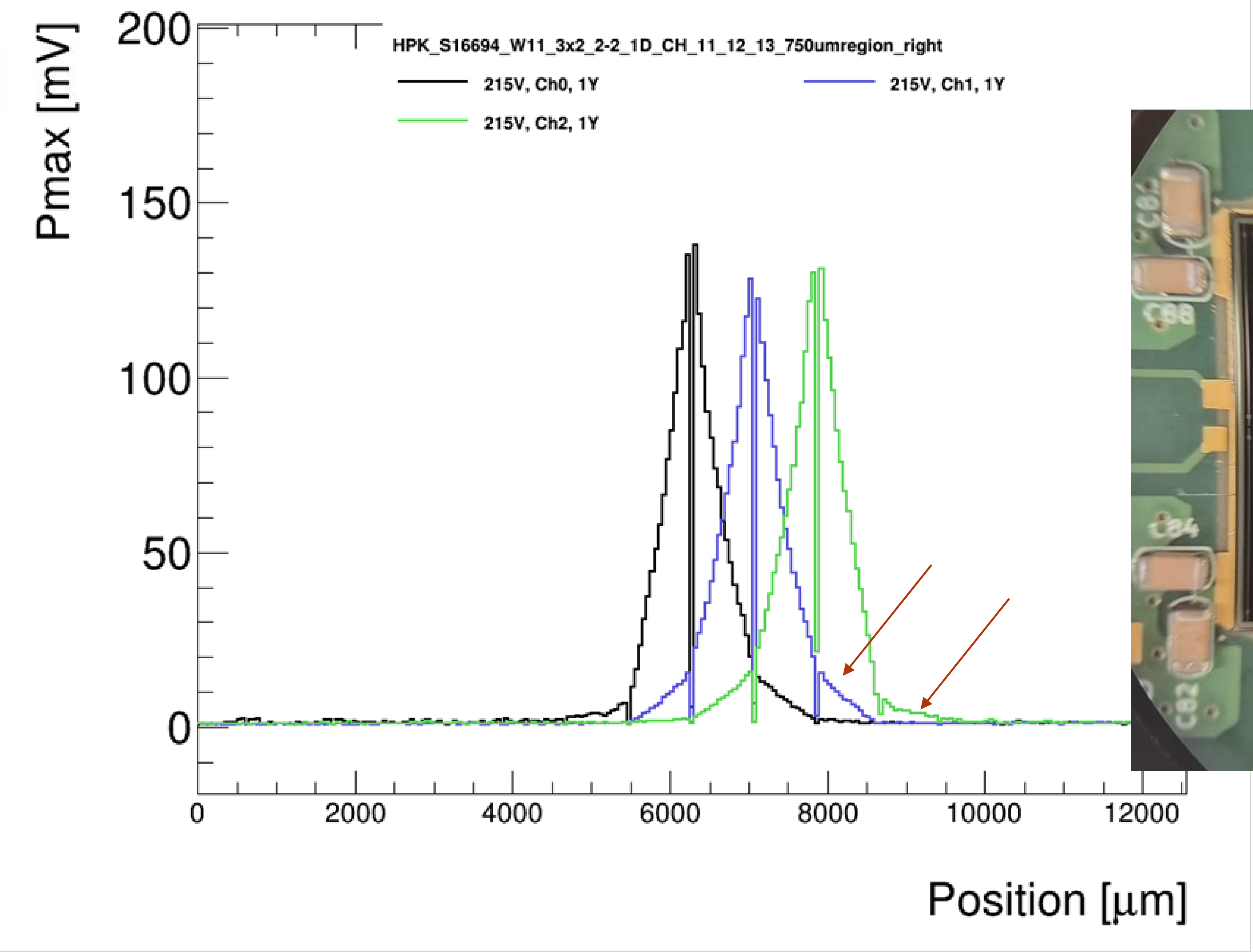
Amplifier shaping time (1/Bandwidth)



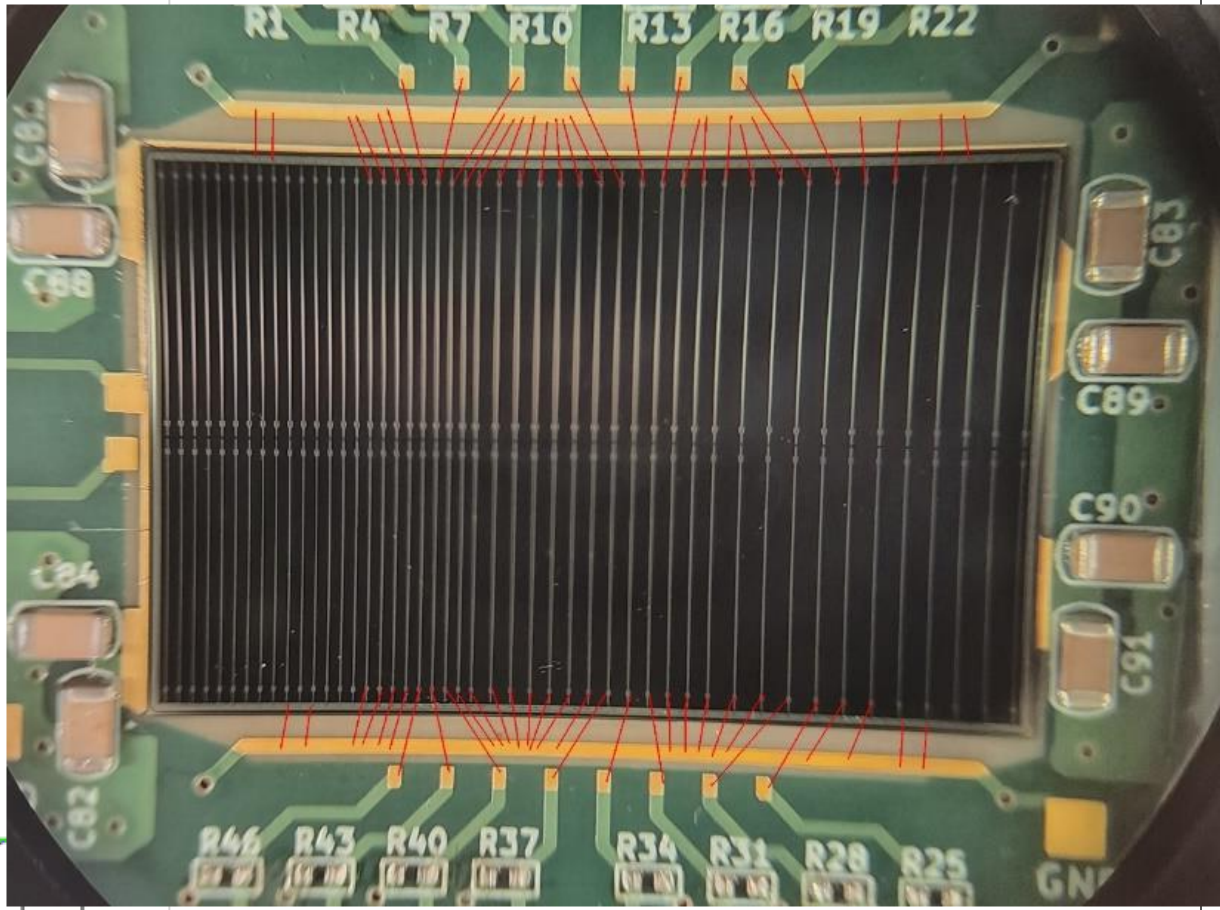
(For a particular set of parameters)

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

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]
Position [µm]
0
50
100
150
200
0
2000
4000
6000
8000
10000
12000

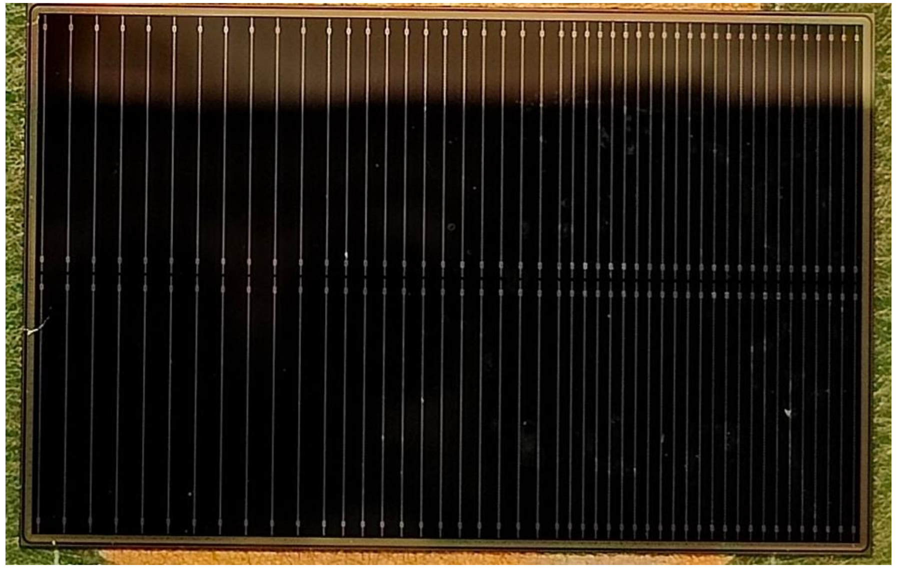


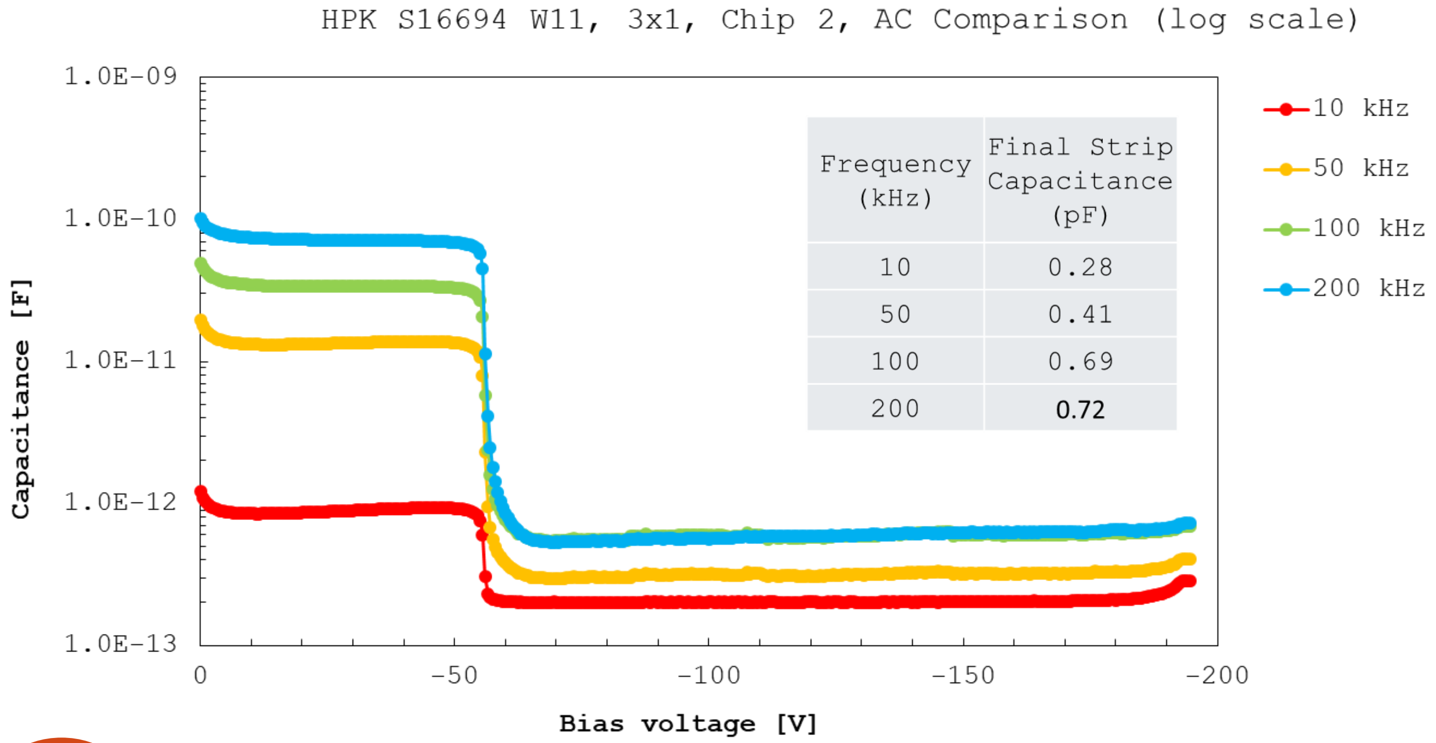
R1
R4
R7
R10
R13
R16
R19
R22
R46
R43
R40
R37
R34
R31
R28
R25
C83
C88
C89
C90
C91
C84

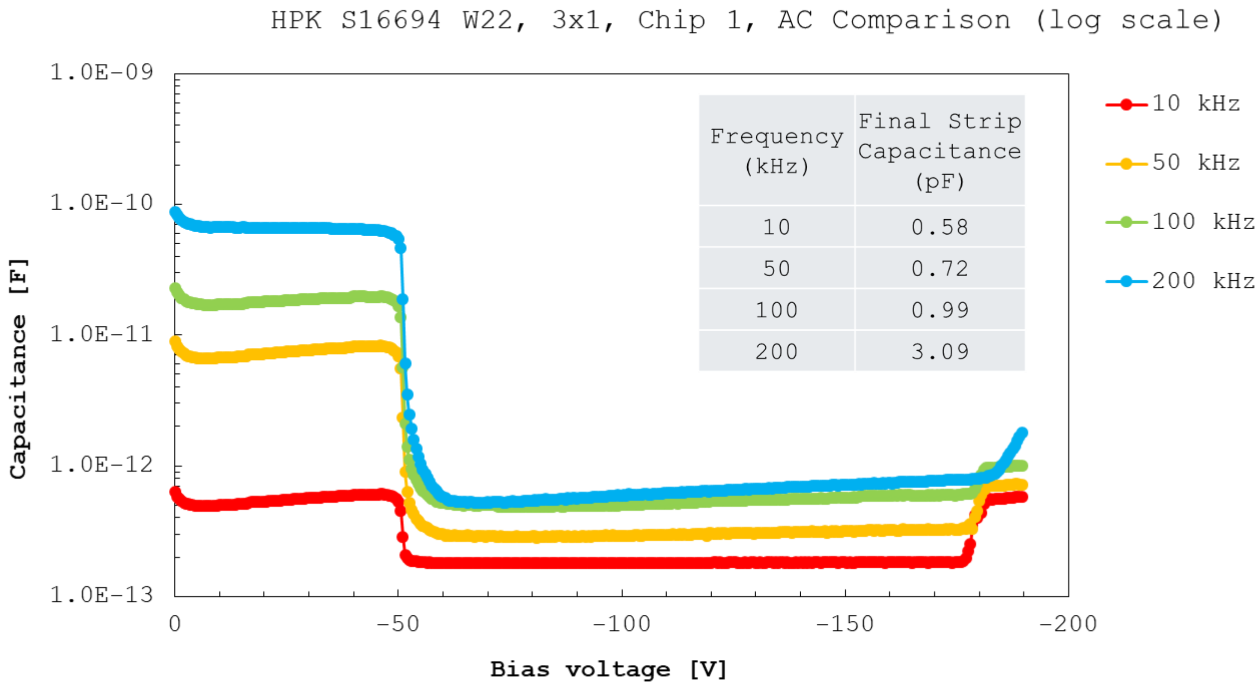
New HPK production

- 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



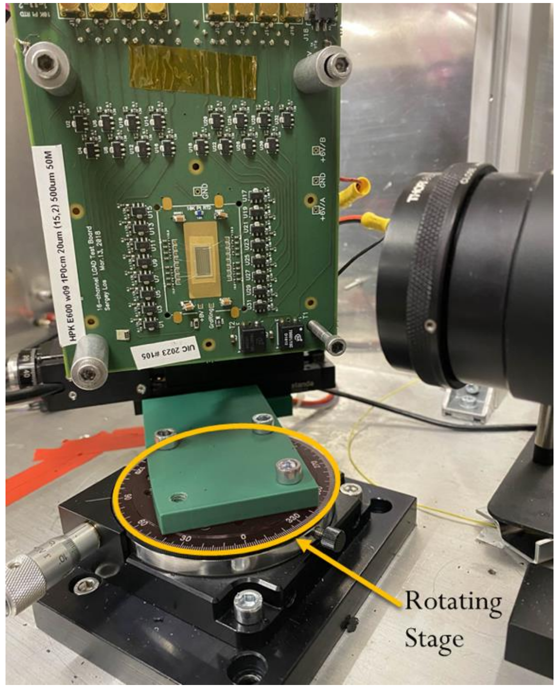


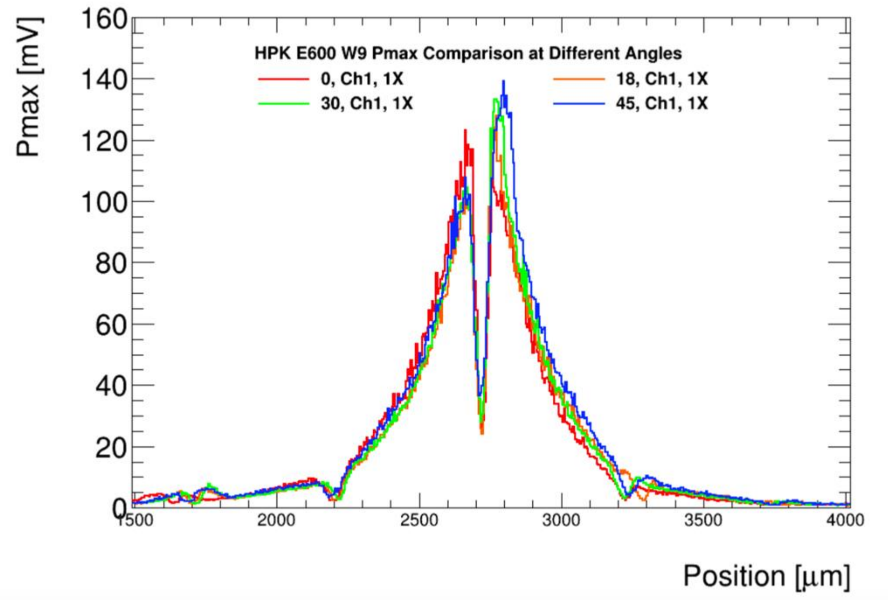


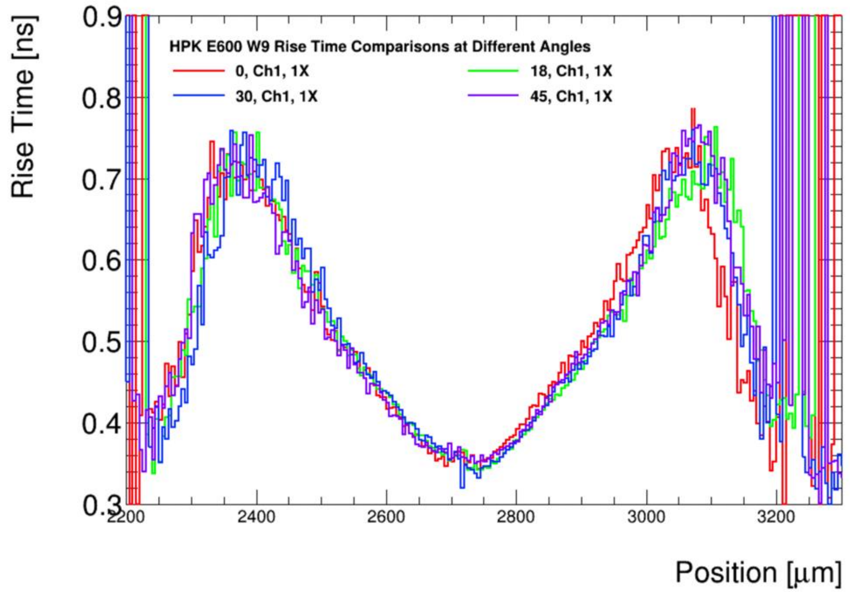
Student: J. Ding

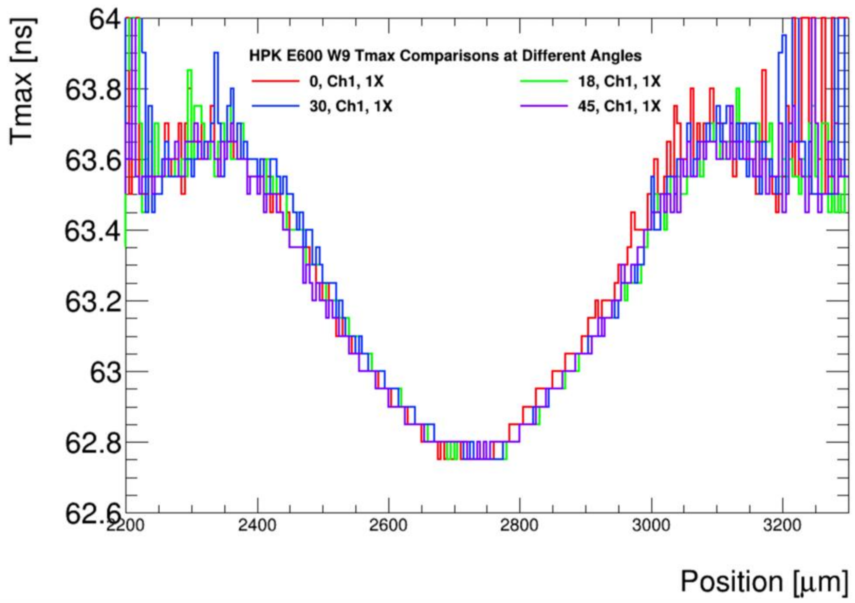
Angled charge injection

- Strip modules in ePIC barrel-TOF are layered with a 18-degree tilt angle in the design baseline, forward disk region also get tracks with large incident angle (up to 30-degree)
  - Laboratory characterization and beam tests so far have been conducted at normal incidence
  - Added a angular stage to our TCT laser setup to study the effects of angle of incidence
- Tested a strip AC-LGAD with the new setup (Pixel next)
  - **At larger angles, signal profile in neighboring strips also shows shift with rotational angle, but effect is small and can be corrected if angle is known**
  - Laser light is shone under strips
- Differences in time-of-arrival and rise time are minimal for the angles measured









Student: J. Ding