Performance of AC-LGADs in radiation hard environment and non standard charge deposition

2° DRD3 Workshop (2024, CERN)

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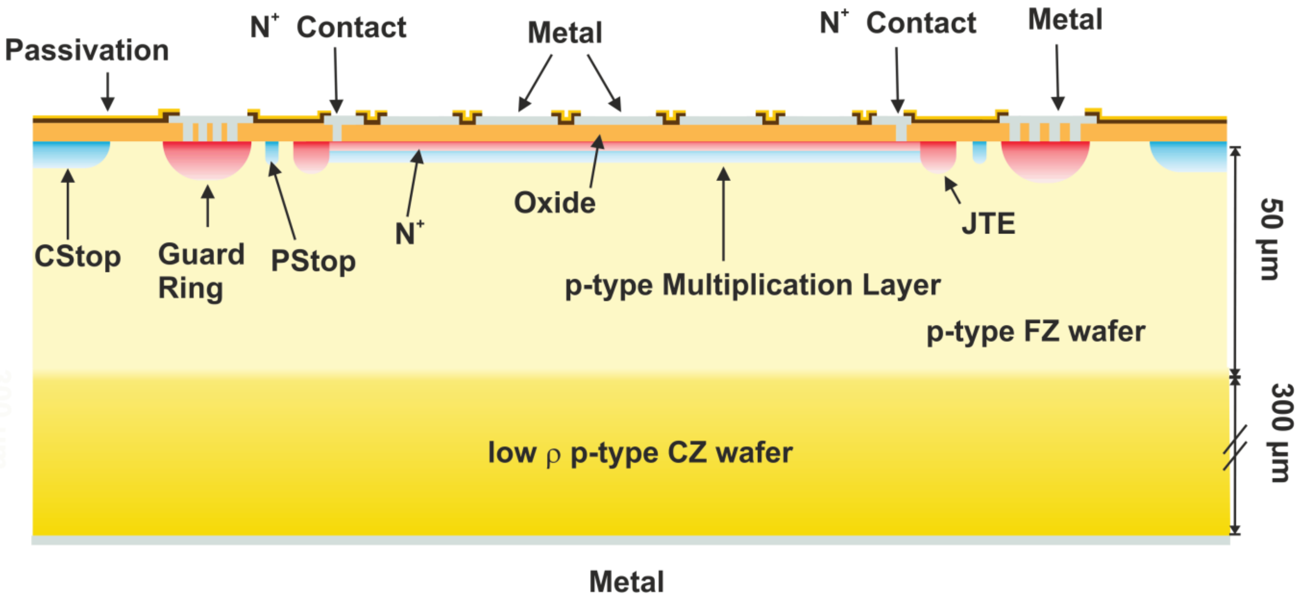
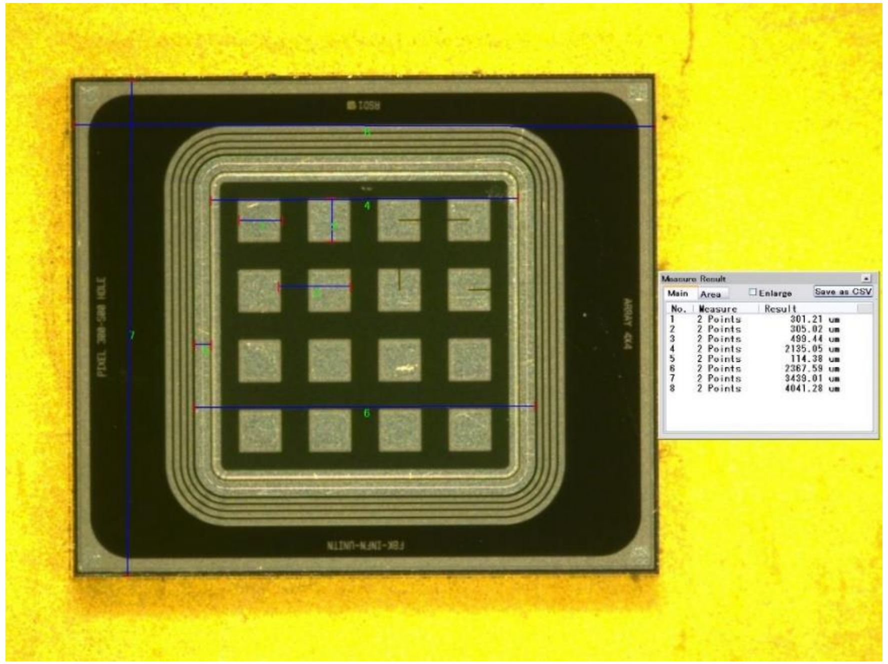
On behalf of SCIPP and ePIC TOF

AC-LGADs

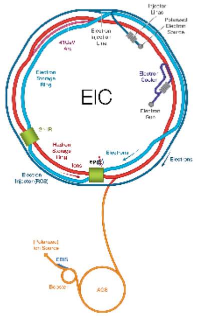
- Most advanced high-granularity prototype is AC coupled LGAD
  - Finer segmentation and easier implantation process
- Continuous sheets of multiplication layer and N+ layer
- **N+** layer is **resistive** and grounded through side connections
- **Readout pads are AC-coupled**
  - Insulator layer between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



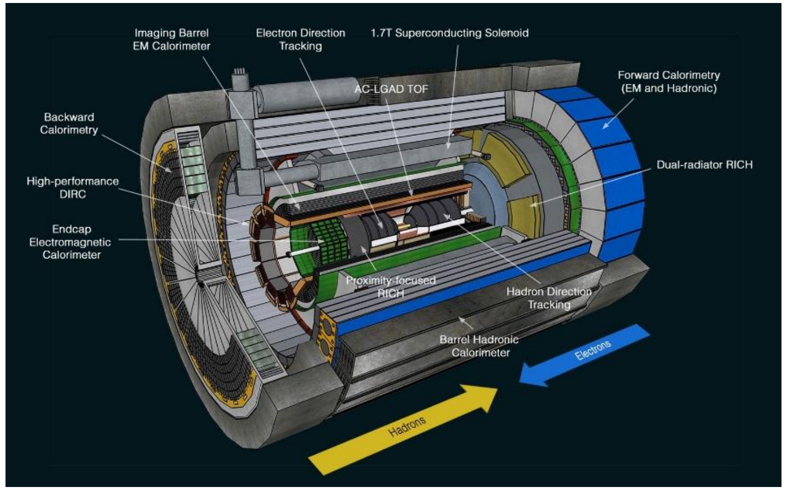
- **The response of the sensors can be tuned** by modifying several parameters
  - Pad geometry and dimension
  - Pad pitch
  - N+ layer resistivity
  - Oxide thickness



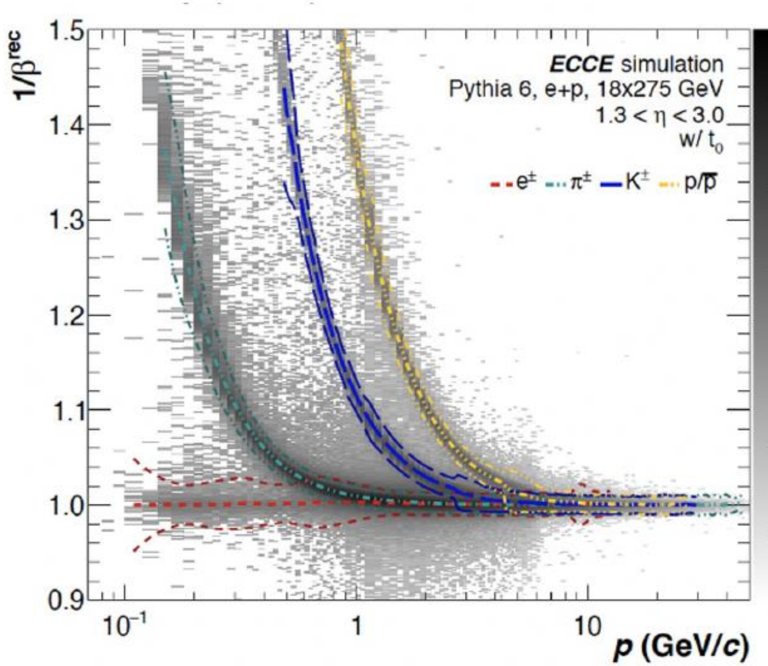
Electron-Ion collider (https://www.bnl.gov/eic/)



- ePIC (EIC detector 1) will provide key measurements:
  - Proton spin, The motion of quarks and gluons in the proton, tomographic images of the proton, QCD matter at extreme gluon density
- Operations scheduled to begin 2032-2034
  - Center-of-mass energy: 20 – 140 GeV
  - electrons: 2.5 – 18 GeV
  - protons: 40 – 275 GeV (ions: Z/A * Ep)
  - Luminosity: $2x10^{34}$ $cm^{-2}s^{-1}$

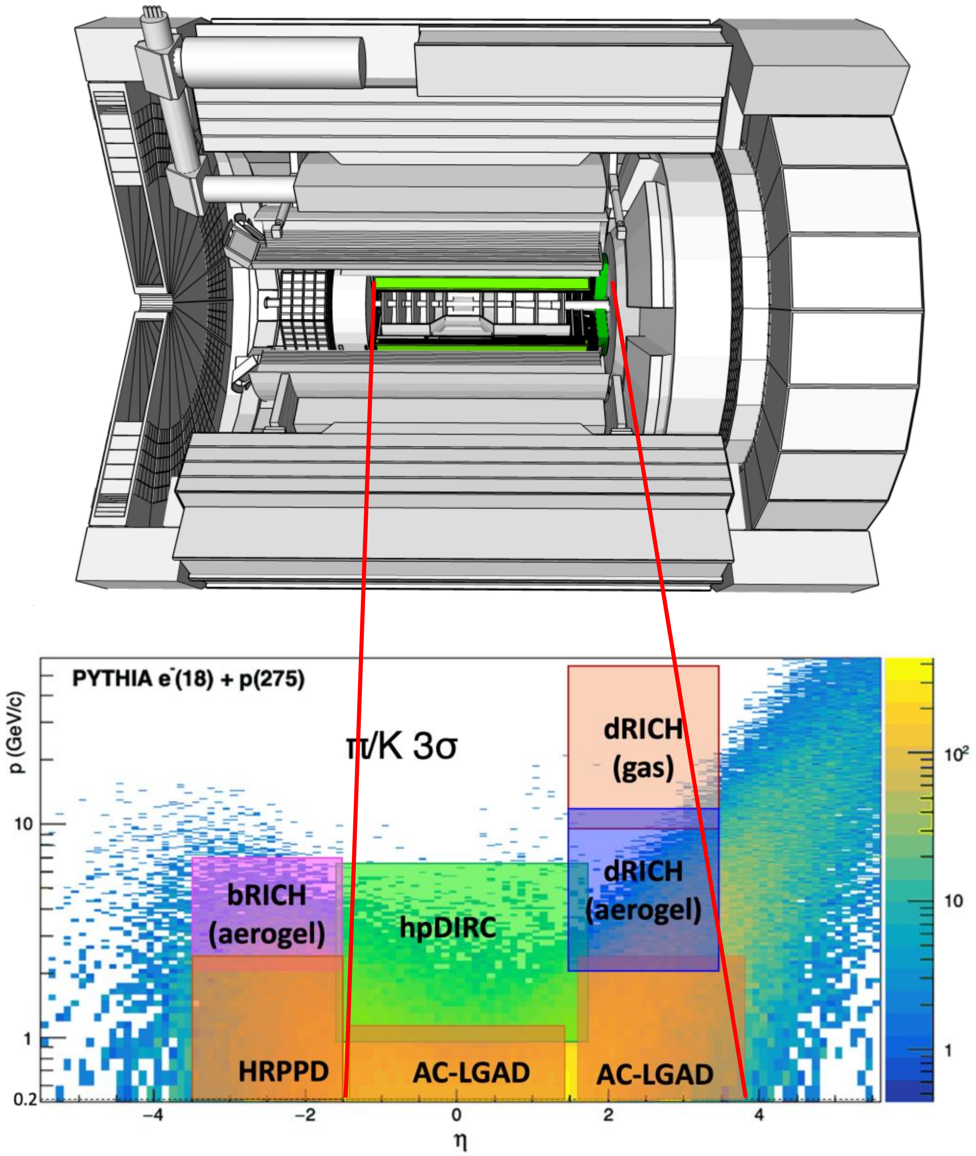


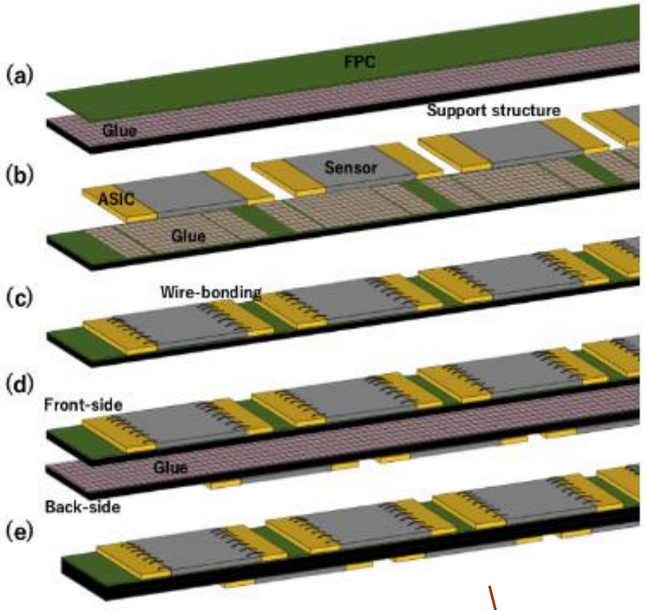
- **A barrel and end-cap TOF layer in ePIC based on AC-LGAD**
  - 500 um x 1 cm strip, ~1-2% X0 for **barrel** (3.2x2.2 cm sensor size)
  - 500 x 500 um pixel, 8% X0 for **end-cap** (1.6x1.6 cm sensor size)
  - 25-35 ps single hit time resolution (end-cap/barrel), ~30 µm spatial resolution
- **Particle identification with time of flight (TOF)**
  - For e/π/K/p at low/intermediate momentum

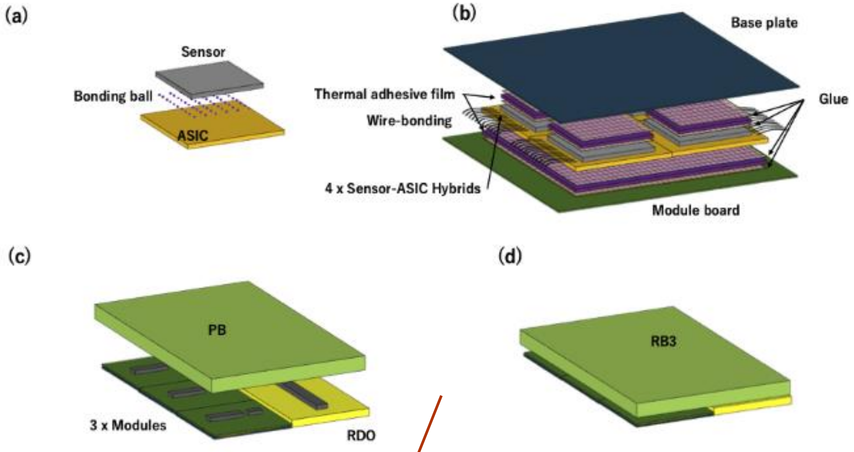


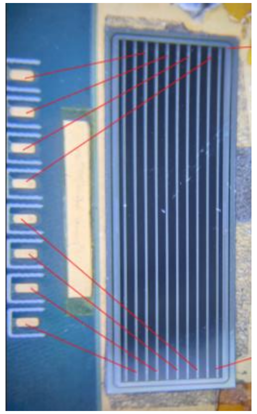
- Studies done in the context of AC-LGAD development for ePIC TOF

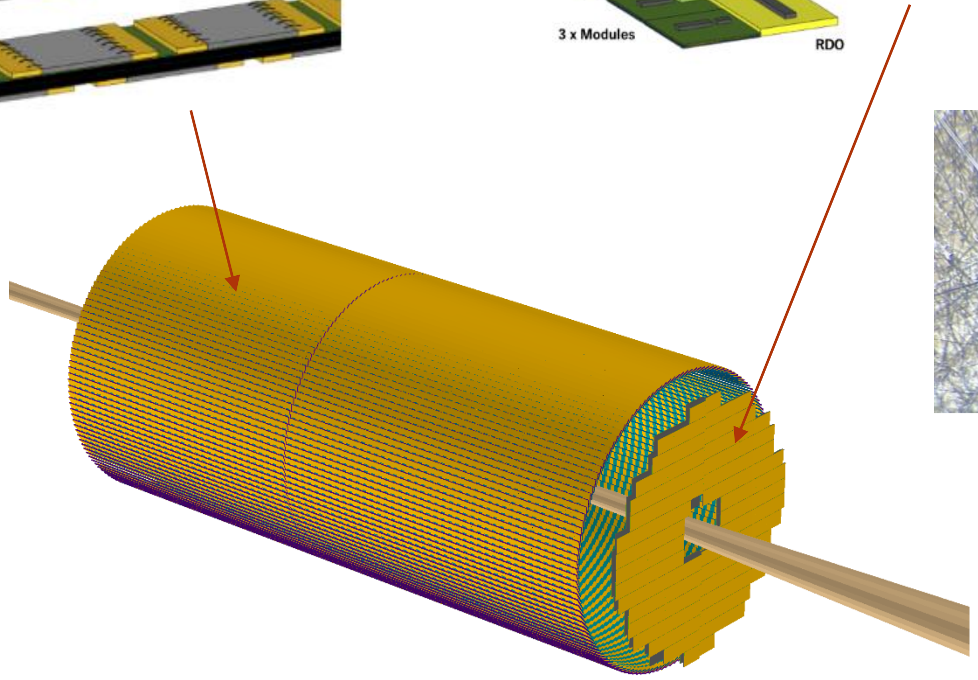
AC-LGAD TOF layout

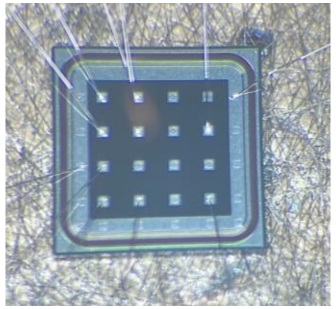








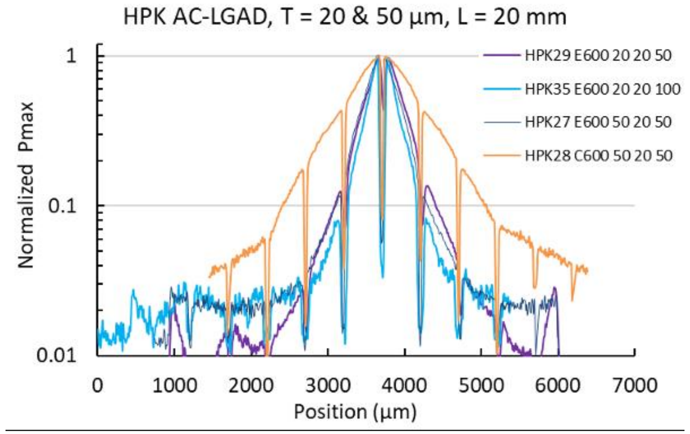


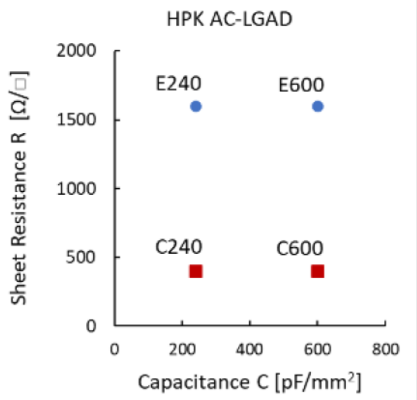


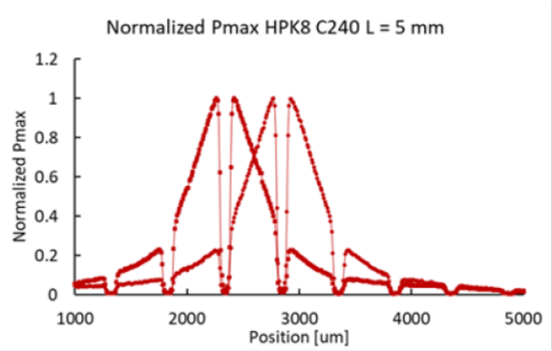
Previous studies

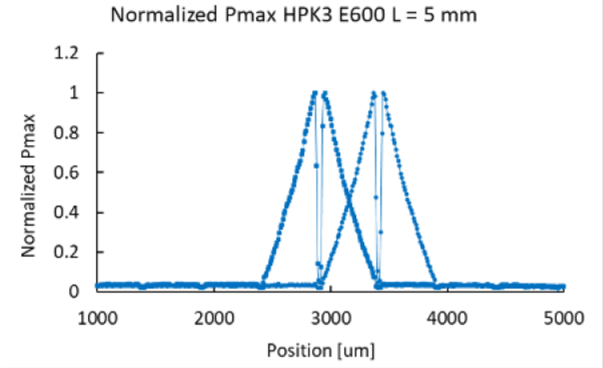
- Previous results from 2023 HPK production shown in these papers
  - https://doi.org/10.1016/j.nima.2024.169478
  - https://arxiv.org/abs/2407.09928 (FNAL test beam)

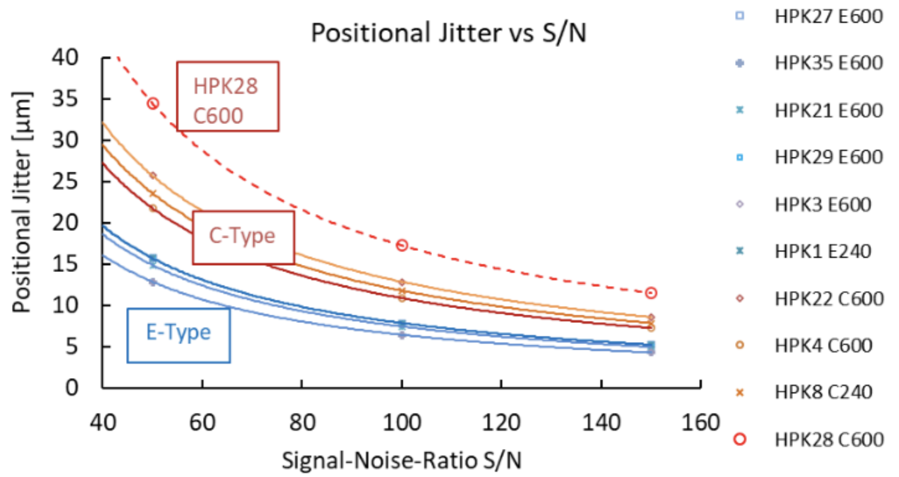
- Conclusions:
  - Type E strips (more resistive) perform much better, oxide thickness has less impact but thinner is better.
  - Large strip length degrades both signal (rise time, Pmax) and has worse charge sharing. 1cm length was selected.
  - Pixel detector needs to have large pitch and small pixel size or position resolution is bad under metal, however this degrades S/N in between pixels. Cross metal design is under investigation.
  - Both pixel and strips have the required time resolution but current pixel design has shortfall in position resolution under metal









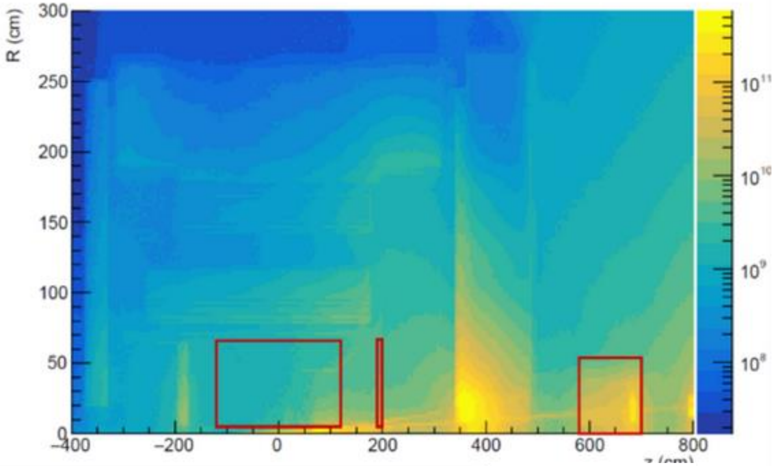


Radiation levels at ePIC

- **Radiation hardness of LGADs has been studied and optimized extensively for the HL-LHC timing end cap upgrades in ATLAS and CMS**
  - Focus on acceptor removal, gain layer doping deactivation
  - Relatively large-pad, conventional (DC-coupled) LGADs

- At the EIC: radiation levels will be much lower than at the LHC: under certain assumptions, sensors should receive < 5e12 cm^{-2} over their lifetime
- However, ePIC will feature AC-LGADs with resistive n^+ layer, which may be susceptible to radiation damage by changes in the n^+ electrode and the coupling dielectric

- HPK (and BNL) sensors were irradiated with reactor neutrons at JSI/Ljubljana and at FNAL ITA (just received)
  - Focus on E type and 50 µm thickness for strips – include 0.5, 1, 2 cm lengths
  - Focus on 150 µm pad size – include more wafers
- Total fluences between 1e12 and 1e15 Neq – some much higher than envisioned at the EIC over the full time of life, but better to have more margin, also taking into account the different doses especially in the forward high-η region



RAW fluence			
System	Average	Min	Max
Barrel	5.4×10^{10}	3.4×10^{10}	5.9×10^{11}
End-cap	1.3×10^{11}	5.1×10^{10}	1.6×10^{12}
B0 trackers	3.9×10^{11}	3.3×10^{10}	1.8×10^{12}
NEQ fluence			
System	Average	Min	Max
Barrel	3.6×10^{10}	1.1×10^{10}	1.3×10^{12}
End-cap	1.2×10^{11}	3.2×10^{10}	8.4×10^{11}
B0 trackers	4.5×10^{11}	2.7×10^{10}	4.2×10^{12}

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

Fluence	V(GL)					
	W2	W4	W5	W8	W9	W11
Thickness	**50 µm**	50 µm	**50 µm**	50 µm	**20 µm**	20 µm
Capacitance	**240**	240	**600**	600	**600**	600
N+ resistivity	**2**	0.5	**2**	0.5	**2**	0.5
1.00E+12	54.5	52	54.5	52	53	
1.00E+13	54.5	51.5	54	51.5	53	
1.00E+14	51	50	51.5	49	50	
5.00E+14	41		42.5		41	38.5
1.00E+15	32				34	31

Pixels

Strips W2

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

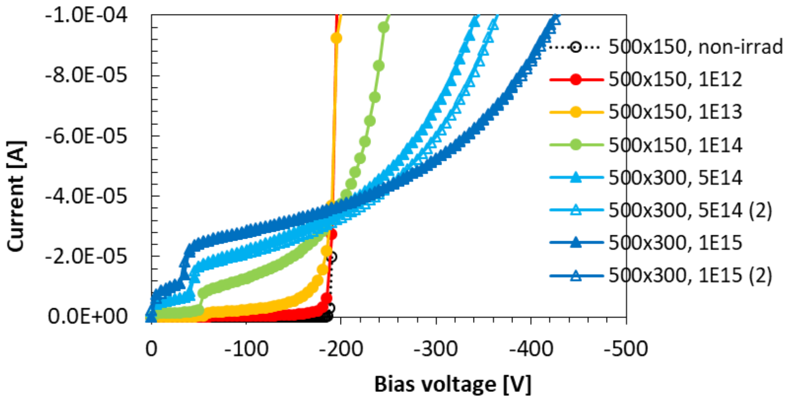
Strips W5

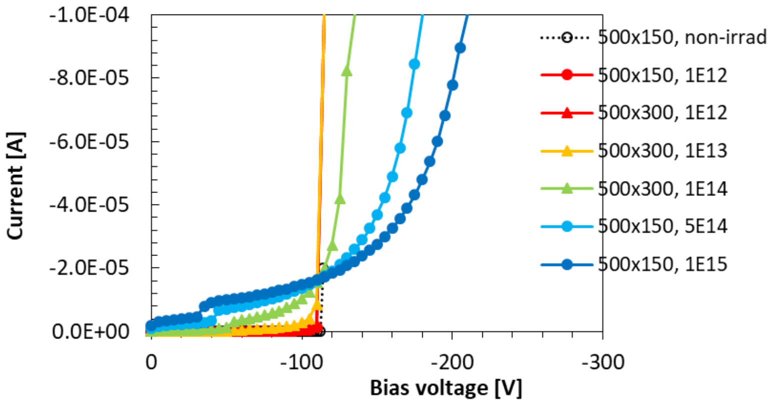
Fluence	0.5 cm	1 cm	2 cm
1.00E+12	54	54	
1.00E+13	42		54
1.00E+14		52	53

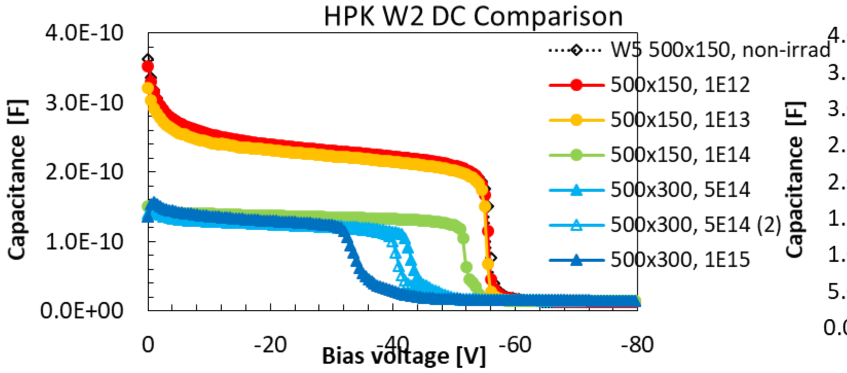
Pixels

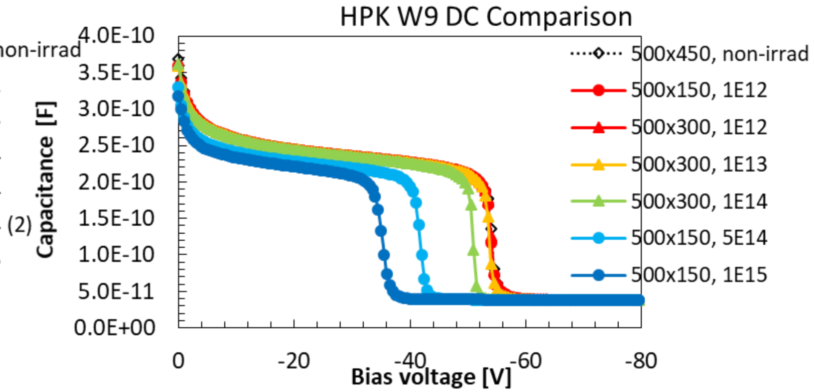
- Up to 1e13 Neq, no significant change in sensor properties
  - Shift in gain layer depletion voltage is recognizable even in IV measurement
  - Leakage current scales with bulk volume: 50 µm thick sensor has higher leakage currents and more prominent ‘step’ at gain layer depletion
- Breakdown voltage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

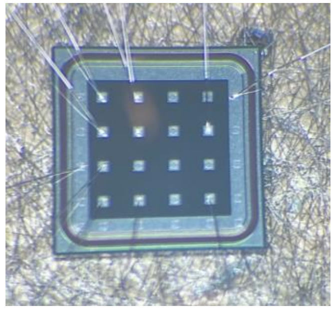
- Up to 1e13 Neq, no significant change in gain layer depletion voltage = gain layer active doping concentration
  - Shift in gain layer depletion voltage with fluence is very clear
- Behavior across wafers is consistent
  - Note higher full depletion capacitance for thinner sensor
  - More trapping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

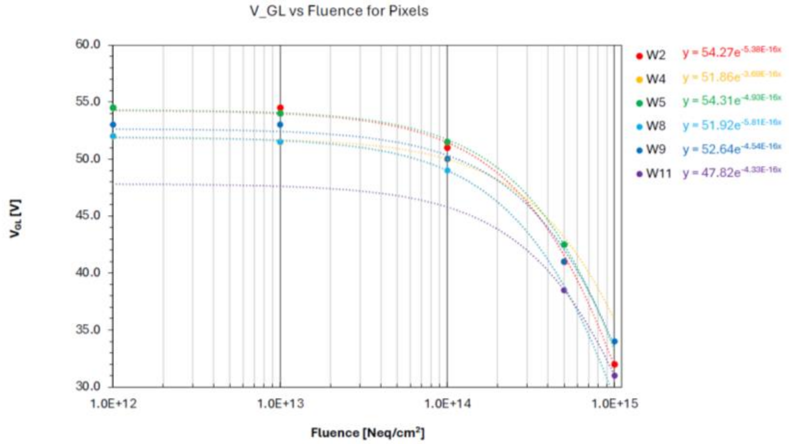












Formula for Fit: $N_D = N_0 e^{-c\Phi}$

c factors:

W2: $5.38 \cdot 10^{-16}$

W4: $3.69 \cdot 10^{-16}$

W5: $4.93 \cdot 10^{-16}$

W8: $5.81 \cdot 10^{-16}$

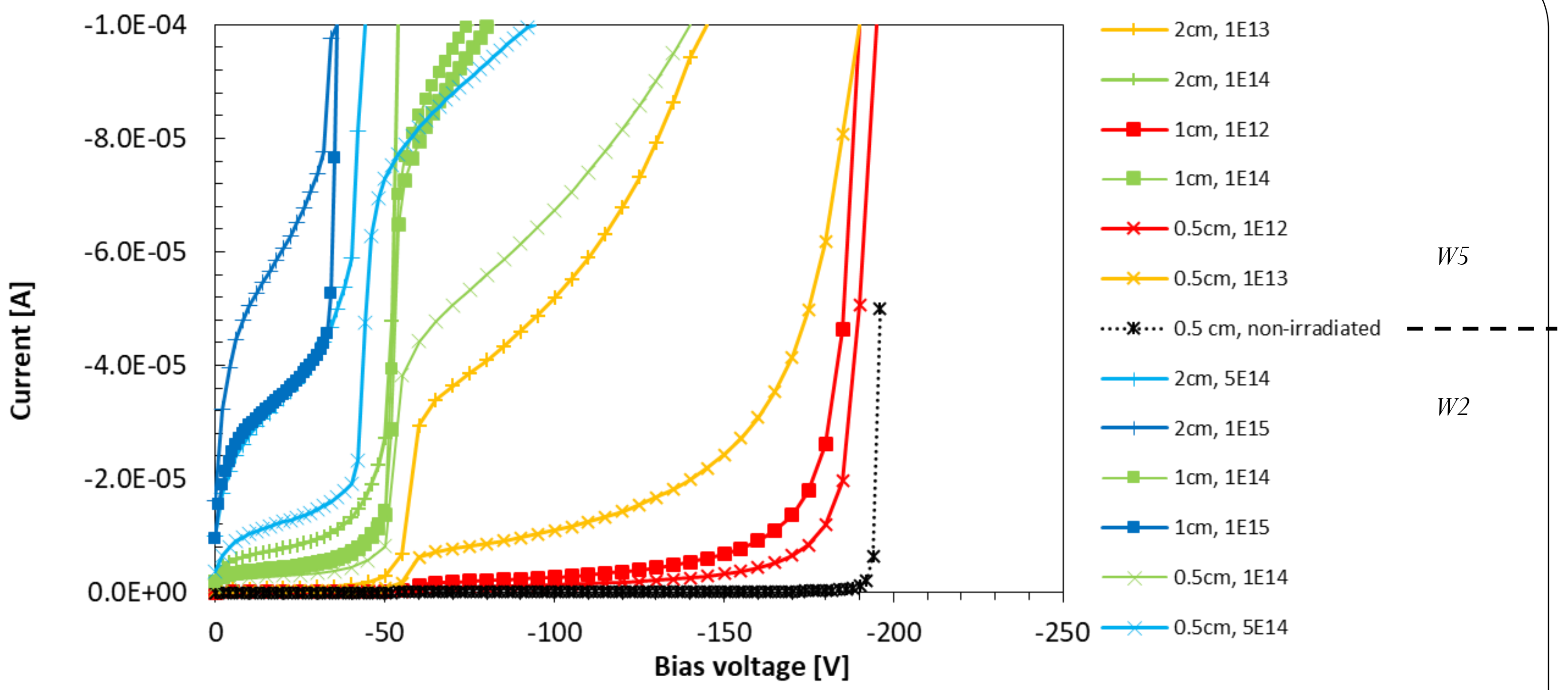
W9: $4.54 \cdot 10^{-16}$

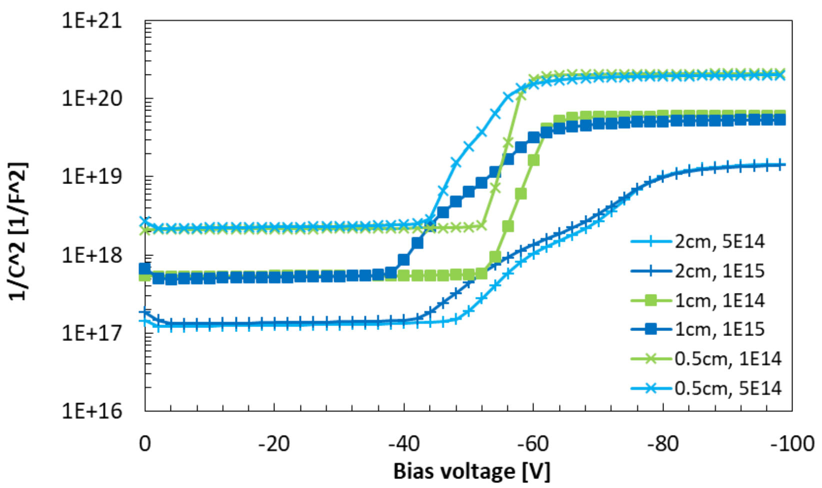
W11: $4.33 \cdot 10^{-16}$

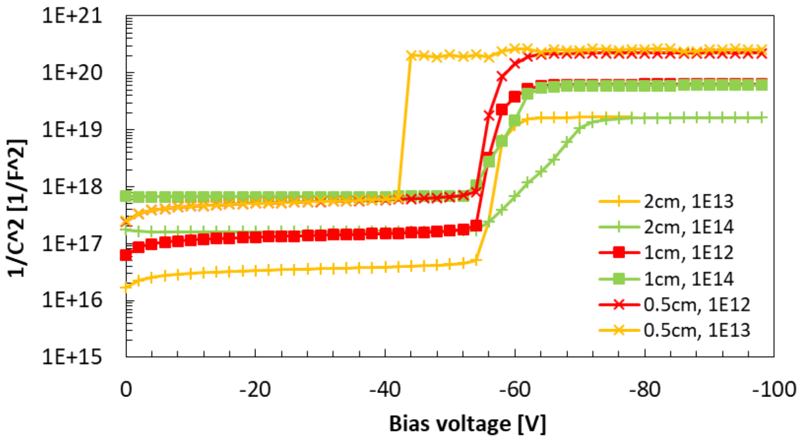
Strips

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

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

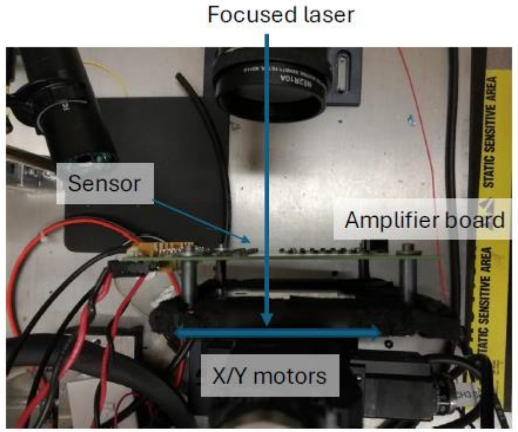


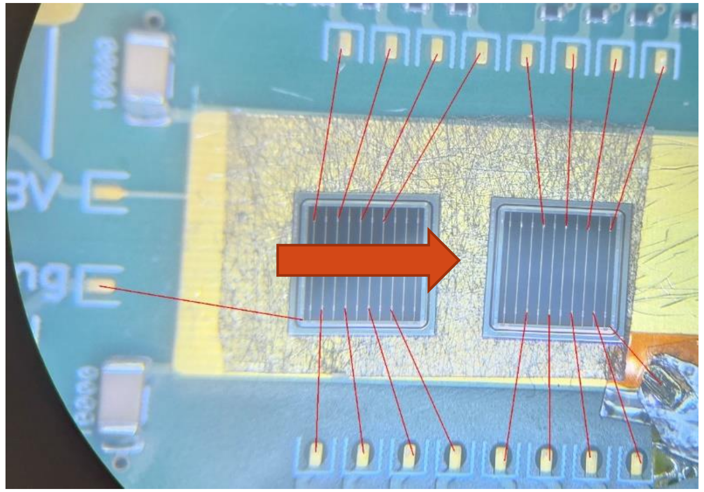


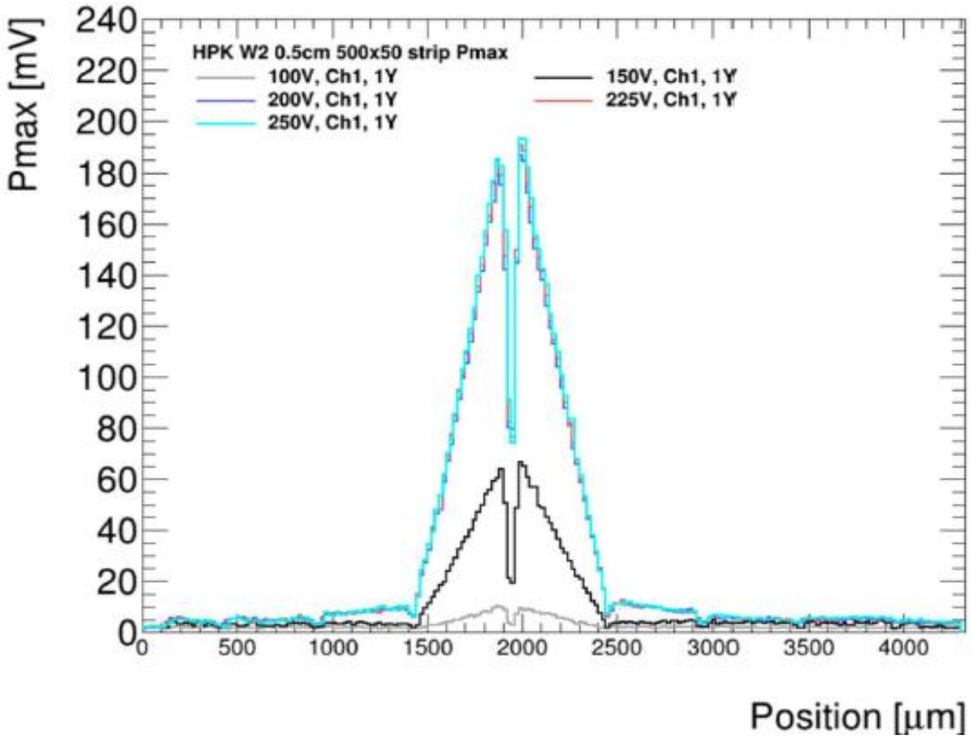


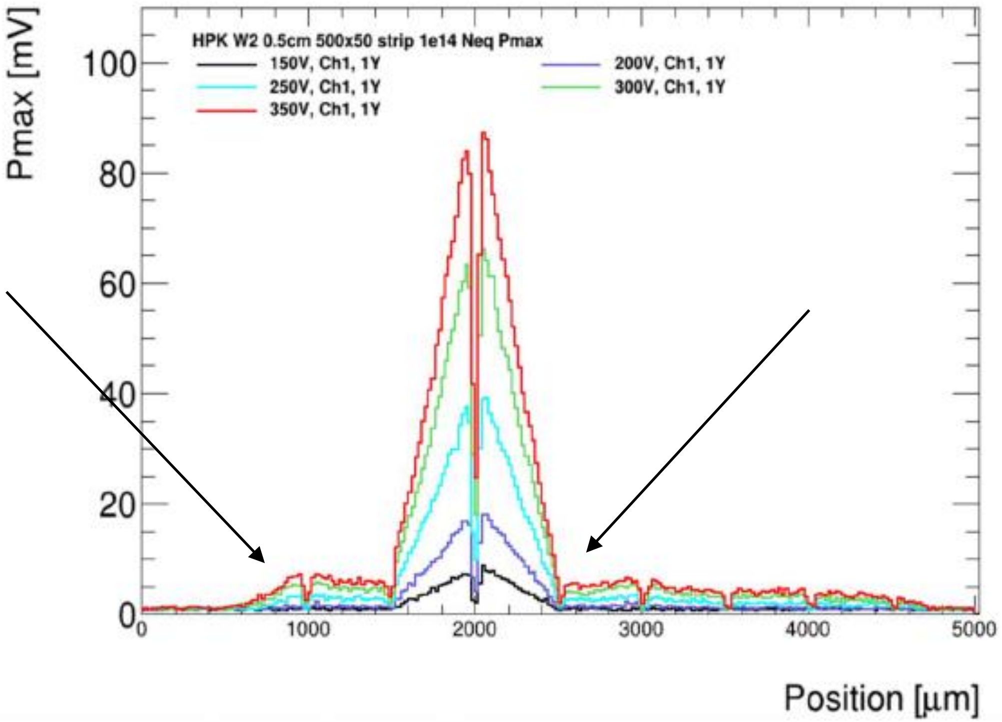
Strip laser studies

- Using laser TCT setup with cooling plate and FNAL 16ch board
- W2 0.5 cm strip, non-irradiated sensor and irradiated to 1e14 n/cm2
  - Cooling with chiller to ~10 C
  - Irradiated sensor was biased to higher voltages
- Pmax profile of the main strip is very similar, but increases beyond the first neighboring strip and at longer distances
- Indicating higher conductivity of the n+ layer and/or radiation damage to dielectric



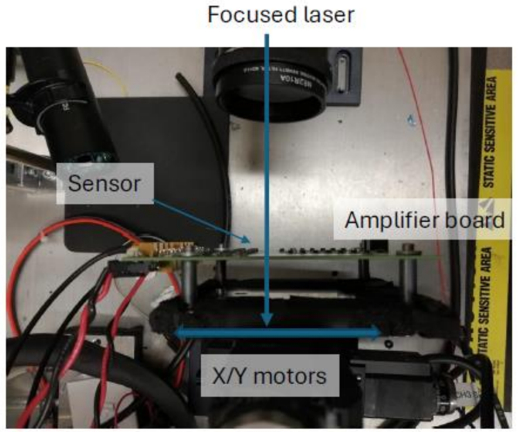


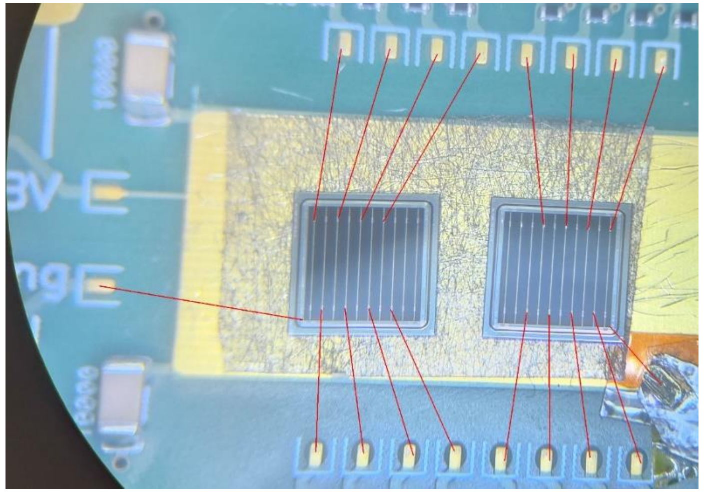


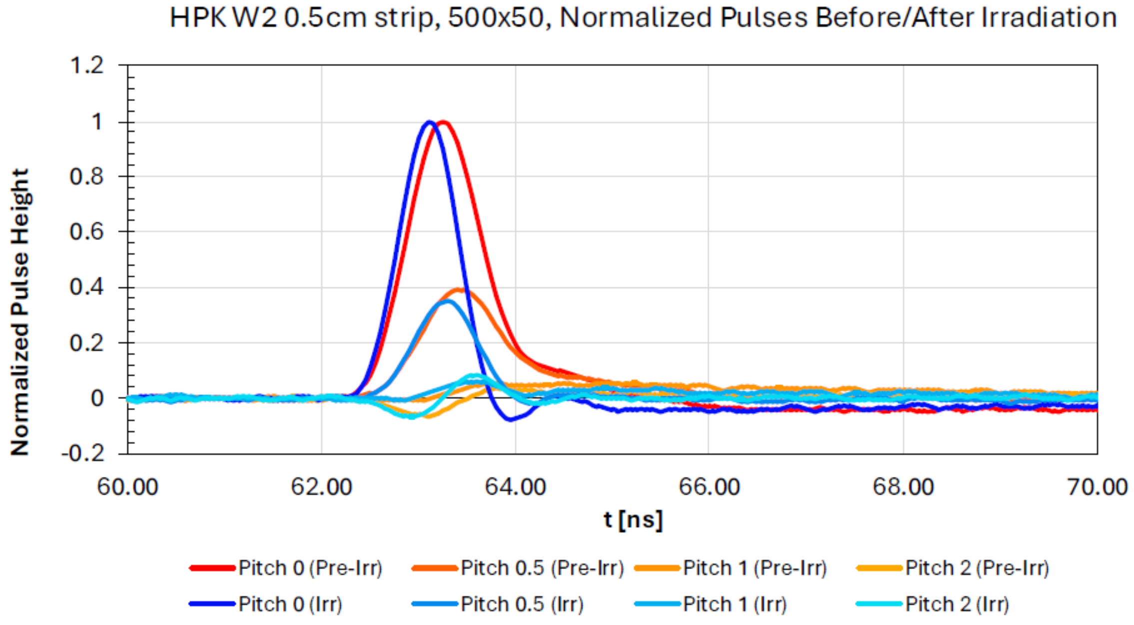


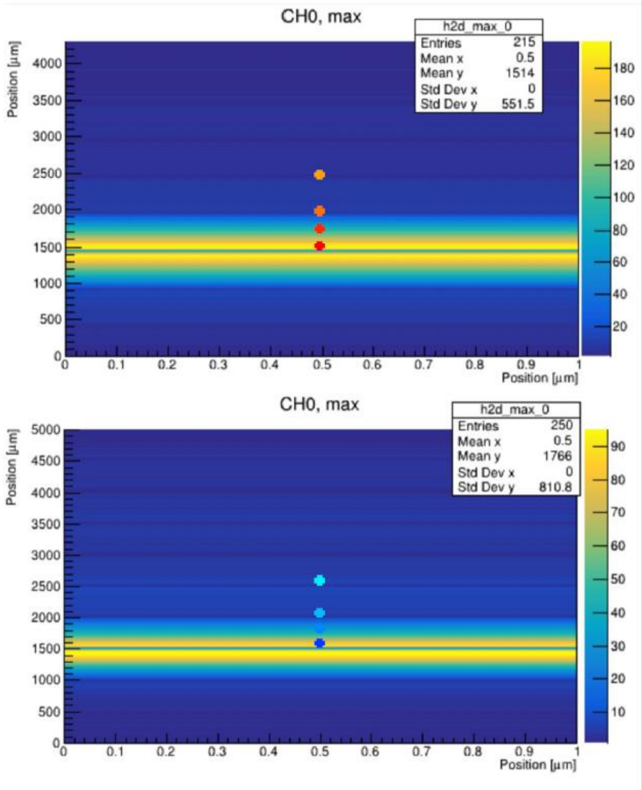
Strip laser studies

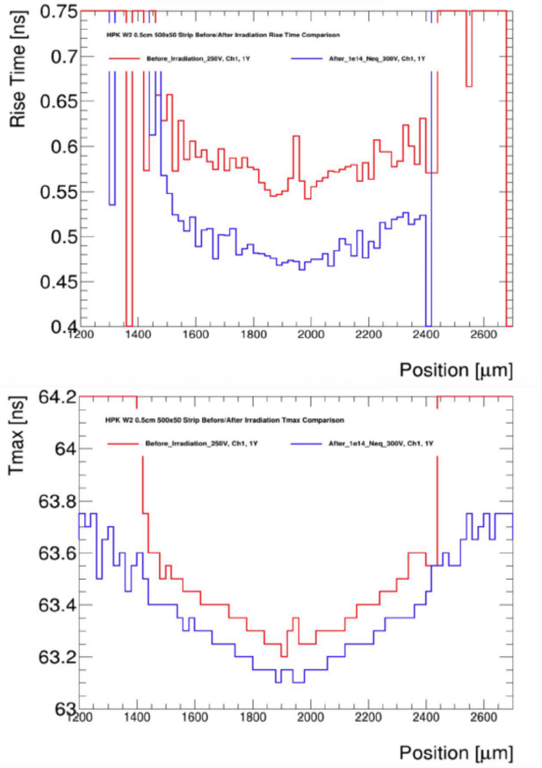
- Higher leakage current, higher breakdown voltage, **lower gain** in irradiated sensors at 1e14 n/cm^2
- **Faster rise time and shorter pulse in irradiated sensor**
  - More distinct rise and fall as opposed to 'tail' after main pulse





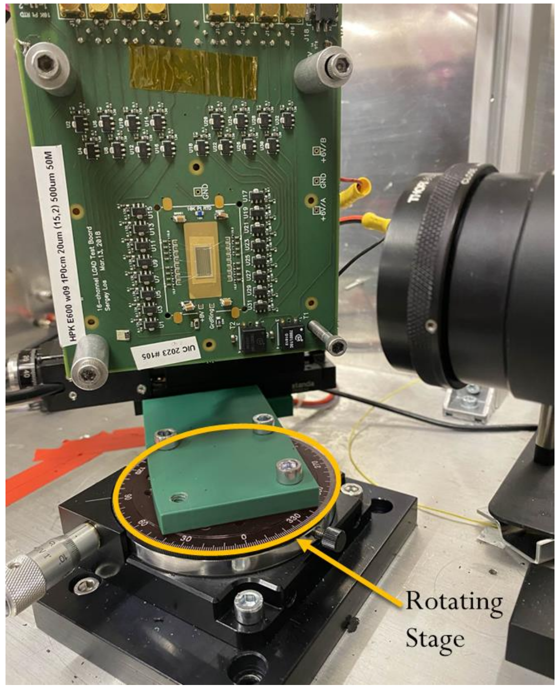


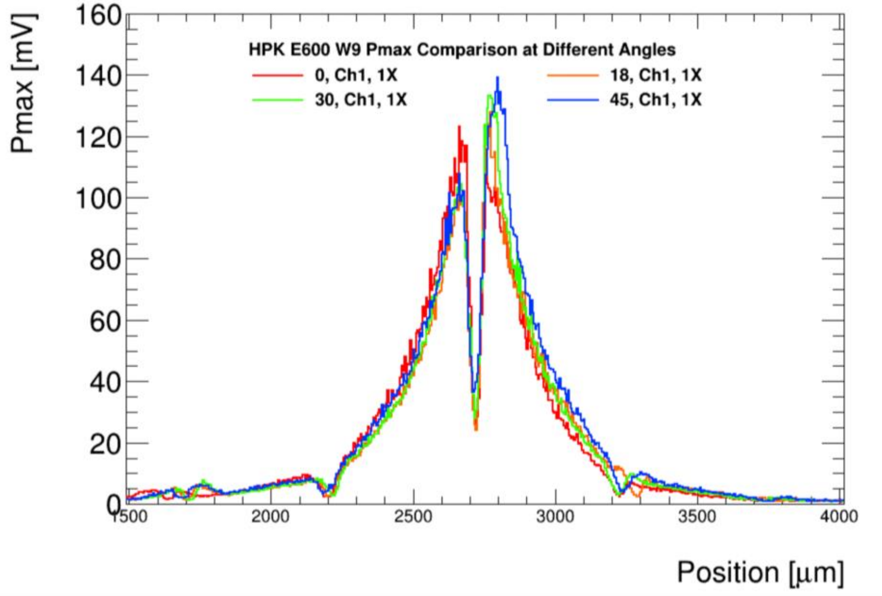


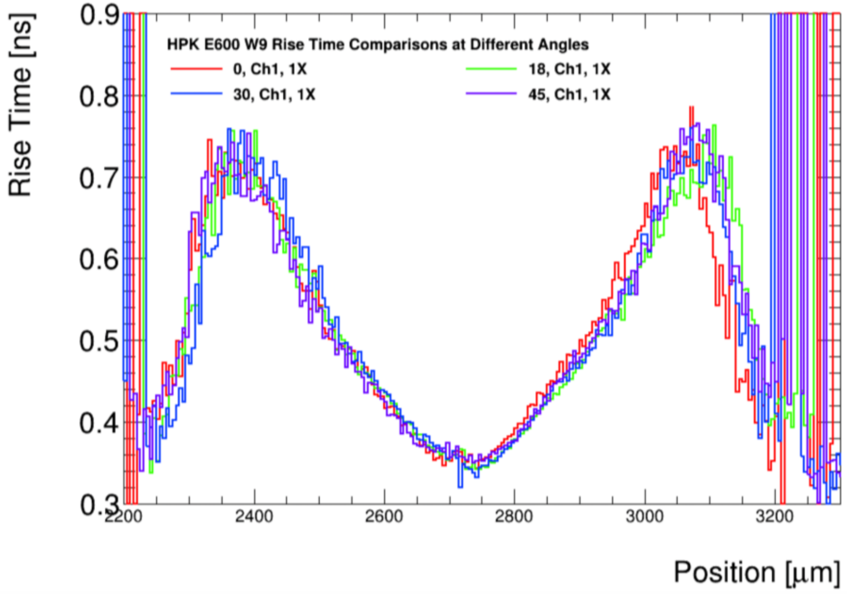


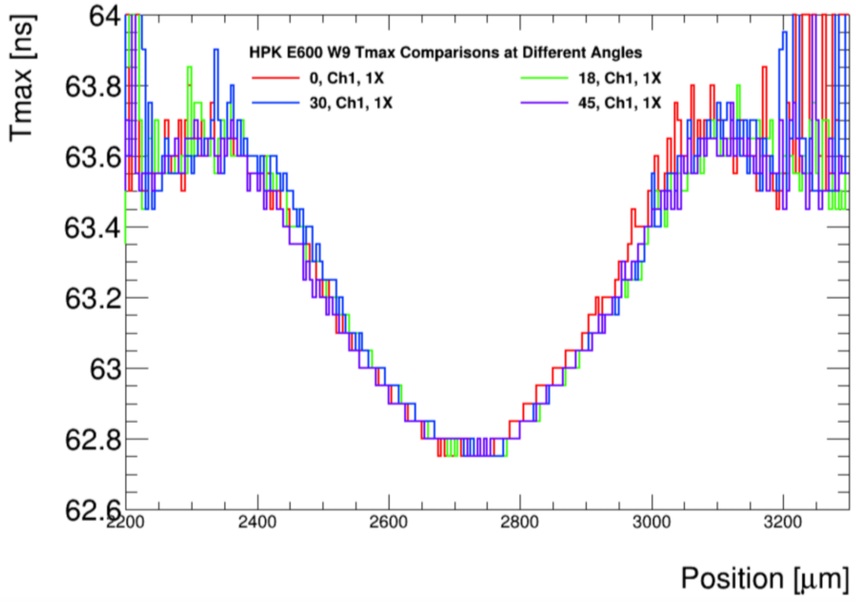
Angled charge injection

- 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





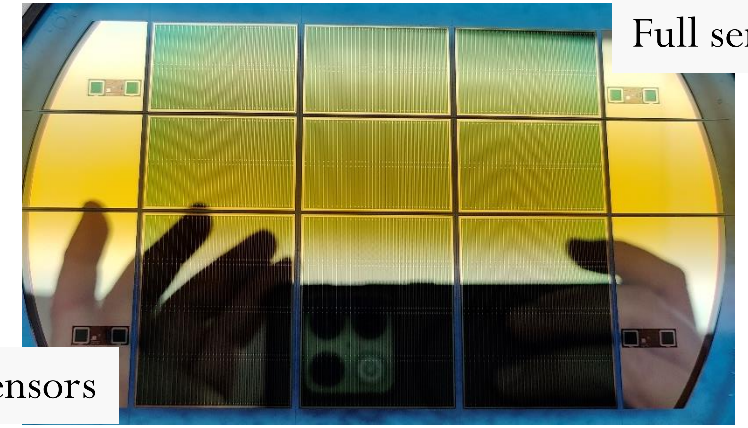




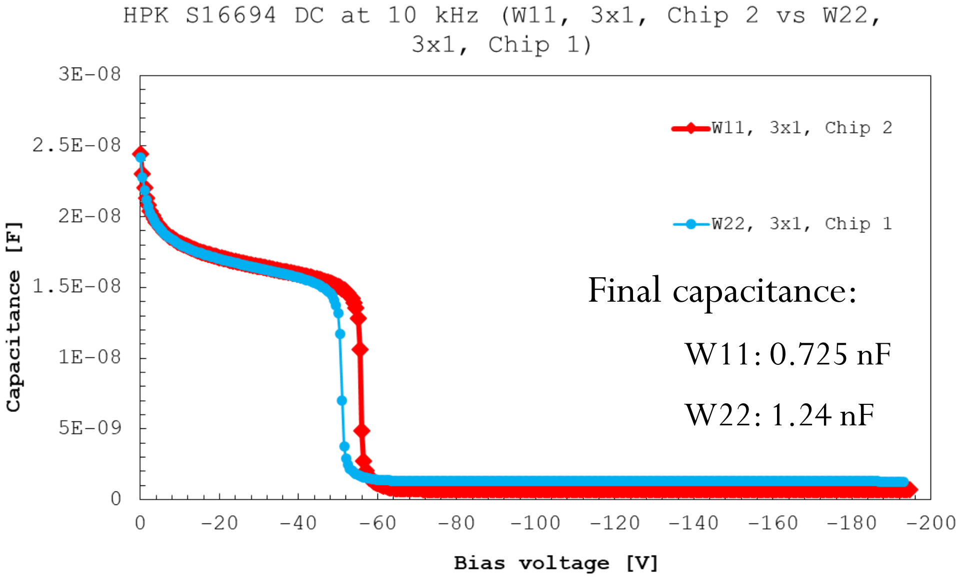
New HPK production

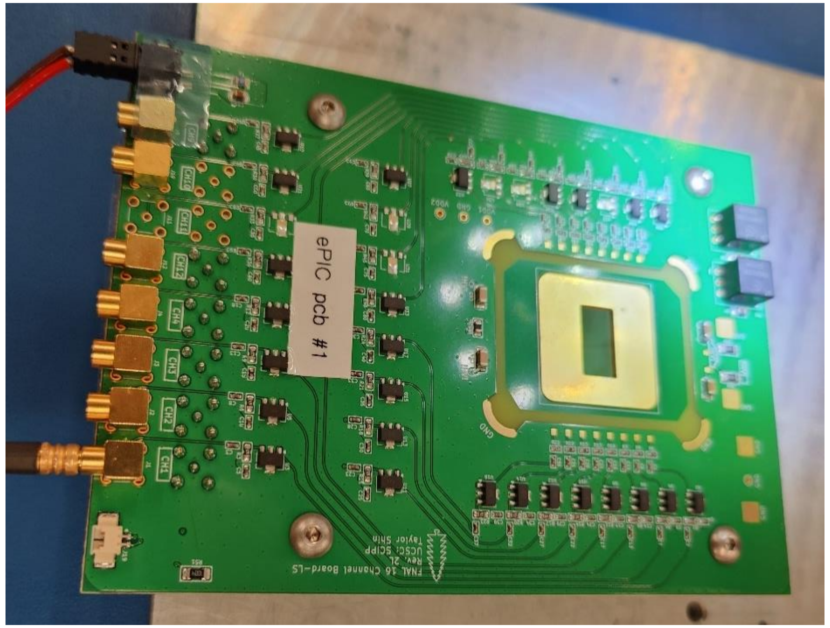
- Received first ePIC full-size production of strip AC-LGADs from HPK with devices up to 3.2x4 cm
  - Nominal size 3.2x2.2 cm with 1cm strip ‘segments’
- Produced a new 16ch board that can house larger sensors
- For now 2 wafers in hand (8 total), one 50um thick (W11) and one 30um thick (W22)
  - Yield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

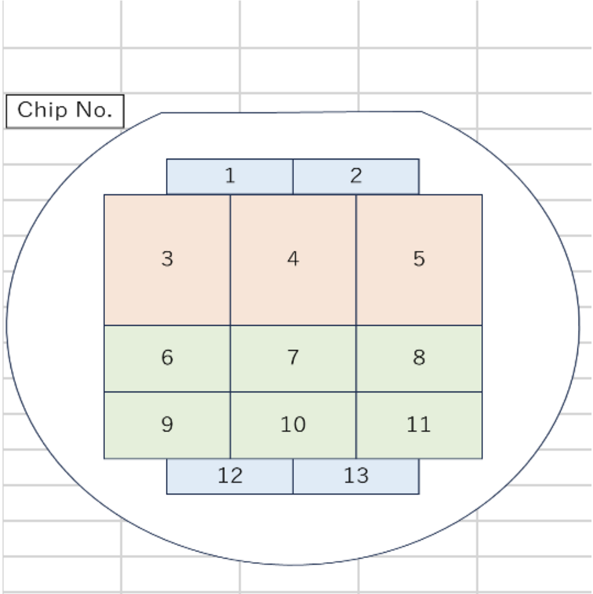

Half sensors


Full sensors

Double sensors



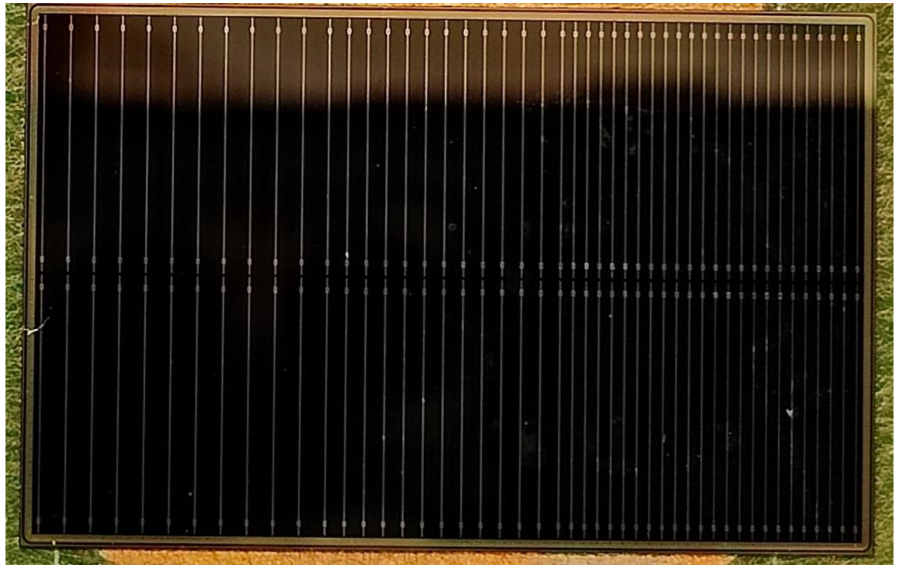


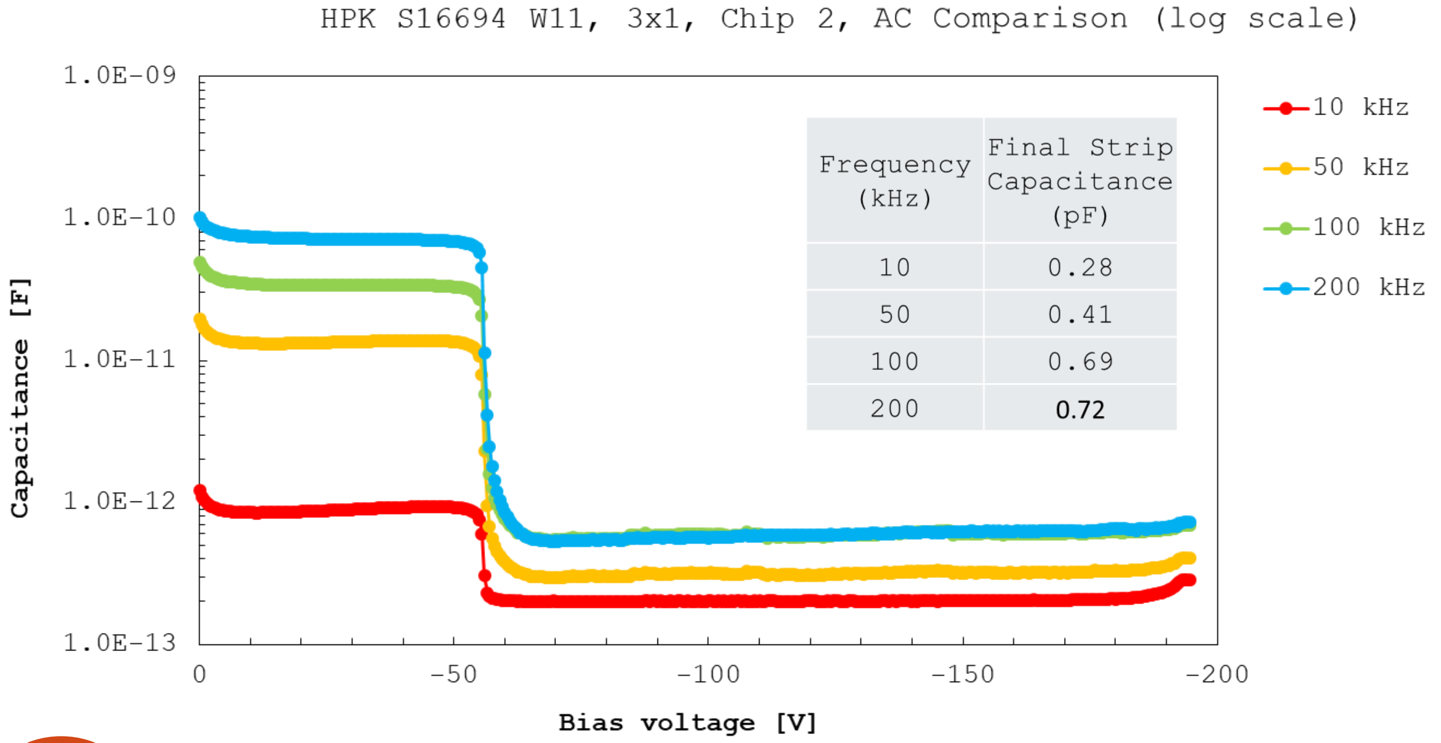


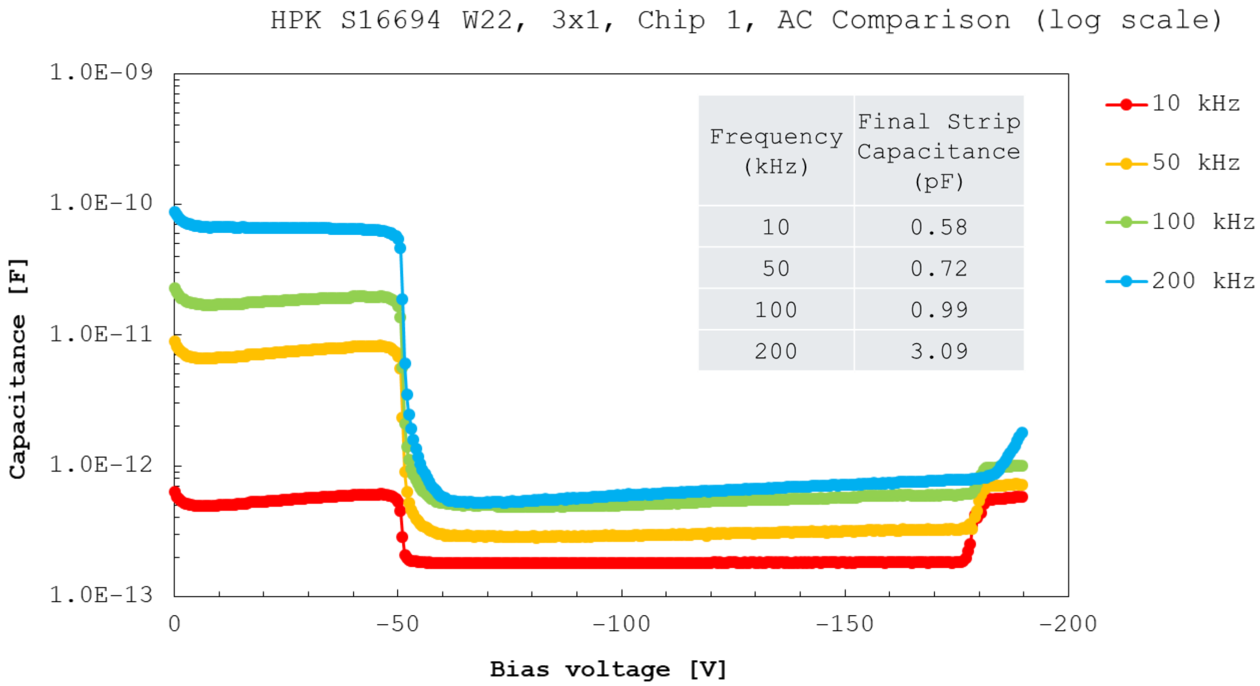
New HPK production

- 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, which seems suspiciously low, studies ongoing
- Laser TCT studies using new board are ongoing

Full sensors

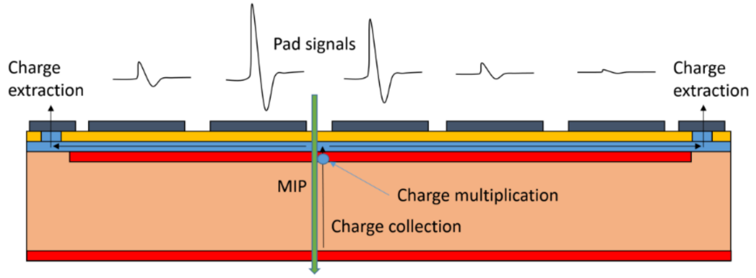


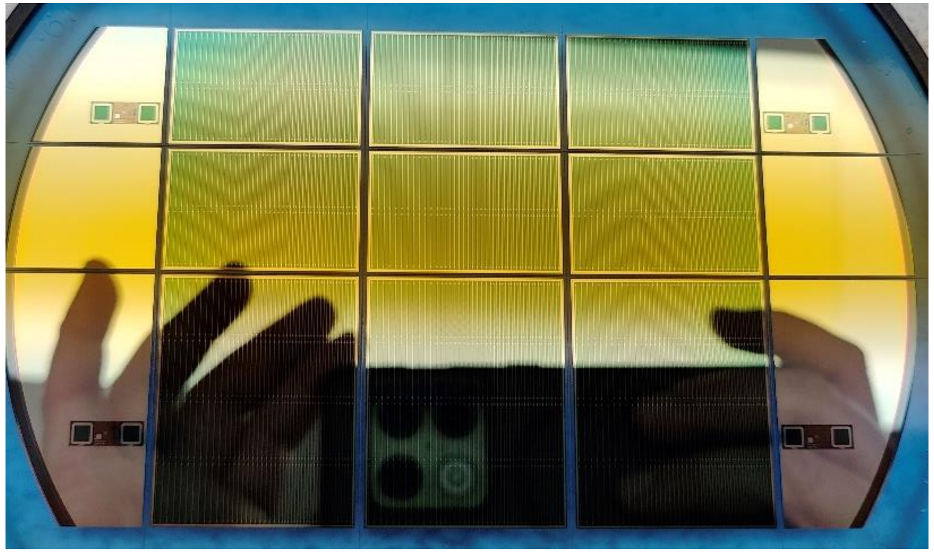




Conclusions

- Ongoing development of AC-LGADs for the ePIC TOF layers
  - Both strips and pixel AC-LGADs will be used in the detector
- First production showed the importance of N+ resistivity, especially for strip geometry
  - 500um pitch 50um width strip are adequate for ePIC requirements
  - Tested pixels with 500um pitch and 150um width have shortfall in position resolution under metal (need design update), new geometries are expected in the new production
- Tested neutron irradiated AC-LGADs (proton irradiated just received)
  - No unforeseen effects in breakdown of gain layer degradation
  - Strange secondary effects seen in charge sharing profile already at 1E14Neq
- Tested sensors with angled charge injection
  - Effects are small with the tested geometries
- Received first large-scale AC-LGAD production from HPK, testing is ongoing





Thanks for the attention

Many thanks to the SCIPP group students and technicians!

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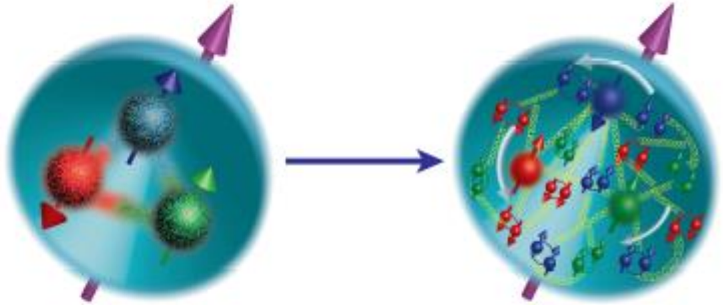
Backup

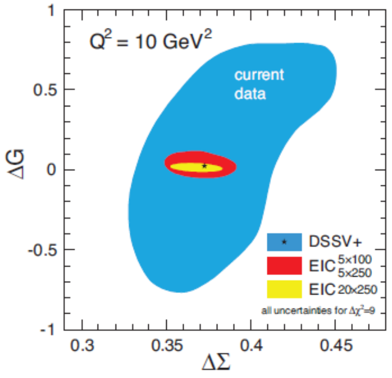
Electron-Ion collider

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

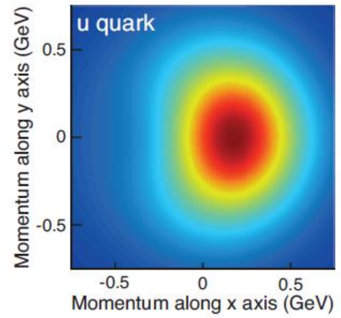


ePIC will provide key measurements:

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

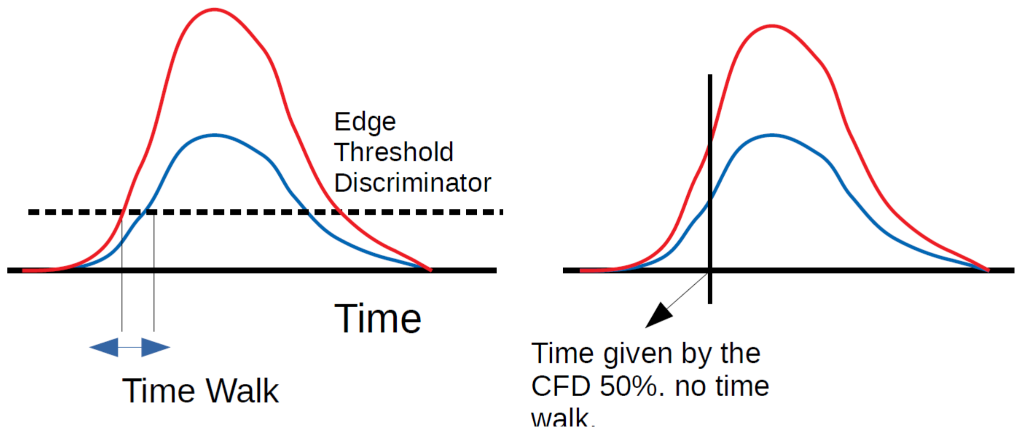


Gluon helicity contribution vs quark helicity contribution

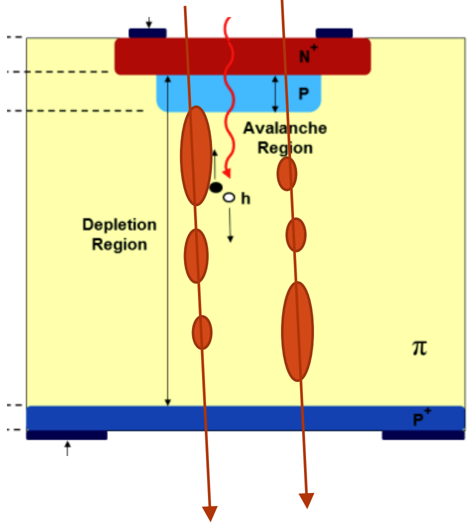


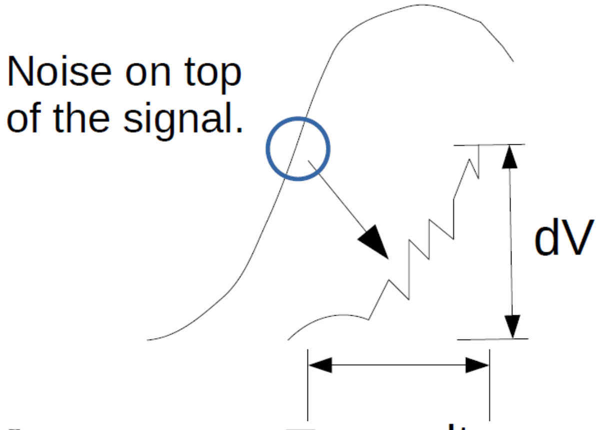
X-Y u quark motion
For proton traveling in Z

Time resolution



Landau variations





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

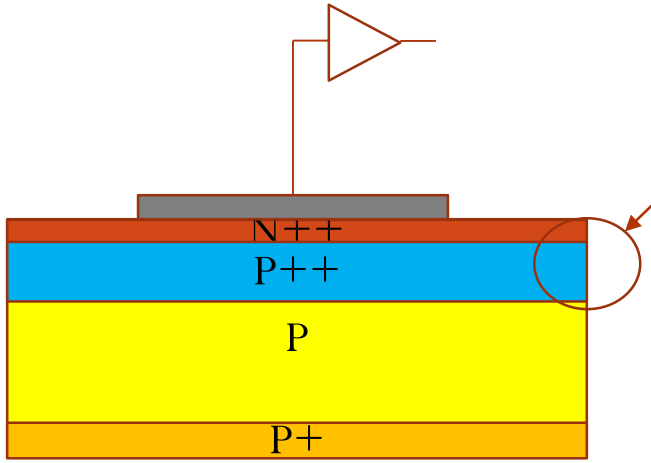
Sensor time resolution main terms

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

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

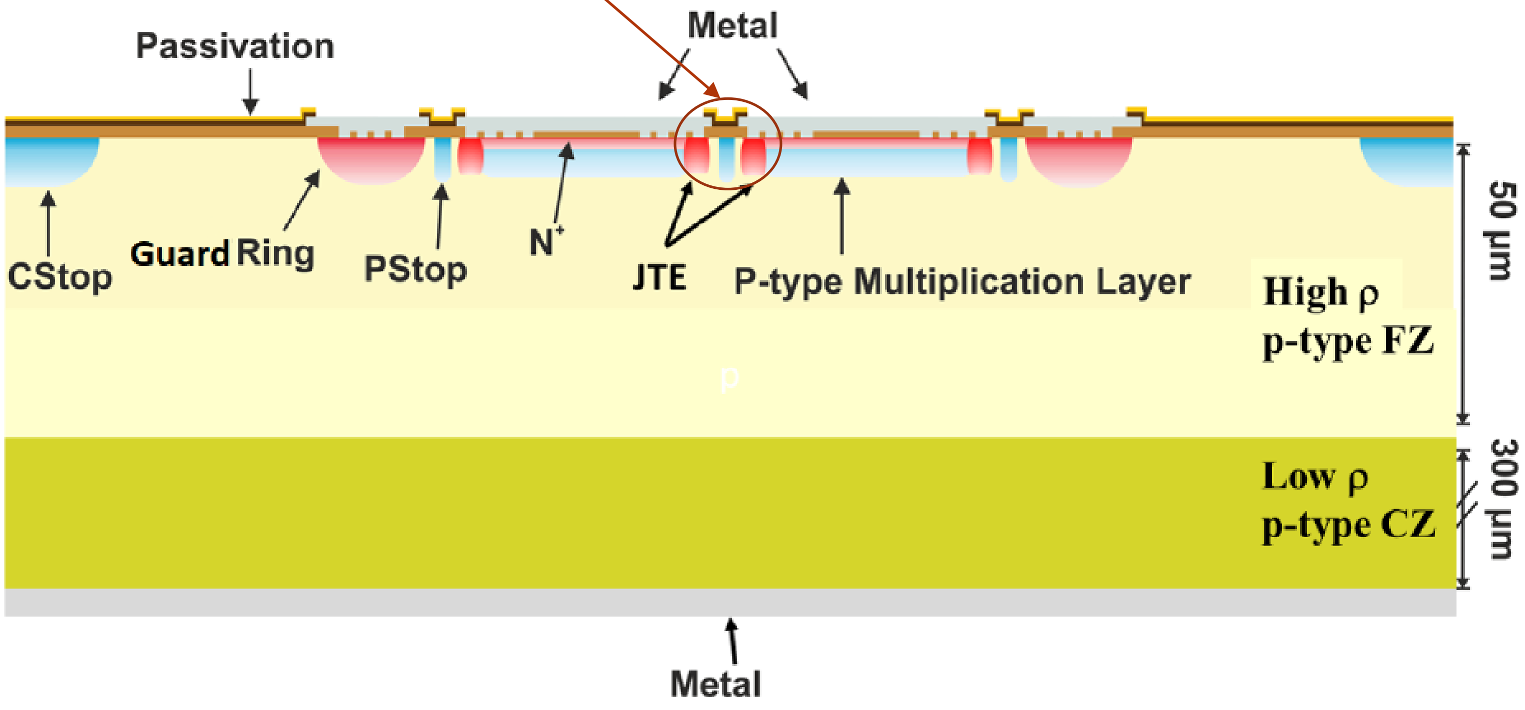
- **Bottom line: thin detectors with high S/N**

LGAD arrays structure



Very high field area, induces early breakdown

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



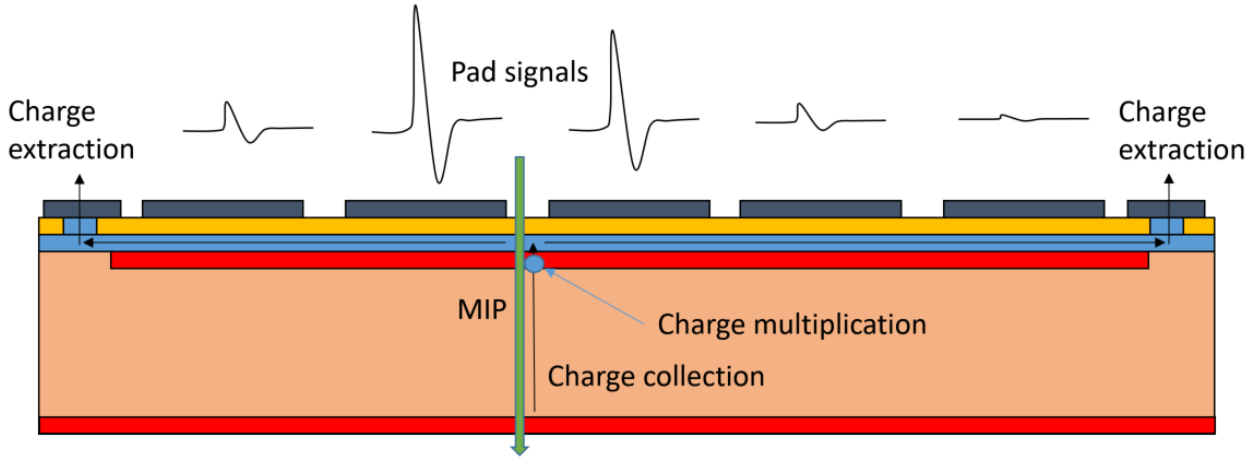
- Protection structures limit the current granularity of LGADs
- ~100 um pixel size would mean ~50% active area
- But intensive R&D is ongoing to overcome this limitation

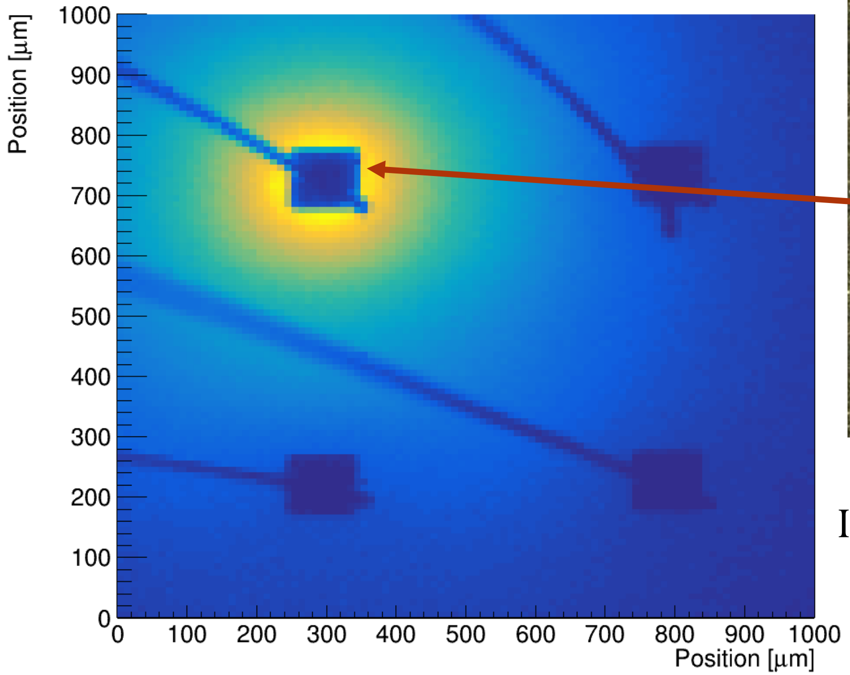
AC-LGAD hit reconstruction

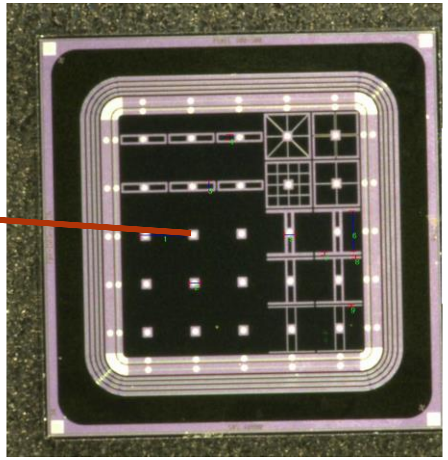
References:
https://indico.physics.lbl.gov/event/1262/
https://indico.cern.ch/event/918298/contributions/3880516/
https://arxiv.org/abs/2006.01999

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

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



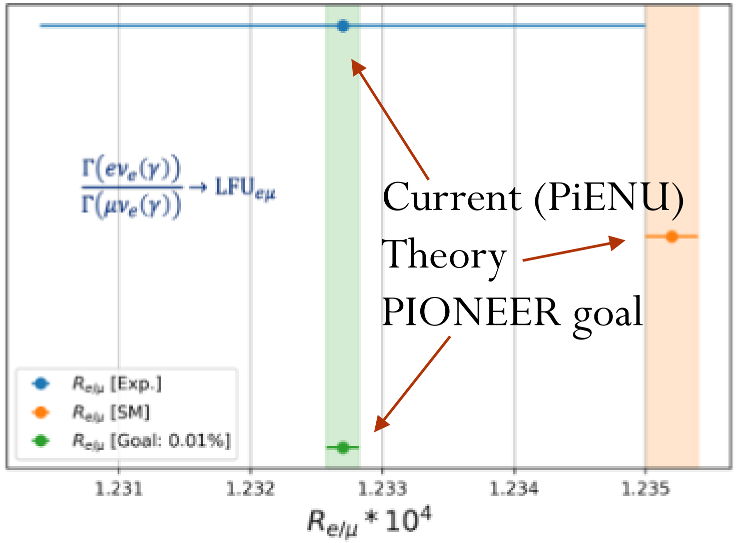


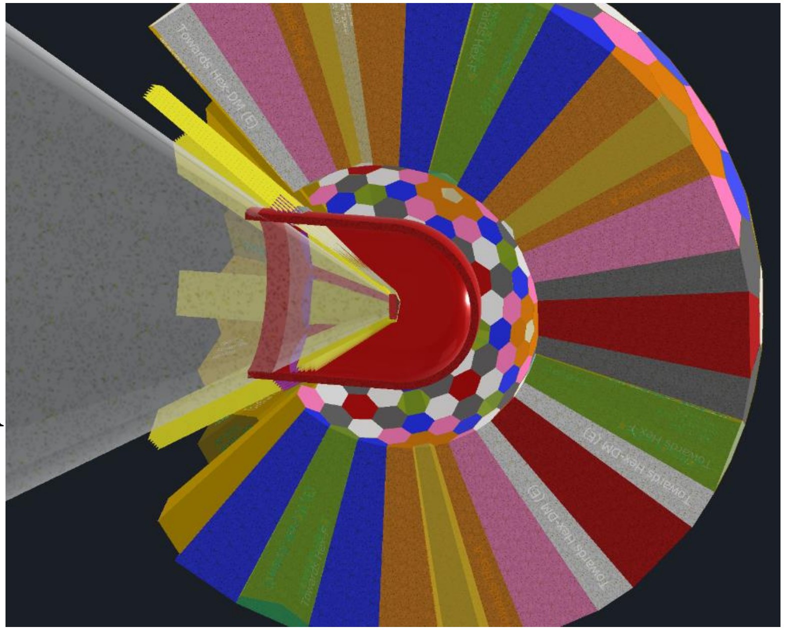


IR laser scan of the device

PIONEER – a 5D tracking application

- **PIONEER** is a next generation rare Pion decay experiment at PSI
  - Phase I: improve measurement of **charged lepton flavor universality $R_{e/\mu}$ by an order of magnitude**, reaching SM calculation precision
  - Phase II/III: **precise measurement of Pion beta decay BF**. Important to test CKM unitarity (clean Vud measurement)
- **In the last year the PIONEER collaboration was officially formed and we're now seeking major funding (U.S. and internationally)**
- Three main detectors: Active Target (ATAR), Calorimeter (LXe or LYSO) with 1-2% energy resolution, Low mass tracker (μ-RGROVE) in between
- **The ATAR is a 2x2 cm wide, 6 mm thick silicon tracker with high granularity in (X/Y/Z) and high position/energy/time resolution**
- **Goal: separation of energy spectra of π→eν and π→μν→eννν**
  - A fraction of events cannot be separated by the energy measurement in the Calorimeter because of the tail overlap
  - **ATAR is crucial to recognize these decay chains**





https://arxiv.org/abs/2203.01981

A high granularity active target for the PIONEER experiment https://pos.sissa.it/420/