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Updates on charge sharing and radiation hardness of AC-LGADs for near-future Higgs factories and nuclear physics experiments

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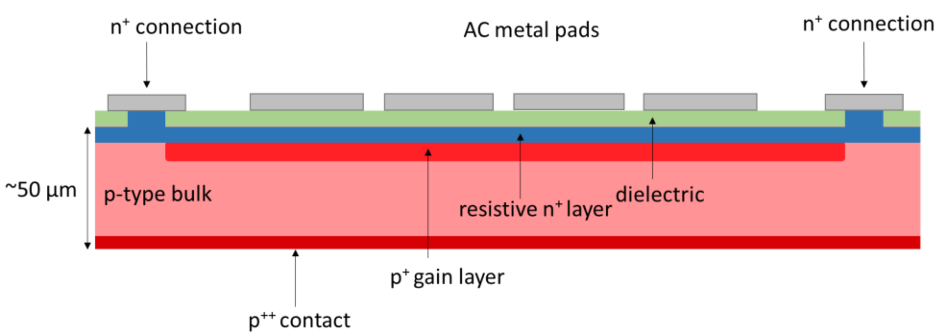
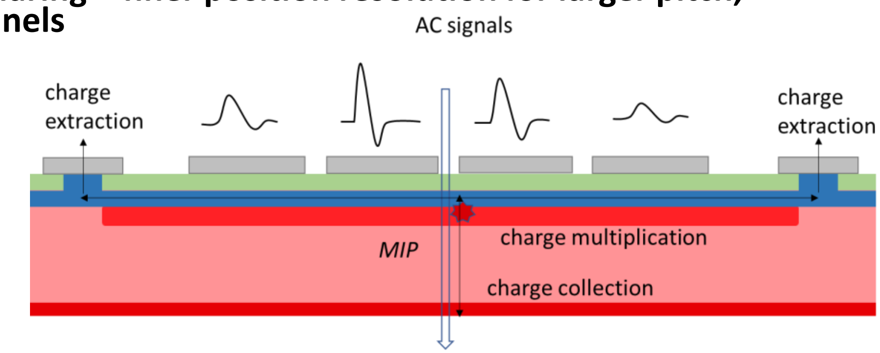
AC-coupled LGADs

- Low to moderate gain (5-50) provided by p^+ multiplication layer
- Thin active volume to reduce charge drift time and Landau fluctuations of energy deposition, typical thickness 50 µm or less – provided on top of low-resistivity support wafer of 200-500 µm

- 'Resistive Silicon Detectors' (RSD): more resistive front side n^+ implant than in standard Si sensors
- Continuous dielectric, n^+ implant, and gain layer; patterned metal readout electrodes
  - No junction termination extension or p-stop between electrodes: fill factor ~100
  - Mirroring of charge at the n^+ layer on the metal pads: AC-coupling
  - Strong sharing of charge between metal pads
  - **Extrapolation of position based on signal sharing – finer position resolution for larger pitch, also allowing for more sparse readout channels**





H. F.-W. Sadrozinski et al, *4D tracking with ultra-fast silicon detectors*, Reports on Progress in Physics 2018, 81, 026101
CMS Collaboration, *A MIP Timing Detector for the CMS Phase-2 Upgrade*, CERN-LHCC-2019-003, 2019
ATLAS Collaboration, *A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade*, CERN-LHCC-2018-023, 2018

AC-LGADs in future detectors

Electron-Ion Collider

- ePIC detector Barrel-TOF, forward-TOF, far-forward/Roman pots
- AC-LGADs for time-of-flight particle ID: t_0 determination and timing, and serving as additional layer in Tracking
- Combination of precise temporal and spatial resolution: 25-35 ps and 30 µm
  - Active thickness
  - Strip and pad electrode geometry
  - Resistivity of n+ layer and capacitance of coupling dielectric
  - **Radiation hardness**
  - **Angular hit performance**

Extensive studies done, presented e.g. earlier in this session

PIONEER

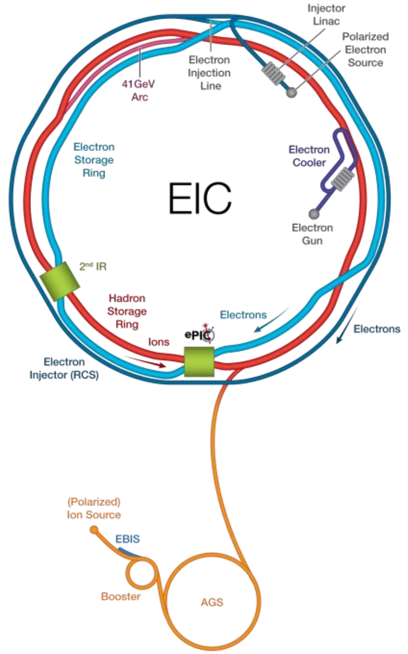
- LGADs (AC- or trench-insulated LGADS) for 4D/5D tracking
  - Thicker sensors to reduce ratio of dead material or gaps
  - More relaxed timing resolution requirements (100-200 ps)
  - **Angular hit performance**

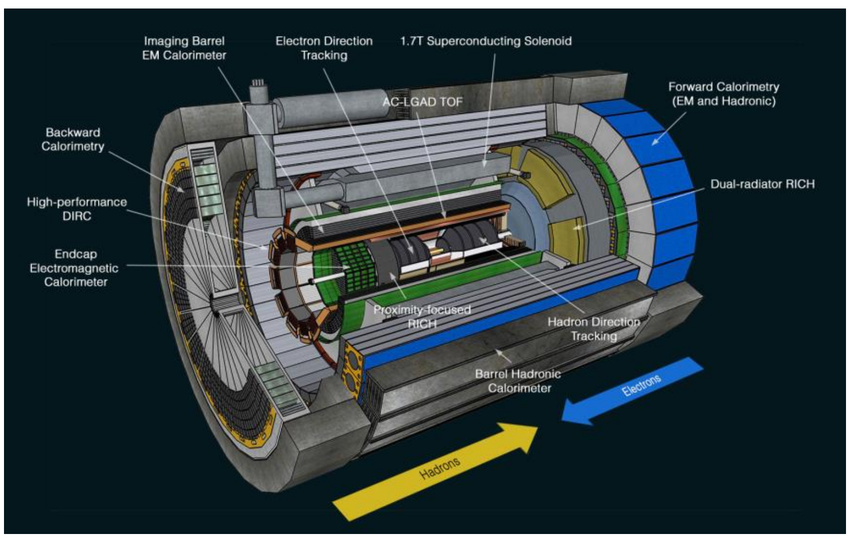
FCC-ee detector designs: IDEA 'silicon wrapper'

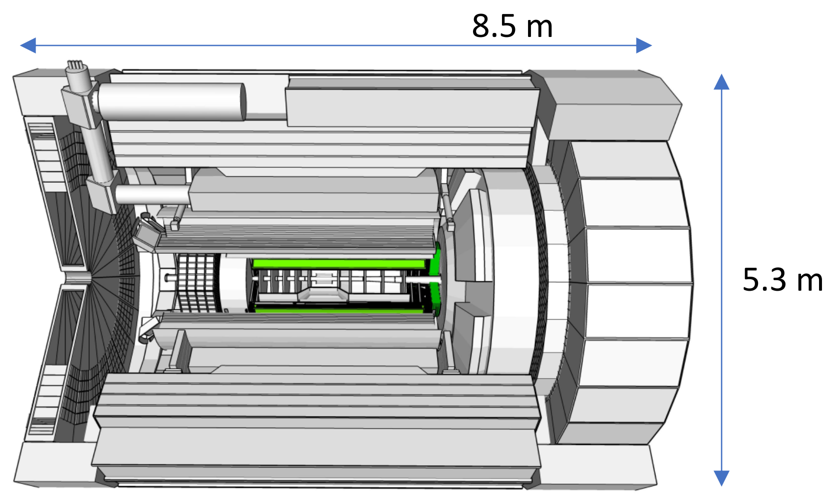
- True 4D tracking in all layers may not be needed in ee phase, but strip AC-LGAD layer would provide a time stamp and good spatial resolution at a comparatively sparse readout channel count

ePIC detector at the Electron-Ion Collider

- EIC Detector 1 → **ePIC Collaboration**
- 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 * E_p)
- **Luminosity: $2x10^{34}$ $cm^{-2}s^{-1}$**
- **Design includes AC-LGADs for time-of-flight particle ID, t_0 determination, and serving as additional layer in Tracking**







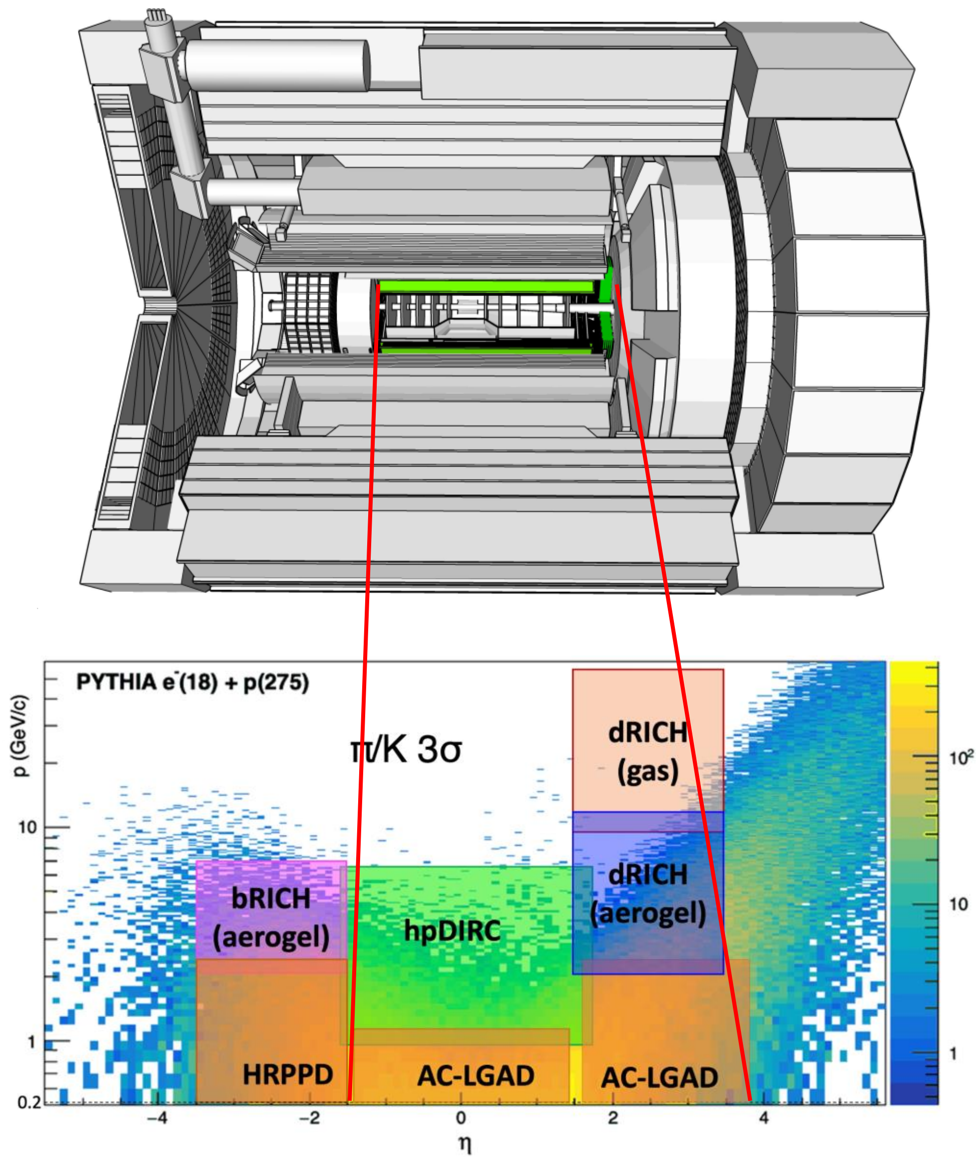
AC-LGAD highlighted

https://indico.bnl.gov/event/17072/contributions/68825/
https://indico.bnl.gov/event/17072/contributions/70500/

Particle-ID in ePIC

- Several detectors for particle ID in inner or outer barrel layers, hadronic endcap, electron endcap
  - Momentum and rapidity range cannot be covered by a single technology
  - Leveraging variants of Cherenkov detectors
  - AC-LGADs replaced by picosecond photodetectors in electron (backward) endcap
  - Excellent performance in distinction of charged particle species at low momenta < 3 GeV

- AC-LGAD barrel and forward-endcap Time-of-Flight PID
  - **Combination of precise temporal and spatial resolution: 25 ps and 30 µm / hit**
  - Low material budget
- Current sensor design baseline:
  - Barrel: **strips, 500 µm pitch and 1 cm length**
  - Hadronic endcap (and Roman Pots): **pads, 500 x 500 µm**



Particle ID systems in ePIC

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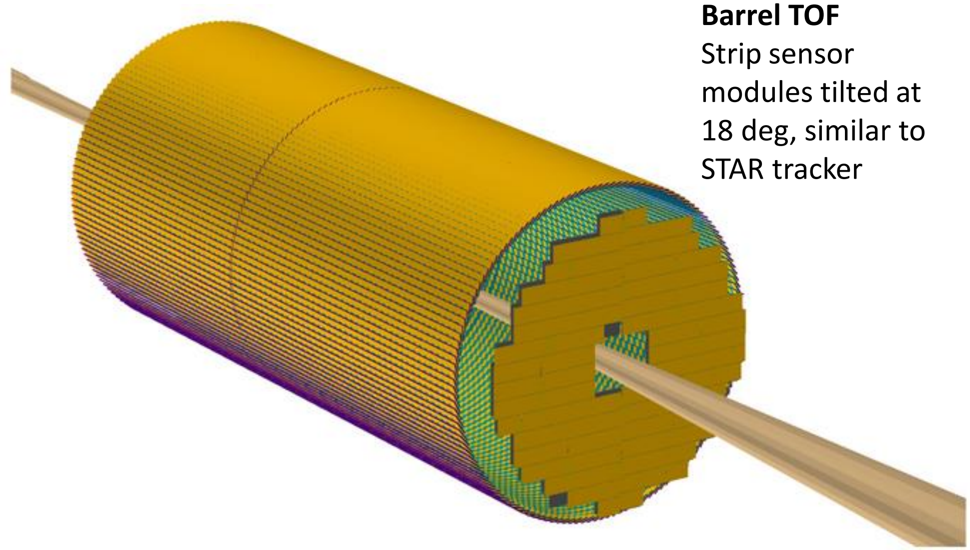
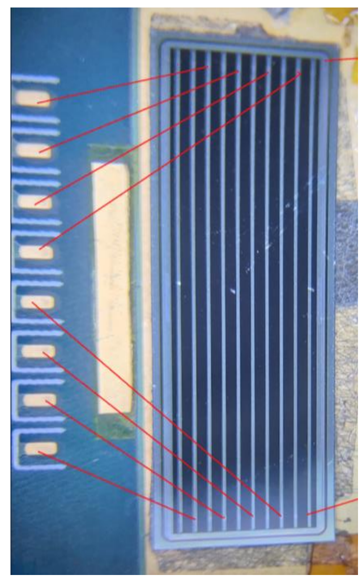
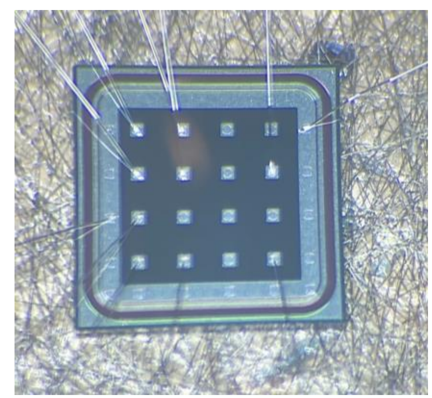


Barrel TOF
Strip sensor modules tilted at 18 deg, similar to STAR tracker



Forward TOF
Similar to CMS ETL



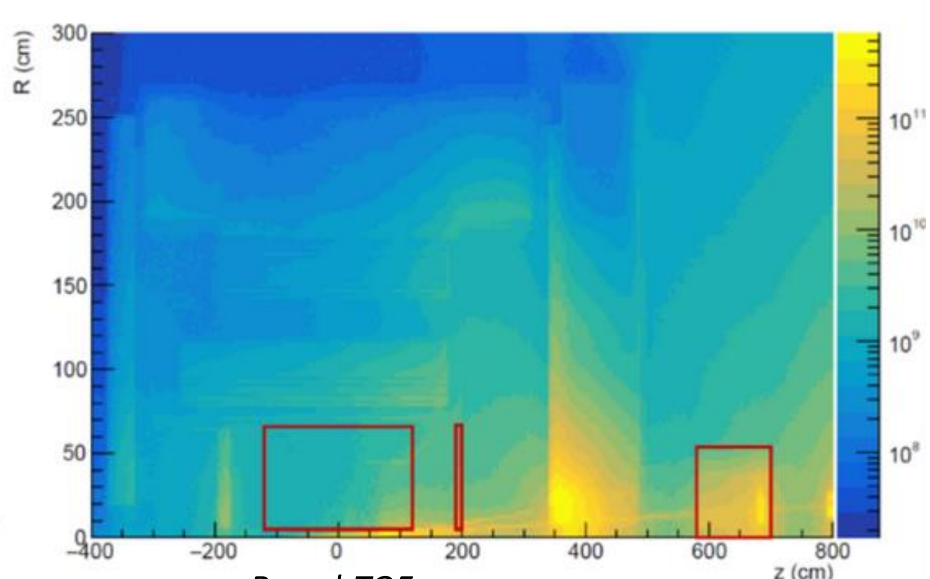
Radiation levels at ePIC

- **Radiation hardness of LGADs has been studied and optimized extensively for the HL-LHC timing endcap 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**
  - **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**

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.



Barrel-TOF
Forward-TOF
Far-forward / Roman pots

J. Ott et al, AC-LGADs, CPAD

Irradiation campaign for AC-LGADs

- Subset of HPK (and BNL) sensors was irradiated with reactor neutrons at JSI/Ljubljana
  - *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 n/cm^2 – 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
- Strip width 50 µm; pixels primarily 150 µm, some 300 µm

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

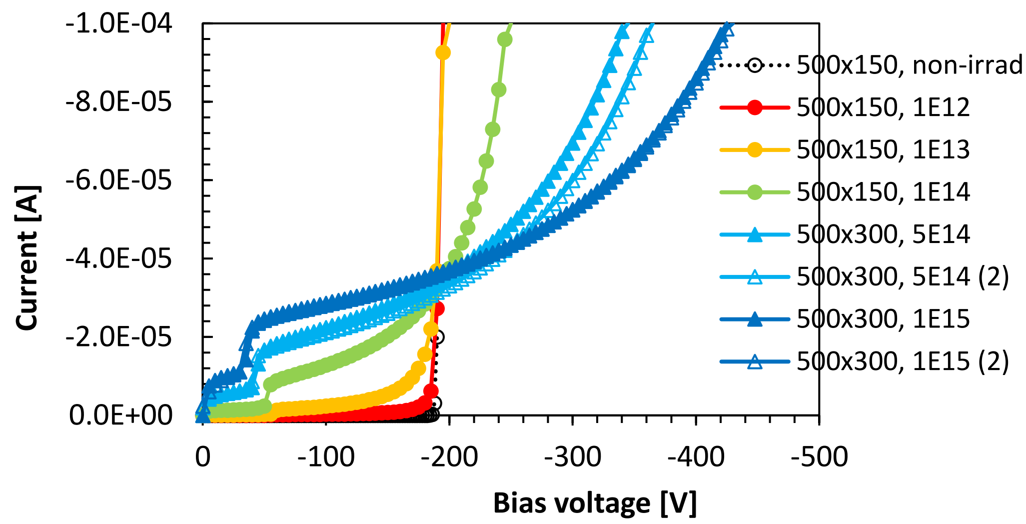
Fluence	0.5 cm	1 cm	2 cm
1.00E+14	52	52	
5.00E+14	44		48
1.00E+15		38	42

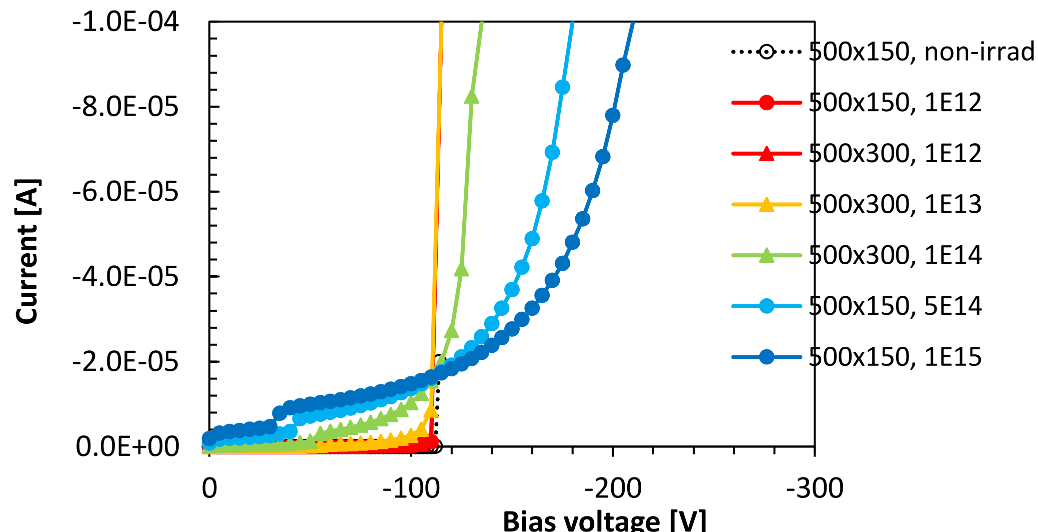
Strips
W5

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

Irradiated AC-LGAD pixels

- Up to 1e13 cm^{-2}, 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

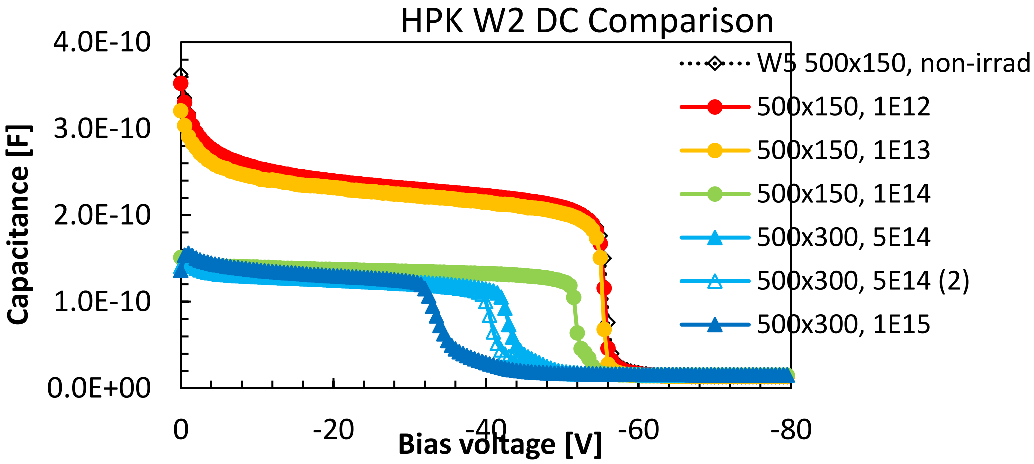


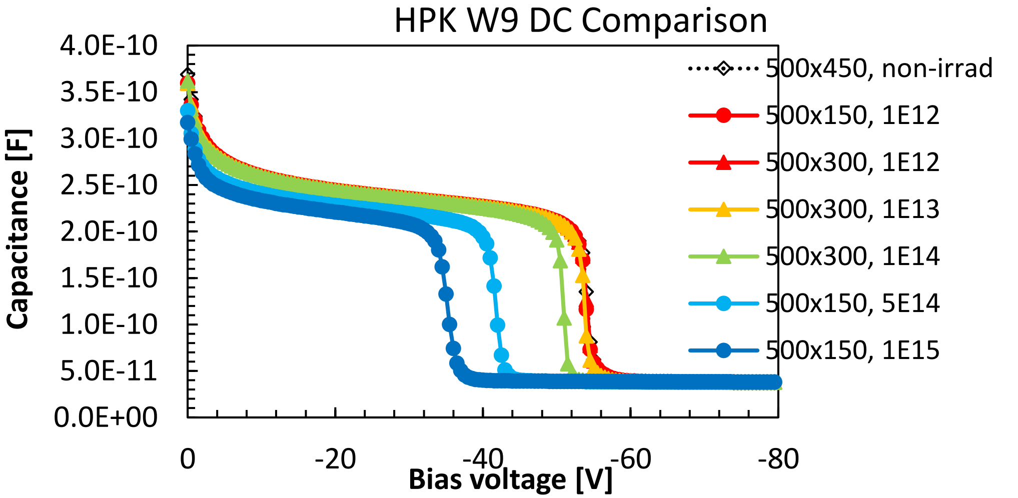


J. Ott et al, AC-LGADs, CPAD

Irradiated AC-LGAD pixels

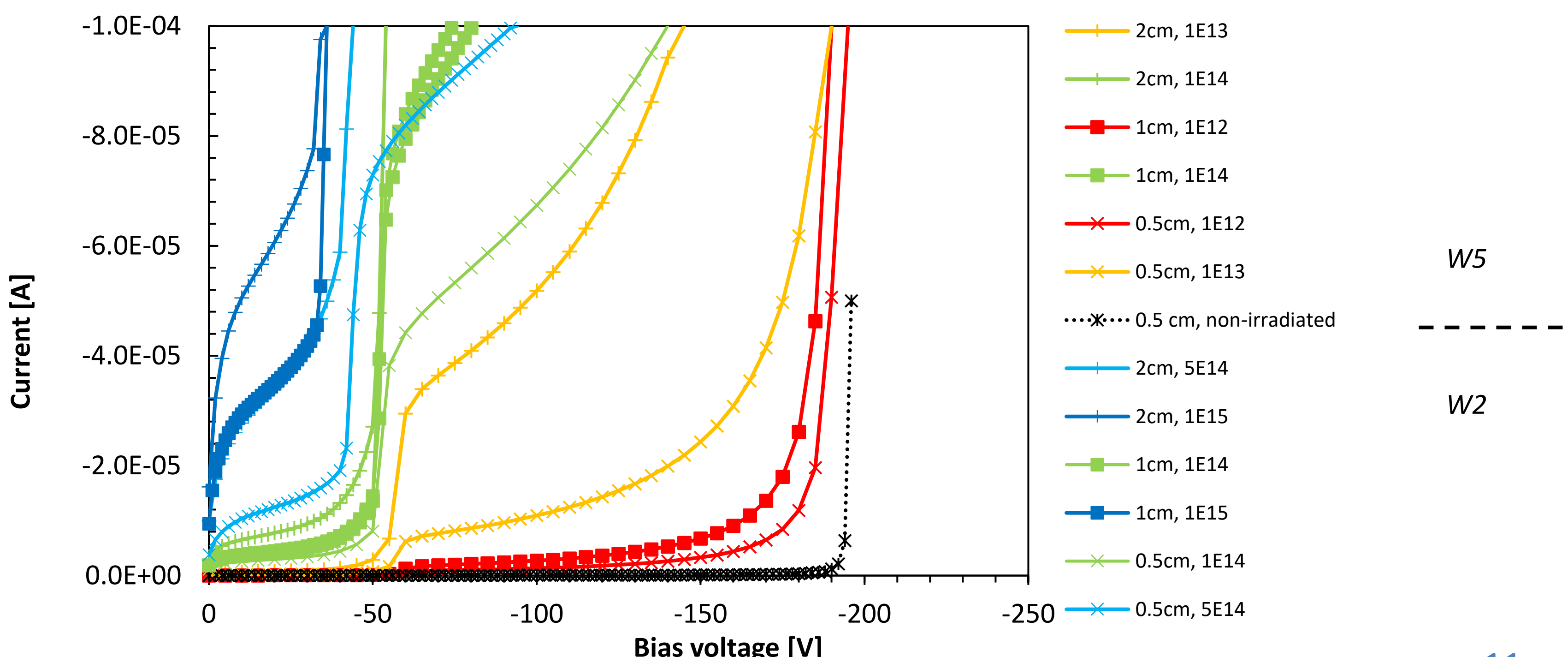
- Up to 1e13 cm^{-2}, no significant change in gain layer depletion voltage = gain layer active doping concentration
- Shift in gain layer depletion voltage with fluence is very clear
- Behavior across wafers is consistent
  - Note higher full depletion capacitance for thinner sensor
  - More trapping / higher drift time in thicker bulk: affects capacitance before depletion





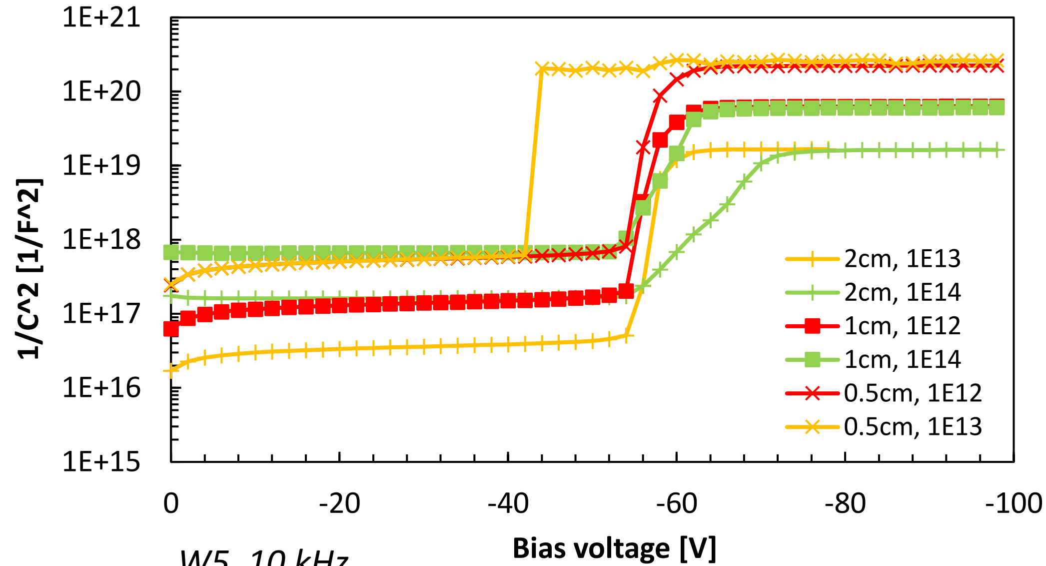
Irradiated AC-LGAD strips

- Strip sensors have larger area, also scales up with strip lengths: changes in leakage current more prominent, already at low fluences after 1e12
- 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



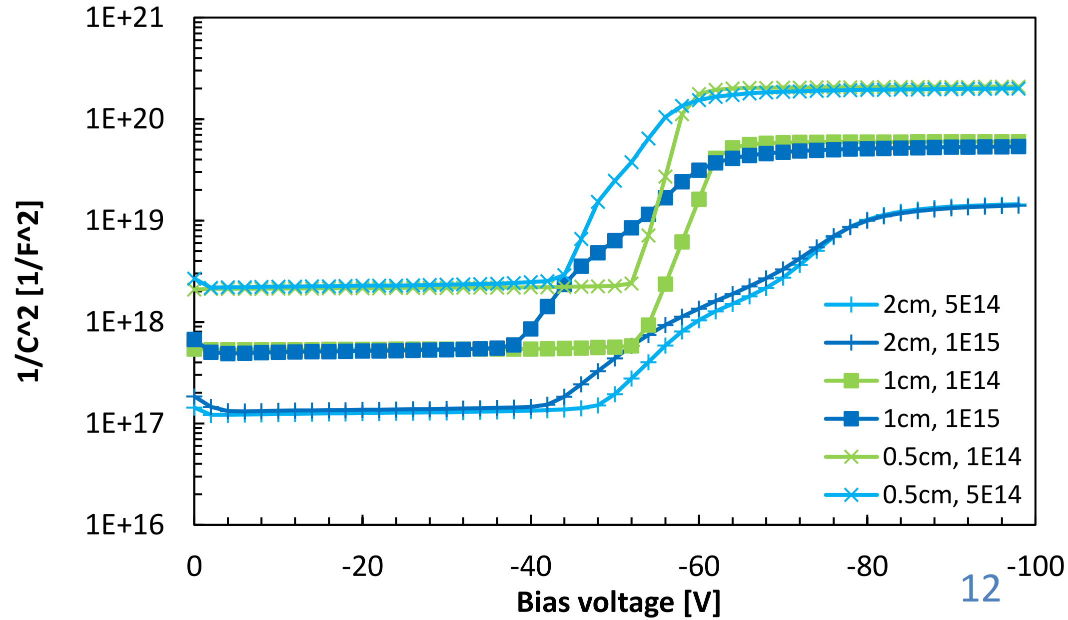
Irradiated AC-LGAD strips

- Up to 1e13 cm^{-2}, 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



W5, 10 kHz

W2, 10 kHz



Irradiated AC-LGAD pixels

	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
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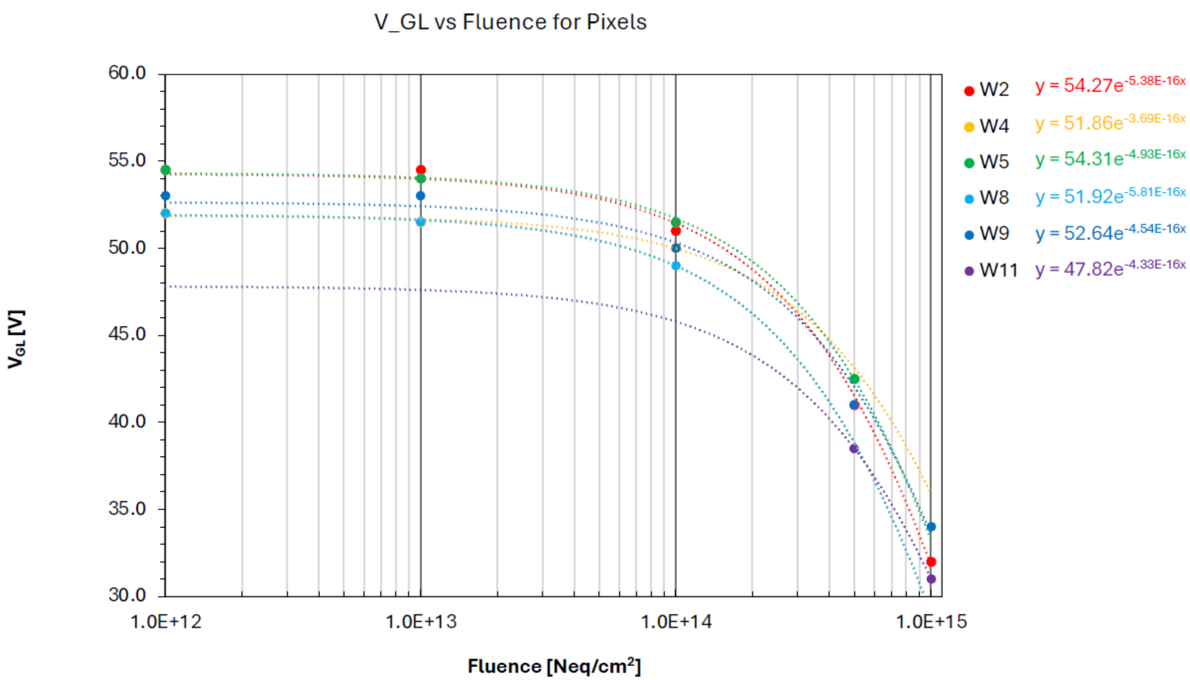
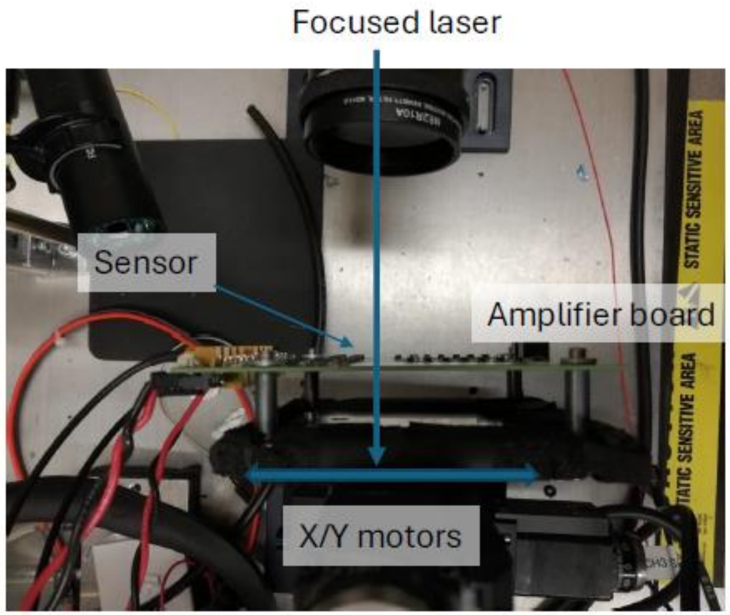


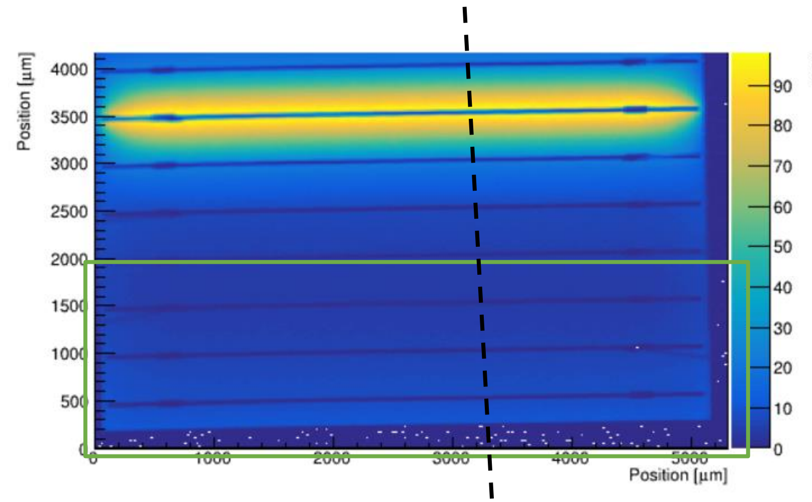
Formula for Fit: $\mathbf{N_D = N_0 e^{-c\phi}}$

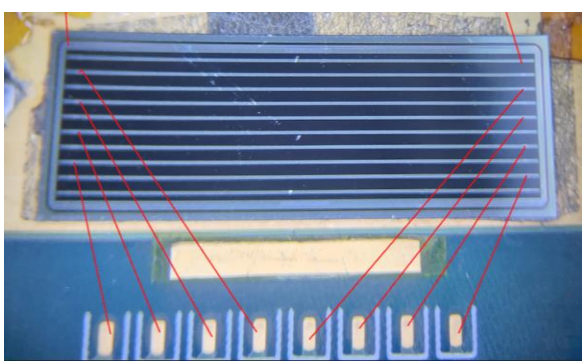
c factors:

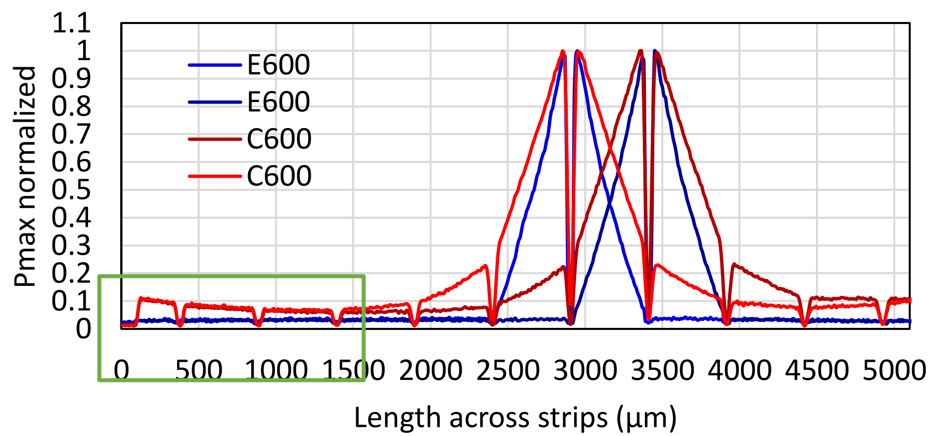
- W2: $5.38 \cdot 10^{-16}$
- W4: $3.69 \cdot 10^{-16}$
- W5: $4.93 \cdot 10^{-16}$
- W8: $5.81 \cdot 10^{-16}$
- W9: $4.54 \cdot 10^{-16}$
- W11: $4.33 \cdot 10^{-16}$

Laser scanning setup





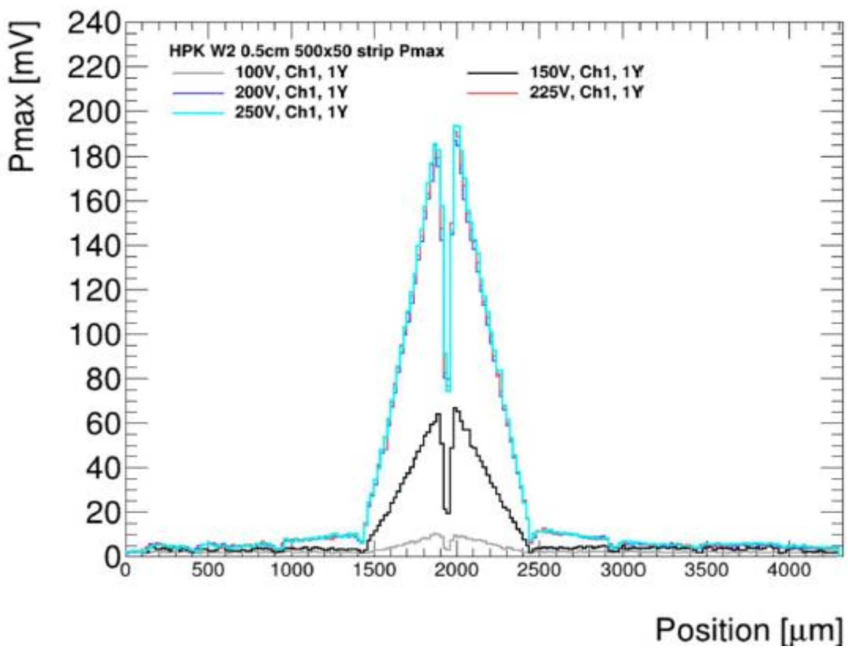


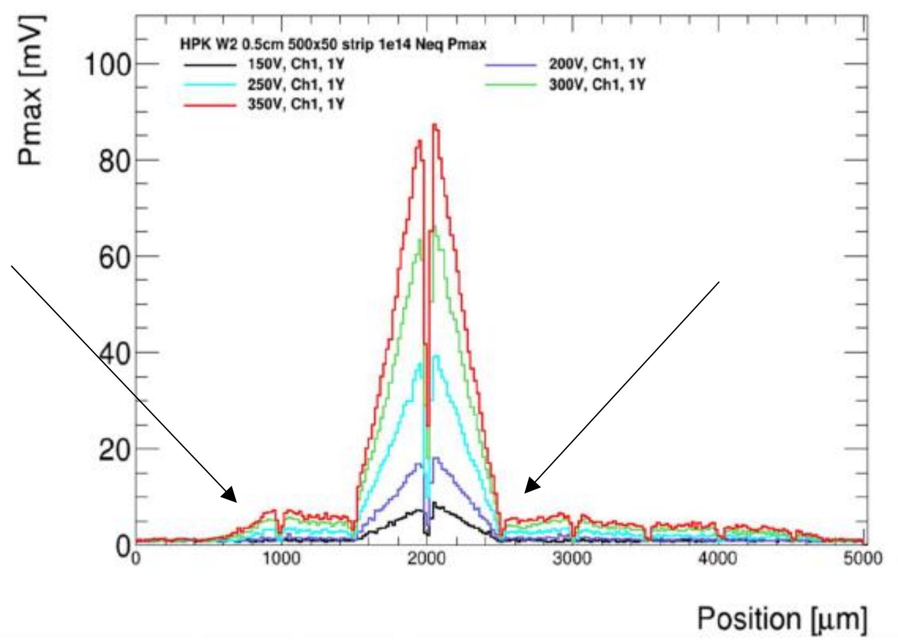


Irradiated AC-LGAD sensors

- W2 0.5 cm strip, non-irradiated sensor and irradiated to 1e14 n/cm^2
- Cooling with chiller to ~10 C
- Irradiated sensor was biased to higher voltages

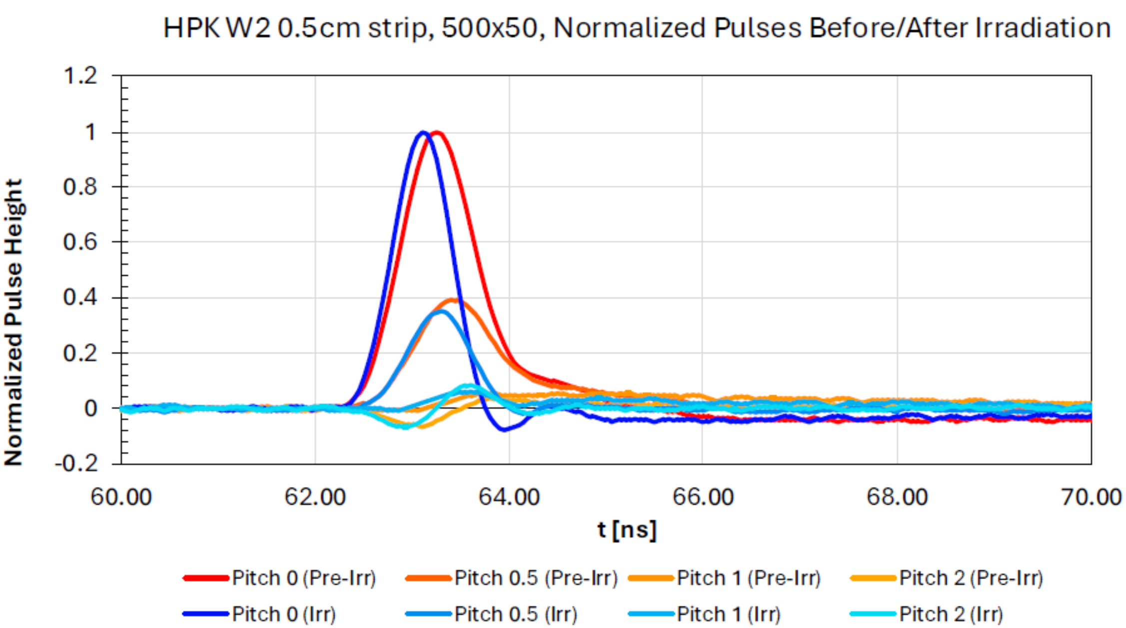
- Pmax profile of the main strip is very similar, but increases beyond the first neighboring strip and at longer distances
  - **Indicating higher conductivity of the n+ layer and/or radiation damage to dielectric**

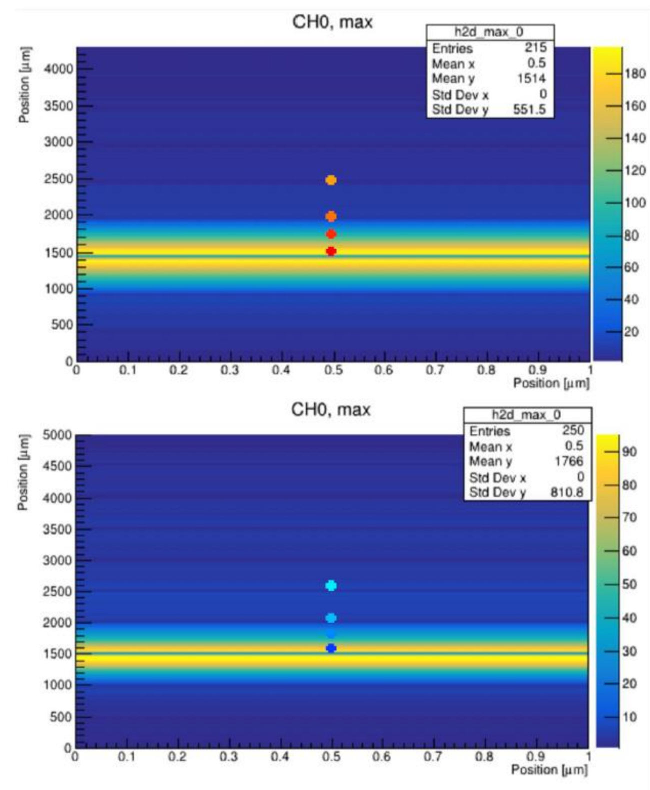




Irradiated AC-LGAD sensors

- 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





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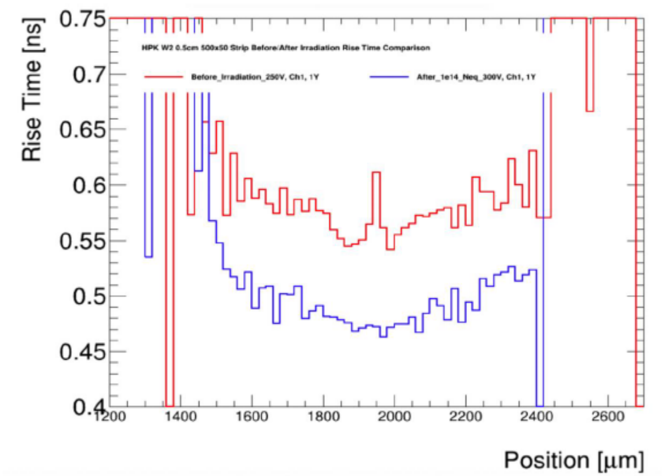
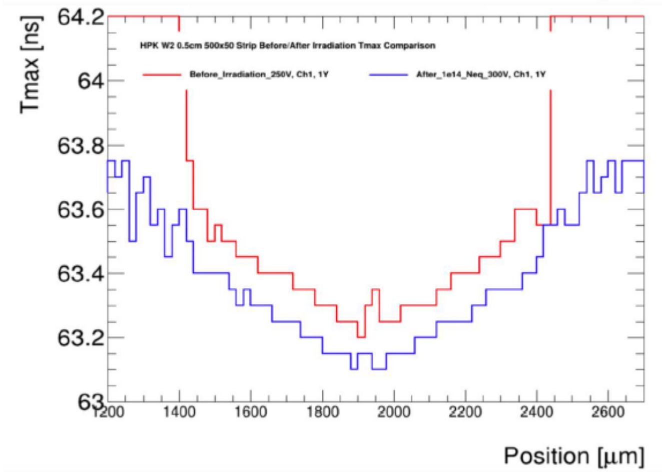
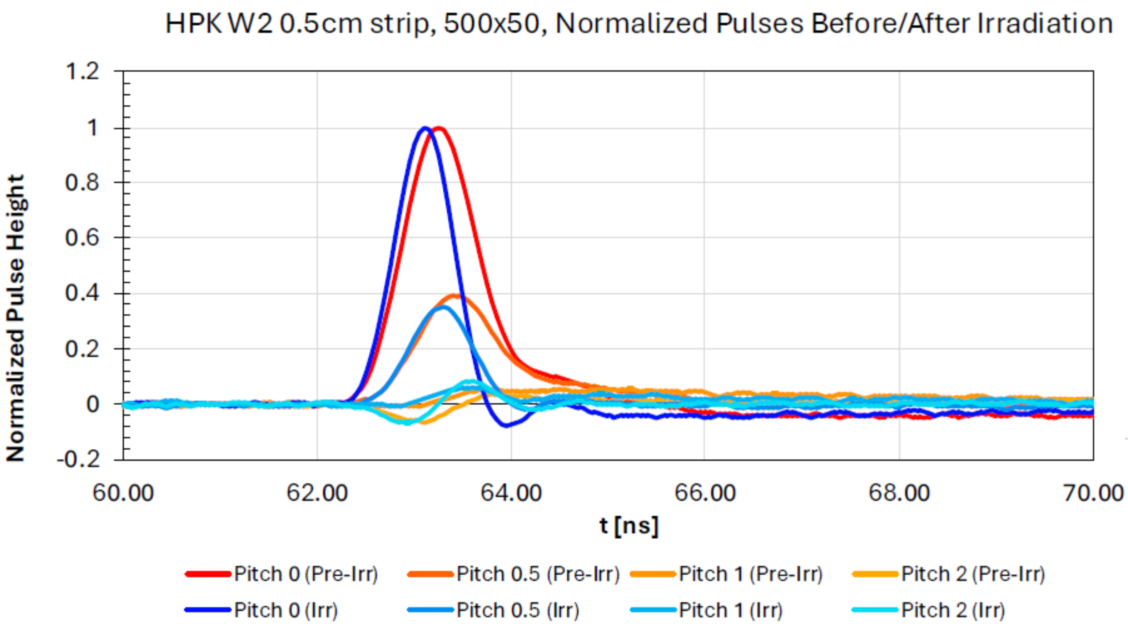
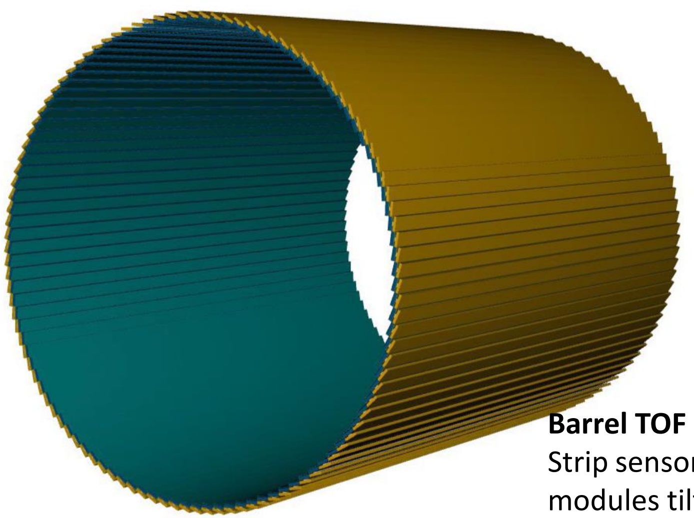




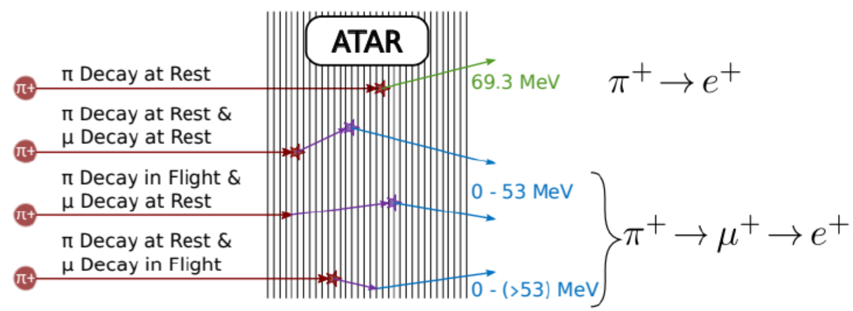


Angular incidence

- Laboratory characterization and beam tests so far have been conducted at normal incidence
- Strip modules in ePIC barrel-TOF are layered with a 18-degree tilt angle in the design baseline, forward disk region may also get tracks at high η
- PIONEER ATAR involves several decay scenarios (in-flight, at-rest) and tracks from pions, muons and positrons: decay products can be emitted at large angle respective to strip plane



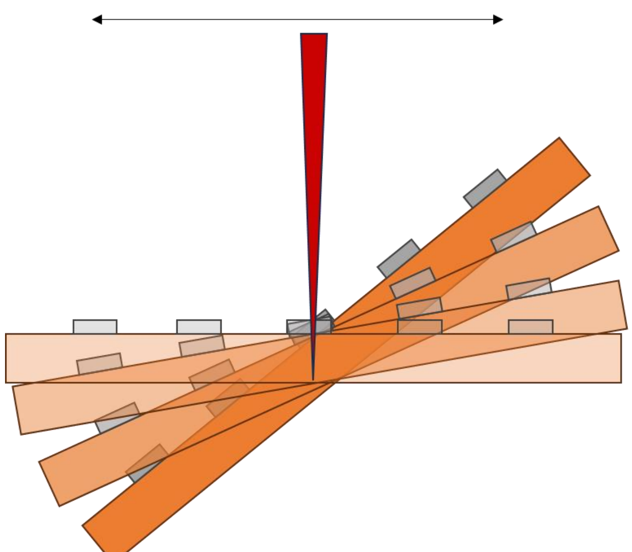
Barrel TOF
Strip sensor modules tilted at 18 deg, similar to STAR tracker

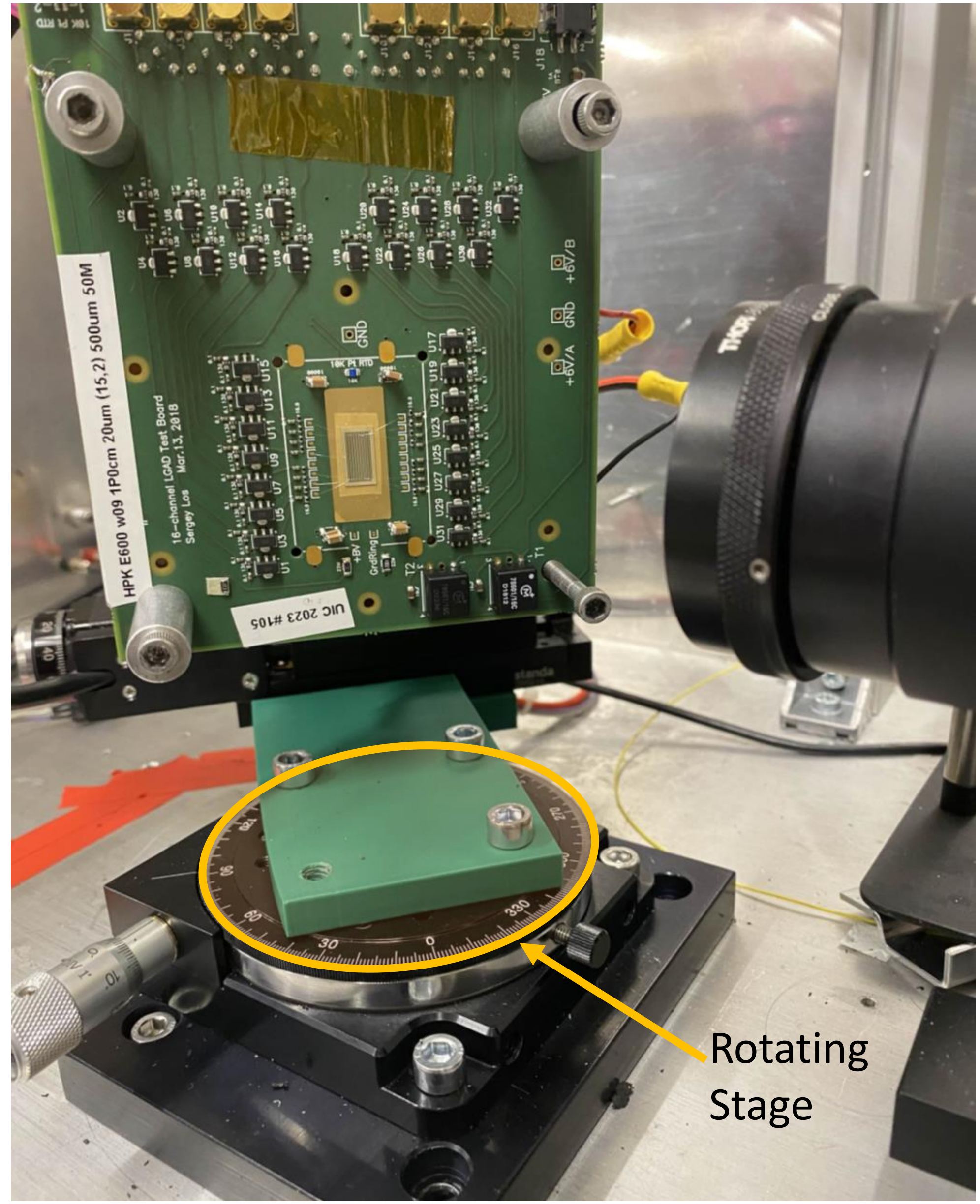


PIONEER ATAR
Strips orthogonal to beam, but there will be other particle species

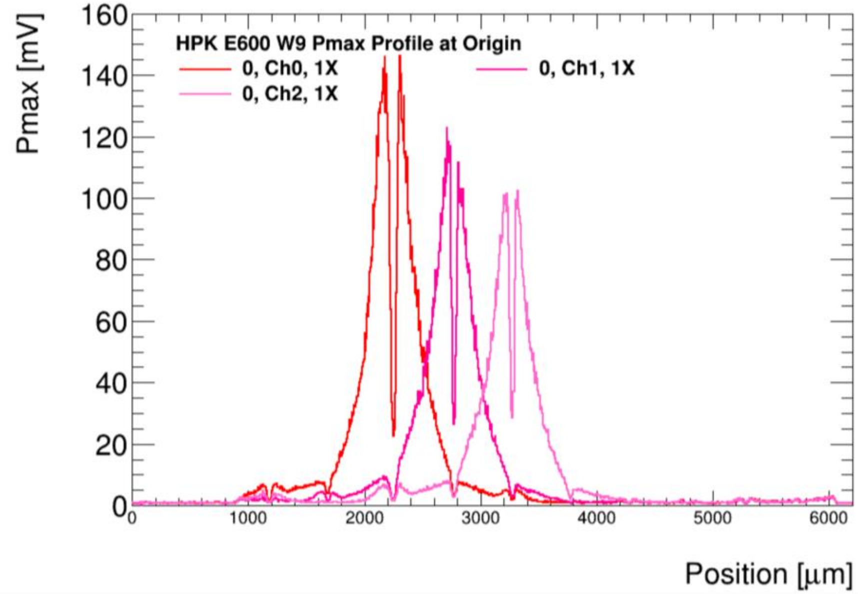
Rotation stage laser setup

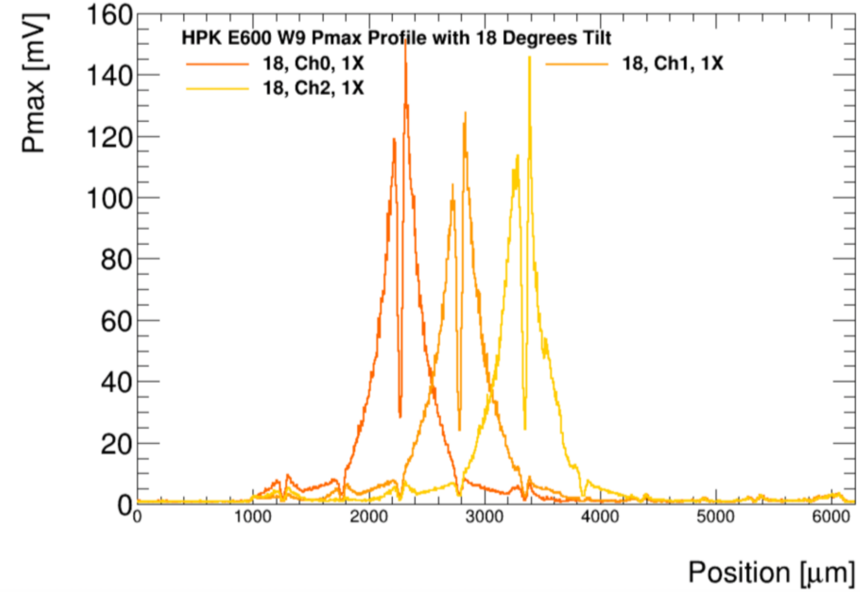
- Rotational stage at the base of the x-y scanning system
- 1 cm strip length, 500 µm pitch, 50 µm strip width, W9 (20 µm active thickness
- Example: setup when taking data at a 45° tilt (technically, at 315°)
- Line scans across the middle of the sensor at: 0°, 18°, 30° and 45°, refocusing at each position

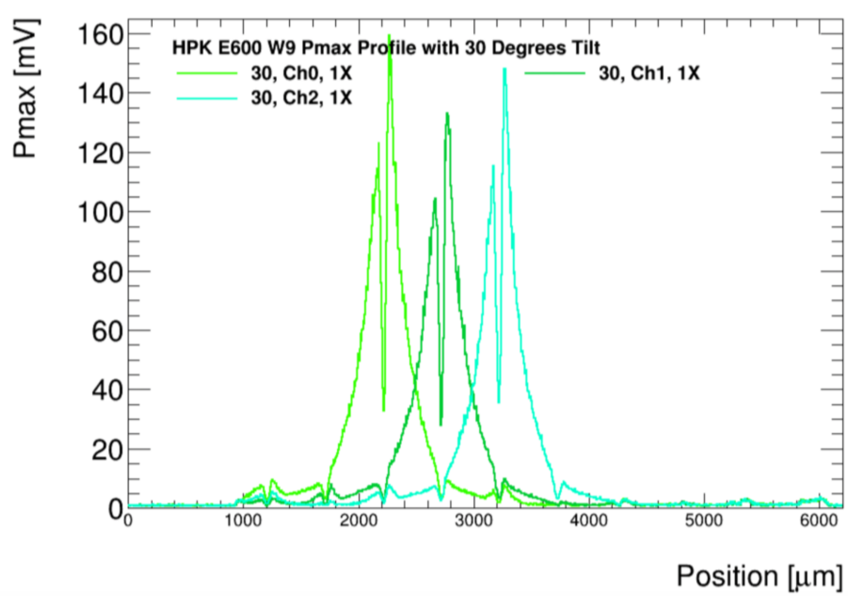


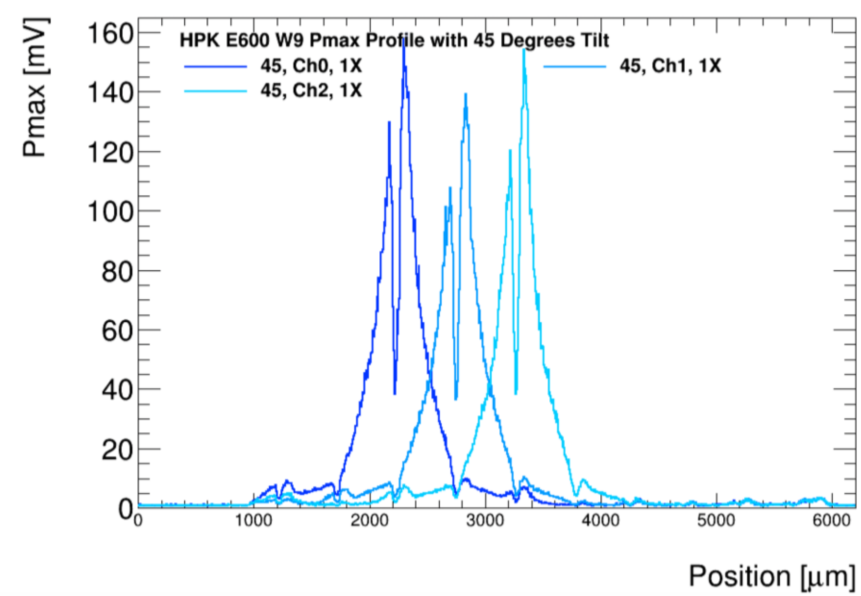


Laser hits at angular incidence



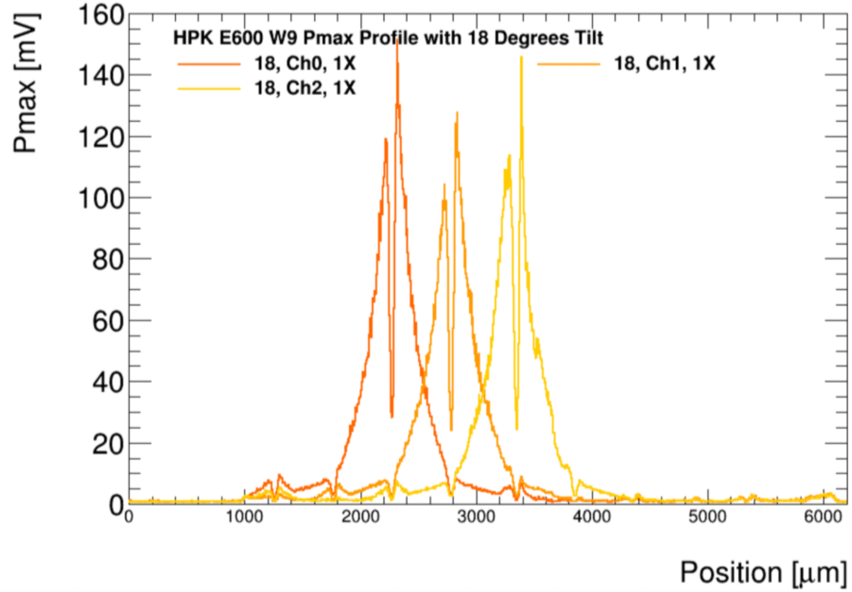


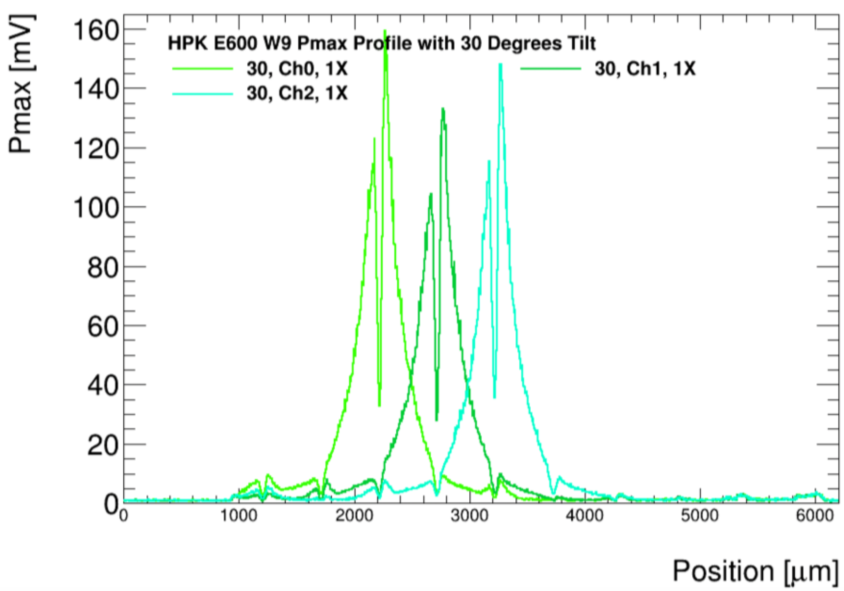


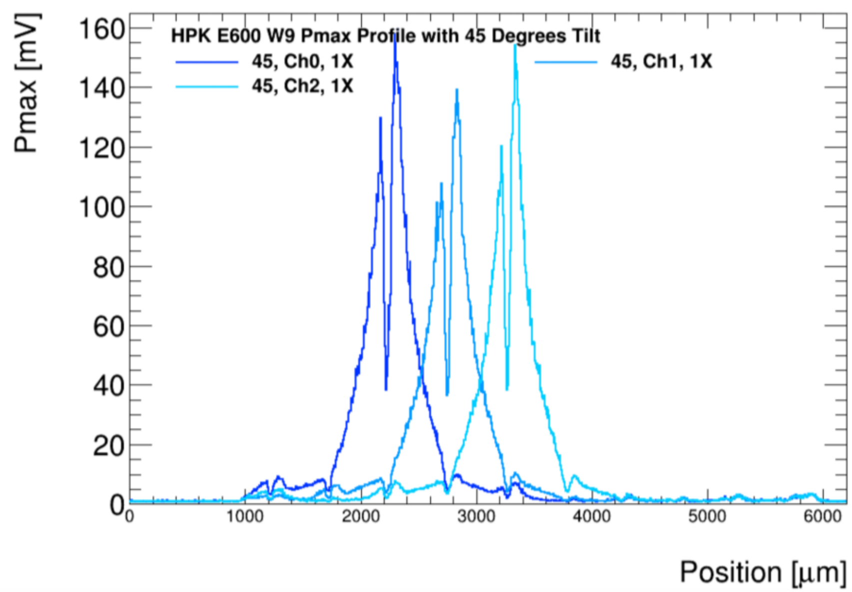


Laser hits at angular incidence

- At larger angles, signal profile in neighboring strips also shows shift with rotational angle
- Laser light is shone under strips – ‘gap’ disappears

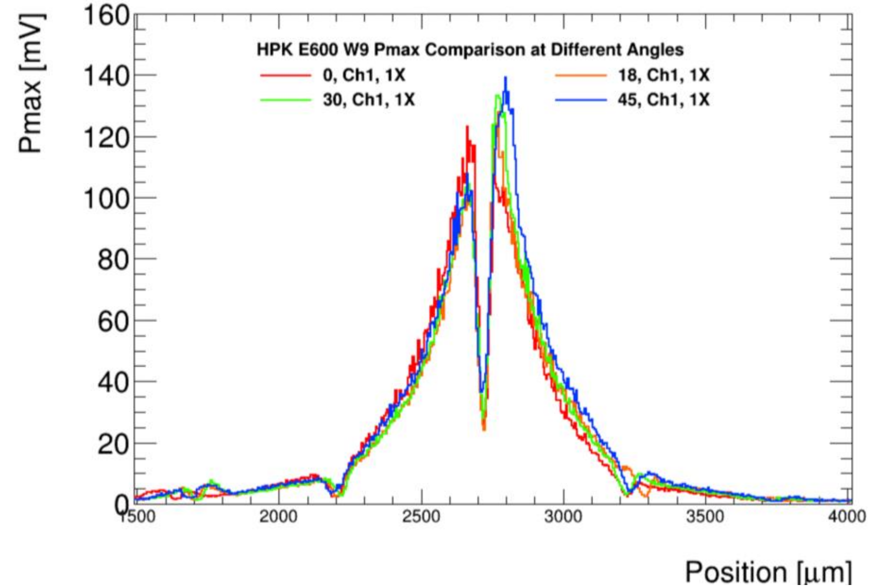


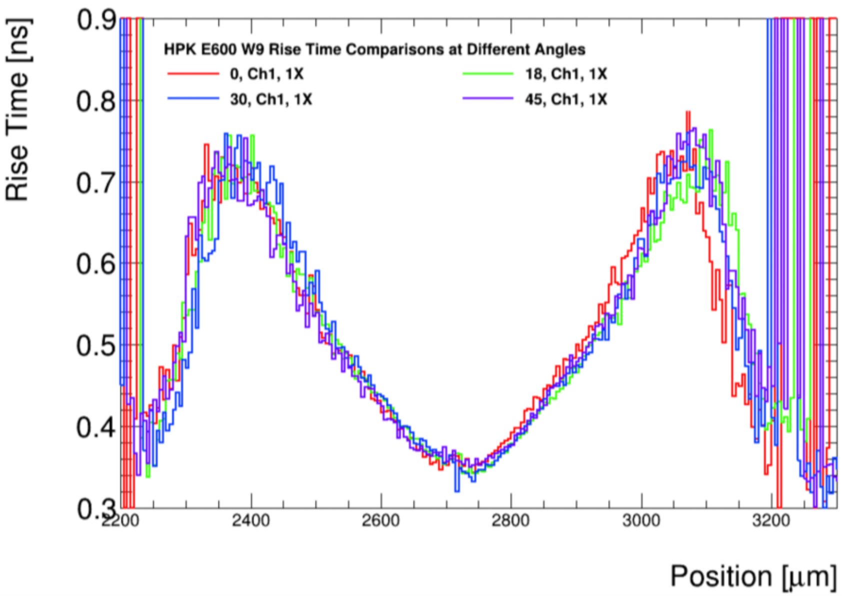


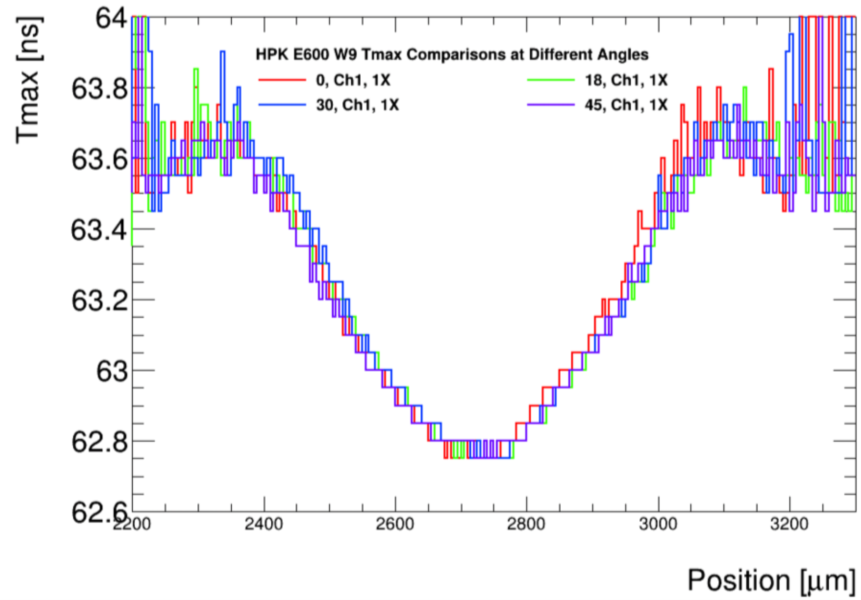


Laser hits at angular incidence

- Differences in time-of-arrival and rise time are minimal for the angles measured here







Summary and outlook

- AC-LGADs are radiation hard in terms of leakage current and gain layer to the fluences that are expected at ePIC, even with some margin: no impact of 1e13 n/cm^2 in baseline design strip and pad sensors; even 1e14 n/cm^2 has moderate effect
  - In large-volume Si, bulk trapping and leakage current generation effects can be pronounced even at relatively low fluences
  - Interesting effects in the charge sharing profile are observed in AC-LGAD strips at higher fluences: to be investigated further
  - ➢ **AC and interstrip capacitance and resistance measurements**
  - ➢ **Verification with a larger statistical sample**
  - Irradiation with charged particles, electrons and gamma should be conducted

- Angular incidence at the angles studied is visible in charge sharing profile, but no apparent impact on rise time and time-of-arrival

- Irradiated and tilted sensors should be tested in a MIP(-like) test beam

Thank you!

Backup

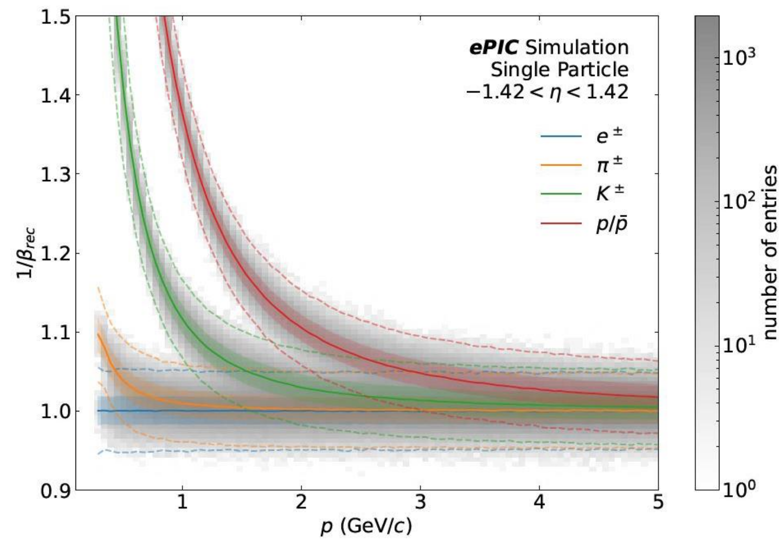
Irradiation campaign for AC-LGADs

- Radiation levels are much lower at the EIC (and future Higgs Factory / FCC-ee) than at e.g. the HL-LHC, but the impact of radiation damage has not been extensively studied for AC-LGADs specifically
- Subset of HPK (and BNL) sensors was selected for irradiation with 800 MeV protons at Los Alamos LANSCE
  - Focus on E type
  - Focus on 600 pF/mm^2 dielectric capacitance
  - Focus on 1cm strip length, 100 µm strip width; 150 µm pad size
- Total fluences between 1e13 and 2e14 p/cm^2 – higher than envisioned at the EIC over the full time of life
- Including attempts at **graded irradiation of strip sensors to study the effects of non-uniform degradation of the gain layer and n-layer** within a long sensor
- Sensors were ultimately transferred to Fermilab Irradiation Test Area – to be delivered soon

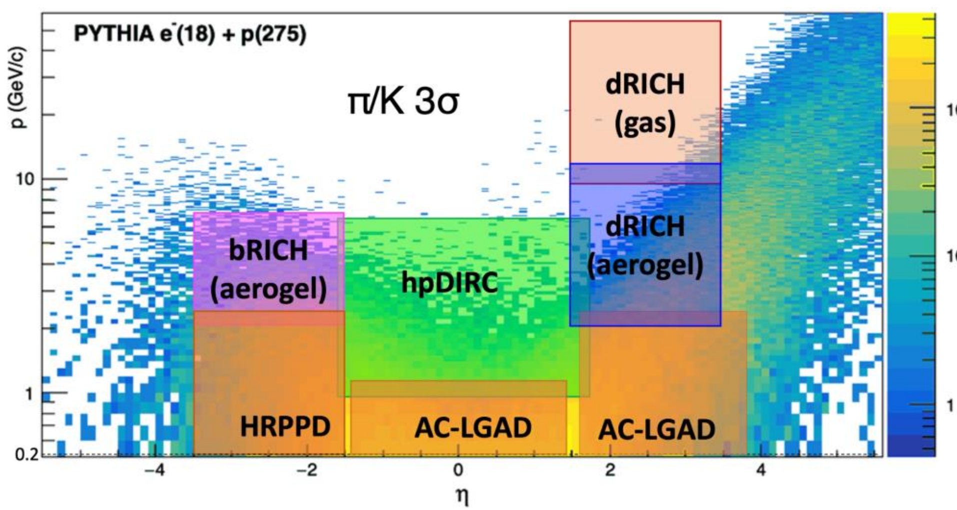
Particle-ID in ePIC

J. Ott et al, AC-LGADs, CPAD

- Several detectors for particle ID in inner or outer barrel layers, hadronic endcap, electron endcap
  - Momentum and rapidity range cannot be covered by a single technology
  - Leveraging variants of Cherenkov detectors
  - AC-LGADs replaced by picosecond photodetectors in electron (backward) endcap
  - Excellent performance in distinction of charged particle species at low momenta < 3 GeV



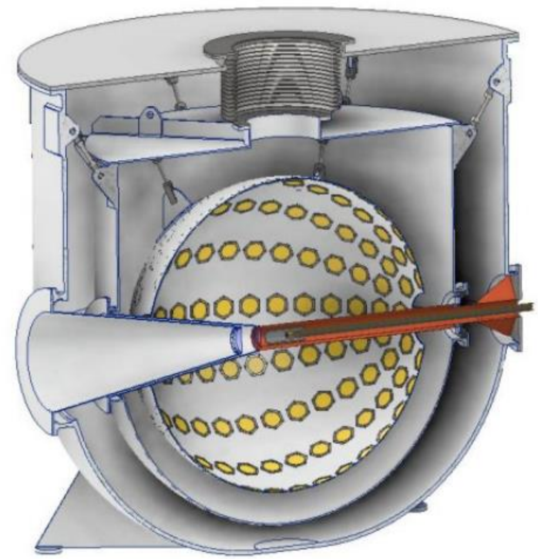
- AC-LGAD barrel and forward-endcap Time-of-Flight PID
  - **Combination of precise temporal and spatial resolution: 25 ps and 30 µm / hit**
  - Low material budget
- Current sensor design baseline:
  - Barrel: **strips, 500 µm pitch and 1 cm length**
  - Hadronic endcap (and Roman Pots): **pads, 500 x 500 µm**

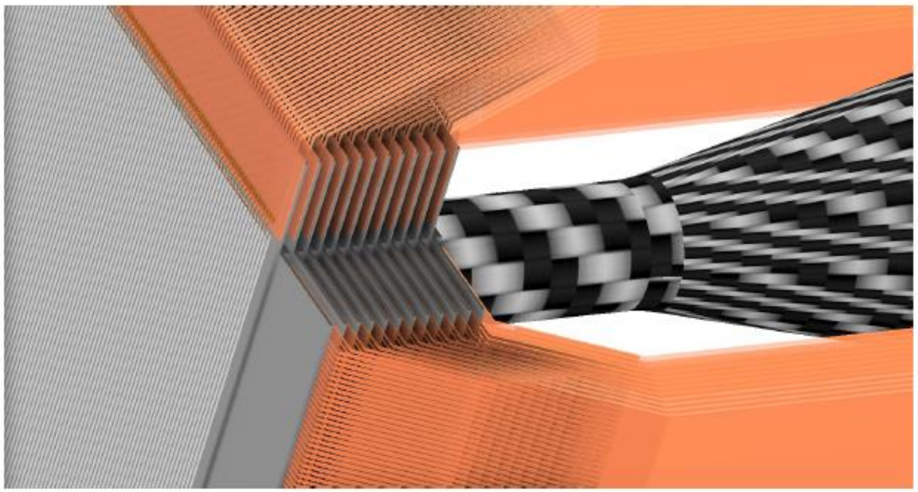


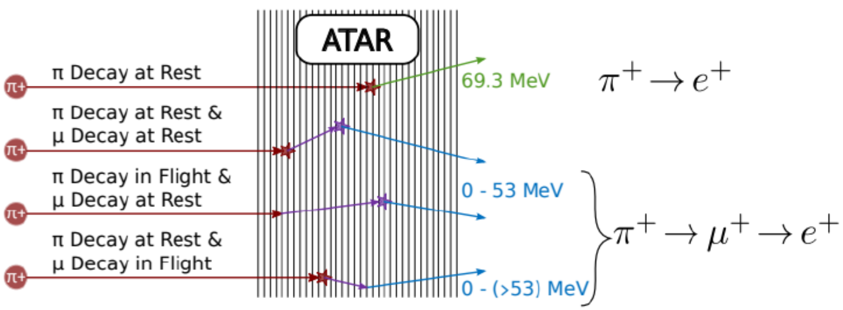
Particle ID systems in ePIC

PIONEER Experiment

- Precision experiment at PSI to determine the branching ratio of charged pion decays: involves several decay scenarios (in-flight, at-rest) and tracks from pions, muons and positrons
- Design baseline for the Active TARget: 2x2 cm^2 area with 48 planes of 120 µm thick AC-LGAD strips, pitch ca. 200 µm
  - Large energy deposition by stopping particles: need sufficient charge sharing to provide good spatial resolution, but not enough to occupy large areas of the sensor from one hit







PIONEER: Studies of Rare Pion Decays, https://arxiv.org/abs/2203.01981 (2022)
S. M. Mazza, An LGAD-Based Full Active Target for the PIONEER Experiment, *Instruments* **2021**, *5*(4), 40