science week/23
Jul 31 - Aug 4

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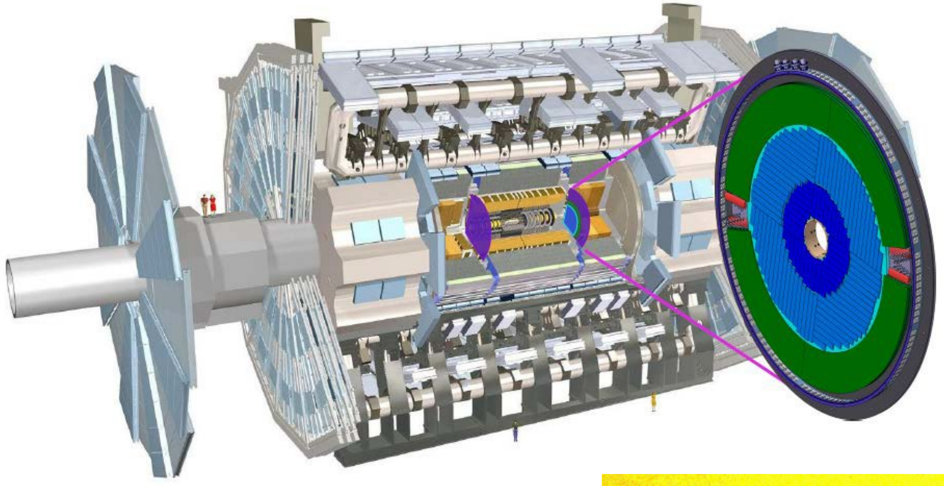
LGADs for particle, nuclear physics and beyond

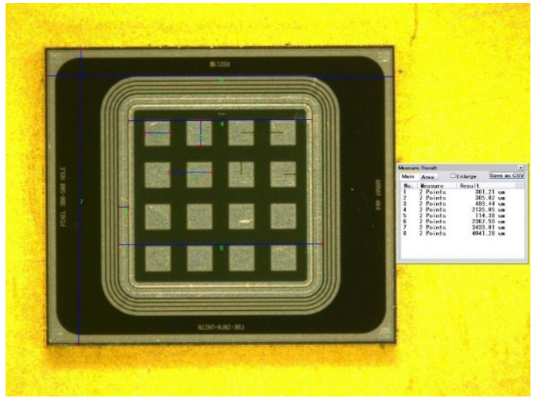
Dr. Simone M. Mazza (SCIPP, UC Santa Cruz)

TRIUMF science week 2023

Talk overview

I. LGAD technology, timing and 4D tracking
II. Radiation resistant LGAD design
III. High granularity LGADs
IV. LGAD applications in HEP and NP
V. X-ray detection with LGADs
VI. Gain suppression effects



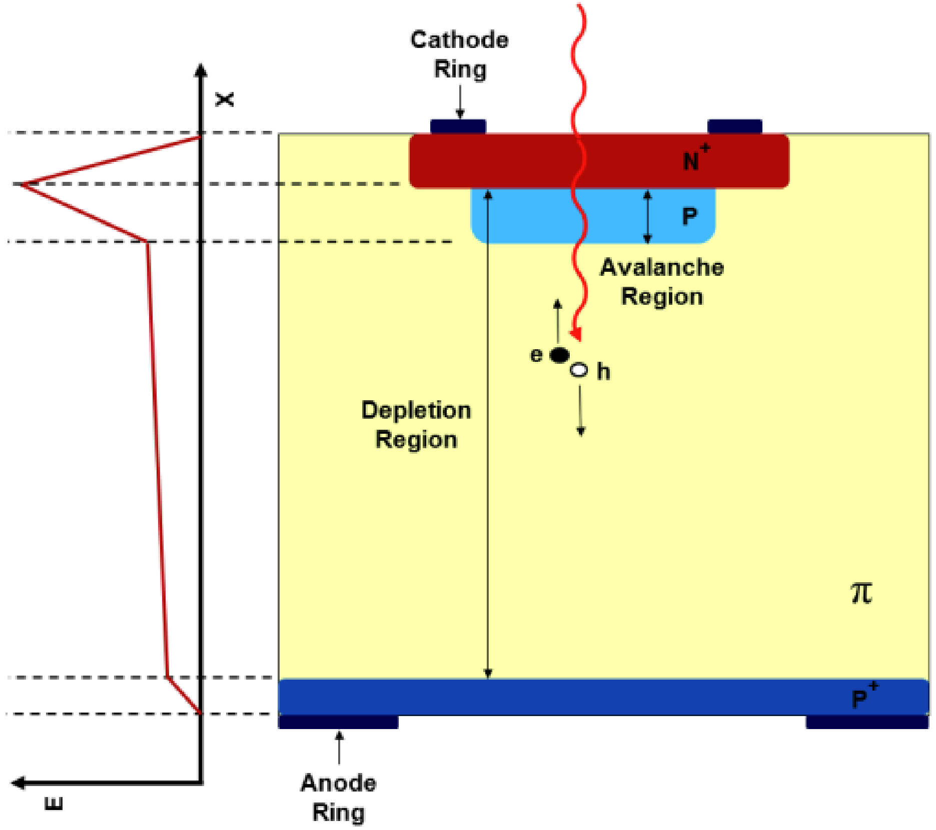


I. LGAD technology

Time resolution challenge

Low Gain Avalanche Detectors

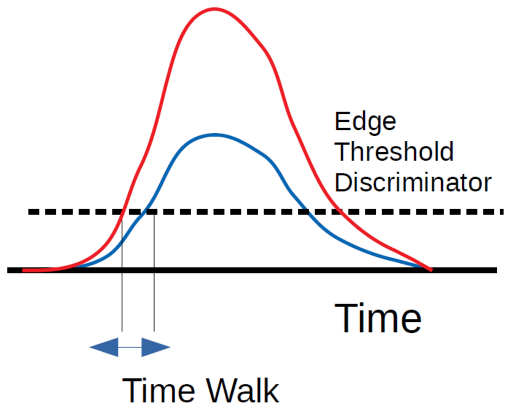
- LGAD: silicon detector with a thin (<5 µm) and highly doped (~10^{16} P++) multiplication layer
  - High electric field in the multiplication layer
  - Field is high enough for electron multiplication but not hole multiplication
- LGADs have intrinsic modest internal gain (10-50)
  - Gain $= \frac{Q_{LGAD}}{Q_{PiN}}$ (collected charge of LGAD vs same size PiN)
  - Not in avalanche mode → controlled tunable gain with applied bias voltage
- **Great hit time resolution: <20 ps!**

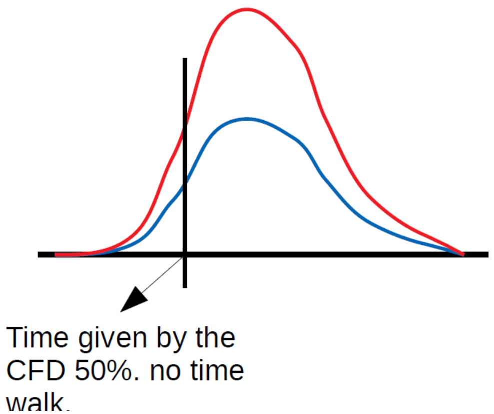


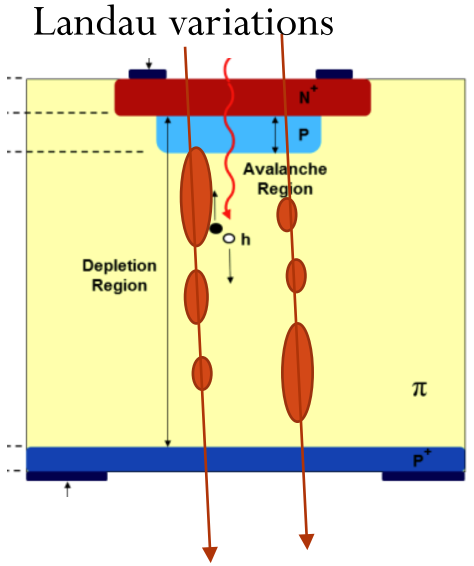
- Several producers of experimental LGADs
  - CNM (Spain), HPK (Japan), FBK (Italy), BNL (USA), NDL (China)

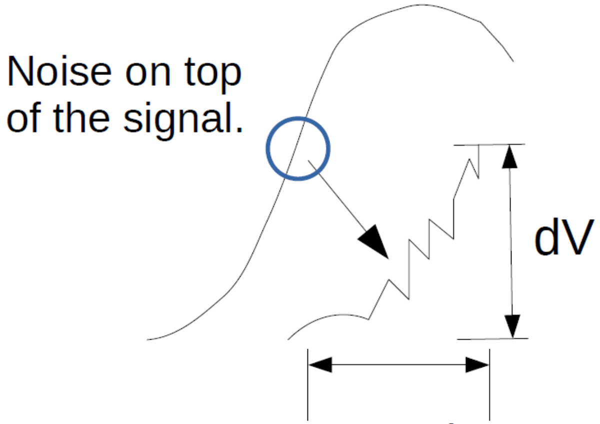
Nucl. Instrum. Meth. A765 (2014) 12 – 16.
Nucl. Instrum. Meth. A831 (2016) 18–23.

Time resolution









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

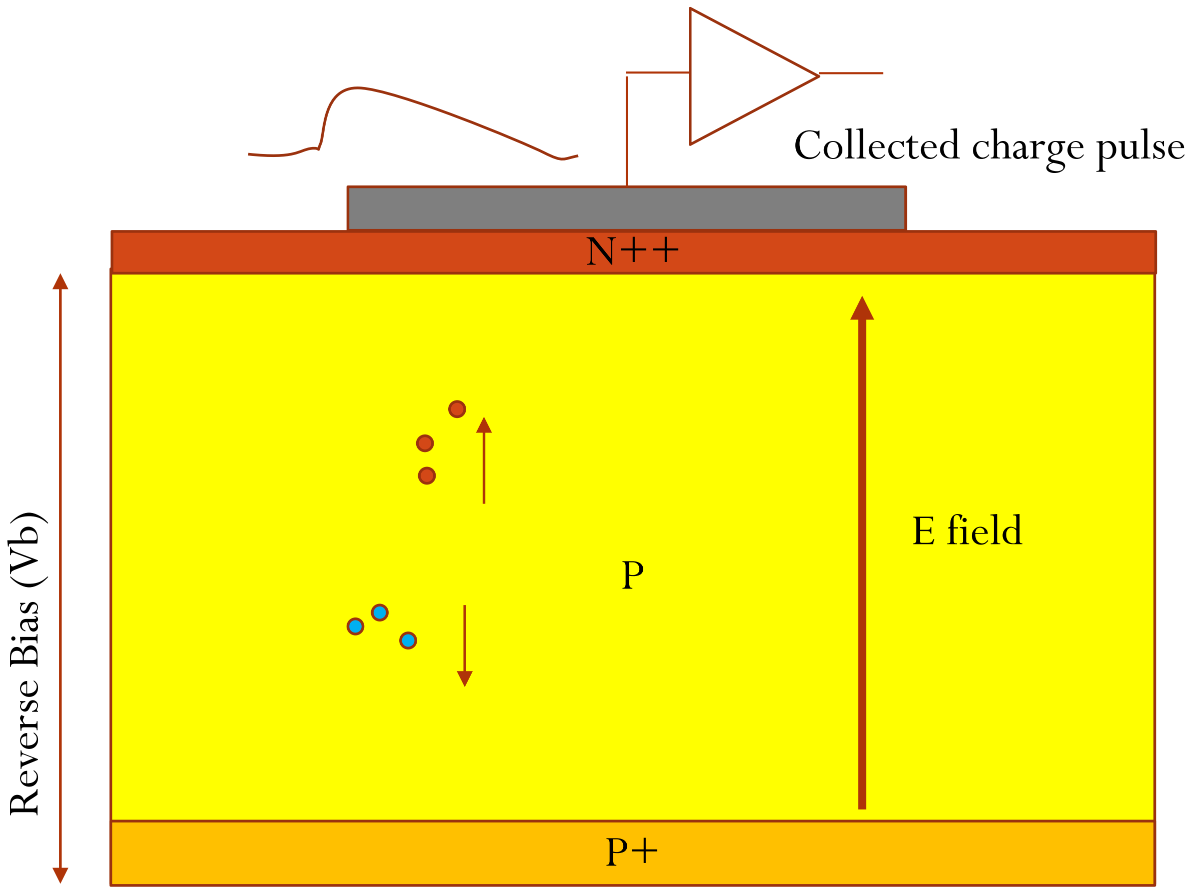
Sensor time resolution main terms

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

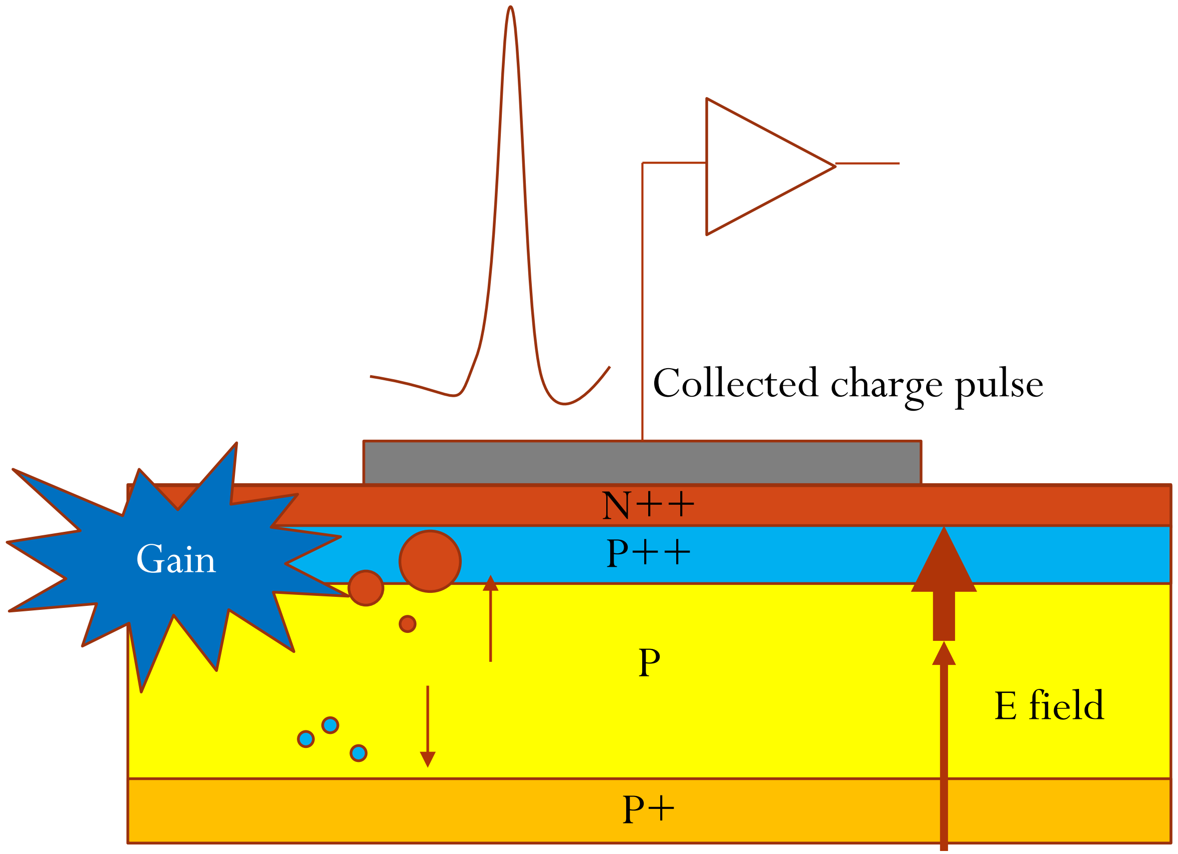
- **Time walk**:
  - Minimized by correcting the time of arrival using pulse width or pulse height (e.g., use 50% of the pulse as ToF)
- **Jitter**: from electronics
  - Proportional to ${}^{1}\!/_{\frac{dV}{dt}}$
  - Reduced by increasing S/N ratio with gain
- **TDC term**: from digitization clock (electronics)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

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

Silicon detector



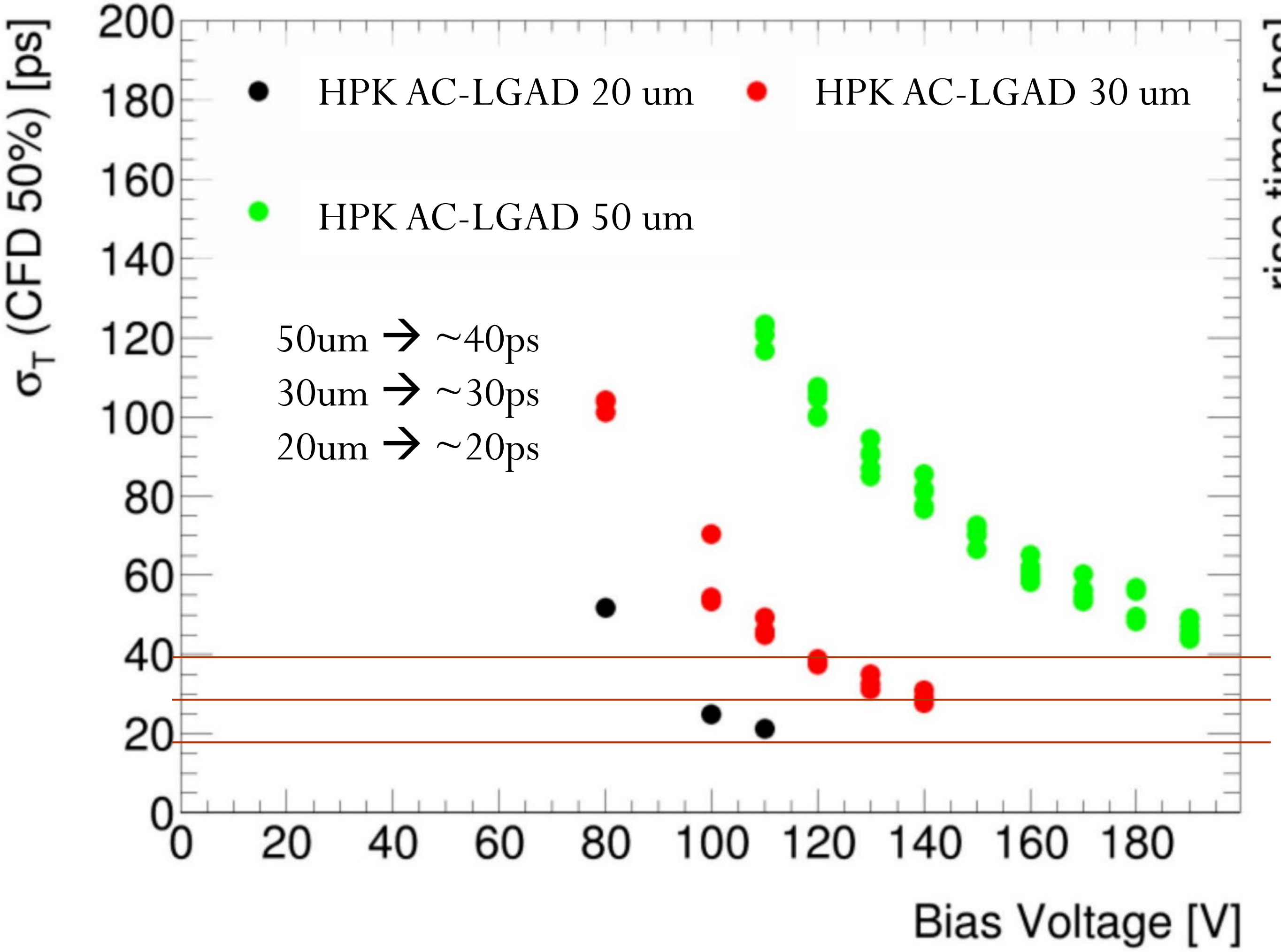
LGAD

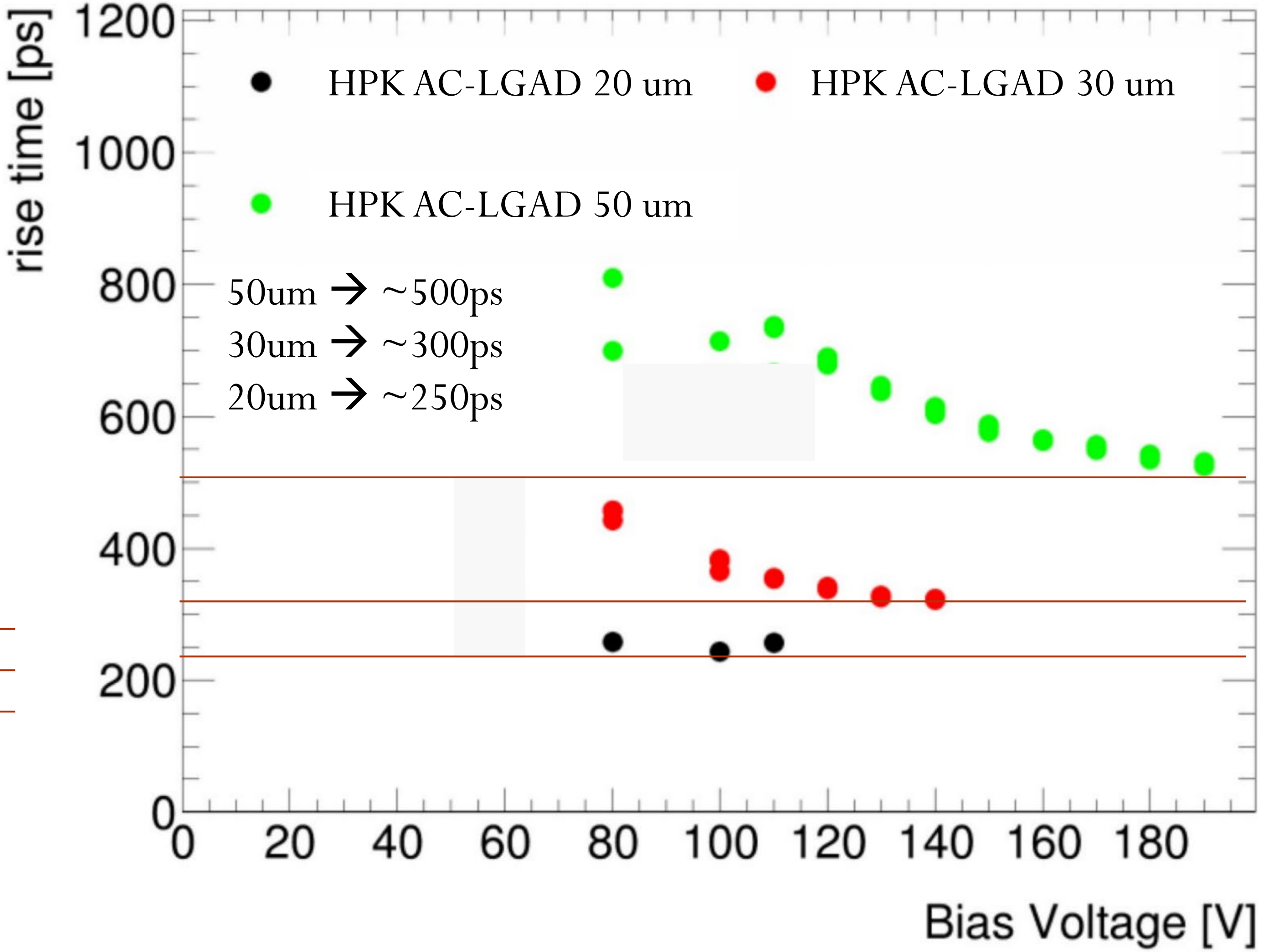


- Collected charge from a MiP is proportional to sensor thickness: a standard silicon detector needs to be a few 100s um thick to get a decent S/N
- **Thanks to gain LGADs can be thinner, with a shorter pulse with better S/N**

Time resolution vs thickness

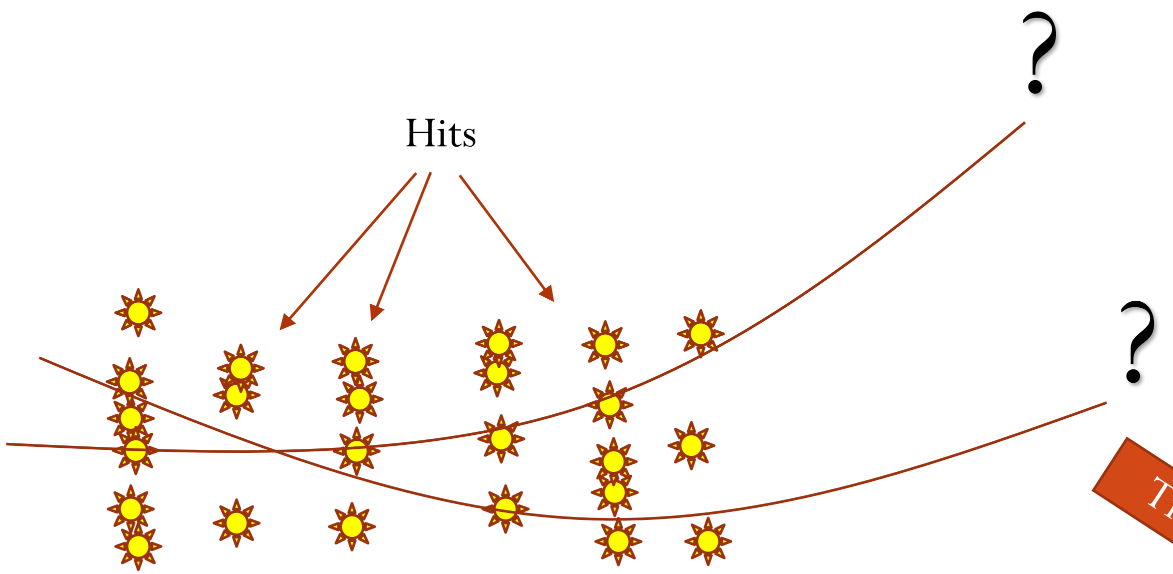
- When sensor has high gain there's **very low jitter contribution** to the time resolution, ultimately driven by Landau component → **Depends on sensor thickness**



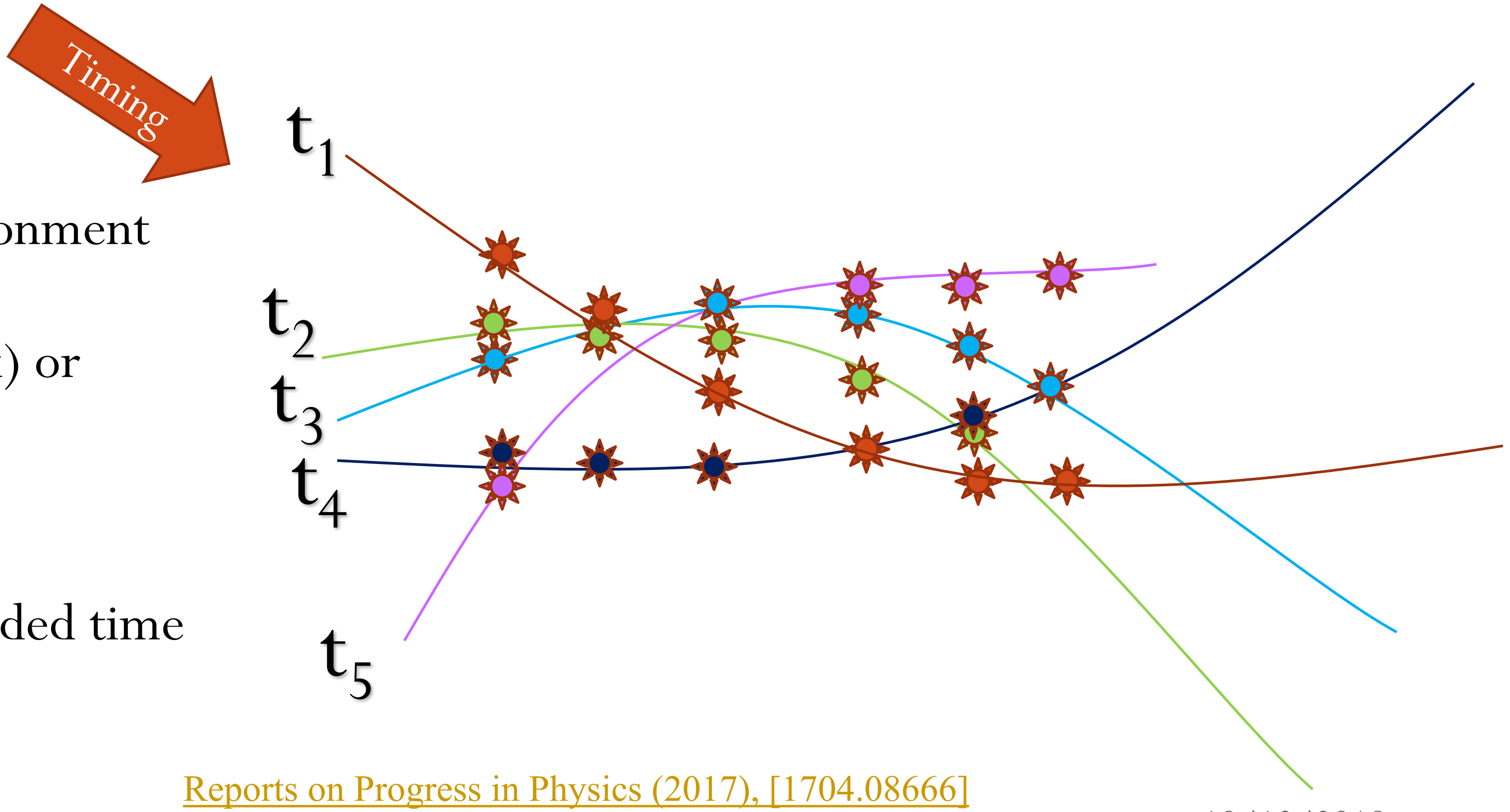


Data by: J. Ding

4D tracking - concept



- Efficient tracking in dense environment
  - Pile-up suppression
  - Long Lived Particle detection
  - Appearing/Disappearing tracks identification
  - ToF-based particle identification
  - Jet flavor tagging enhancement



- Collection of hits for multiple tracks in dense environment
  - Harder to reconstruct tracks with usual algorithms
- But if particles have different initial position (vertex) or delayed in time (from pileup)
  - We can exploit the **time** of the single hits
- Easier to reconstruct single tracks
- ~ps → ~mm at speed of light, 1→100ps is the needed time resolution for usual collider beam spot size

Reports on Progress in Physics (2017), [1704.08666]

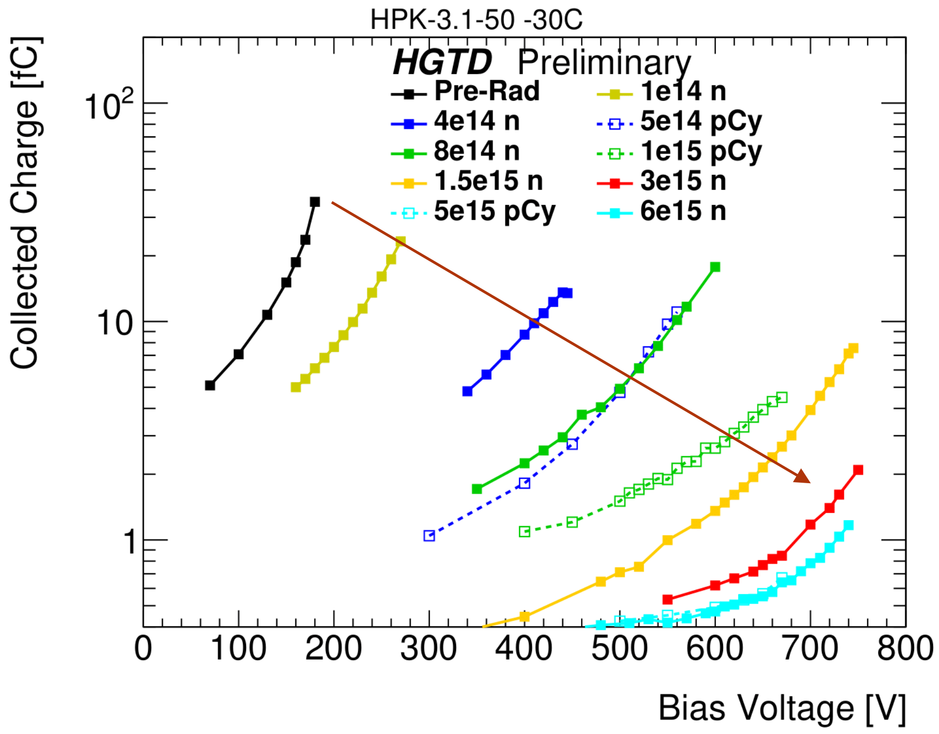
II. Radiation resistant LGAD design

Radiation hardness challenge

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LArHGTDPublicPlots#2018_2019_Sensor_Performance_TDR

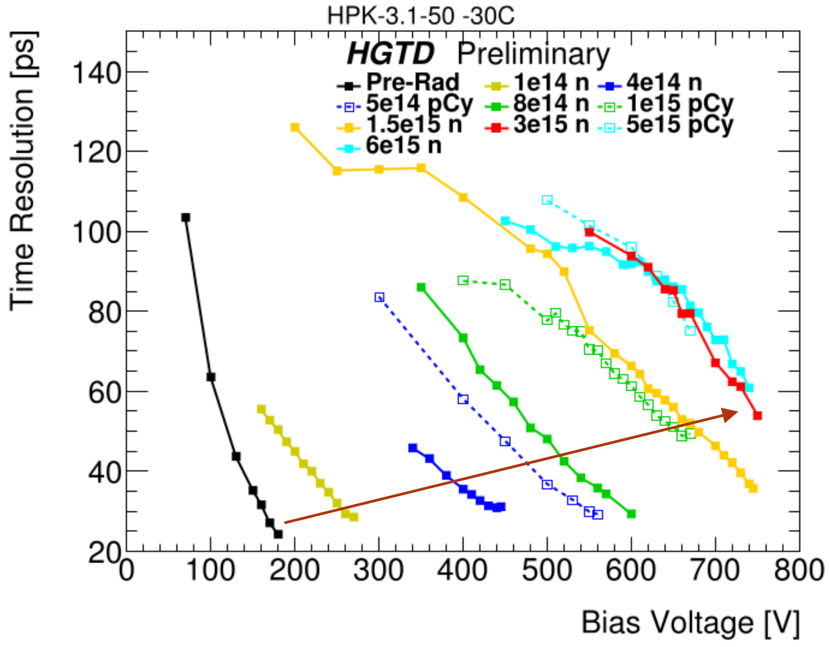
LGAD and radiation damage

- LGADs while operating in high energy physics experiments will sustain radiation damage
  - Both in terms of fluence and ionization dose
- Change in performance caused by reduced doping concentration in the gain layer by **acceptor removal mechanism**
  - Some details: https://doi.org/10.1016/j.nima.2018.11.121



Performance effects of radiation damage (E.g. on 50um sensor)

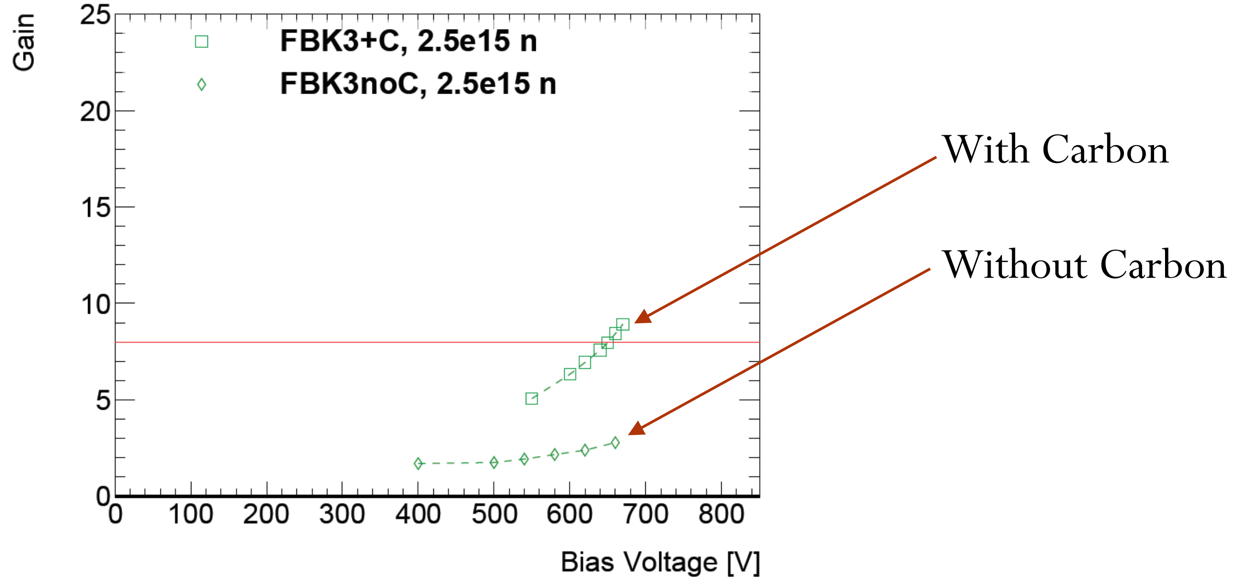
- Partly the performance can be recovered by increasing the bias Voltage applied to the diode (~200V → ~700V)
- **Reduction of gain and collected charge**
  - Charge collected up to 30fC (Gain ~50) before irradiation to 1fC (gain 2-3) after a fluence of 6E15 Neq/cm^2
  - (Neq: equivalent 1 MeV neutrons on cm^2)
- **Increased time resolution**
  - Time res. of 25ps to 60ps after a fluence of 6E15 Neq/cm^2



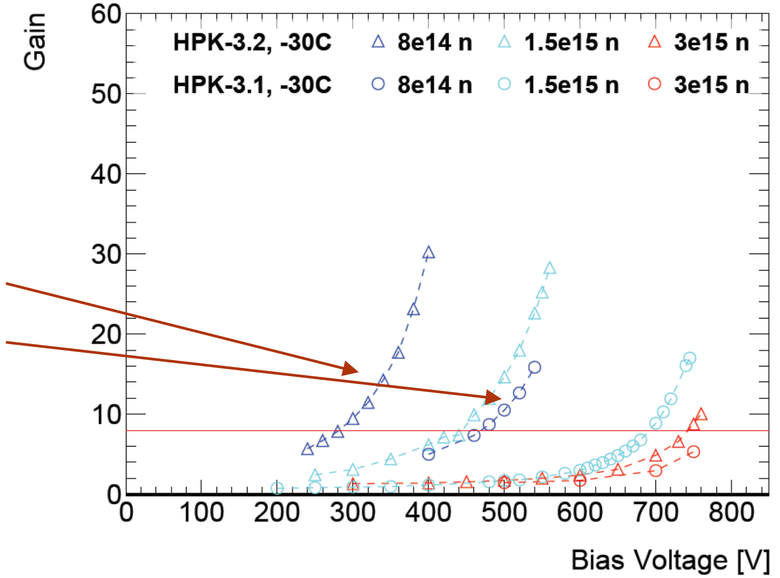
Radiation hard LGAD design

Radiation hardness of LGADs can be increased by:

- **Thin but highly doped gain layer**
- **Addition of Carbon**
  - Carbon is electrically inactive (no effect pre-irradiation), catches interstitials instead of Boron, reduces acceptor removal after irradiation
- **Deeper gain layer**
  - High field for larger volume
  - Allows for better recovery of the gain from increased bias voltage after radiation damage
- The combination of all techniques (by FBK) allowed to **produce a sensor with gain ~20 at 2.5E15 Neq**

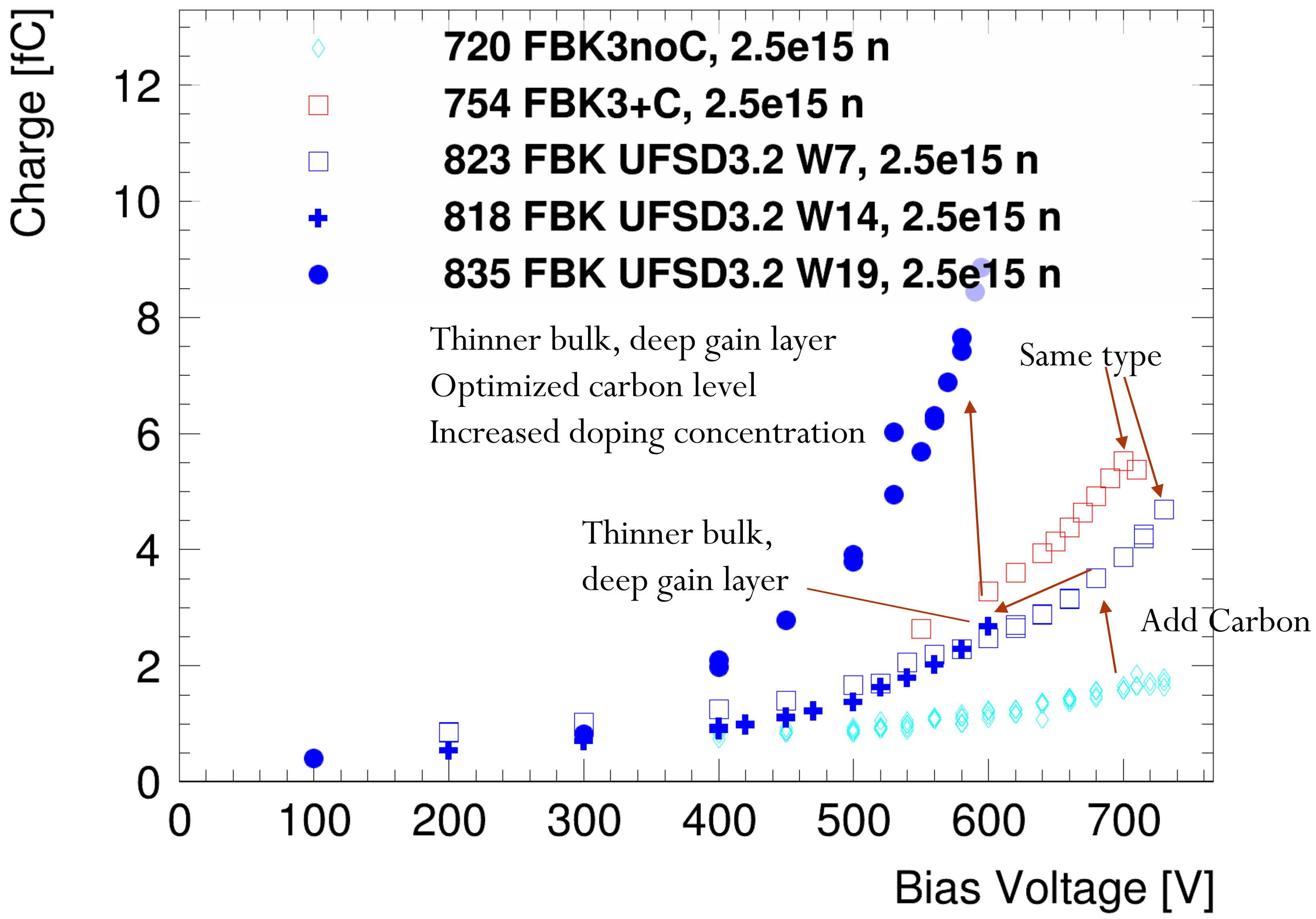


Deeper gain layer (triangles)
Less deep gain layer (circles)
(same color, same fluence)



- Resources
  - https://iopscience.iop.org/article/10.1088/1742-6596/2374/1/012173/meta
  - https://iopscience.iop.org/article/10.1088/1748-0221/15/10/P10003
  - https://www.sciencedirect.com/science/article/pii/S0168900218317741
  - https://doi.org/10.1088/1748-0221/15/04/T04008
  - https://doi.org/10.1016/j.nima.2018.08.040

FBK LGAD performance at maximum irradiation



- **FBK UFSD3.2 sensors show the great potential of deep gain layer and Carbon implantation**
- FBK3noC (no carbon) has the worse performance
- FBK3+C and FBK UFSD3.2 (same structure with Carbon) have much better performance
- FBK UFSD3.2 W14 with deep gain layer is similar to FBK3+C but has thinner bulk
  - lower initial charge, but better time resolution
- FBK UFSD3.2 W19 (highly doped, deep gain layer, optimized Carbon) best performance
  - **W19 has a higher starting point in gain layer doping to increase the radiation reach**

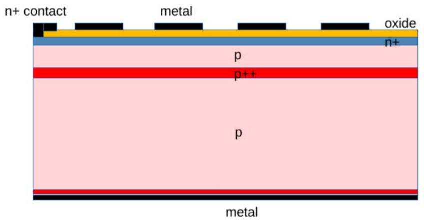
https://indico.cern.ch/event/983068/contributions/4223171/attachments/2191347/3703735/020221_TREDI_LGAD_radhard.pdf
https://indico.cern.ch/event/983068/contributions/4223173/attachments/2191413/3703863/17022021_MarcoFerrero.pdf
https://indico.cern.ch/event/983068/contributions/4223215/attachments/2192222/3705404/Siviero_TREDI2021.pdf

Radiation hardness for future colliders

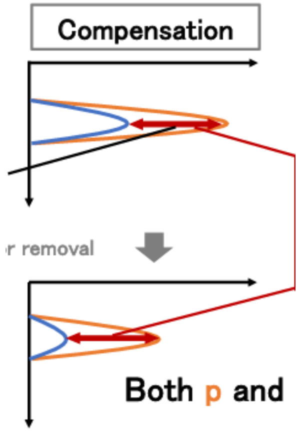
- **New technology** needs to be developed for future colliders with **high radiation hardness requirements** ($10^{16\text{-}17}$ Neq/cm^2) and **high occupancy** (e.g.: FCC-hh)
- With R&D effort in ATLAS/CMS in ~6 years **x10 improvement in radiation hardness,** up to 2.5E15 Neq/cm^2
  - Need for order of magnitude increase in radiation hardness and higher granularity
- **Many efforts are ongoing to push the radiation hardness of LGADs**
  - Rad-hard timing electronics also needs to be developed hand-in-hand

Radiation hard

Buried-LGAD

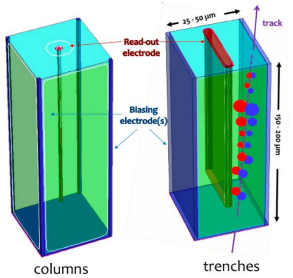


Compensated gain layer

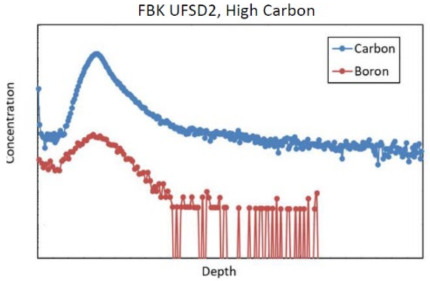


?

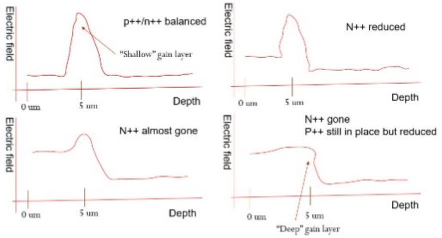
3D trenches



Carbon implantation
Carbon shielding



Adaptive gain layer



Inactive Boron,
Low diffusion

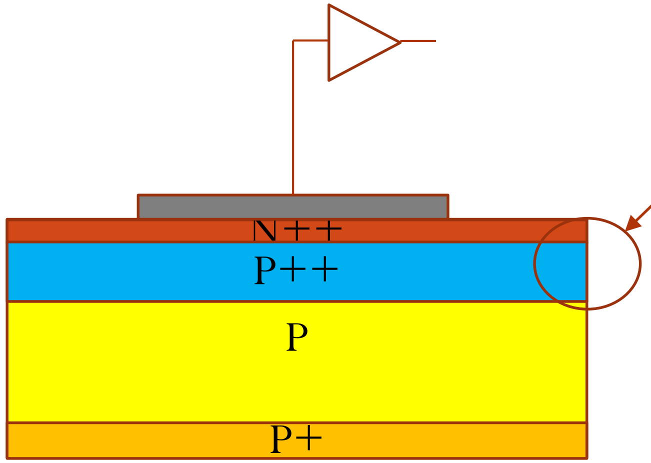
LGAD CMOS

Snowmass papers: 4D tracking paper, CMOS, Electronics, SiC, 3D integr.

III. High granularity LGADs

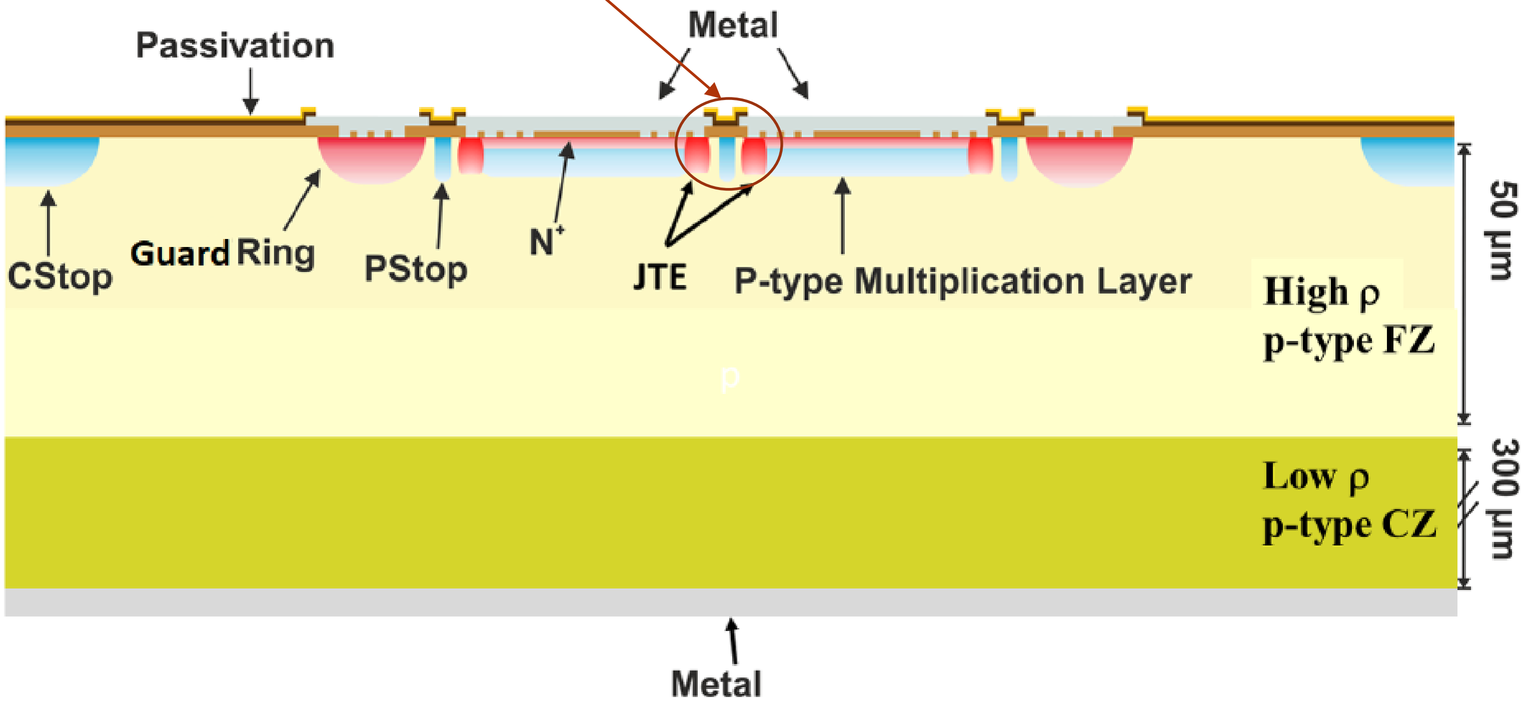
Granularity challenge

LGAD arrays structure



Very high field area, induces early breakdown

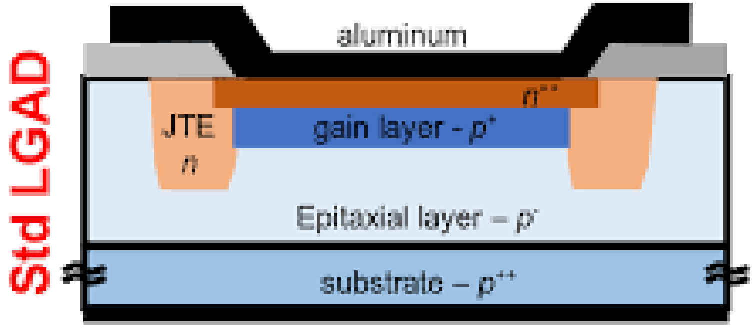
Structure to avoid high field line concentration at the edges
Junction Termination Extension (JTE)
Separation between the pads of an array **~50-100 um**



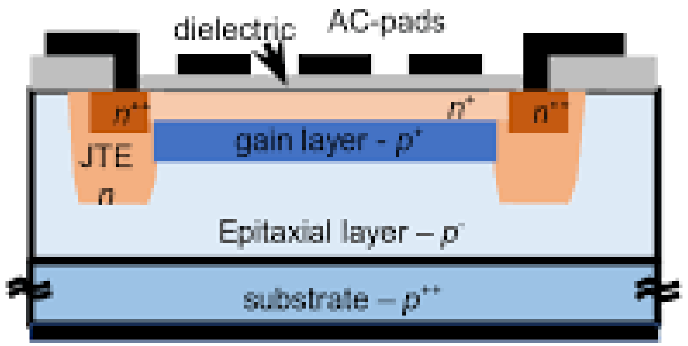
- Protection structures limit the current granularity of LGADs
- ~100 um pixel size would mean ~50% active area
- But intensive R&D is ongoing to overcome this limitation

High granularity LGADs

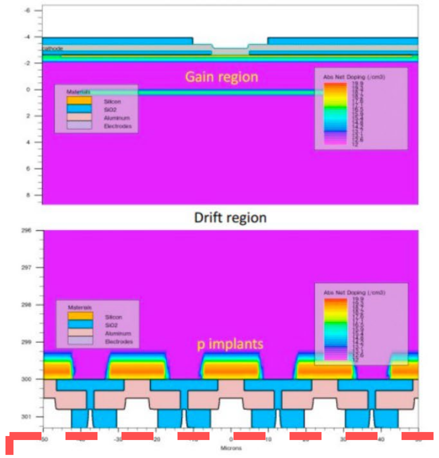
- First LGADs relatively new (6-7 years ago)
- **Many recent innovative prototypes to increase LGAD granularity**



Traditional LGAD

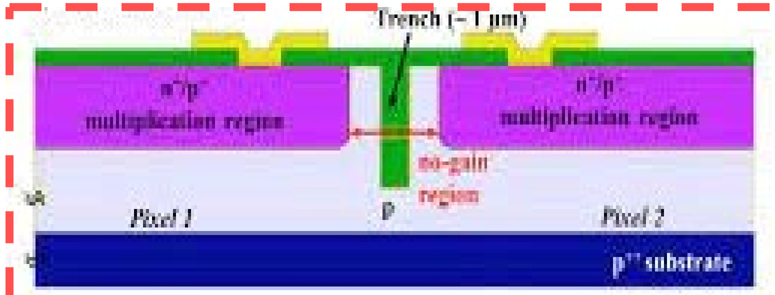


AC LGAD

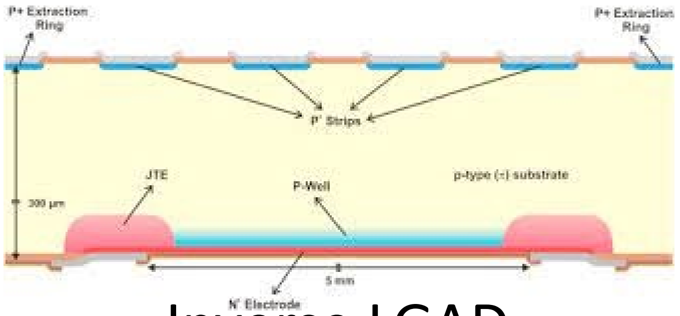


High granularity

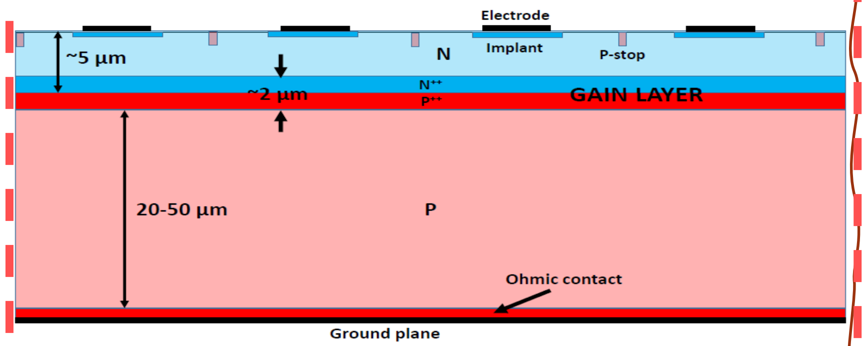
DS-LGAD



Trench-Isolated LGAD



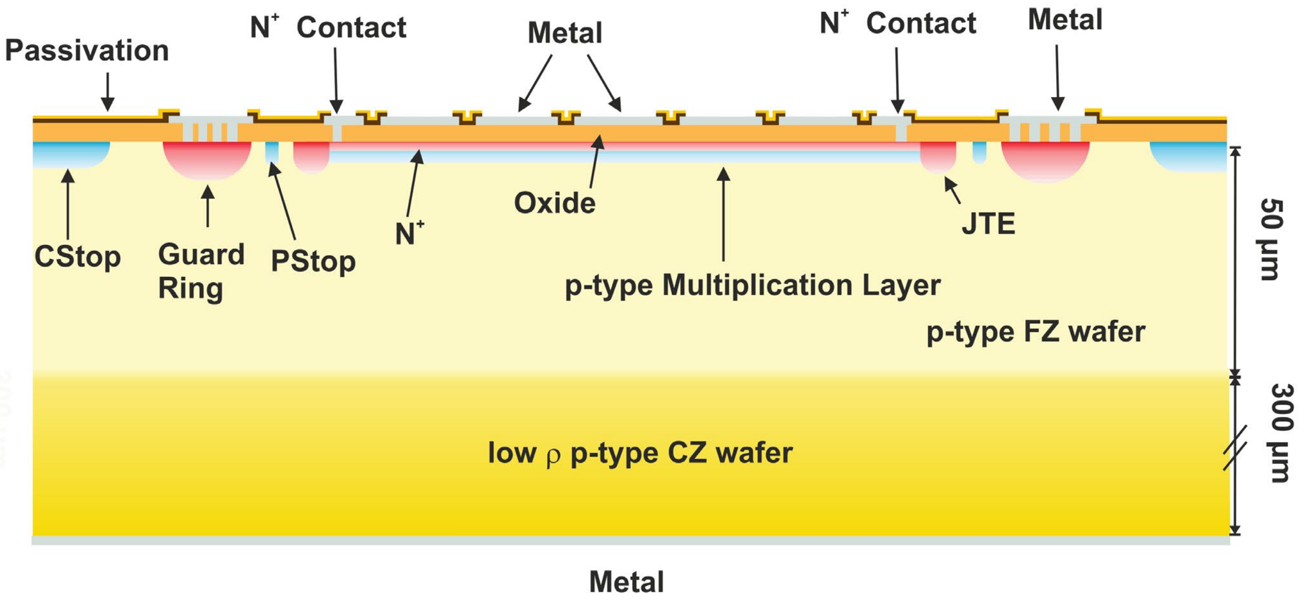
Inverse LGAD



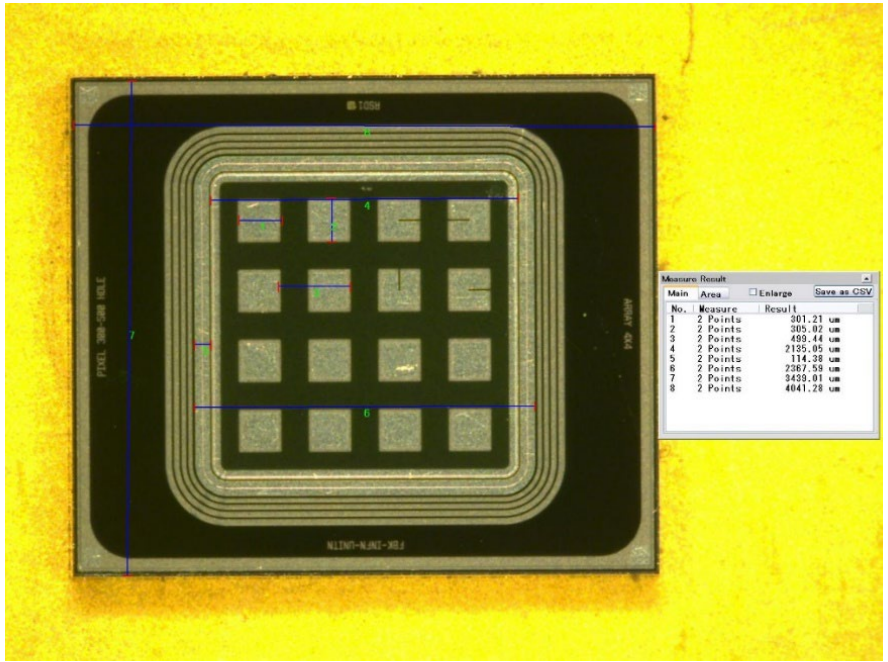
Deep-Junction LGAD

AC-LGADs

- Most advanced prototype are 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

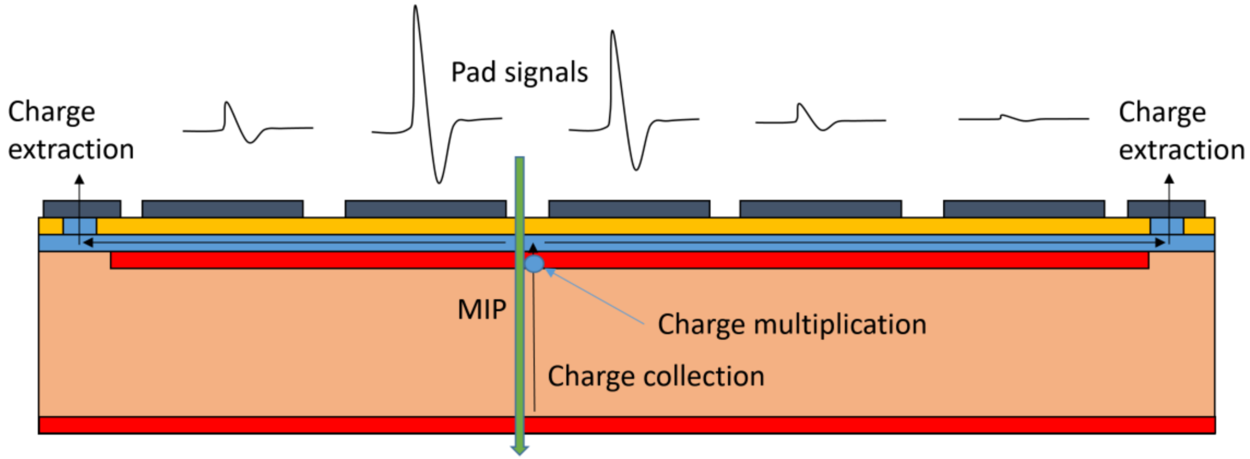


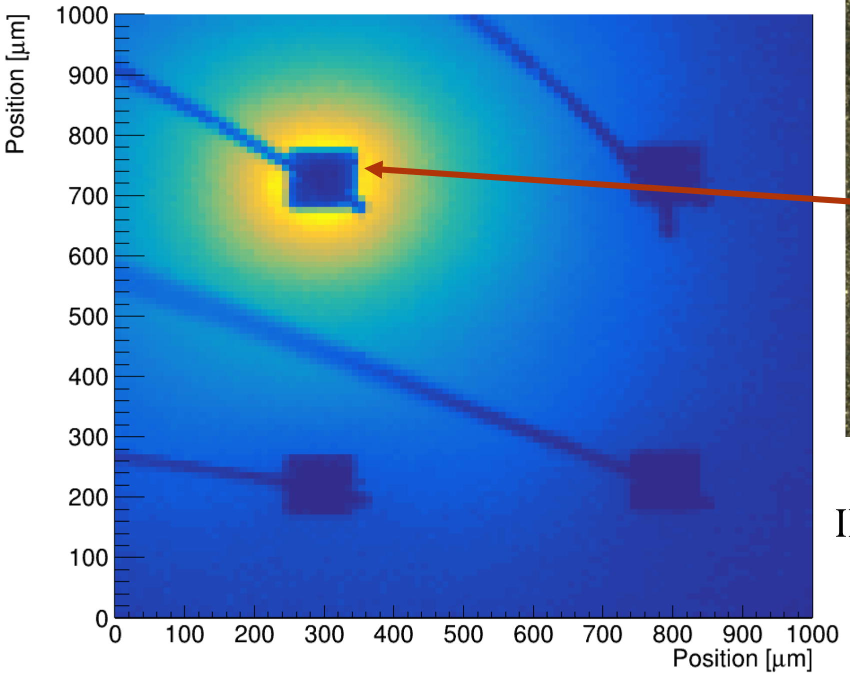
AC-LGAD hit reconstruction

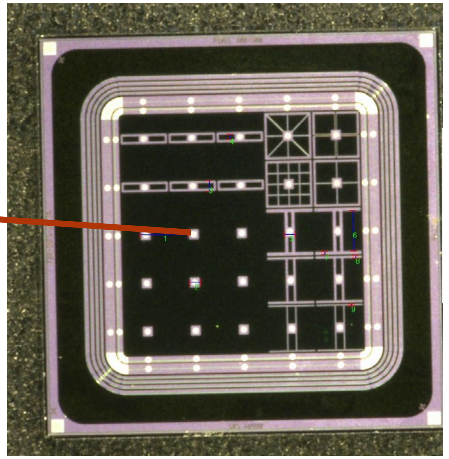
References:
https://indico.physics.lbl.gov/event/1262/
https://indico.cern.ch/event/918298/contributions/3880516/
https://arxiv.org/abs/2006.01999

- 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



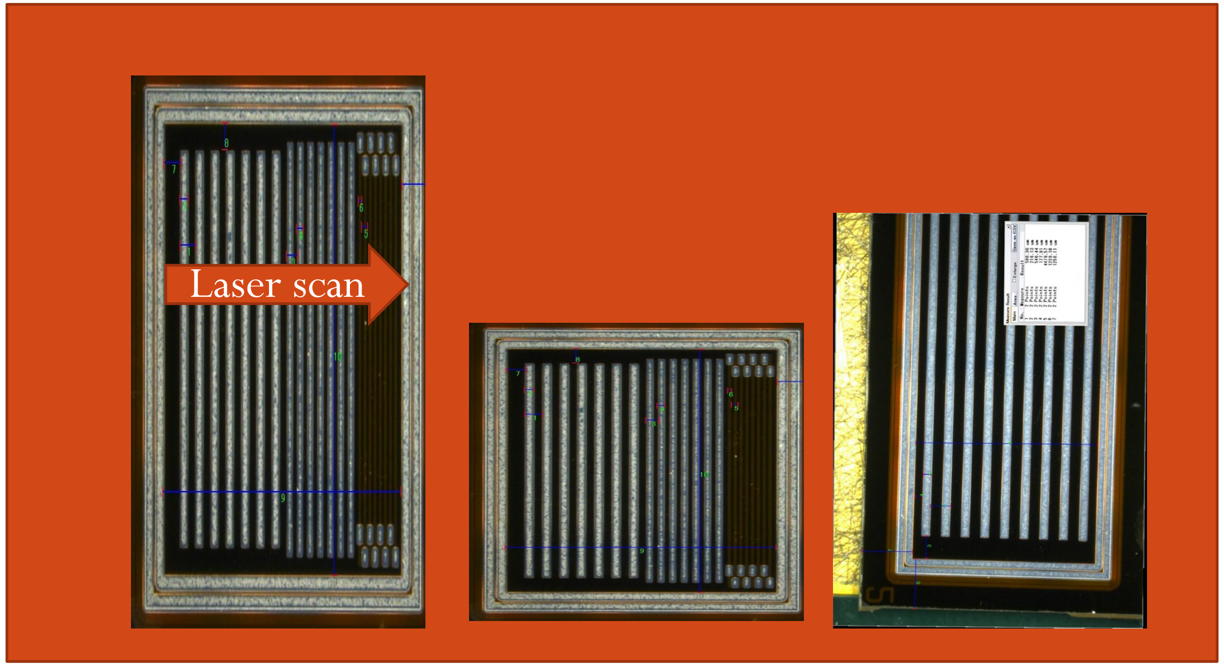


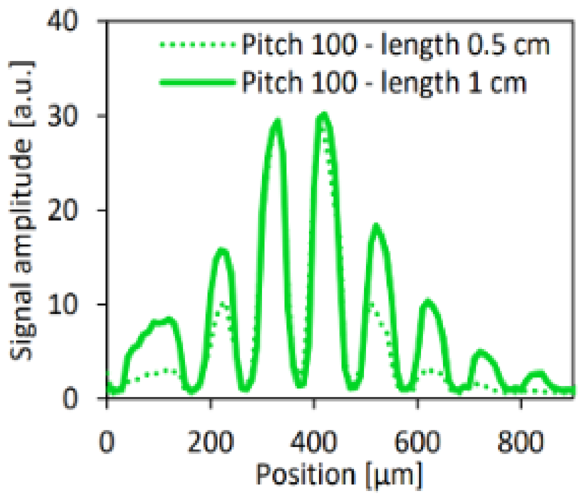


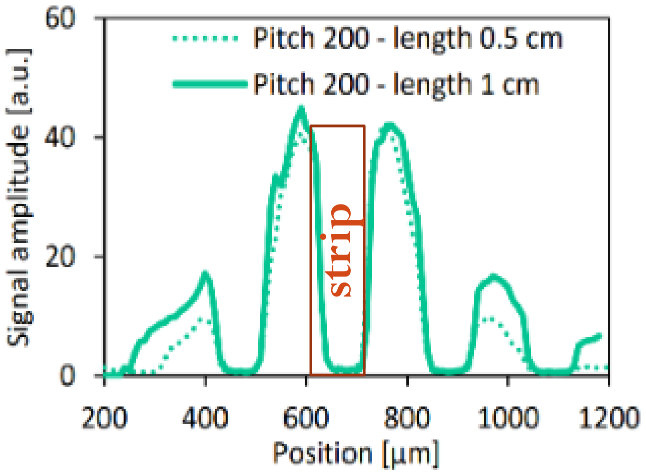
IR laser scan of the device

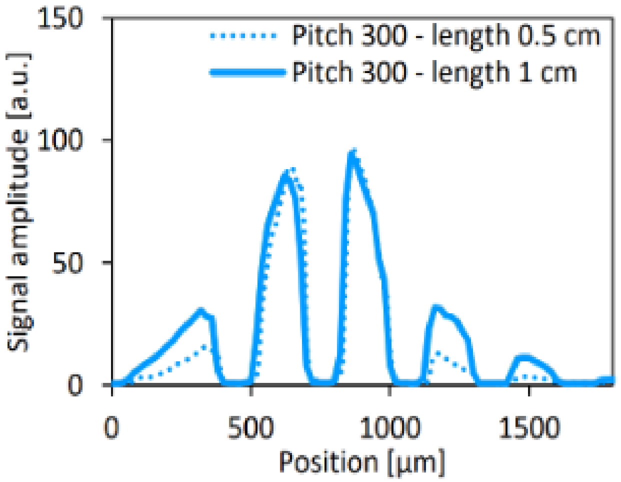
AC-LGAD strips studies

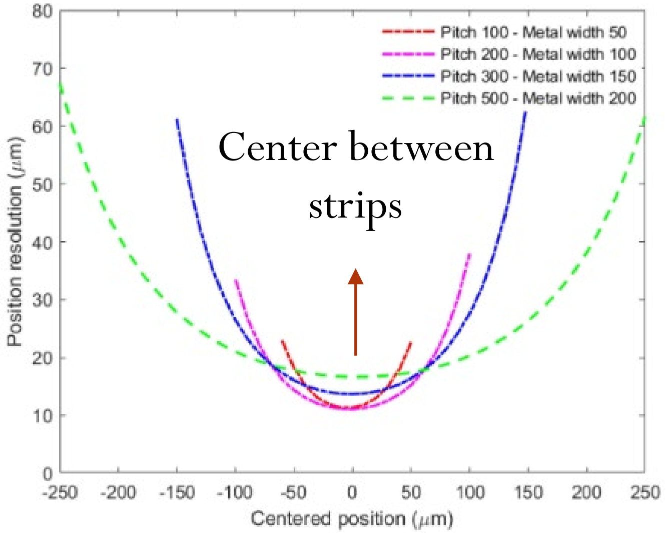
- BNL strip AC-LGADs with same geometry but different lengths
- Pitch and width in three configurations (width = pitch/2)
  - 300-150 um, 200-100 um, 100-50 um
  - 0.5 cm and 1 cm long sensors
- 2.5 cm long sensor with strips of 500-200 um
  - Charge sharing present up to ~2mm
- Direct comparison of geometry shows that **longer strips have increased charge sharing,** also depending on strip pitch/width
- Position resolution is similar in the 4 sensors in the center between strips, increases under the strip
  - **Position resolution is << than pitch/√12!**









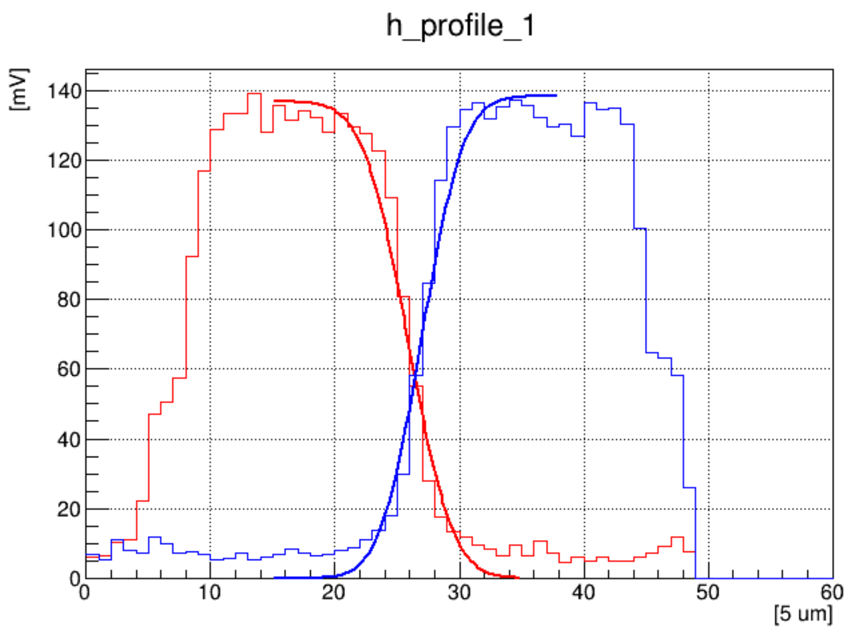


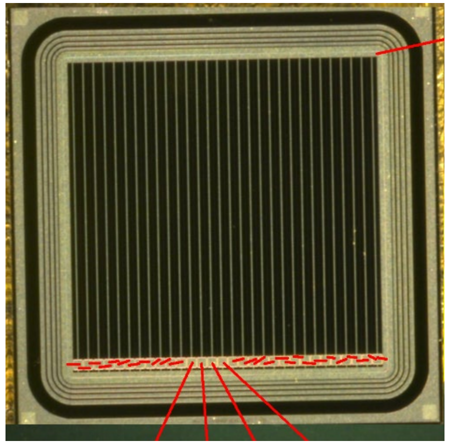
Response of one strip, data taken with IR laser (metal strips are opaque)

Data by: A. Das, C. Bishop, N. Yoho

Other high granularity LGAD technologies

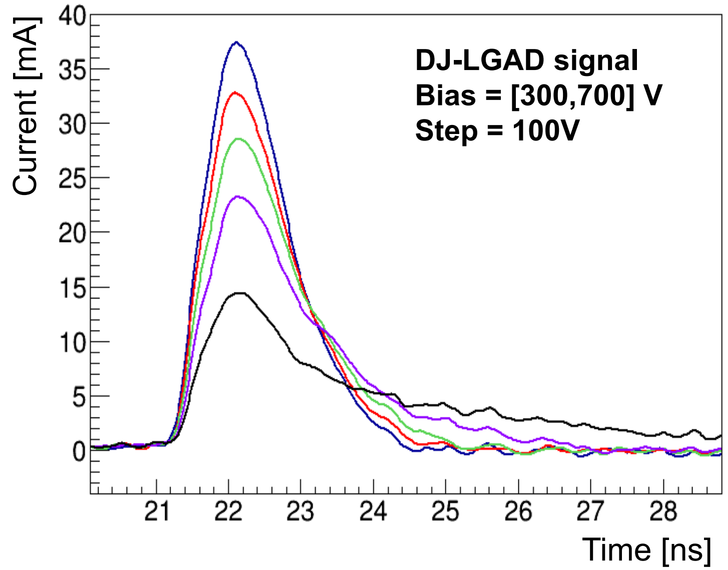
- **Trench insulated LGADs (TI-LGAD)**
- Pads insulated by deep trenches filled with oxide
- First prototypes successfully produced by FBK:
  - https://indico.cern.ch/event/861104/contributions/4514658/
- Very good performance observed!
  - IP gap 5-10 um or less
- Similar granularity as regular silicon sensors

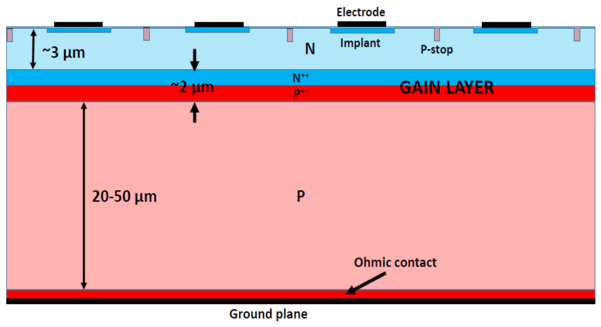




Prototype FBK TI-LGAD

- **Deep-Junction LGAD (DJ-LGAD)**
- Gain layer is buried, so the top can be segmented as in normal silicon detectors
  - https://arxiv.org/abs/2101.00511
- **First production completed** by Cactus material in collaboration with BNL and UCSC
  - Promising performance (gain of ~5) and good pad insulation (few um IP gap)
- Similar granularity as regular silicon sensors





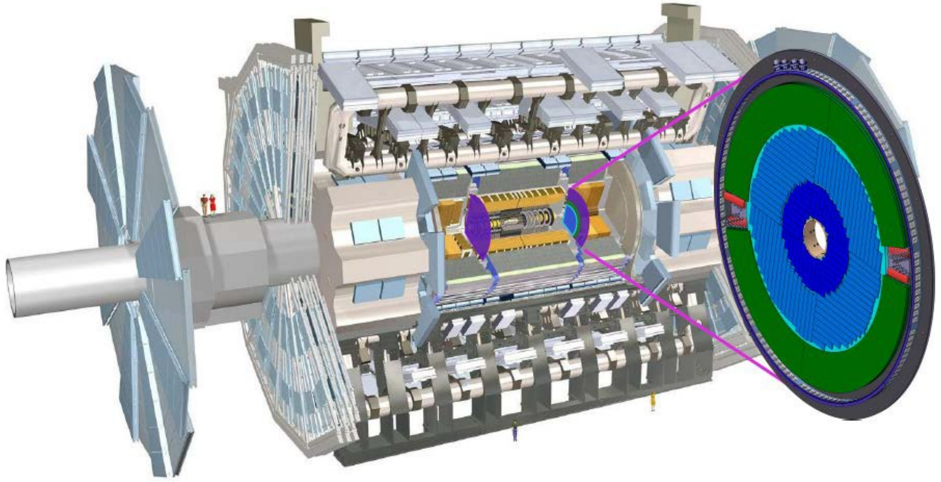
IV. LGADs application in HEP and NP

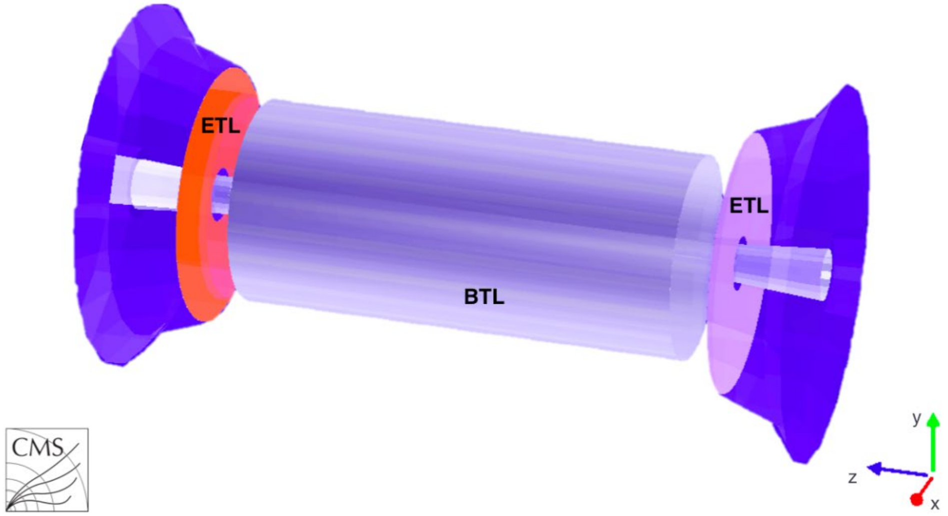
ATLAS and CMS timing layers

- First application of LGADs in HEP experiments at HL-LHC (~2027)
  - **Timing layers in the end-cap (forward) region to mitigate pile-up**

- **ATLAS** High Granularity Timing Detector (HGTD)
  - https://cds.cern.ch/record/2719855
- LGAD requirements for HGTD:
  - Radiation hardness to 2.5E15Neq, 4MGy
  - Time resolution <50ps per hit, collected charge ~10fC
  - Power (sensor-only) <100mW/cm^2
- As of now we have prototypes that satisfy and exceed these requirements!

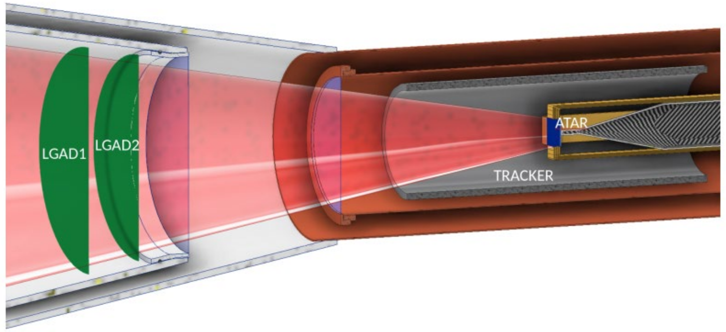
- **CMS** Endcap Timing Layer (ETL)
  - https://cds.cern.ch/record/2667167
  - CMS will also feature a timing layer in the barrel but with different technology (LYSO bars + SiPM readout)



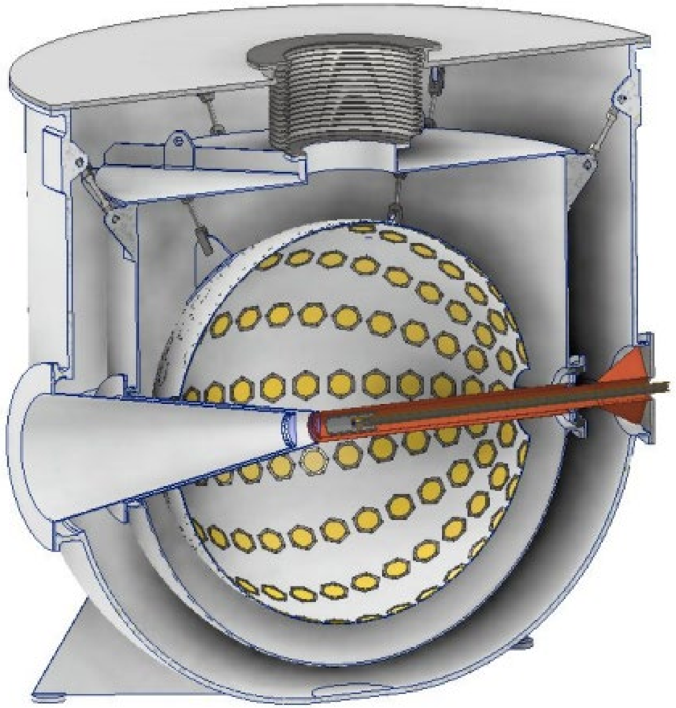


PIONEER

- **PIONEER** is a new rare pion decay experiment at PSI
  - https://arxiv.org/abs/2203.01981
- The goal is to **improve the precision of $R_{e/\mu}$** and **$B(\pi^+ \rightarrow \pi^0 e^+ \nu)$** by an order of magnitude
  - **$R_{e/\mu}$** is the ratio of pion decay to electron a muon: precision measurement of **lepton flavor universality**
  - **$B(\pi^+ \rightarrow \pi^0 e^+ \nu)$** is the cleanest measurement of Vud: very important to test **CKM matrix unitarity**

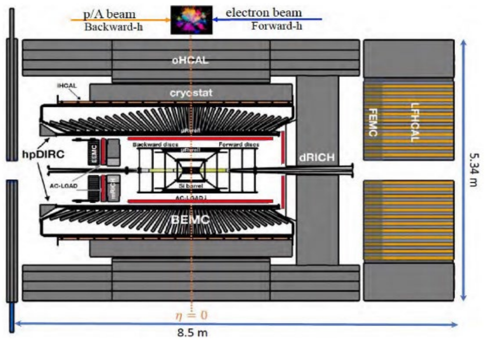


- PIONEER will feature a high granularity, time resolved fully silicon active target (a 5D tracker!)
  - 'Live' tracking of pion decay to see positron and muon decay channels
  - **Based on LGAD timing technology**
  - https://www.mdpi.com/2410-390X/5/4/40

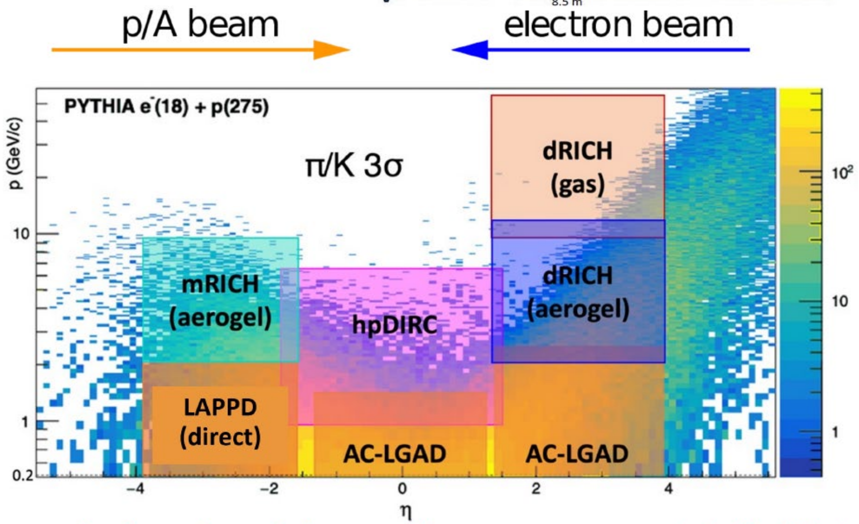


Electron-Ion collider (https://www.bnl.gov/eic/)

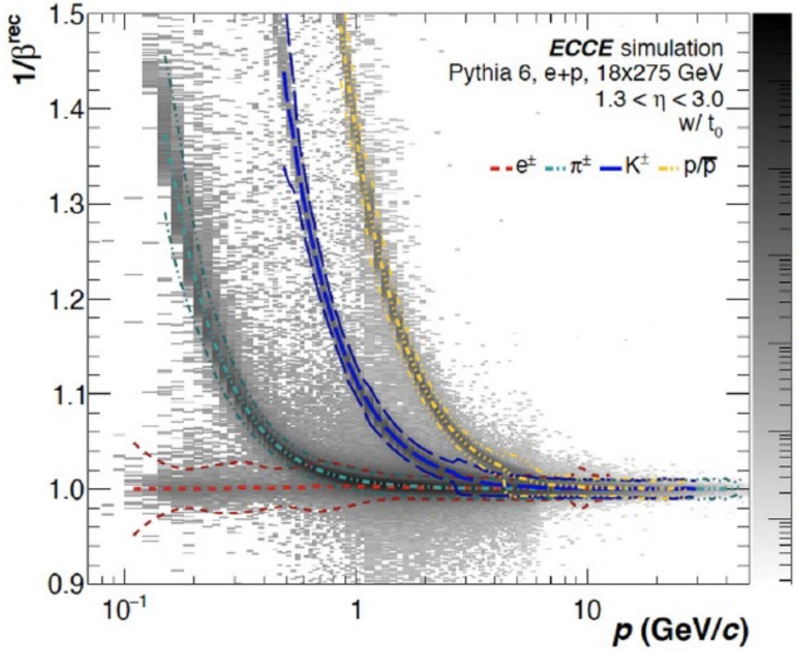
EPIC detector



- **4D tracking will be used in the EPIC detector**
- **AC-LGAD** is foreseen for both barrel and end-cap in EPIC
  - 500 um x 1 cm strip, ~1% X0 for **barrel**
  - 500 x 500 um pixel, 8% X0 for **forward**
  - 25 ps single hit time resolution
  - ~30 µm spatial resolution



- **Particle identification with time of flight (TOF)**
  - For e/π/K/p at low/intermediate momentum
- Require good time resolution and meaningful flight distance
  - Better with 4π coverage for t_0 determination



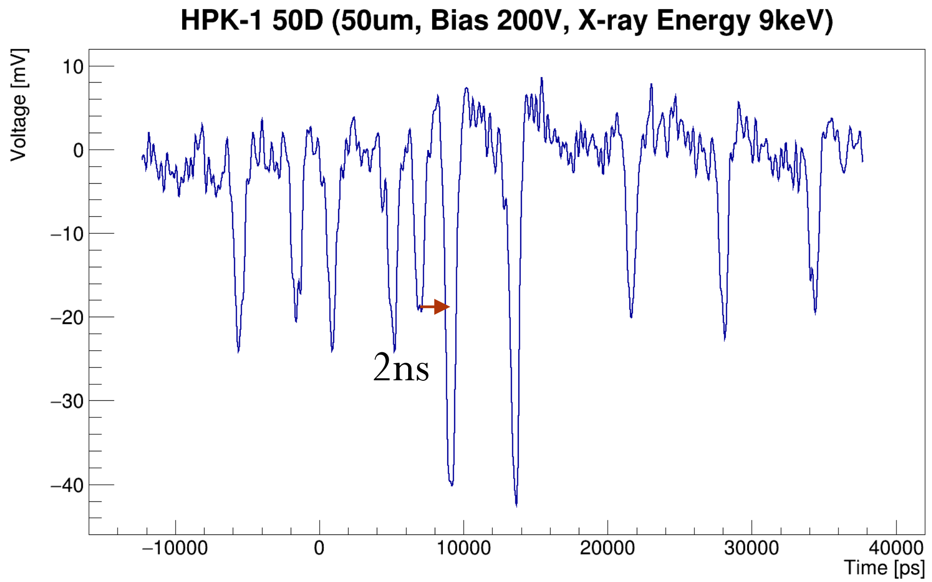
- E.g. around 30 ps at 0.5m (70ps at 1m) is required to have PID with momentum <0.5 GeV in the barrel
- https://indico.bnl.gov/event/13566/contributions/56042/attachments/38002/62629/LGADsConsortium_EIC_WeiLi_11012021_v1.pdf

V. X-ray detection with LGADs

X-rays detection with LGADs

- LGAD tested for X-ray detection at the **SLAC** Stanford Synchrotron Radiation Light source **(SSRL)**
  - Last test beam in November 2022, BL 11-2
- X-rays of energy range [5, 70] KeV
  - 50 um and 20 um thick detectors
- 50 um LGAD full collection time ~1 ns (can push to GHz repetition rate)
  - Definite pulses even with a **2 ns beam separation**
  - Small influence on shape from close-by pulses

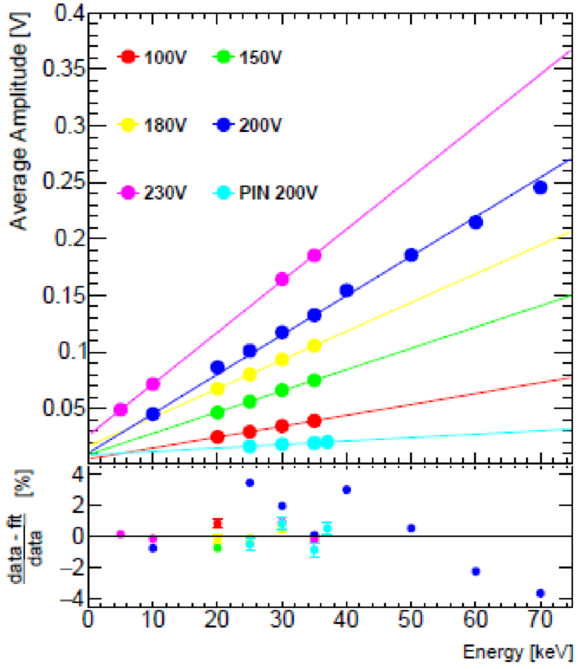
- Results on https://arxiv.org/abs/2306.15798 (submitted to JINST)

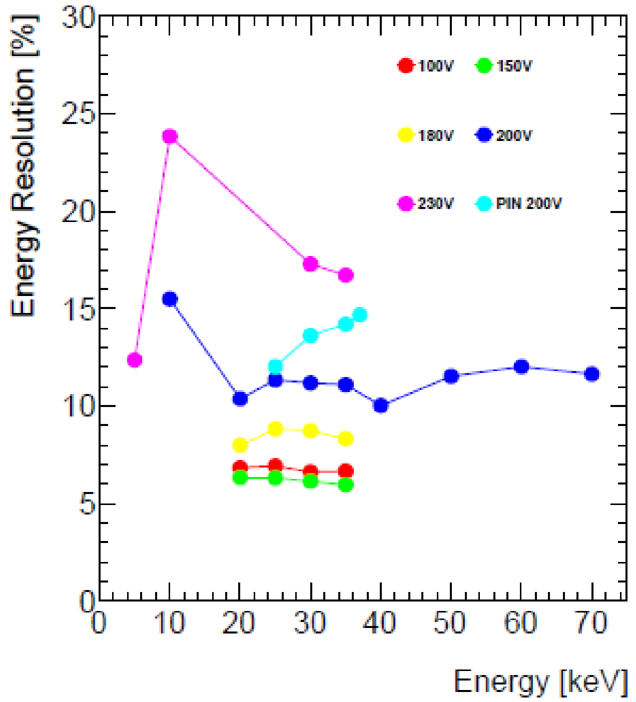


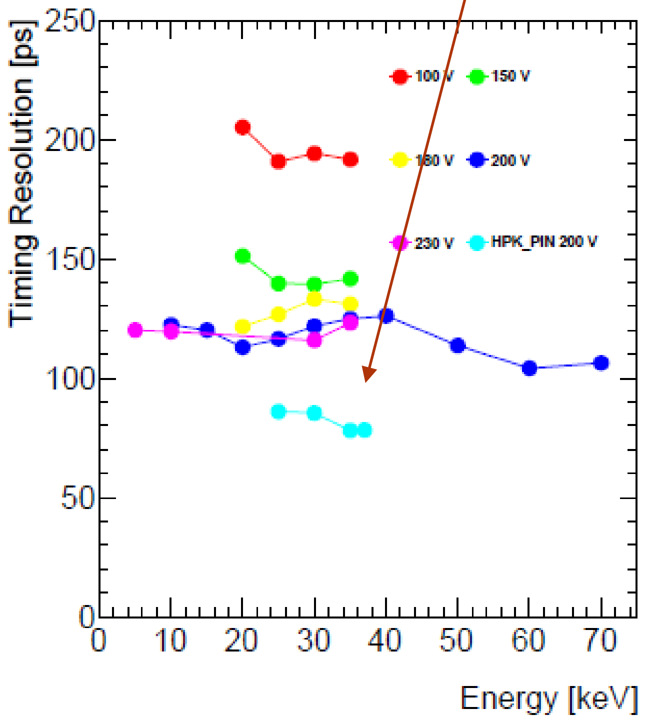
X-rays detection with LGADs

- Linearity and the energy resolution of different LGADs at different bias voltages
  - Good linearity, best energy resolution at lower voltages (low gain) of <10%
  - Thin PiN (no gain) device has energy resolution 10-15%
- **Time resolution 100-150 ps**: higher than MiP affected by X-ray interaction
- Shown results for HPK 3.1 (ATLAS HGTD production)
  - Tested AC-LGAD strip devices as well, energy resolution 10-20%

Why is PiN better at time resolution?
See next slide!

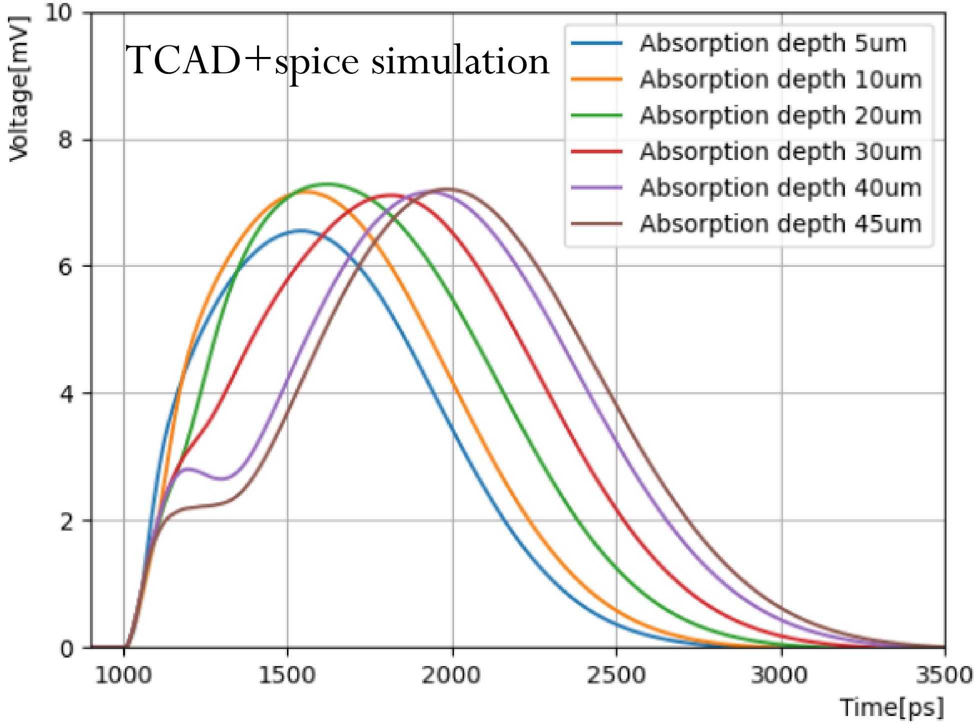




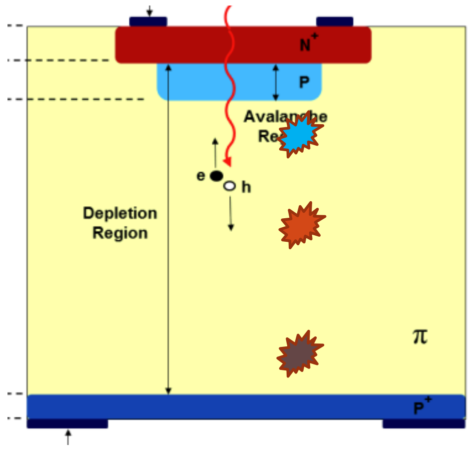


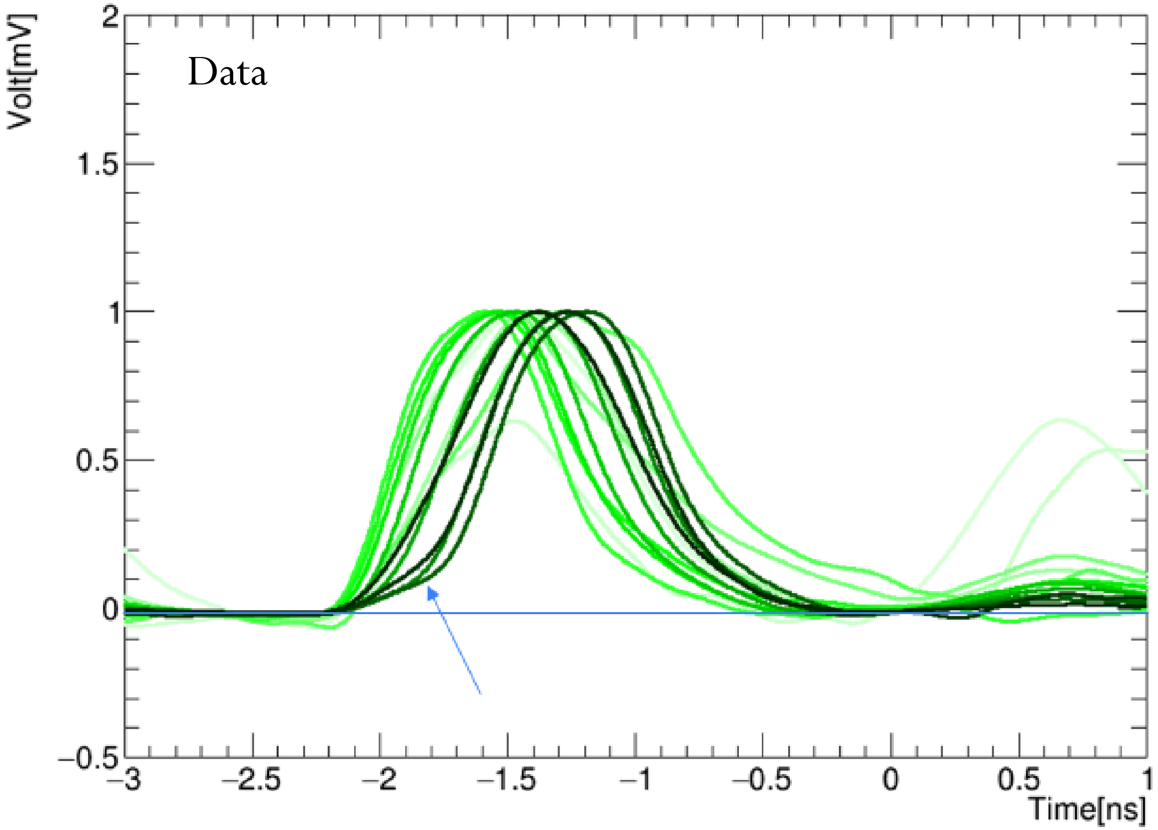
X-rays detection with LGADs

- X-ray interactions at different absorption depth in the LGAD: simulate with TCAD Sentaurus
  - Initial "flat top" of the pulse because of charge travel to the gain layer, delaying the gain process
- Observed the same behavior in the data
- This doesn't happen in the PiN since current is instantaneous



(b) Convoluted voltage signal with TIA.



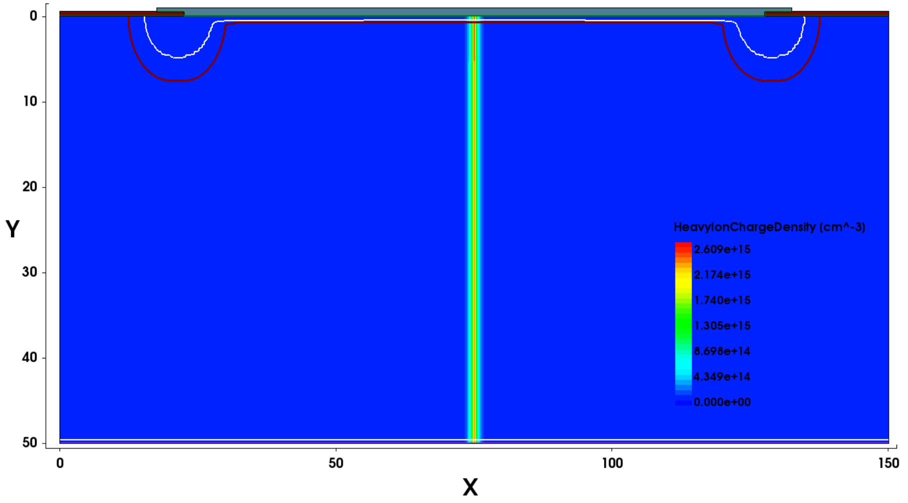


VI. Gain saturation

Gain challenge

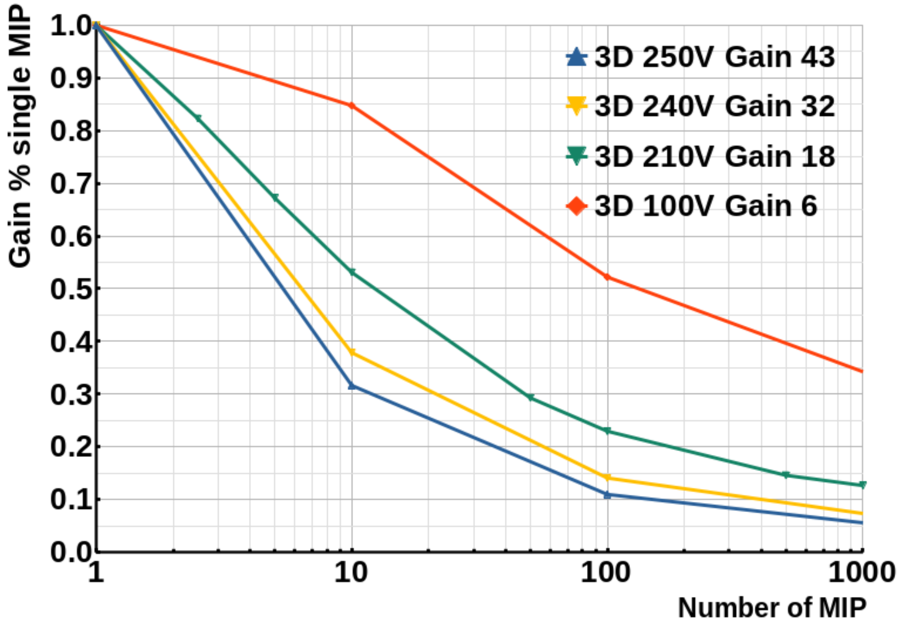
Gain saturation

- **LGAD gain suppression mechanism** being studied recently (https://indico.cern.ch/event/983068/contributions/4223231/)
  - Gain suppression observed experimentally with large energy depositions
  - Caused by the field shielding effect from the gain electrons/holes
  - Tested by many groups with an ion beams, lasers, alpha sources etc…
- Just tested at CENPA's (University of Washington) ion accelerator



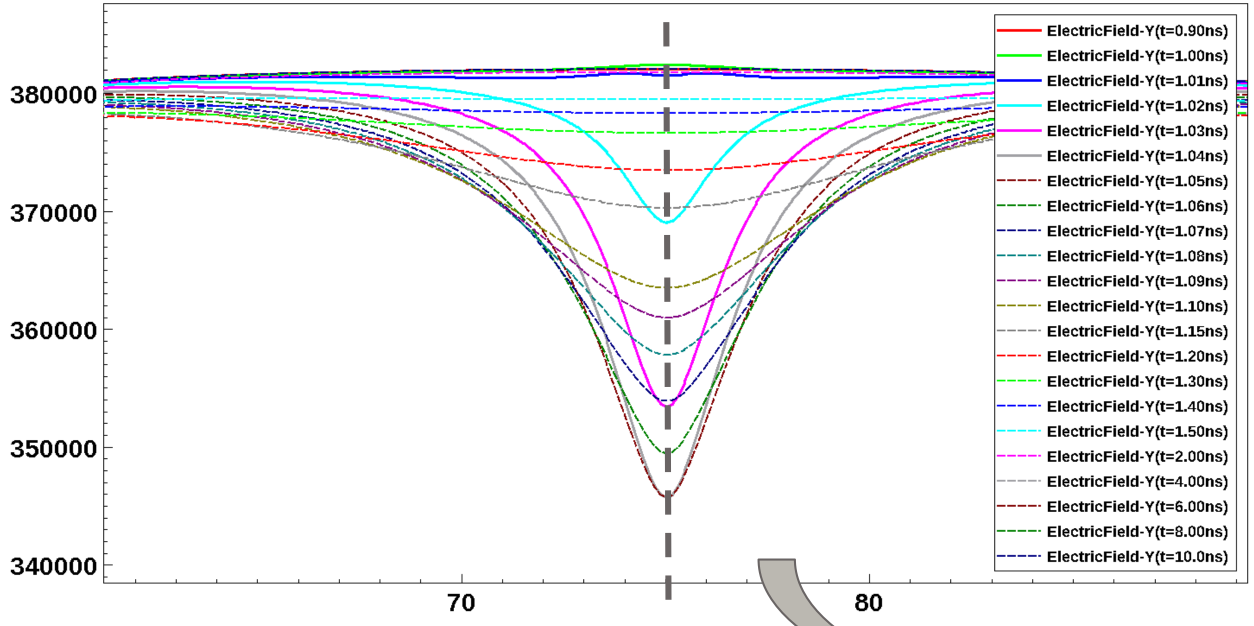
- **Effort to try and minimize this effect**
- Explore and characterize the gain suppression effects using **TCAD simulation**
  - Significant gain loss for high gain detector and high deposition
- **Simulation shows that with a low gain sensor the gain reduction is less**
  - Gain suppression can be reduced with adjustment in the sensor design
  - See: https://indico.bnl.gov/event/17072/contributions/70497/

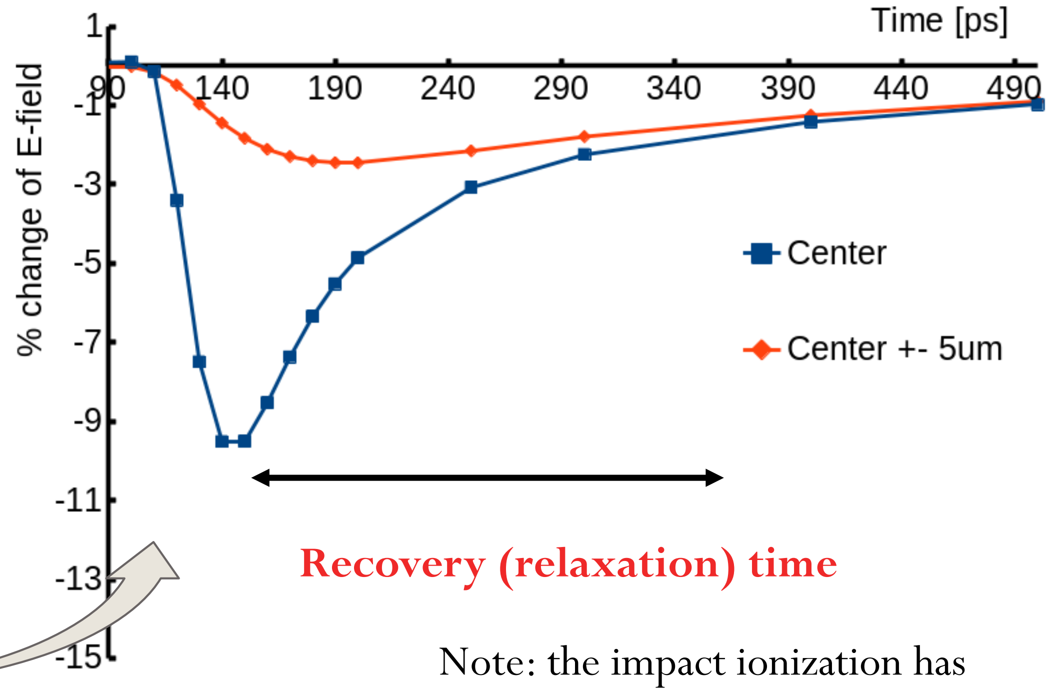
Gain suppression simulated with Sentaurus



Recovery (Relaxation) time of Electric Field

- Change in electric field in time and space
  - The **effect is local (range of 5 um)** and the **Electric fields returns to normal in few 100s of ps**
- **Recovery (relaxation) time**: the required time duration for the electric field within the gain layer to recover to steady state after the impact ionization process





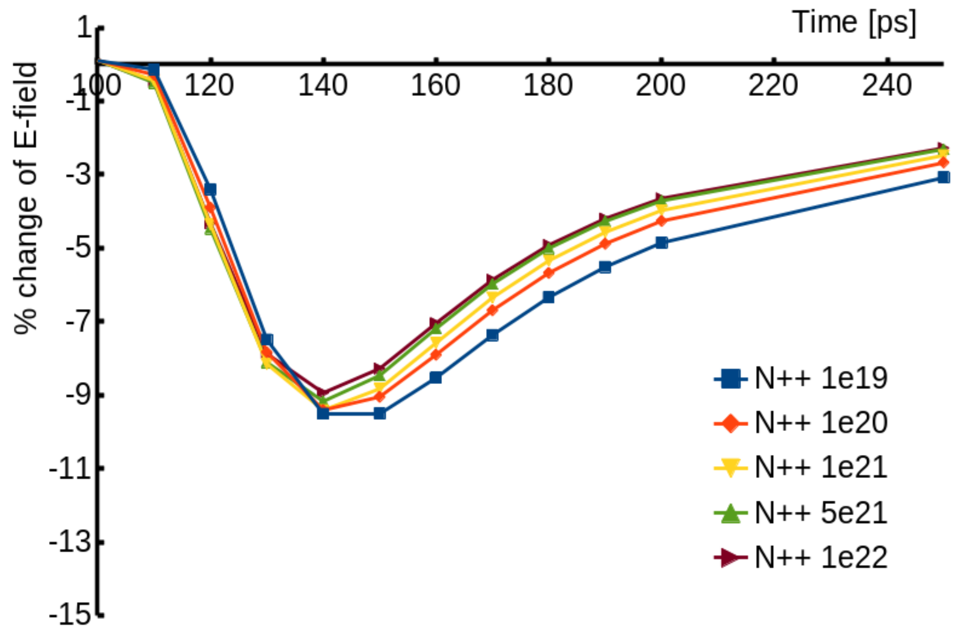
Snapshot of the electric field within the gain layer at different time for localized input charge.

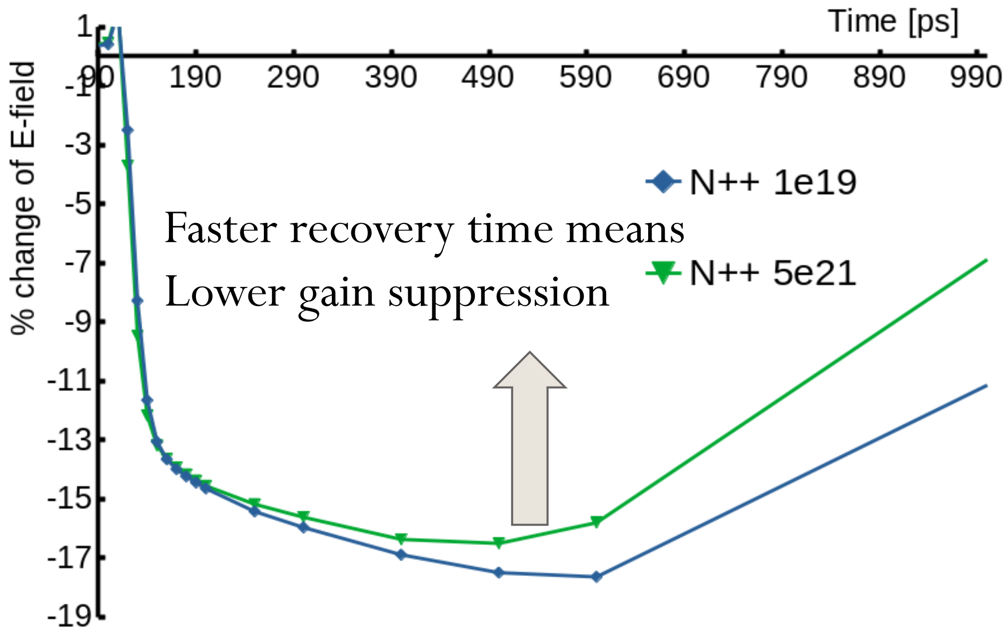
Note: the impact ionization has exponential dependence on the field.

Courtesy of Y. Zhao

Improving the Recovery Time

- The recovery time of the electric field depends on how fast the generated charges from impact ionization process are “drain” away.
- One approach is to **increase the conductivity of the gain layer profile configuration**. E.g. increasing the n++ doping concentration.
  - No more changes above doping of 5e21 N/cm^3
  - Reach limitation from transport of space charge in the gain layer itself.
- Another option: **increase the area where the multiplication happens** (deeper gain layer but lower field)
- Or spread out the charge as it gets collected: simulations and data taking ongoing

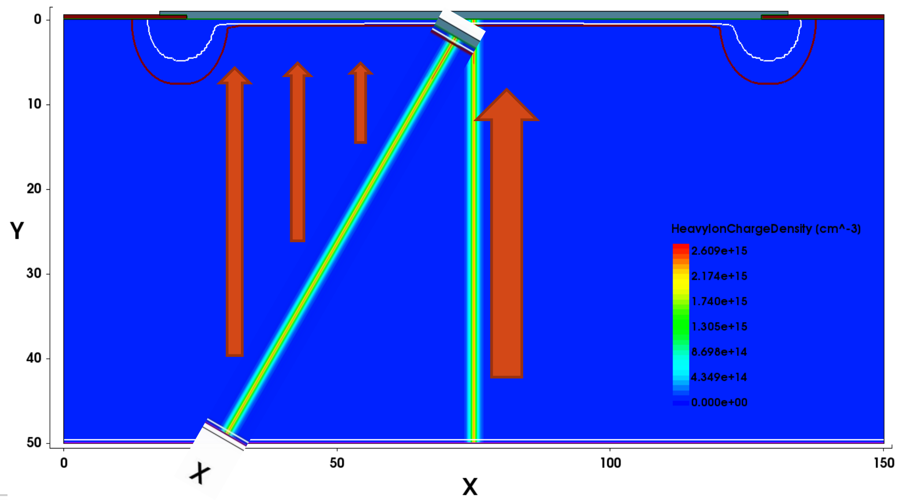


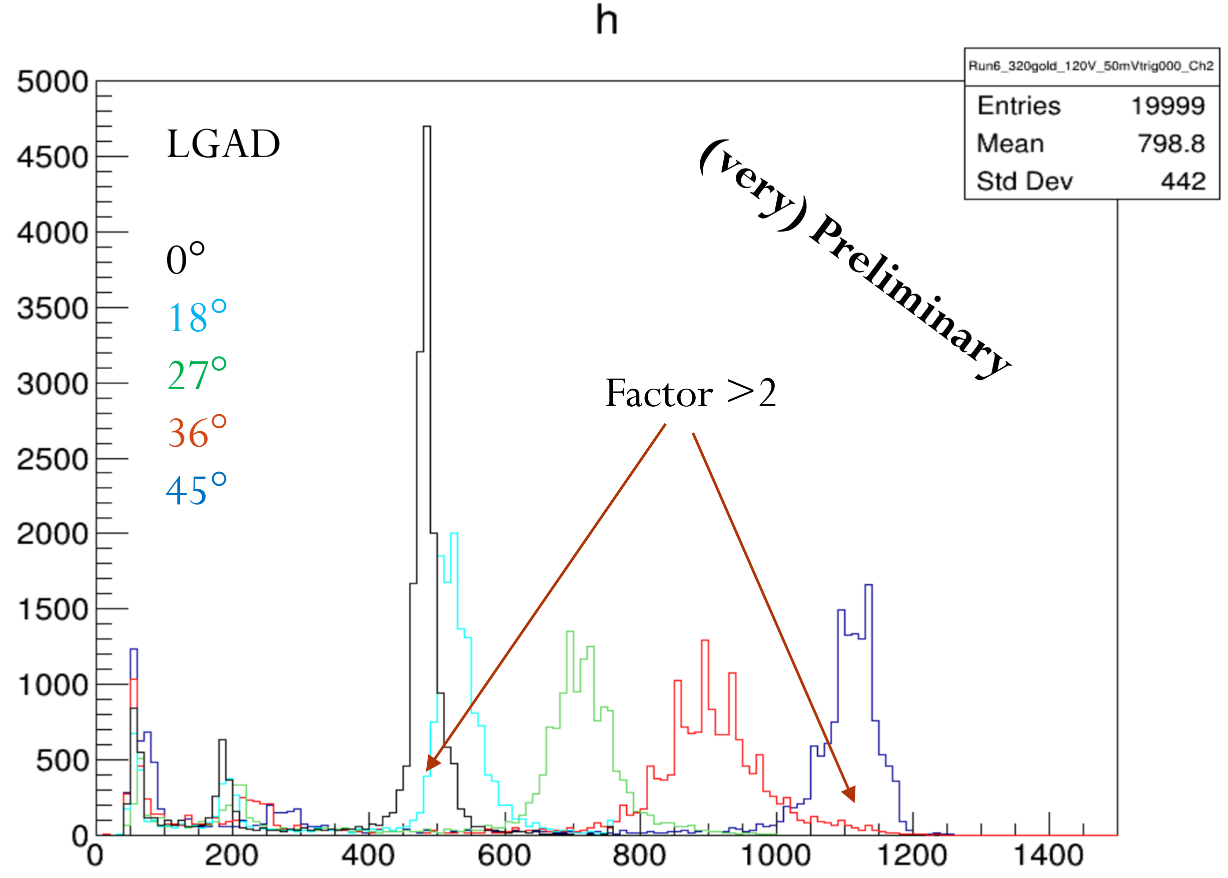


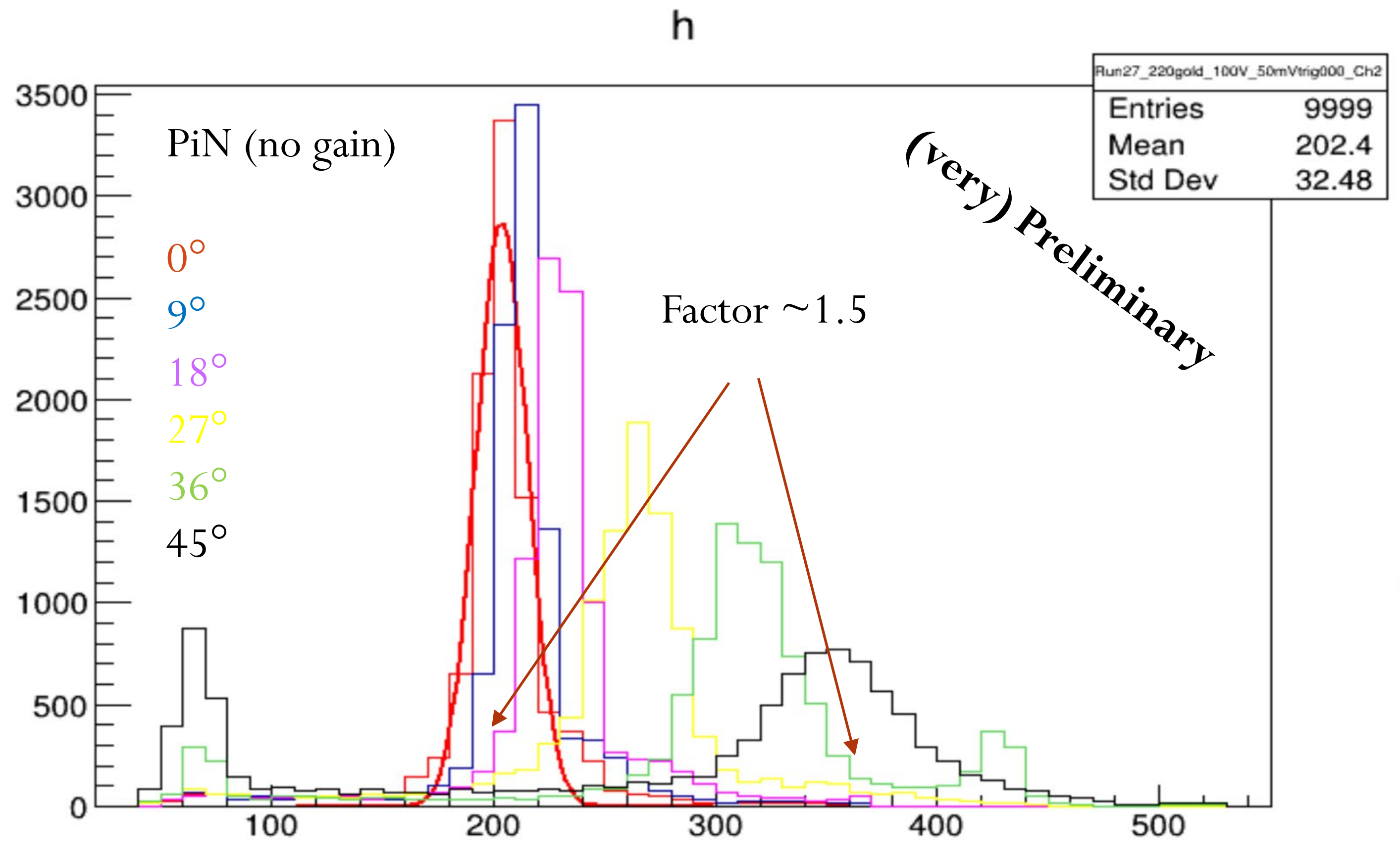
Courtesy of Y. Zhao

Ion beam studies at CENPA tandem accellerator

- Study of the gain suppression effect at the CENPA tandem accelerator
- Injection of large amount of charge with low energy protons
  - 2 MeV and 3 MeV protons, deposited charge of 30-70 minimum ionizing particles (MIP) equivalent
- Data taken at different angles, PiN response change linearly with angle, LGAD gain suppression makes it non-linear
  - Between 0° and 45° there should be a $\sqrt{2}$ factor. For LGADs is a factor >2 because of increased gain suppression at 0 °
- (very preliminary, data taken last week)



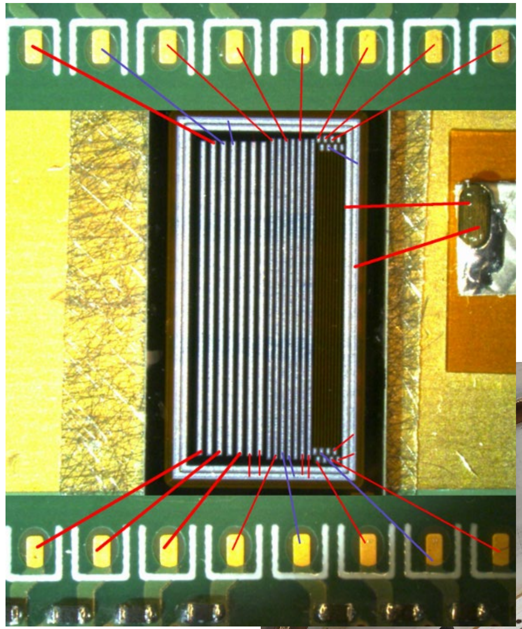


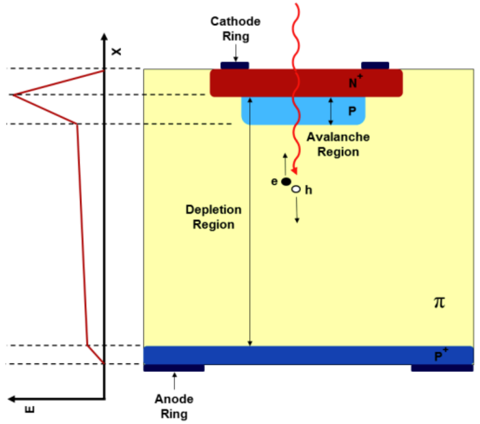


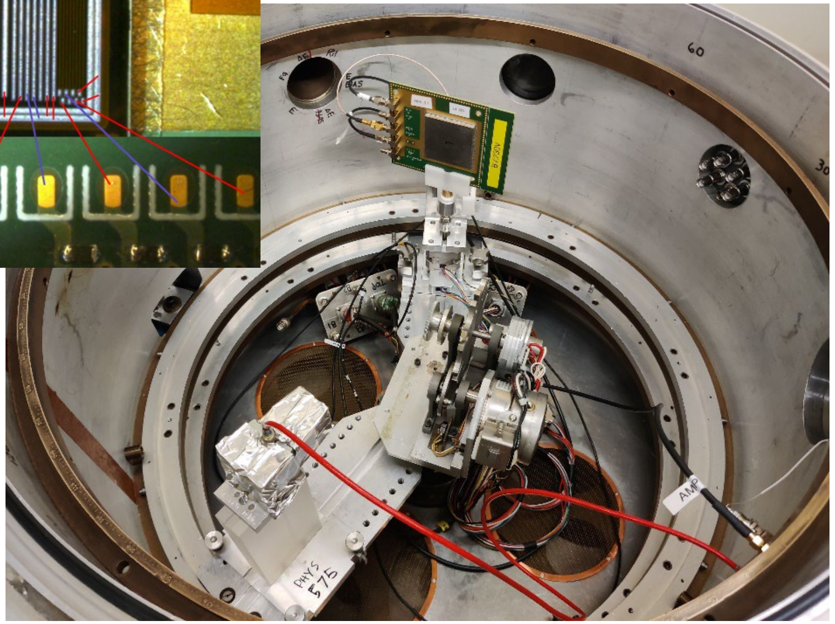
Conclusions

Conclusions

- **LGADs** are an interesting "new" technology
  - Fast pulses (~1ns), internal gain of 20-50, **exceptional time resolution**
- **Radiation hardness** proven up **to few 1E15 Neq**
  - Push to reach 1E16 Neq and beyond for future colliders
- **New technologies will allow dense LGAD pixelation**
  - TI-LGADs, iLGADs, AC-LGADs, DJ-LGADs
  - Maintain fast pulses (~1ns), internal gain of 20-50 and exceptional time resolution of LGADs but allow dense LGAD pixelation
- **AC-LGADs** are an innovative high density LGAD technology
  - Charge sharing mechanism reduces the channel count in low pileup environment
- **Future LGAD applications in many fields**
  - High energy physics (ATLAS/CMS)
  - Nuclear physics (ePIC, PIONEER)
  - Low energy X-ray detection
  - Fast beam monitoring
  - … Medical science (TOF PET) … space …











Thanks for the attention

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Thanks to FBK, HPK, BNL to have provided sensors for this study

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grant DE-FG02-04ER41286

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CACTUS DJ-LGAD SBIR
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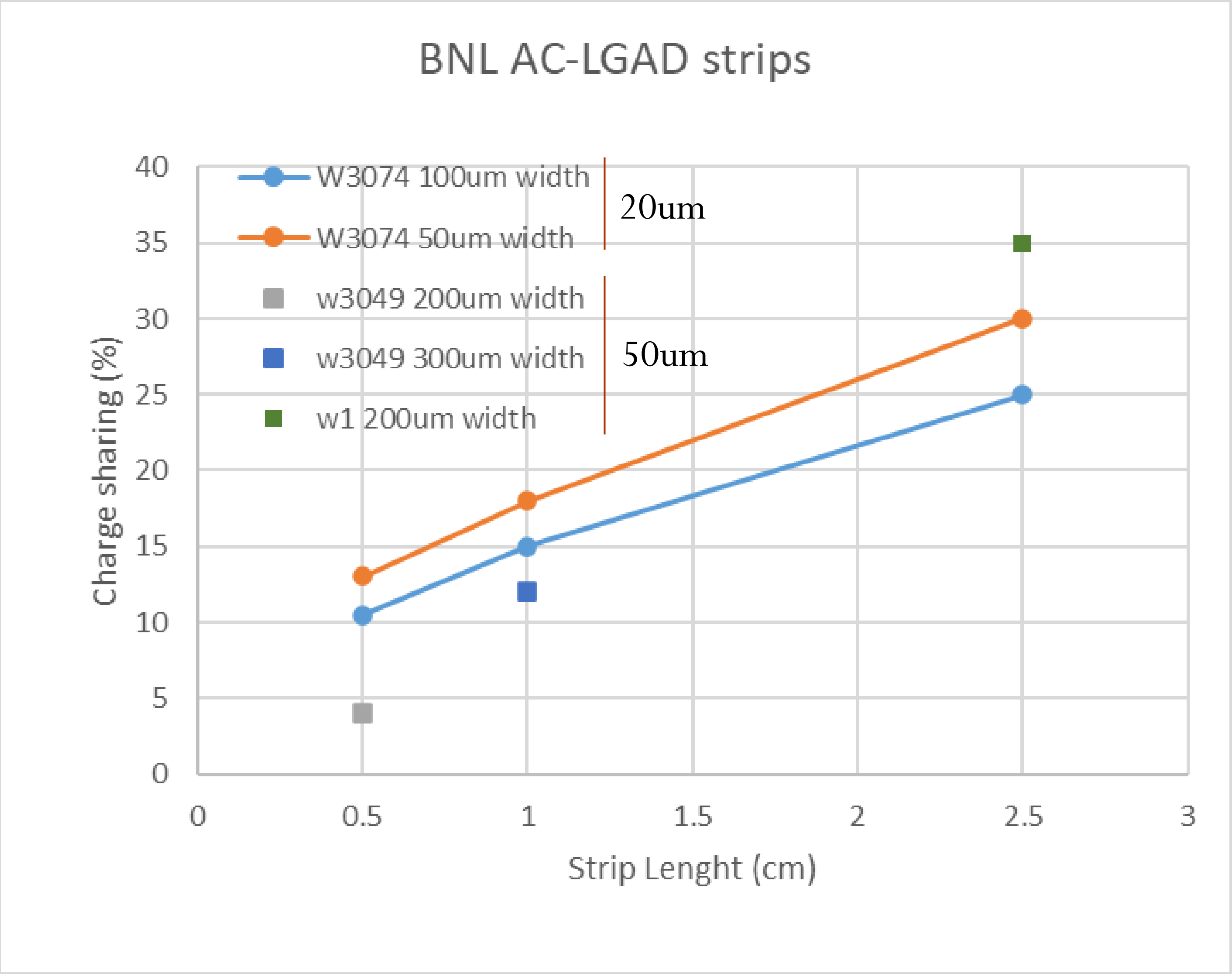
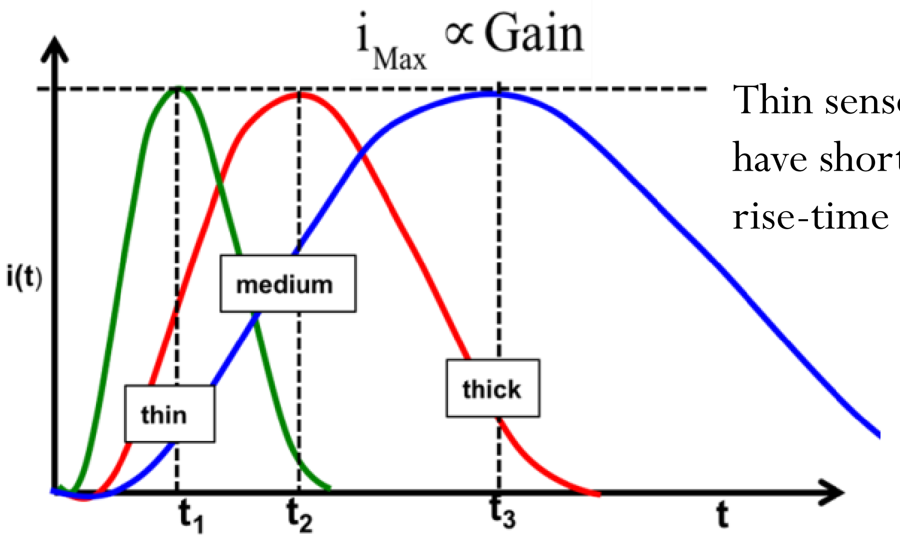
(preliminary) charge sharing comparison

- Plot: charge sharing % after second neighbor for different sensors length and strip width but same pitch (500um)
- Charge sharing changes with strip pitch/width, strip length and bulk thickness
- Some preliminary conclusions
  - With larger strips there's less charge sharing
  - Charge sharing increases with strip length
  - Thicker sensors increase charge sharing

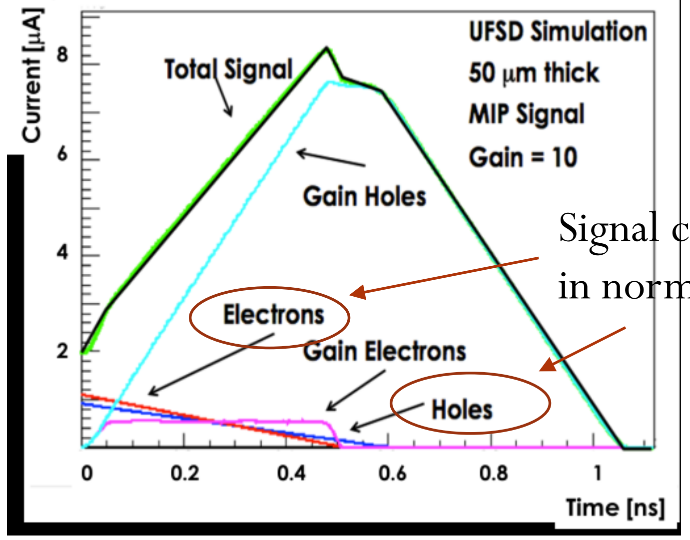


Pulse shape for LGADs



Thin sensors have shorter rise-time

Entire pulse is ~1ns

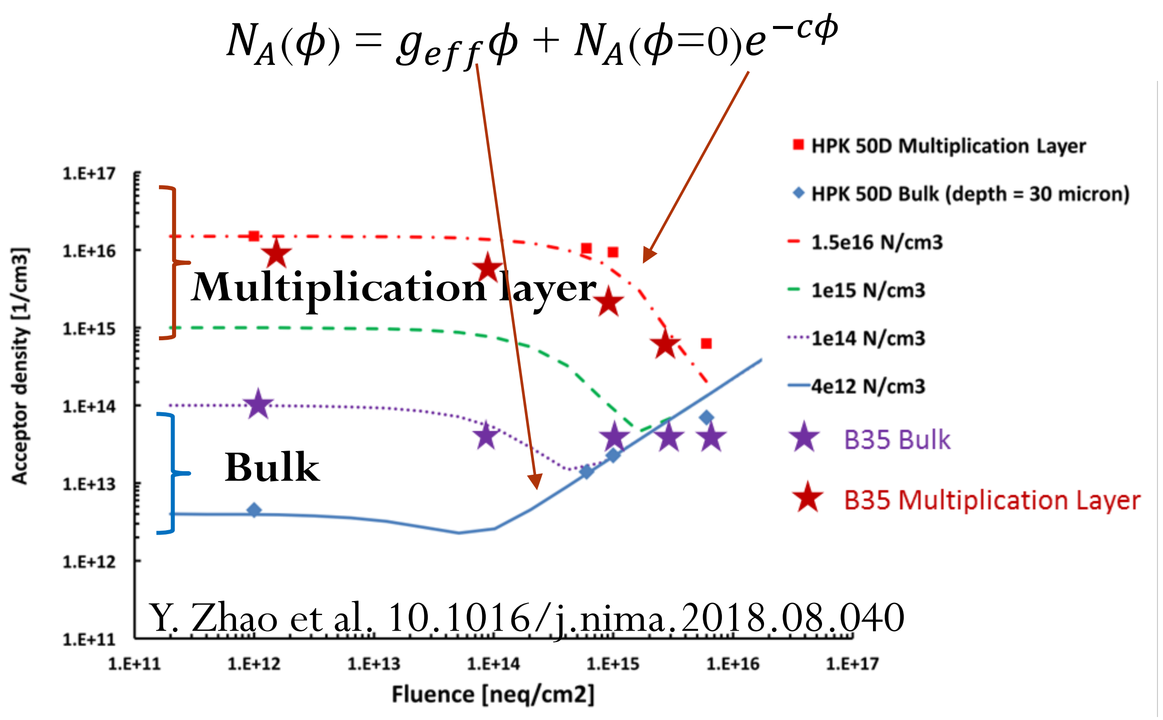


Signal components in normal silicon

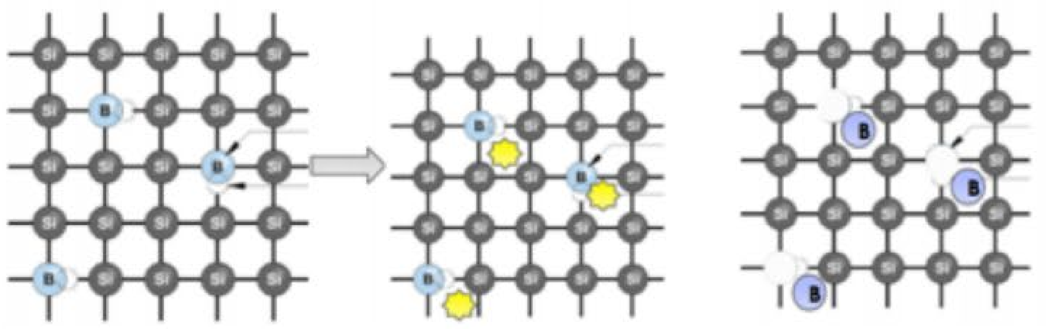
- Collected charge from MiP is proportional to thickness of a silicon detector
  - Thin detectors have low collected charge (50 um → ~0.5 fC)
- Thanks to gain LGADs can go thinner than normal silicon detectors
  - Down to 50 um and 20 um!
- **Thinner detectors have shorter rise time and less Landau fluctuations**
  - Furthermore, the full charge collection time is fast (~1 ns)
  - All with a **great signal to noise ratio**
- Better signal to noise ratio and thin detectors means improved timing resolution
  - **Time resolution down to 20 ps**

Radiation damage model

- Radiation damage for LGADs can be parameterized
  - $N_A(\phi) = g_{eff}\phi + N_A(\phi{=}0)e^{-c\phi}$
- Acceptor creation: $g_{eff}\phi$
  - By creation of deep traps
- Initial acceptor removal mechanism: $N_A(\phi{=}0)e^{-c\phi}$
  - Reduction of doping concentration in the multiplication layer → reduction of gain
  - **C-factor (acceptor removal constant) depending on detector type**



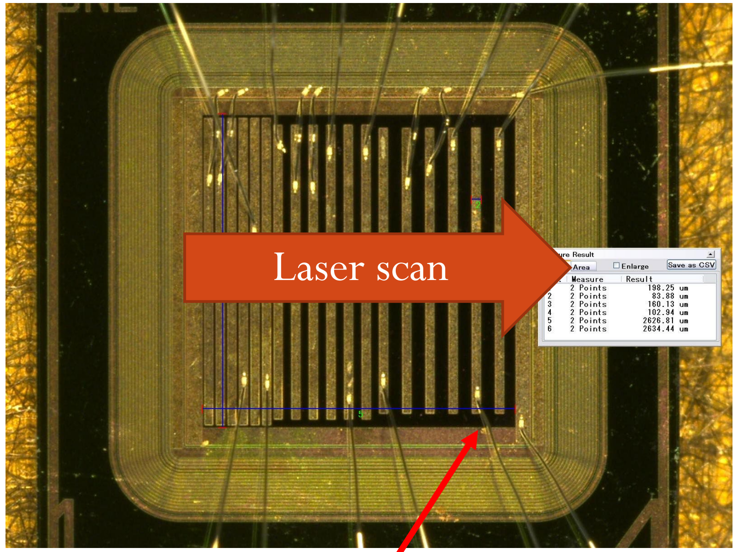
Y. Zhao et al. 10.1016/j.nima.2018.08.040



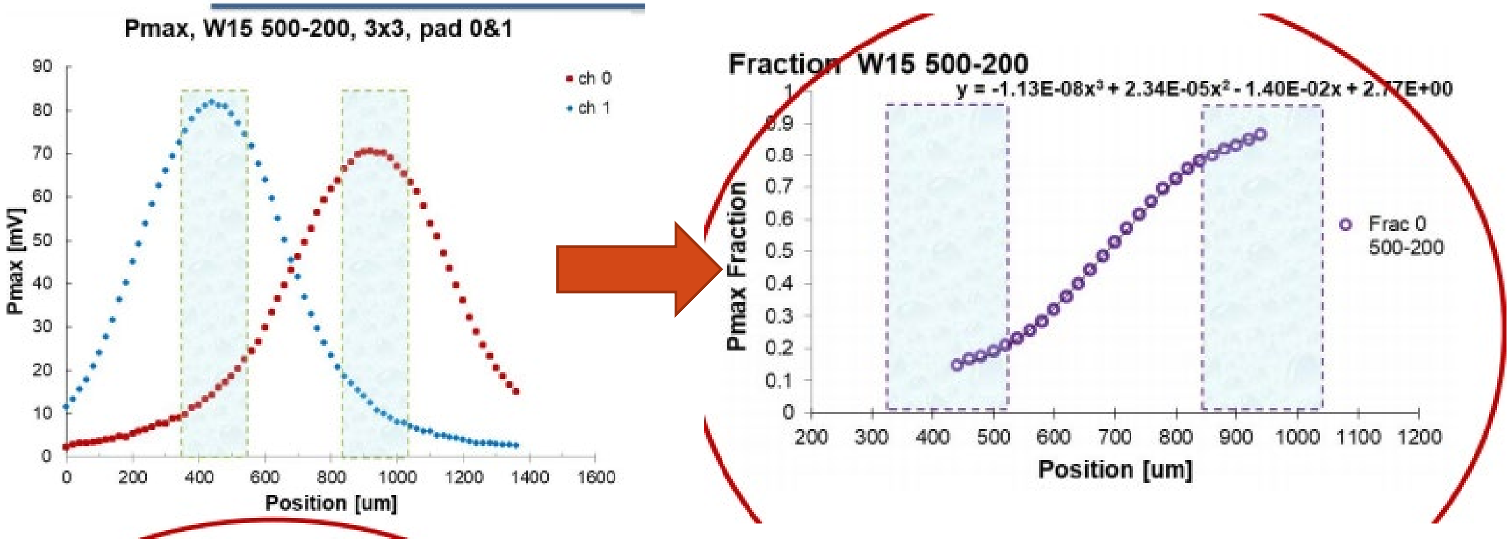
Boron
Radiation creates interstitial defects that inactivate the Boron: Si_i + B_s → Si_s + B_i
B_i might interact with Oxigen, creating a donor state

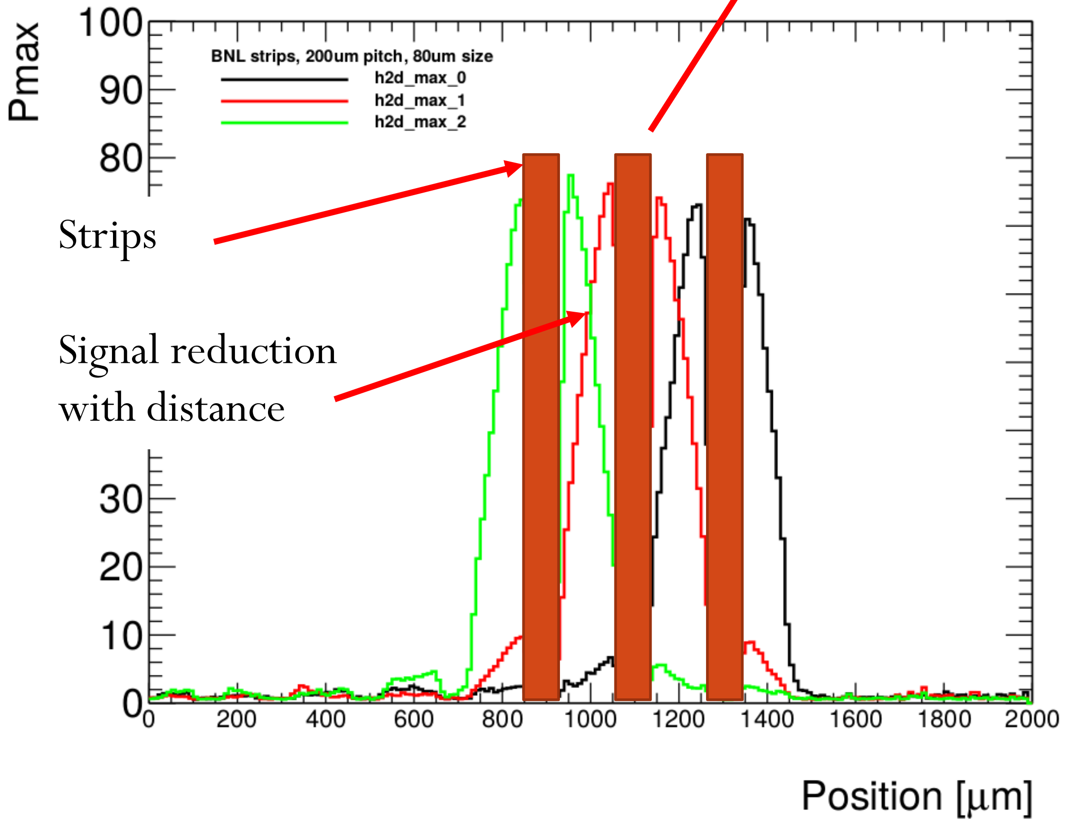
AC-LGAD strips

- Since the signal is AC-coupled the signal goes down with distance
  - On a normal DC-coupled sensor there would be a constant signal
- The position of an event can be reconstructed by looking at the fraction in between the strips
  - E.g. when the signal is split 50-50 the event is exactly between strips
  - Next-neighbor can be used to refine reconstruction



Example reconstruction by fraction on an FBK sensor





https://indico.cern.ch/event/1029124/contributions/4411193/attachments/2268966/3852924/RD50.pdf

Position reconstruction

For master formula method see: https://arxiv.org/abs/2007.09528

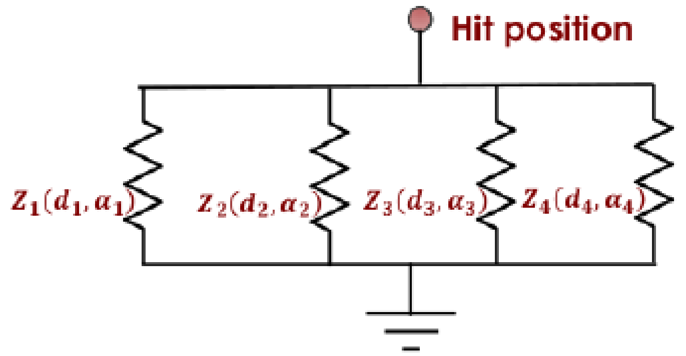
- Simple fractional method works with strips
- **However for complicated geometries (hexagons, squares, etch) more than 2 channels are needed, fractions need to be calculated taking into account multiple pads**
- Master formula method for position reconstruction: Use signal fractions in between channels to reconstruct position

The fraction of signal seen in each pad is:

$$S_i(\alpha_i, d_i) = \frac{\frac{\alpha_i}{\ln(d_i)}}{\sum_1^n \frac{\alpha_j}{\ln(d_j)}}$$

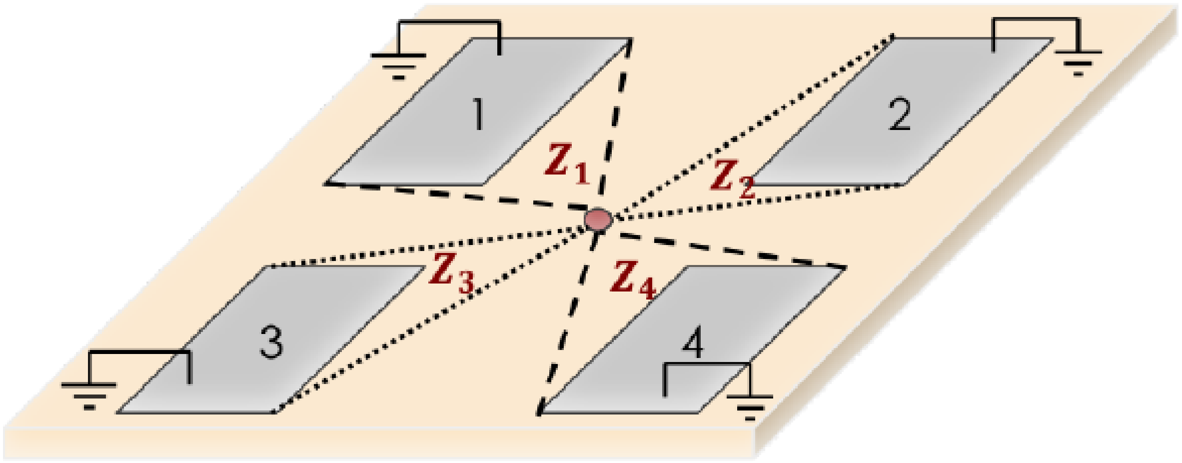
where:

- d_i= distance hit-pad
- α_i= angle of view hit-pad



Important points:

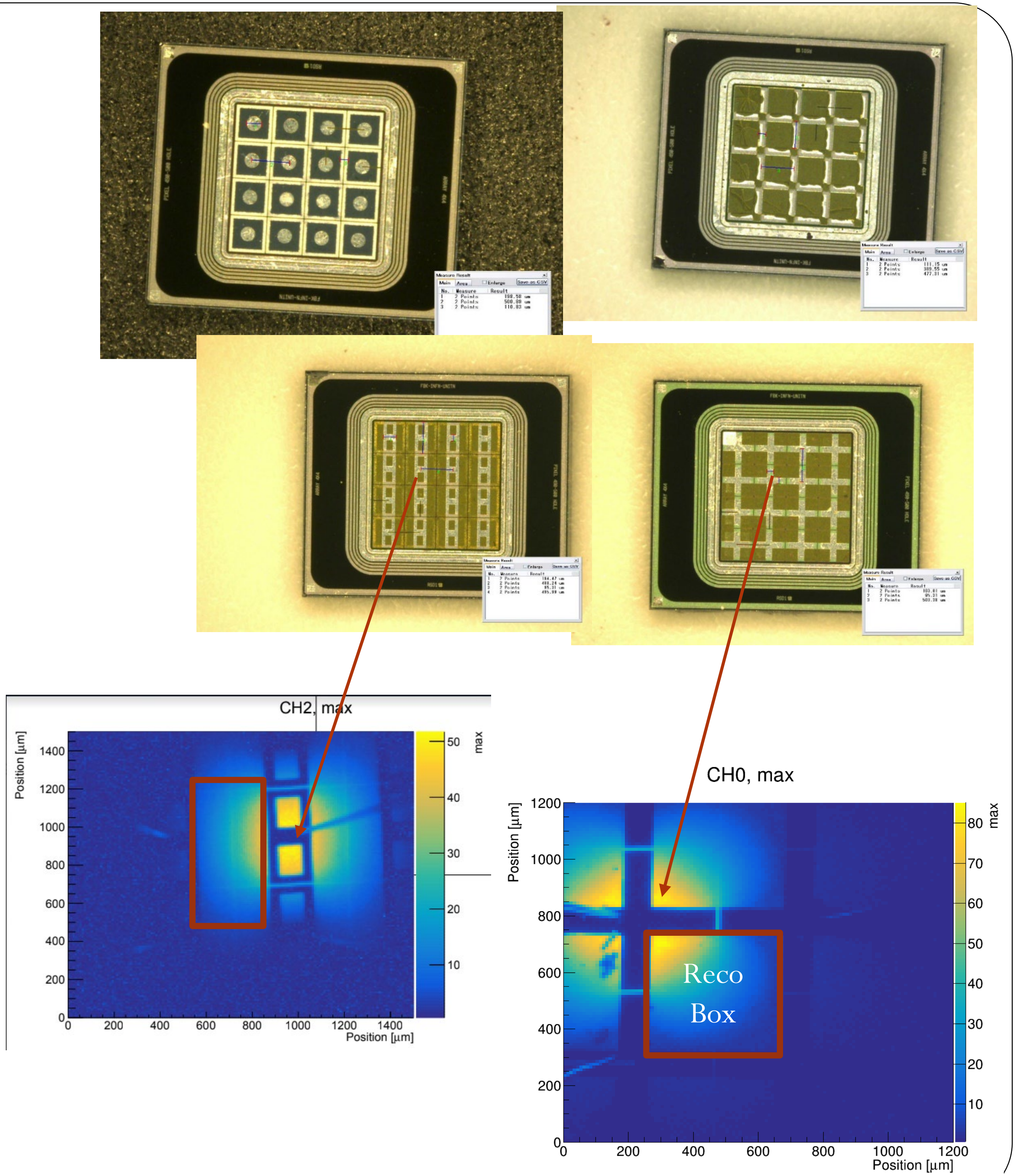
- The signal seen in a pad depends upon how many other pads are nearby
- A signal can be seen by 2,3 or 4 pads, depending on the hit location



AC-LGAD geometries

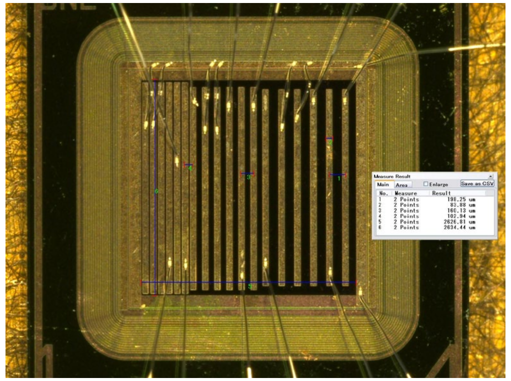
- With AC metal it is possible to create new geometries
  - Simple metal pattern on top, no underlying structures
- **FBK AC-LGAD metal etched at BNL to create non-conventional metal structures**

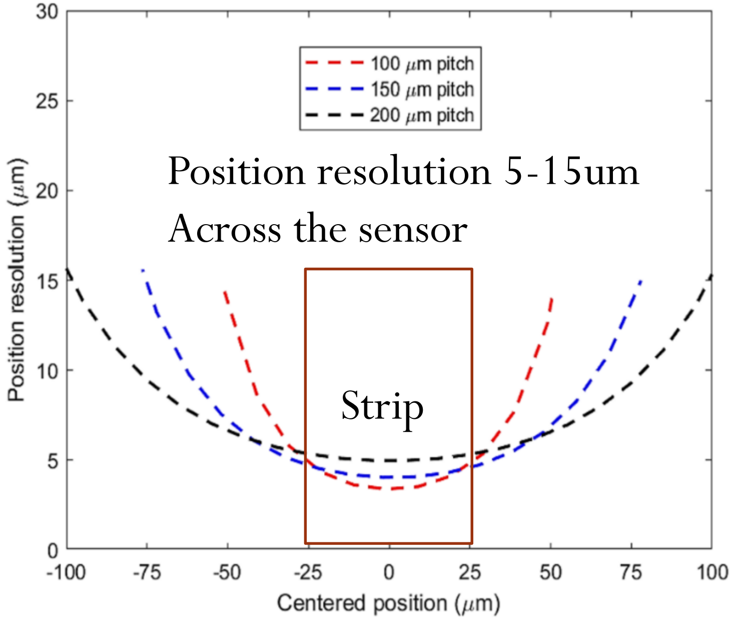
- Sensors with circular pads, crosses, micro-strips etc…
  - Simplify the position reconstruction process
  - If simple enough it can be done on-chip
  - Achieve needed X-Y position resolution (might have different requirements) vs channel density
- E.g.: Cross have separated boxes were reconstruction can be done with fractions from one cross to the next in X/Y
  - Fraction can also be decoupled in X and Y



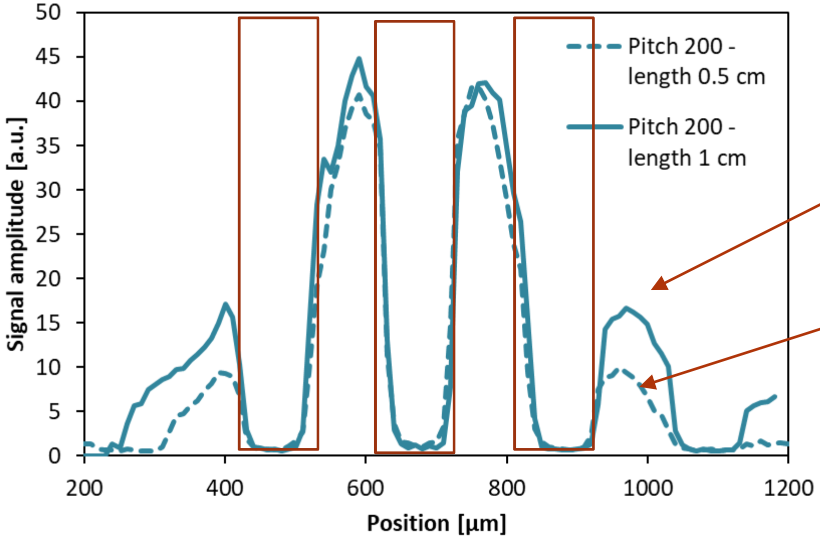
AC-LGAD strips

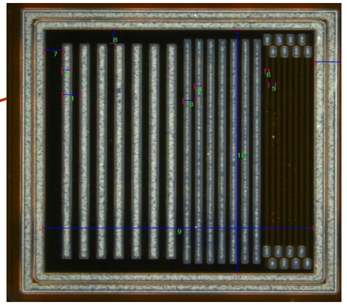
- Testing of **AC-LGAD prototype strip sensors** (50 um thick) with several geometries
  - Sensors produced at BNL for the EIC
- Same strip length and width, different pitches
  - Finer strips show a slightly better resolution, but higher channel count
  - Hit position resolution in direction perpendicular to the strip 5-15 um
  - Study made with FNAL TB data
- Same geometry but with different lengths (study made with focused IR laser TCT)
  - Sensors with longer strips show increased charge sharing profile
  - Effect to be understood with simulation
- **For PIONEER 2 cm long strips with substrate thickness of 120um**
  - **Best behavior**: charge shared only between two strips to have largest S/N
  - TCAD Simulation to study the charge sharing

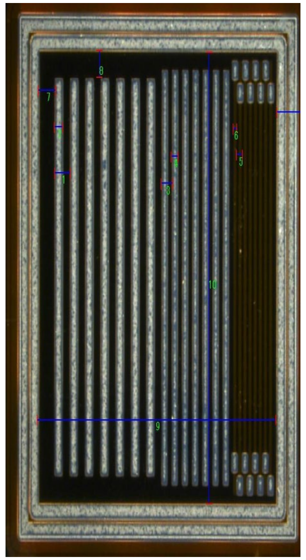




Position resolution vs position
for AC-LGAD strips of different pitch

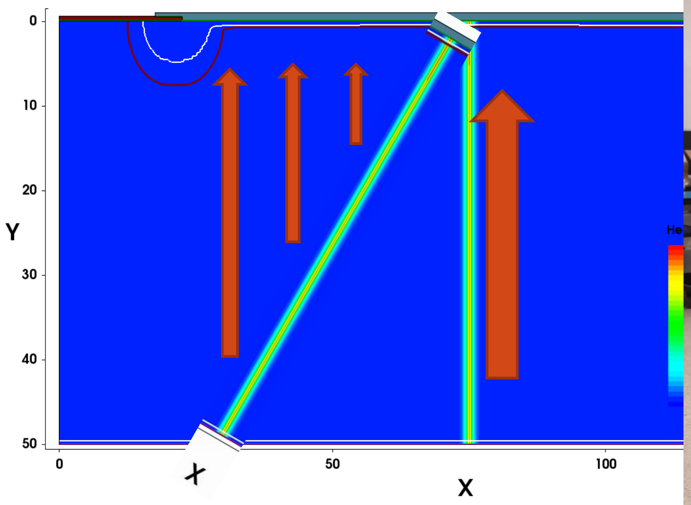


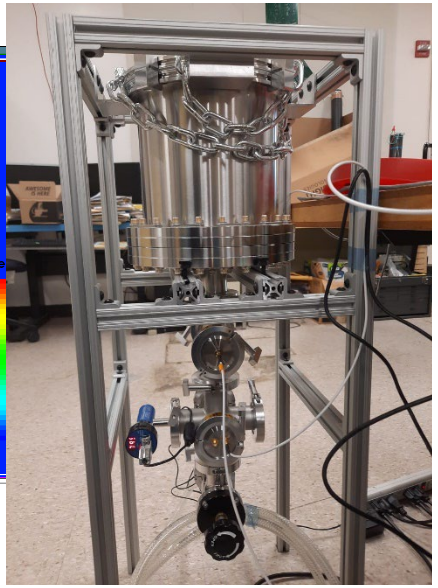




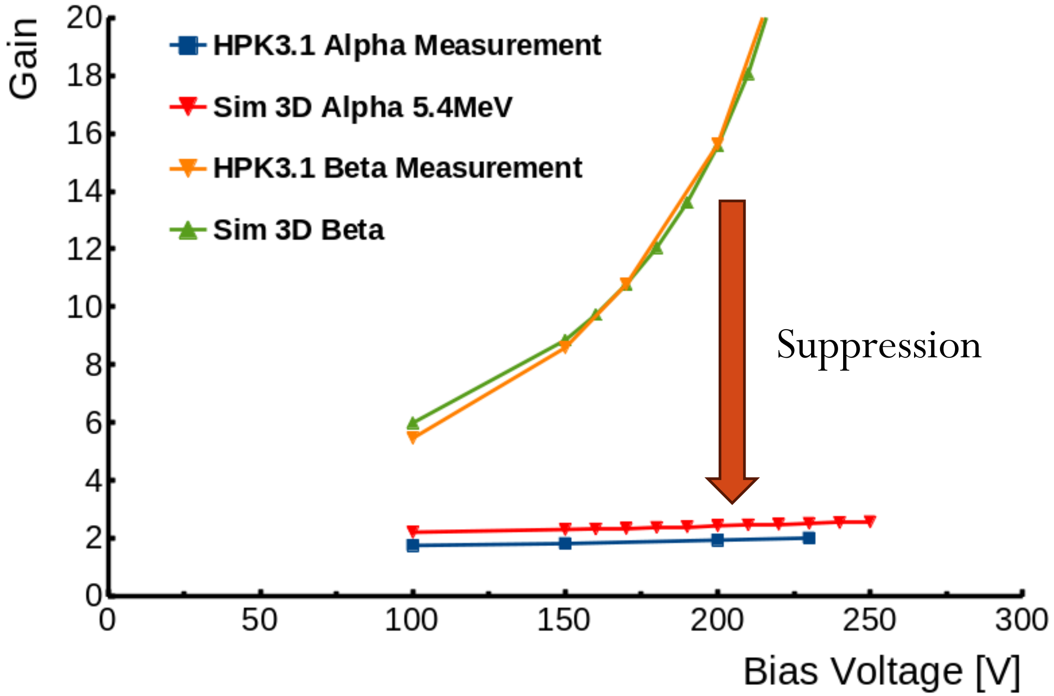
Alpha particle

- Gain suppression studied with **alpha particles**
  - Deposition of ~100 MiP
  - Studied in a vacuum chamber to reduce energy spread
- High gain suppression observed for high gain sensor
  - **Several types of gain layer design under study**
- The effect is expected to change with angle of incidence
  - What matters is the local charge concentration in the gain layer, so the "projection" of the track to the gain layer
- **Compare the suppression with alpha particles with simulation**





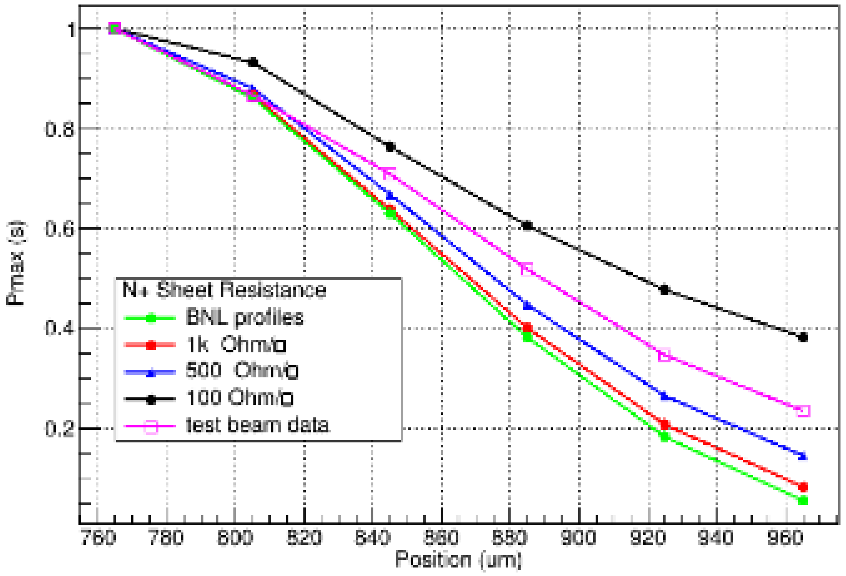
Gain suppression observed with alpha particles



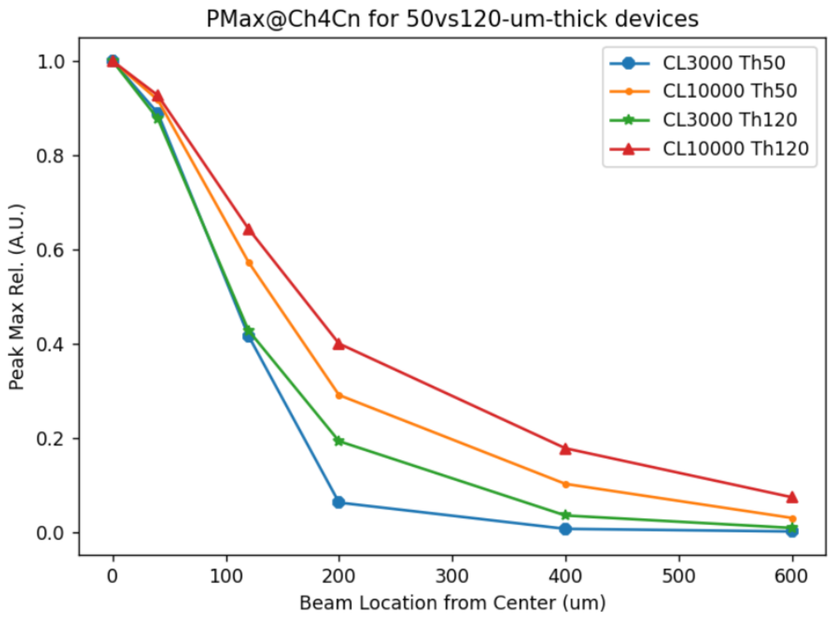
Courtesy of M. Nizam

AC-LGAD device simulation

- **TCAD simulations to study AC-LGAD parameters variations**
  - Studies done with TCAD Silvaco and Sentaurus
- Study the effect of the N+ doping concentration to the charge sharing profile
  - **More resistive N+ reduce the charge sharing**
- Investigate strip geometry (pitch, length, width) effect on charge sharing
  - **Longer strip increase the charge sharing**
- Sensors studied are 50um thick, simulation is crucial to understand the behavior of 120um thick sensors for the baseline design
  - **Thicker sensors have a broader charge sharing profile**
- For most simulations TCAD in 3D mode is necessary to have realistic results



TCAD Silvaco simulation of charge sharing profile for different N+ resistivity



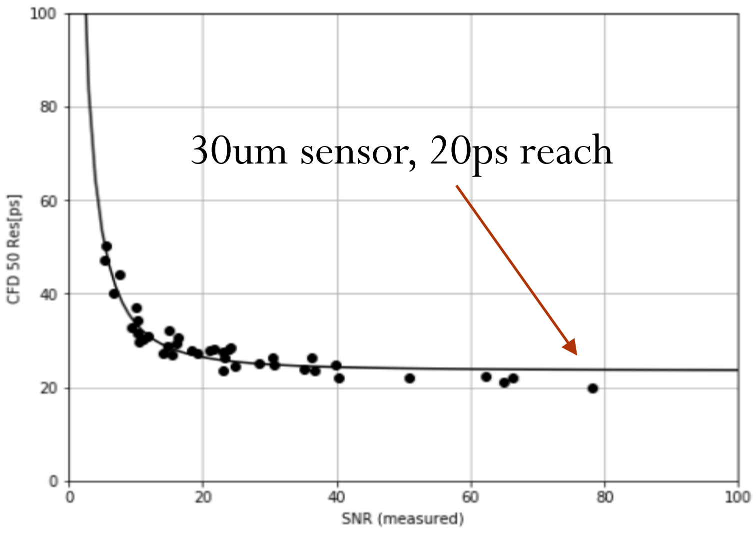
TCAD Sentaurus 3D simulation of charge sharing profile for different strip lengths and sensor thicknesses

Very thin LGAD sensors future uses

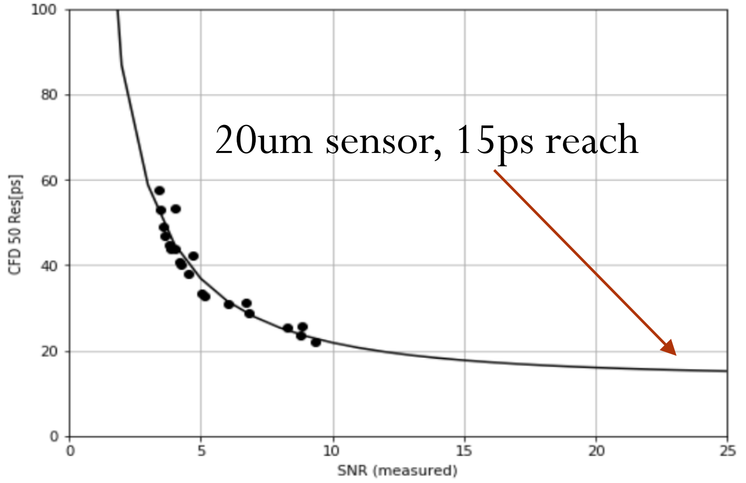
- **Very thin 20 um prototype LGAD**
- Possible improvements down to 15ps of time resolution
- Compared with 50um sensors (30-35 ps reach) and 30um sensors (25ps reach)
  - https://arxiv.org/abs/2006.04241
- However, new productions of 20 um devices from BNL, HPK and FBK still at 20ps level
- **Proper design is needed to surpass 20ps of resolution**

- **Very thin sensors** are also be candidates **for extreme radiation environments**
  - After substantial radiation damage thick detectors requires 1000s of V for depletion (Even though there is evidence of Charge trapping saturation)
- But a 50um sensor at 1E17Neq is fully depleted at 500V
- Gain helps in having sufficient collected charge
- Can be operated in extreme radiation environment
- e.g. for vertex detection very close to the beam line in colliders
  - https://doi.org/10.1016/j.nima.2020.164383
  - https://agenda.hep.wisc.edu/event/1391/session/12/contribution/60

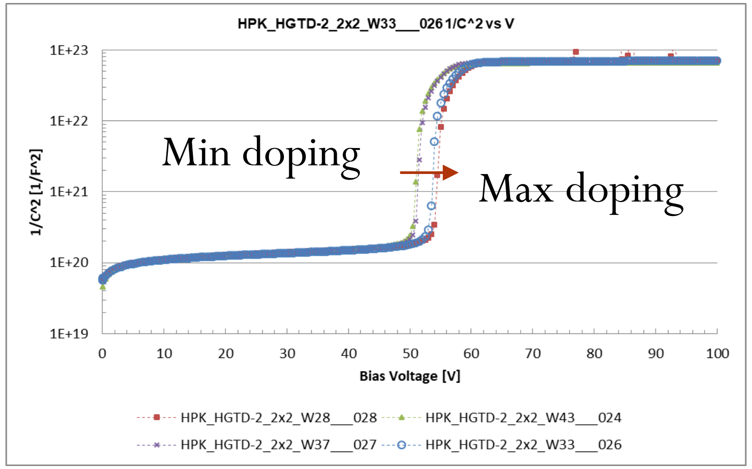
G30 sensor

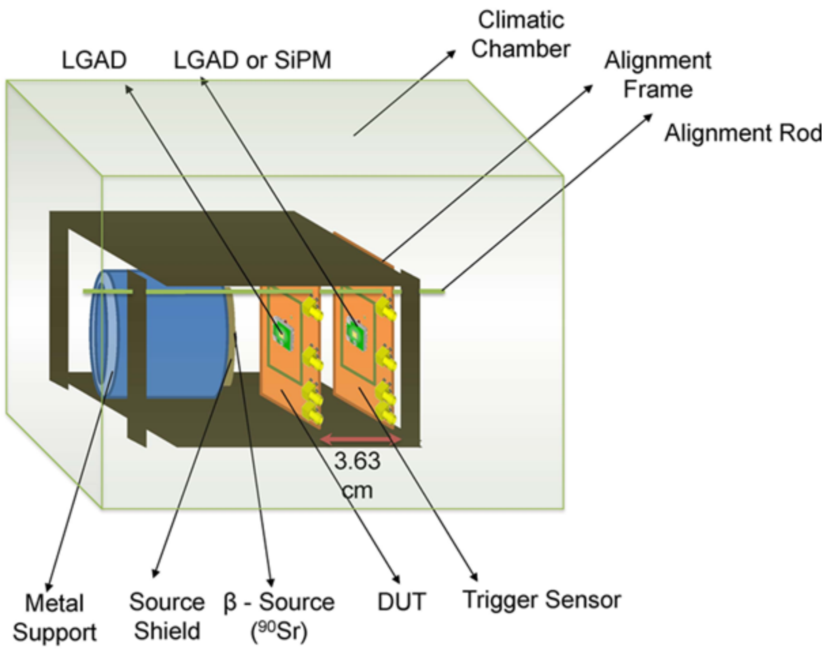


H20 Sensors



Sensor testing –probe station, charge collection





- **Probe station electrical testing**
- Current of voltage (IV) and Capacitance over voltage (CV)
- CV is used to probe the doping profile of the gain layer

- **Laboratory charge collection**
- Using MiP electrons from a Sr90 β-source (β-telescope)
  - Signal shape, noise, **collected charge**, gain, **time resolution**
- Using Alpha source in vacuum (Am237), ~100 MIPs deposition
- Using X-ray gun

- **Laser TCT studies**
  - IR laser mimics a MiP response and allows charge injection as a function of position
  - Particularly useful to test arrays and AC-LGADs (see later)

- **Test beam at facilities (CERN, DESY, FNAL)**
  - Allows the study of MiP response with position information through an external tracker