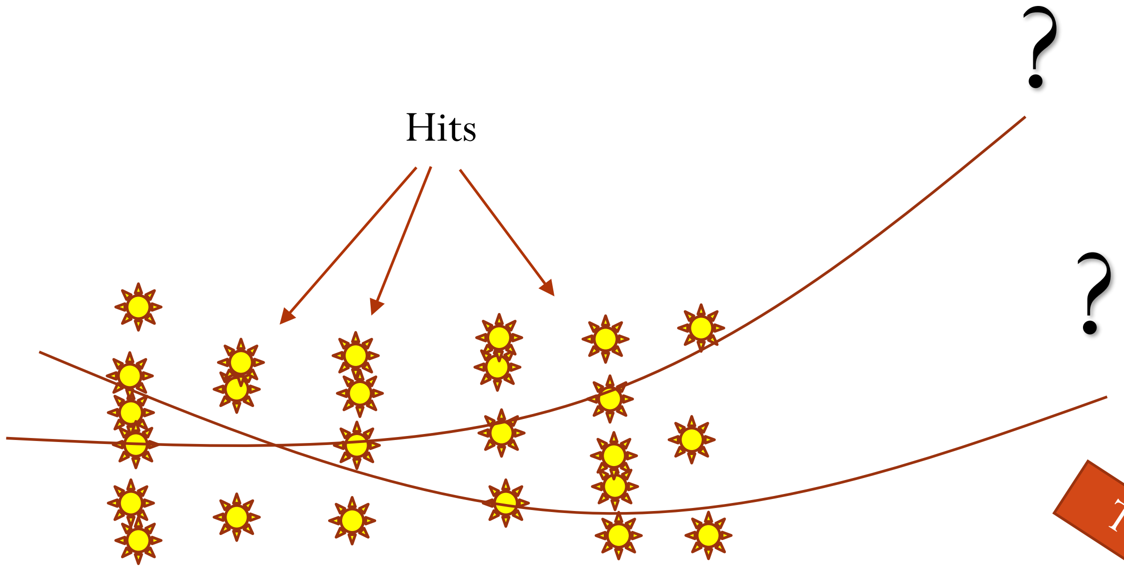
Fast silicon detector technologies for 4D tracking in future HEP experiments

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

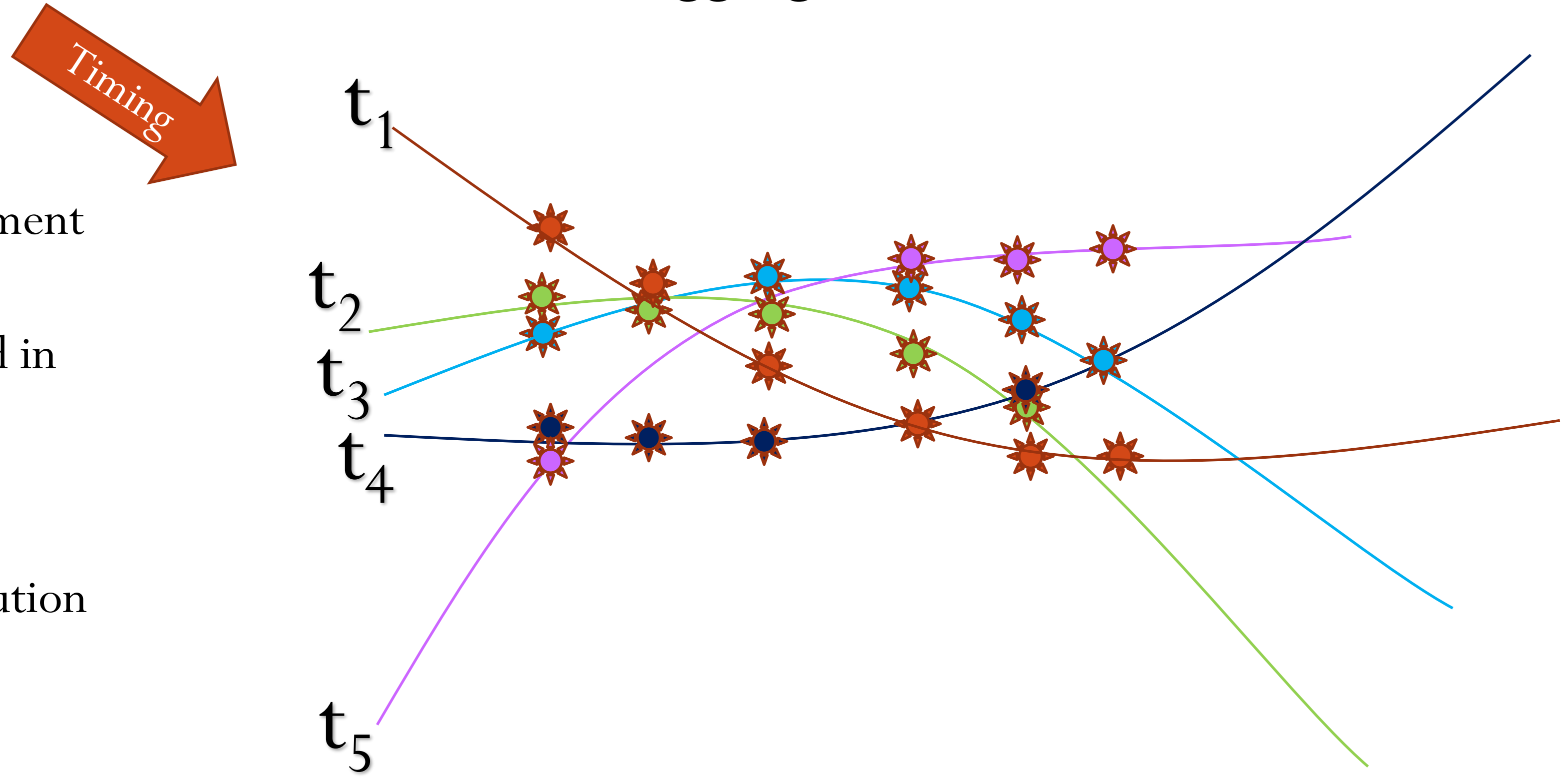
DND 2020 - TRIUMF

4D tracking - concept

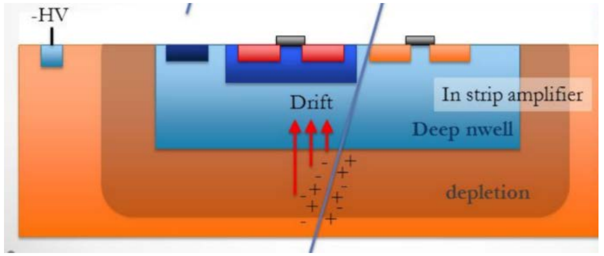


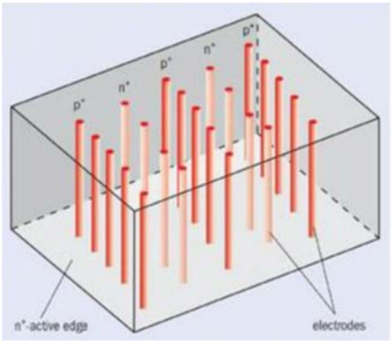
- Collection of hits for multiple tracks in dense environment
- Hard to reconstruct tracks
- But if particles have different initial position or delayed in time
  - We can exploit the **time** of the hits
- Easier to reconstruct single tracks
- ~ps → ~mm at c, 1→100ps is the needed time resolution for usual collider beam spot size

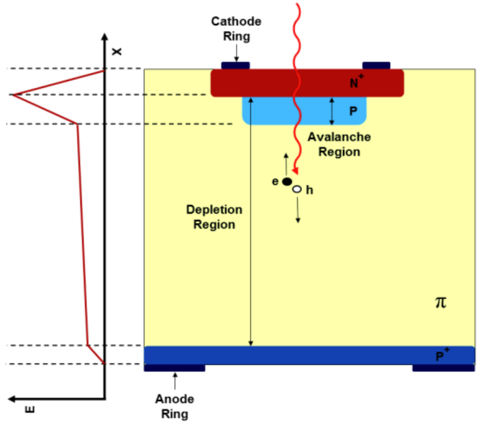
- Efficient tracking in dense environment
- Pile-up suppression
- Long Lived Particle detection
- Appearing/Disappearing tracklets identification
- ToF-based particle identification is possible
- Jet flavor tagging enhancement



Time precision sensors





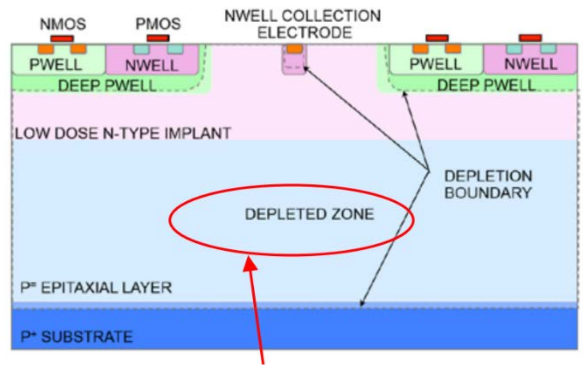


- Which technology has sufficient time resolution?
- SiPM (Silicon photomultiplier)
  - But very little radiation hardness and low granularity
- HV CMOS detector
  - Embedded amplification in the design, down to ~50 ps of time resolution
- 3D sensors
  - Perpendicular charge collection, no gain, ~20-30ps of time resolution
- Low Gain Avalanche Detectors (LGADs)
  - Intrinsic gain, thin bulk, ~ 20-30ps of time resolution

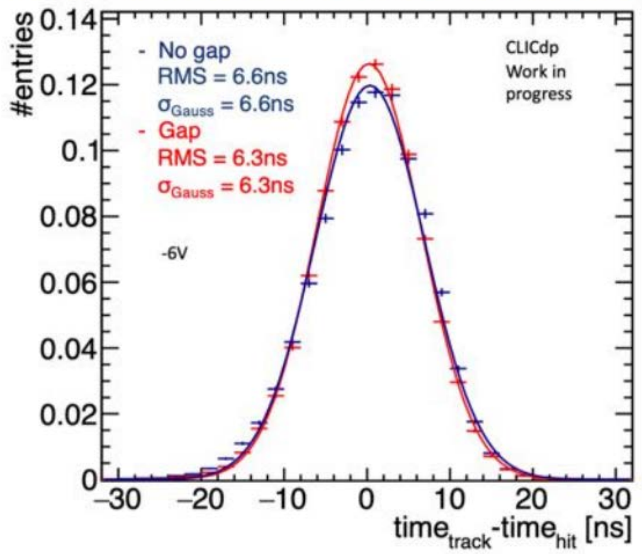
HV-CMOS

HV-CMOS timing performance

- Internal amplification allows for fast signal shaping
  - Monolithic chip: no need for bump bonding process
  - Lot of RnD in the past year to get to a fully depleted sensor with 100% efficiency
  - Promising in terms of timing! But keep an eye on power consumption
- HV-MAPS (Monolithic Active Pixel Sensor) MuPix7
  - https://arxiv.org/pdf/1803.01581.pdf
  - https://arxiv.org/pdf/1603.08751.pdf
  - Time resolution of MuPix7 ~10-14ns, ~40um spatial resolution
- HR-CMOS CLICTD (for CLIC experiment)
  - https://indico.cern.ch/event/813597/contributions/3730879/attachments/1989317/3315977/CLICTD-TREDI2020-Vienna-18Feb2020.pdf
  - ~6ns time resolution, ~6um spatial resolution

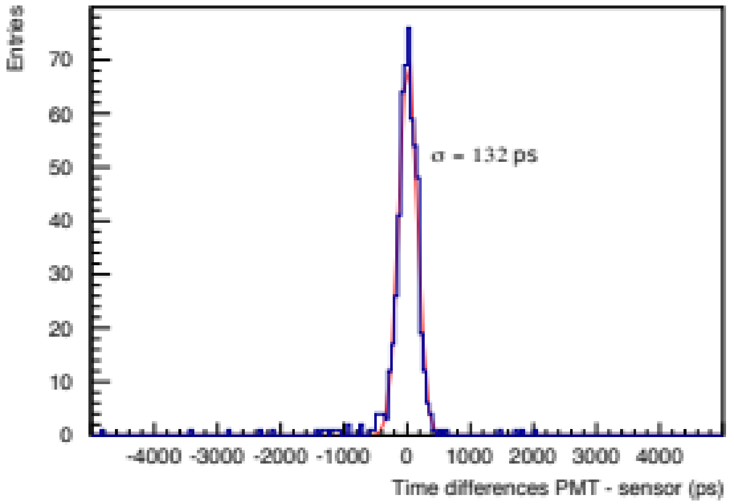


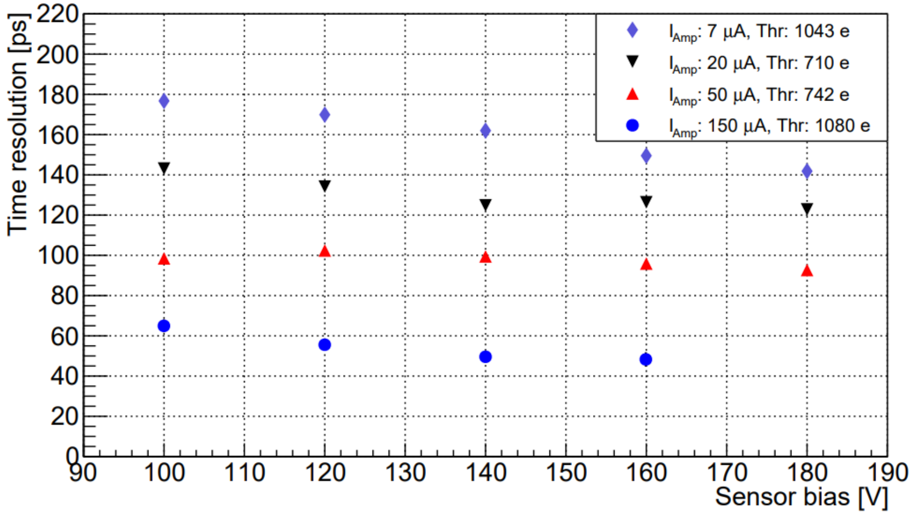
Hit-time residuals after time-walk correction



HV-CMOS timing performance

- DMAPS CACTUS (future colliders)
  - https://authors.library.caltech.edu/103788/1/2003.04102.pdf
  - 150nm process, 1mm pixel pitch
  - Power 145mW/cm^2
  - ~180-60ps of time resolution depending on thickness (100-200um)
- SiGe BiCMOS SG13G2 (for ToF PET)
  - https://iopscience.iop.org/article/10.1088/1748-0221/14/11/P11008/pdf
  - https://arxiv.org/pdf/2005.14161.pdf
  - ~25um thickness, 65um pixel size (very low pixel capacitance)
  - Time resolution depends on power consumption 12→375uW per channel
  - Down to ~50ps time resolution
- **Few examples of good HV-CMOS for timing**
  - In general time resolution of the order of 50ps-10ns
  - Good in terms of spatial resolution and cost
- Issue of power density at low pitch, eg: 400uW/ch would give ~300mW/cm^2 at ~400um pitch
  - HGTD (1.3mm pitch, timing) power limit is 300mW/cm^2, ITk (50um pitch, standard tracking) is 800mW/cm^2

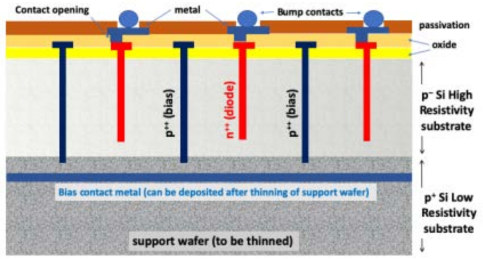


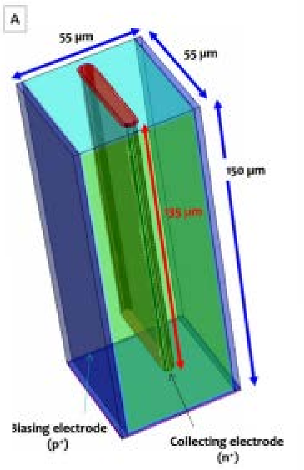


3D detectors

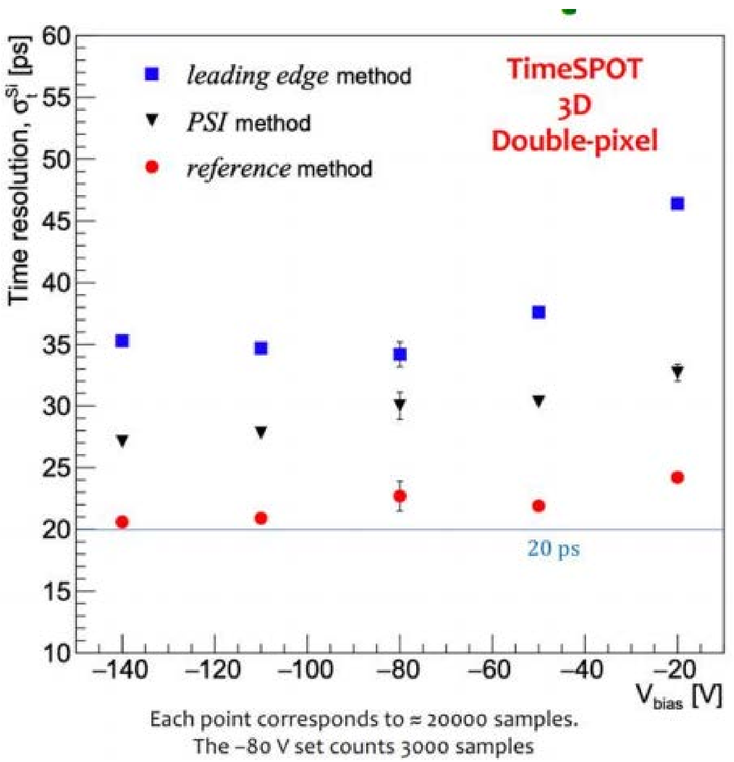
3D sensors timing performance

- Charge collection is perpendicular to particle incidence
- No internal gain or amplification (low collected charge)
- Pixel pitch is proportional to charge collection time (crucial for time resolution)
- Charge sharing if MiP is not ~perpendicular
- Might be a good candidate technology for vertexing with timing





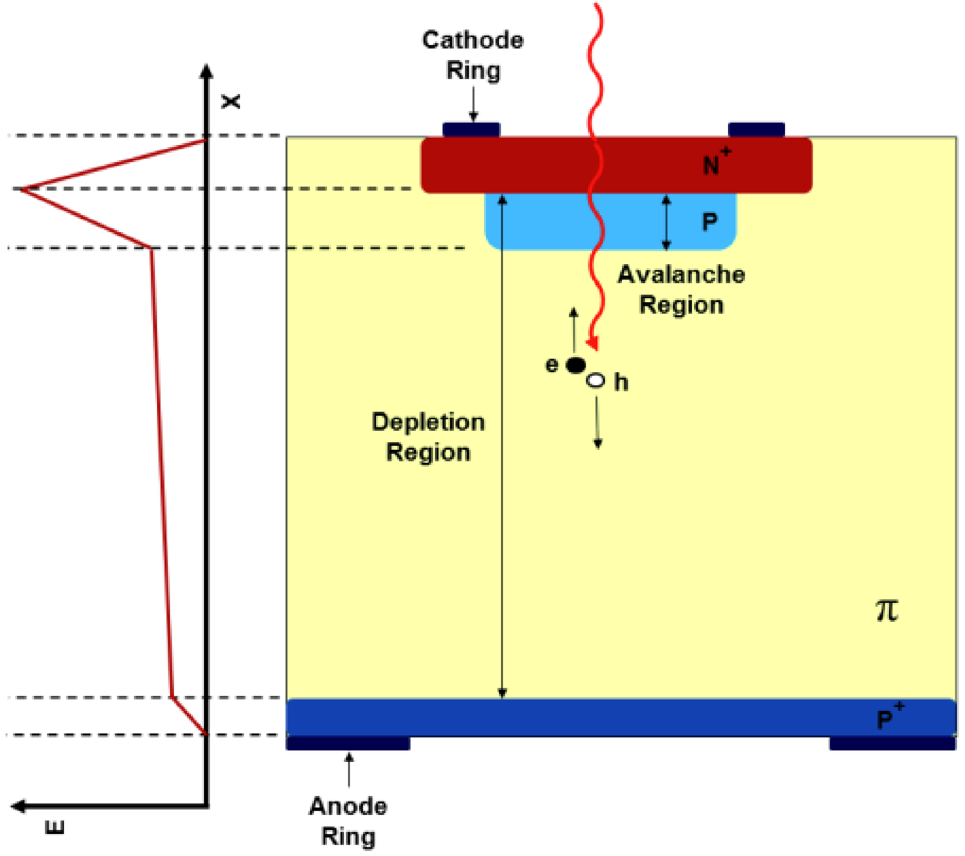
- Small cell 3D sensor
  - https://arxiv.org/pdf/1901.02538.pdf
  - 50um pitch size, ~50ps time resolution
  - Issue: Electric field goes down as 1/r
- TimeSPOT: Trench 3D sensors
  - Large rectangular trenches as electrodes
  - Optimized electrodes to have constant field and minimize charge collection time
  - 150um bulk but charge is collected in 50um
  - Time resolution down to 20ps!
  - https://indico.cern.ch/event/895924/contributions/3993250/attachments/2111174/3565760/Vertex2020ALai_20ps_re.pdf
  - https://iopscience.iop.org/article/10.1088/1748-0221/15/09/P09029/pdf



LGADs

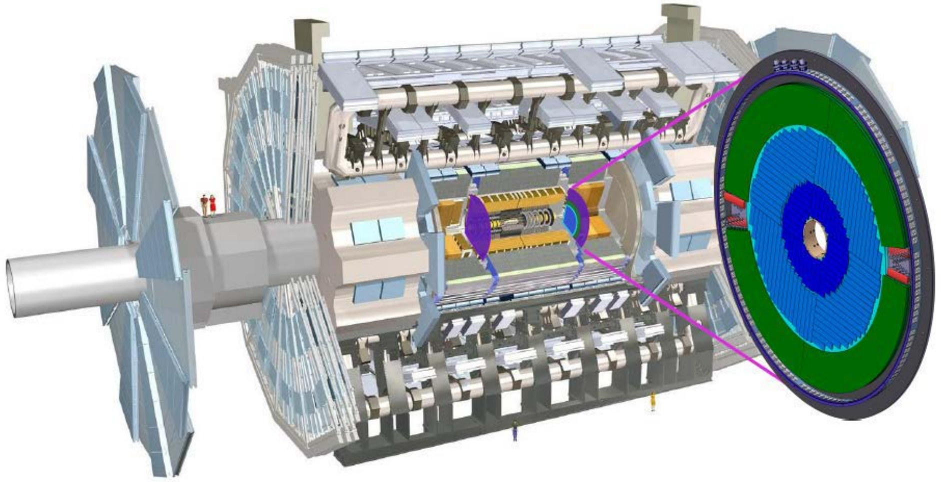
Low Gain Avalanche Detectors

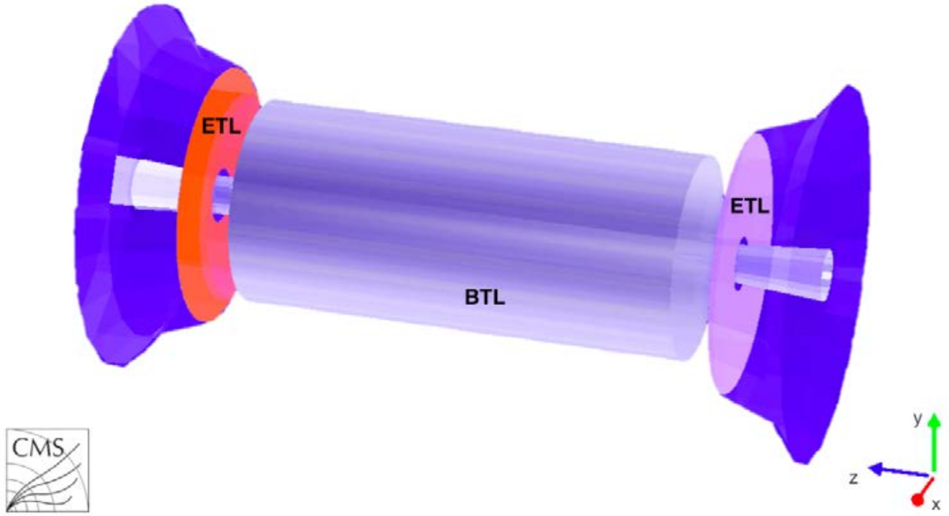
- LGAD: silicon detector with a thin (<5μm) and highly doped (~10^{16} P++) multiplication layer
  - High electric field in the multiplication layer
  - Electron multiplication but not hole multiplication (not in avalanche mode, controlled gain)
- LGADs have intrinsic modest internal gain (10-50)
  - Gain $= \frac{Q_{LGAD}}{Q_{PiN}}$ (collected charge of LGAD vs same size PiN)
  - Better signal to noise ratio, sharp rise edge
- Better signal to noise ratio and thin detectors means improved timing resolution
  - **Time resolution < 30 ps**
- Several vendors of experimental LGADs
  - CNM (Spain), HPK (Japan), FBK (Italy), BNL (USA), NDL/IME (China)



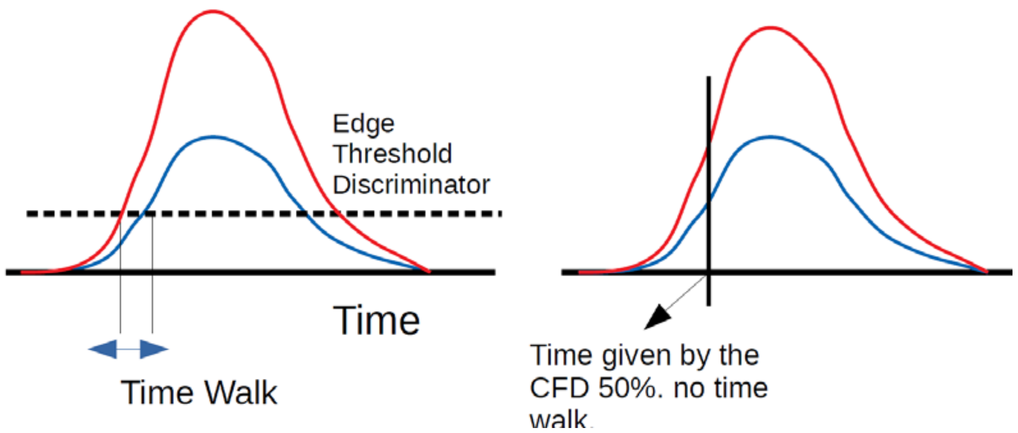
ATLAS and CMS timing layers

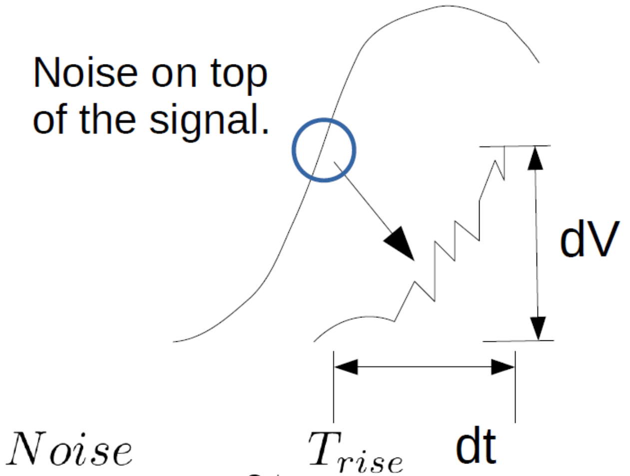
- First application of LGADs in HEP experiments at HL-LHC (starting ~2026)
  - Timing layers in the end-cap (forward) region to mitigate pile-up
- ATLAS High Granularity Timing Detector (HGTD)
  - https://cds.cern.ch/record/2719855
- LGAD requirements:
  - Radiation hardness to 2.5E15Neq, 4MGy.
  - Time resolution <50ps per hit, collected charge ~10fC.
  - Power (sensor-only) <100mW/cm^2
- 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)





Time resolution





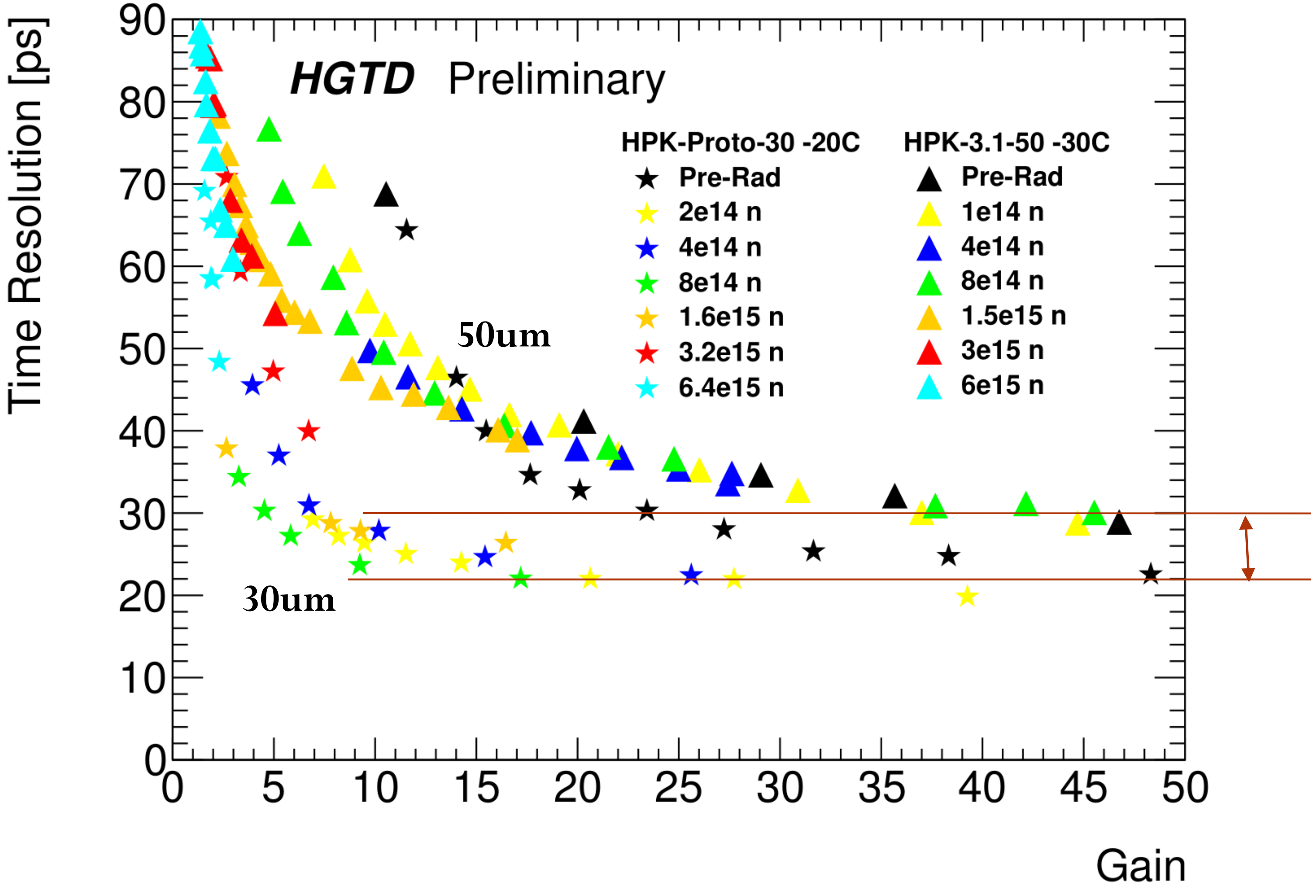
$$\sigma_{Jitter} = \frac{Noise}{dV/dt[CFD\%]} \approx \frac{T_{rise}}{SNR}$$

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
- Landau term: proportional to thickness
  - Reduced for **thinner sensors**
  - **Dominant parameter at high gain**
- TDC term: from digitization clock

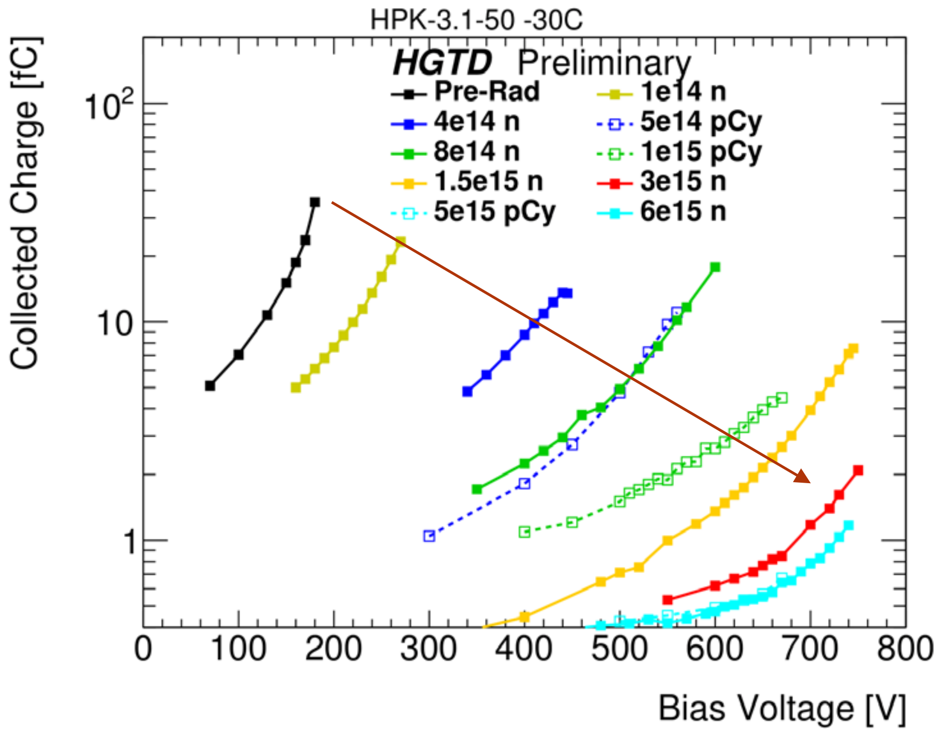
LGAD sensors 50 um vs 30 um



- High gain → very low jitter contribution to the time resolution
- Time resolution is ultimately driven by Landau component
  - Depends on sensor thickness
- 30ps for 50um sensors
- 20ps for 30um sensors
- 15ps possible with 20um sensors

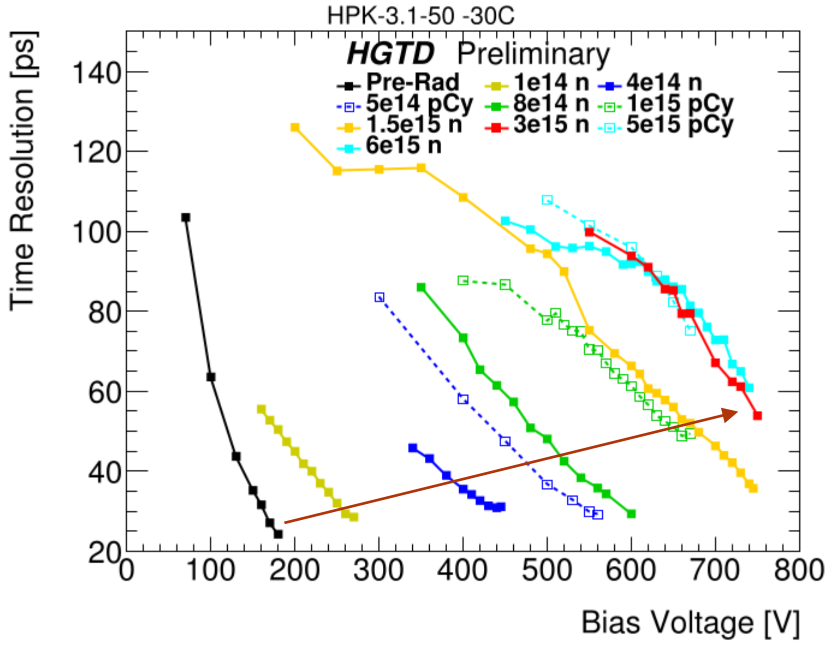
LGAD and radiation damage

- 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)

- 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
  - (equivalent 1 MeV neutrons on cm^2)
- Increased time resolution
  - Time res. of 25ps to 60ps after a fluence of 6E15 Neq/cm^2
- Partly the performance can be recovered by increasing the bias Voltage applied to the diode (~200V → ~700V)



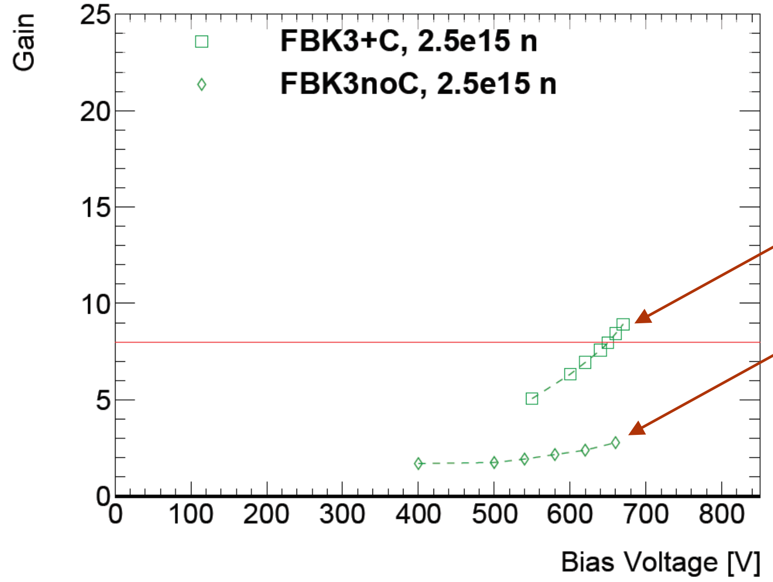
Radiation hard LGAD design

- Two ways to increase the radiation hardness of LGADs

- Addition of Carbon
  - FBK (Fondazione Bruno Kessler) sensors
  - Carbon is electrically inactive (no effect pre-irradiation), catches interstitials instead of Boron, reduces acceptor removal after irradiation

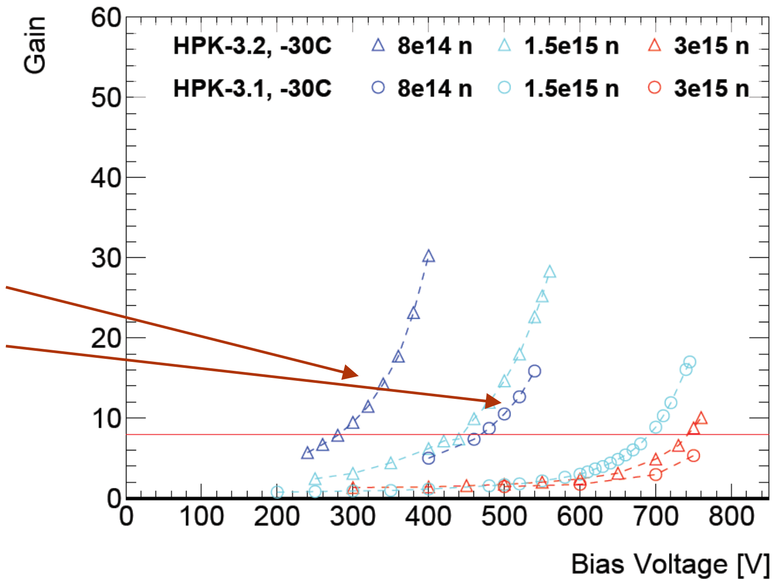
- Deeper gain layer
  - HPK (Hamamatsu Photonics) sensors
  - High field for larger volume
  - Allows for better recovery of the gain from increased bias voltage after radiation damage

- Resources
- 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



With Carbon

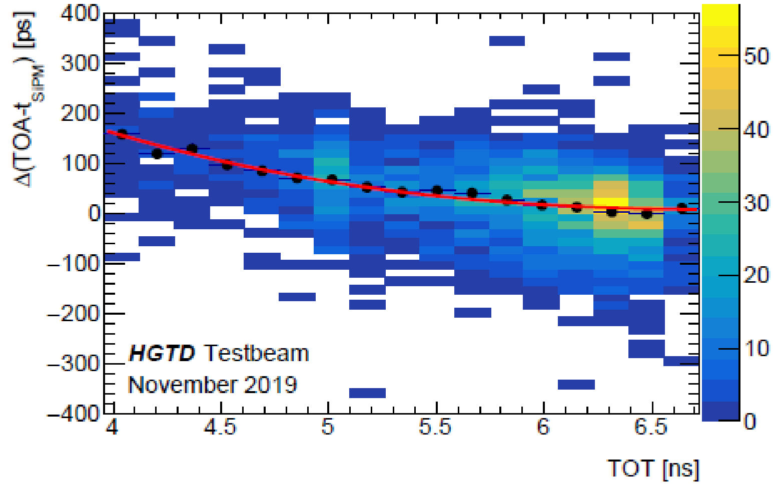
Without Carbon

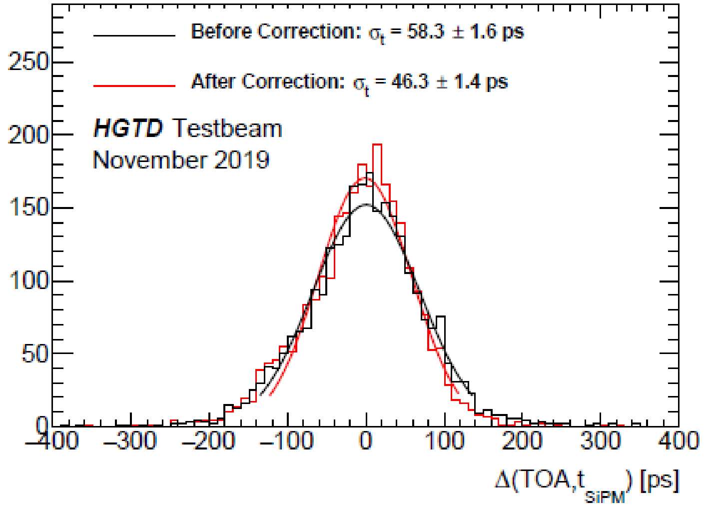


Deeper gain layer (triangles)
Less deep gain layer (circles)
(same color, same fluence)

ROC (Read Out Chip) challenge

ATLAS readout chip (ALTIROC) ToT timing correction to ToA for time resolution evaluation

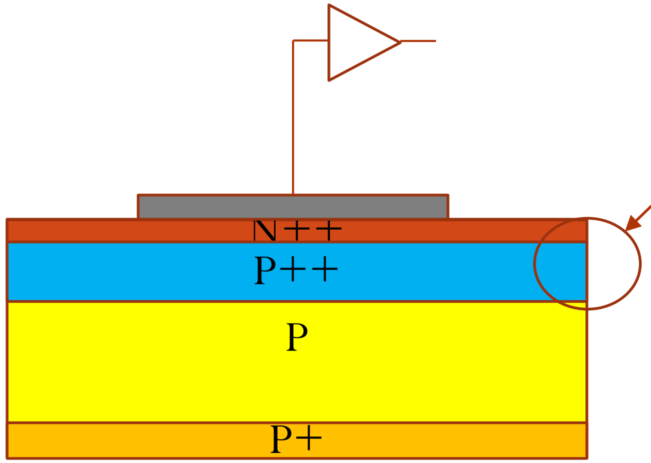




- Readout electronics to maintain the time resolution of the sensor
  - Needs fast amplifier to follow the fast LGAD rise-time
- Simple ToA (Time of Arrival) method for timing not sufficient
  - Prone to time walk uncertainty
- Time needs to be corrected in some way:
  - Using ToT correction (Time over Threshold) which measures the length of the pulse, current method used by ATLAS and CMS electronics
  - Using a variable threshold (eg: at 50% of the Pmax) → (CFD) Constant Fraction Discriminator
  - Use zero-crossing of the derivative
  - Etc…?
- Current electronics in development require high power and a high collected charge to work properly
  - Also LGAD sensors after irradiation tend to need high current and voltage
  - Especially when the granularity is lower than ~1mm
  - **Power consumption is and will be an issue for timing layers**

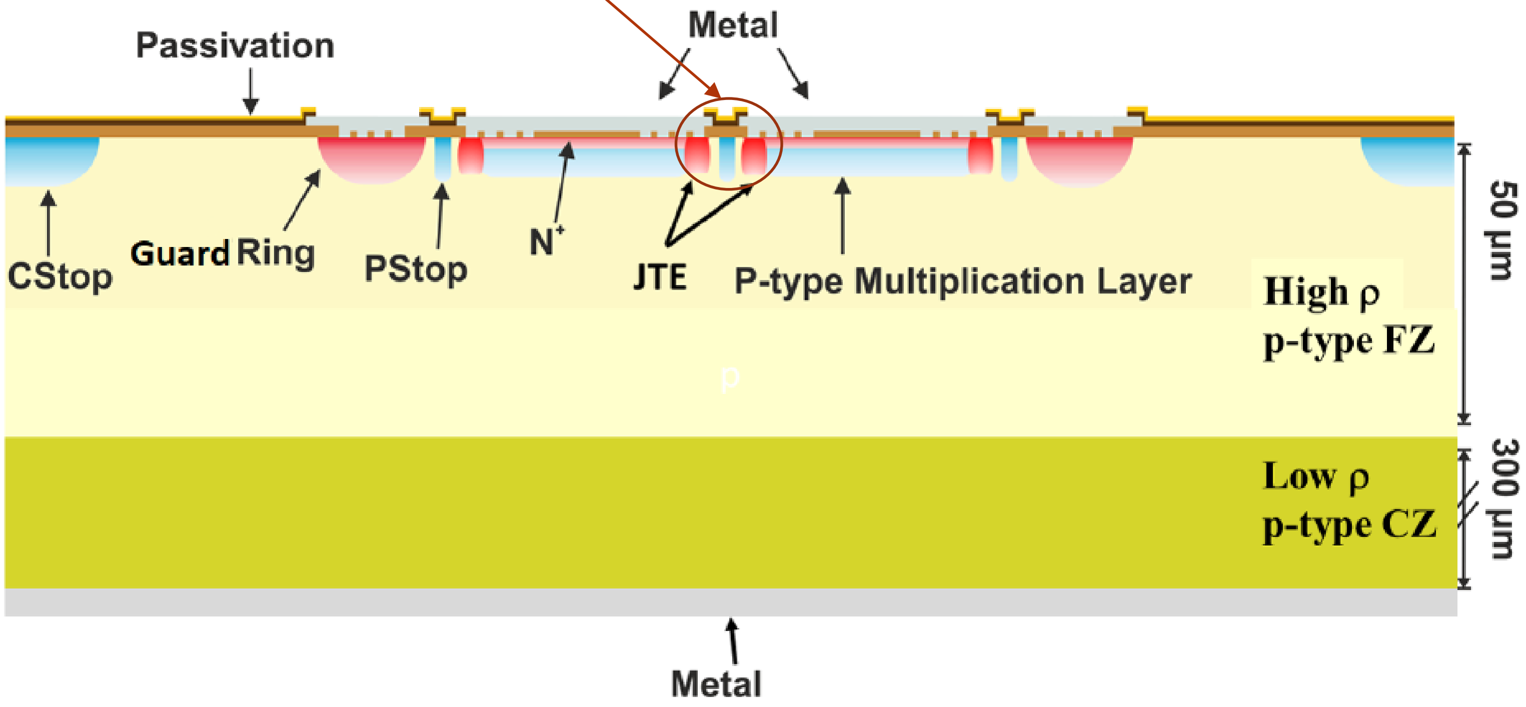
LGAD granularity

LGAD arrays structure



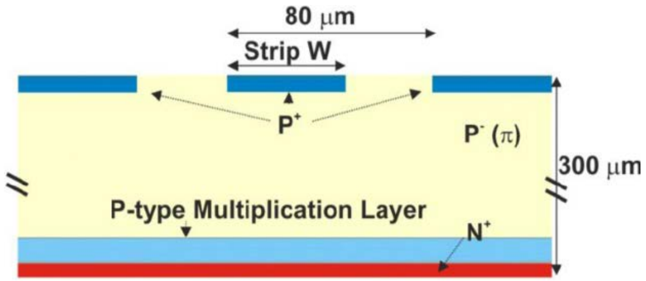
Very high field area, induces early breakdown

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

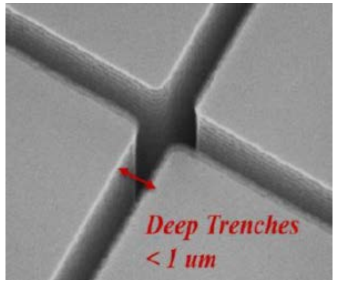


- Protection structures limit the current granularity of LGADs
- ~100um pixel size would mean ~50% active area
- But intensive R&D is ongoing to overcome this limitation

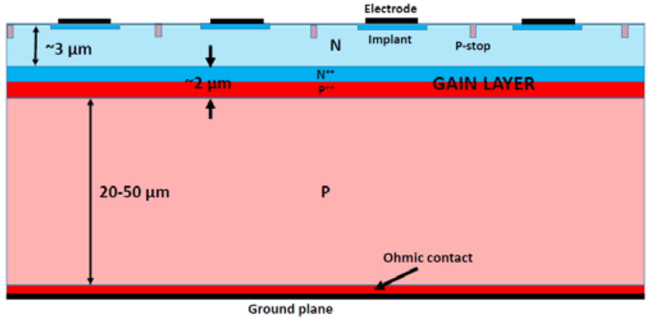
Higher granularity LGADs



- Reverse position of gain layer → iLGAD



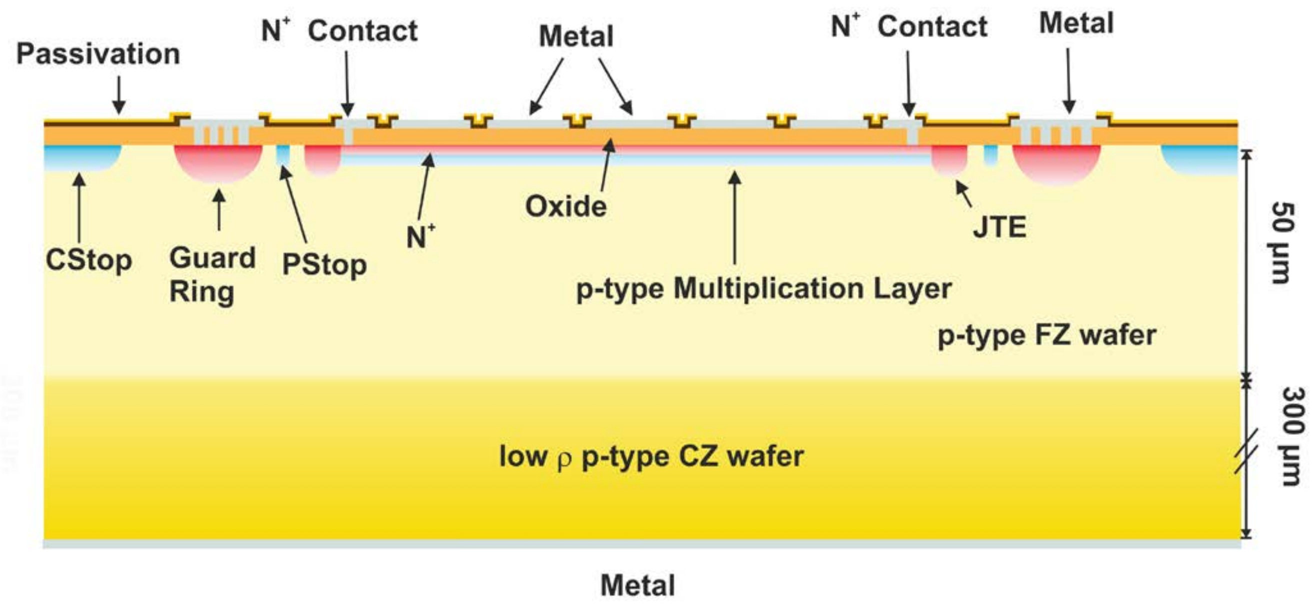
- Trench insulation of pads → TI-LGAD

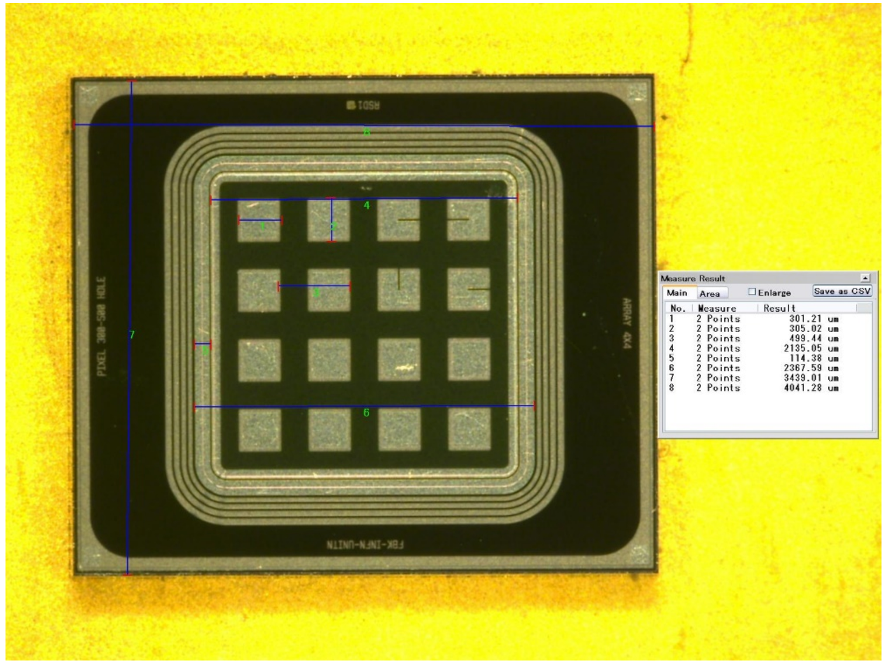


- Deep junction → DJ-LGAD (Patent Application SC 2019-978 (UCSC))

AC-LGAD detectors

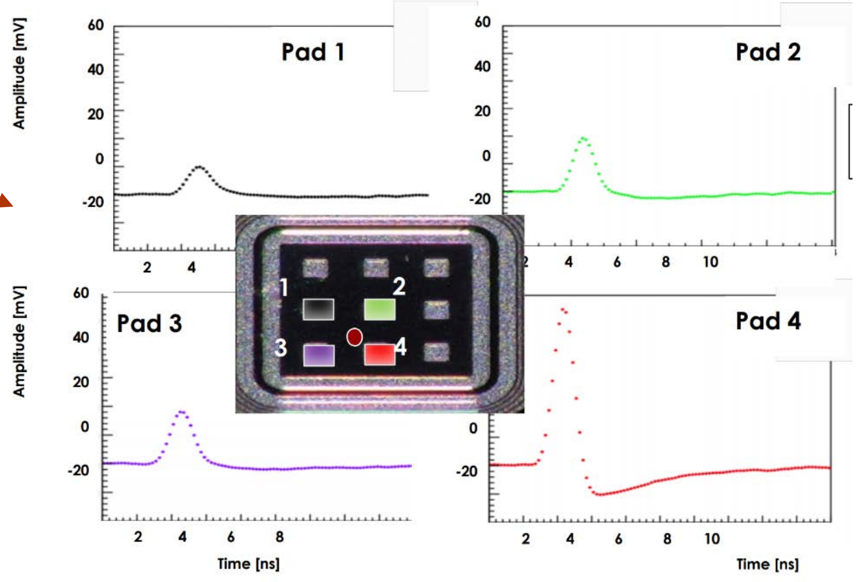
- AC coupled LGAD (UCSC - US patent N. 9,613,993 B2, granted Apr. 4, 2017)
  - Goal: finer segmentation and easier implantation process
- Continuous sheets of multiplication layer and N+ layer
- N+ layer is grounded through side connections
- Readout pads are AC-coupled (Insulator layer between N+ and pads)

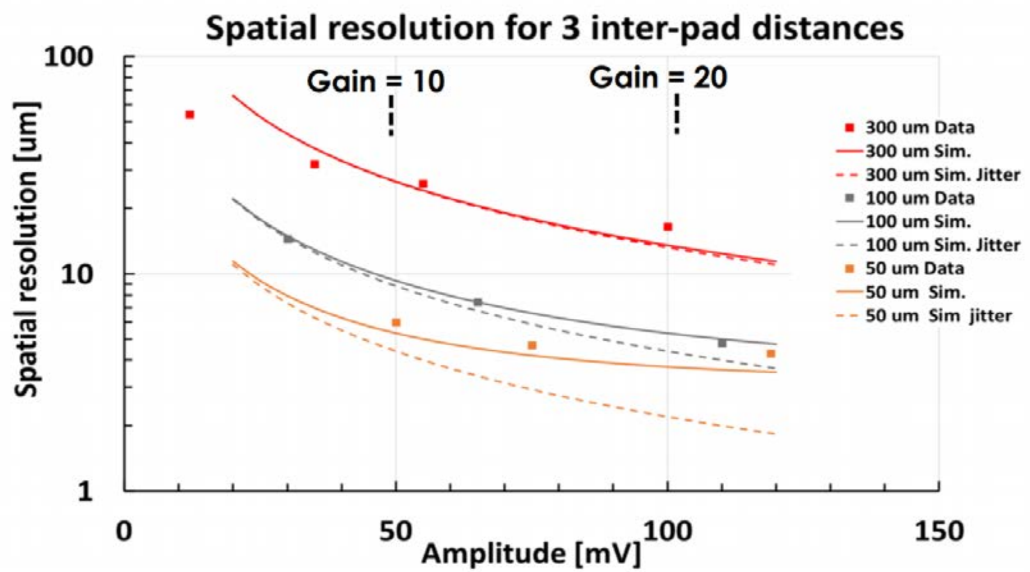




AC event reconstruction and performance

- AC-LGAD has intrinsic charge sharing between pixels
- Charge sharing might be a great feature for low density tracking environment
- Using information from multiple pixels for hit reconstruction
- **With a sparse pixelation of 300um a <10um hit precision can be achieved!**
  - Time resolution can benefit too, using the time of several channels the Jitter component of the time resolution can be reduced
- Extremely useful for both power dissipation and cabling
- Still in a early R&D phase, proposed technology for future EIC experiment at BNL





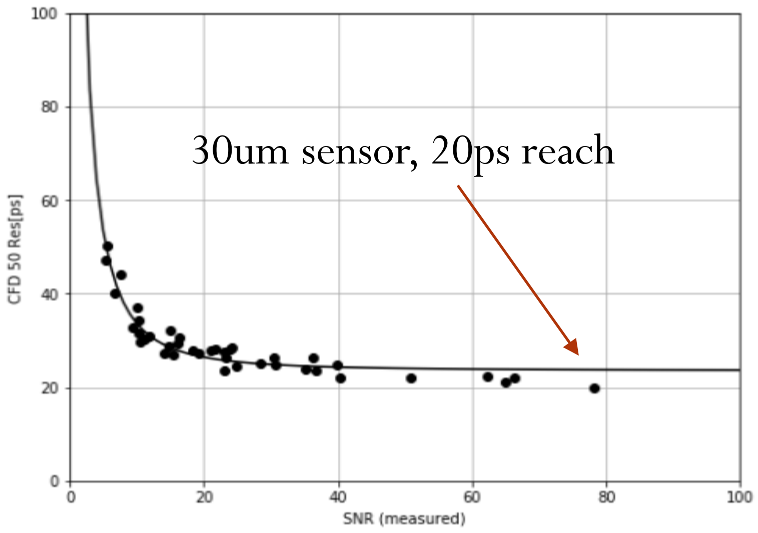
- Resources
  - https://indico.physics.lbl.gov/event/1262/
  - https://indico.cern.ch/event/918298/contributions/3880516/
  - https://arxiv.org/abs/2006.01999
  - https://indico.cern.ch/event/895924/contributions/3968867/attachments/2119055/3565898/Vertex2020_KEKLGAD_20201008_upload.pdf

Thin sensors future improvements

Thin LGAD sensors future uses

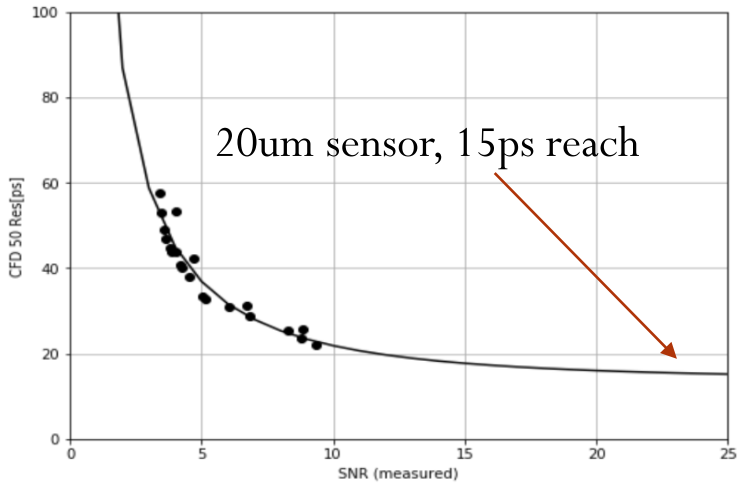
- First results with a 20um prototype LGAD
  - With issues, gain layer has to be optimized
  - However shows possible improvements down to 15ps of time resolution
- Compared with 50um sensors (30ps reach) and 30um sensors (20ps reach)
- https://arxiv.org/abs/2006.04241

G30 sensor



- Very thin sensors can also be candidates for extreme radiation environment
- Issue: 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
- Can be operated in extreme radiation environment
- https://doi.org/10.1016/j.nima.2020.164383
- https://agenda.hep.wisc.edu/event/1391/session/12/contribution/60
- https://indico.desy.de/indico/event/24272/session/0/contribution/13/material/slides/0.pdf

H20 Sensors

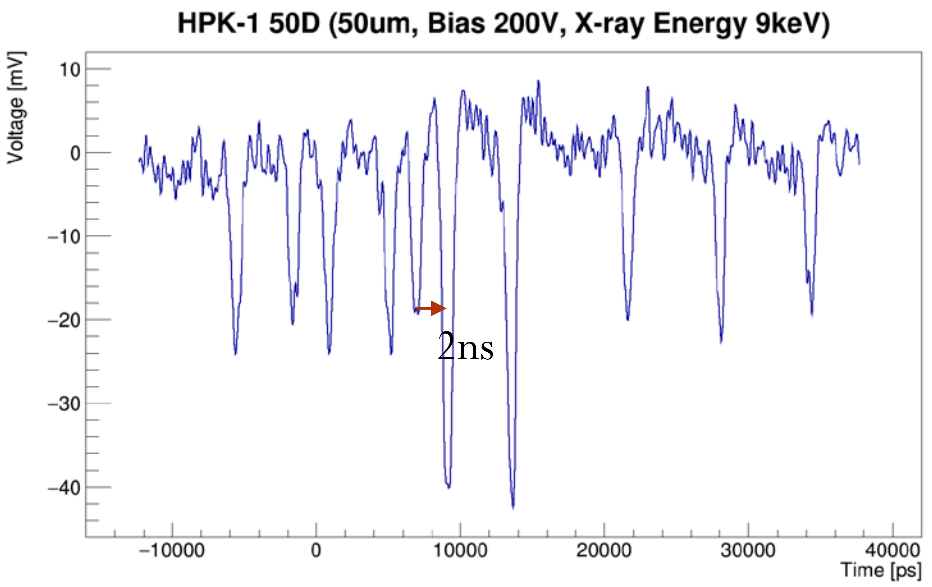


LGADs with X-ray - SSRL

- LGAD tested at SLAC SSRL
  - **Stanford Synchrotron Radiation Light source**

- X-rays of energy range [6, 16] KeV
  - 80, 60, 50, 35 um detectors
- Very good **time resolution ~100ps**
- Fair energy resolution ~10%
- Full collection time ~1ns correspond to GHz repetition rate
- Definite pulses even with a **2ns beam separation**
  - No influence on shape from close-by pulses
- https://doi.org/10.1016/j.nima.2019.01.050

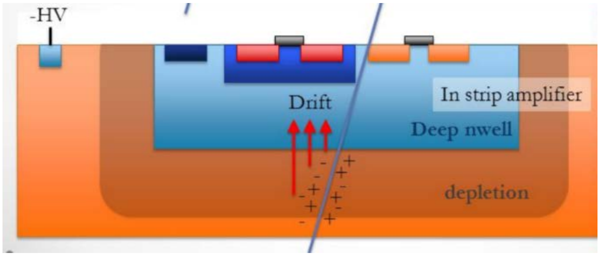
- Application other than HEP are being pursued for LGADs, such as fast beam monitoring
  - Challenge: reach 10 GHz of repetition rate



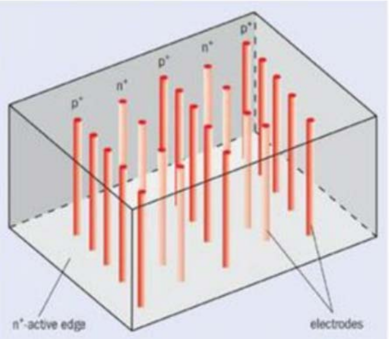
Conclusions

Fast sensors current performance

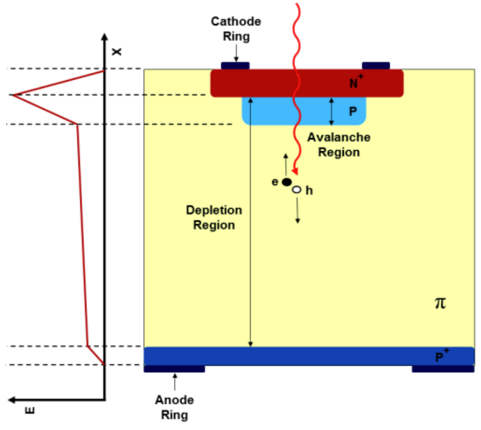
- HV-CMOS, Monolithic chip with internal amplification
  - Good time resolution (~50ps) and avoids bump bonding procedure
  - Low production cost
  - Power consumption might be too high



- 3D sensors, No amplification, perpendicular charge collection
  - Trench 3D sensors can reach ~20ps or time resolution
  - Pitch size proportional to charge collection time
  - Good radiation hardness, but low collected charge and charge sharing
  - Candidates for vertexing with timing

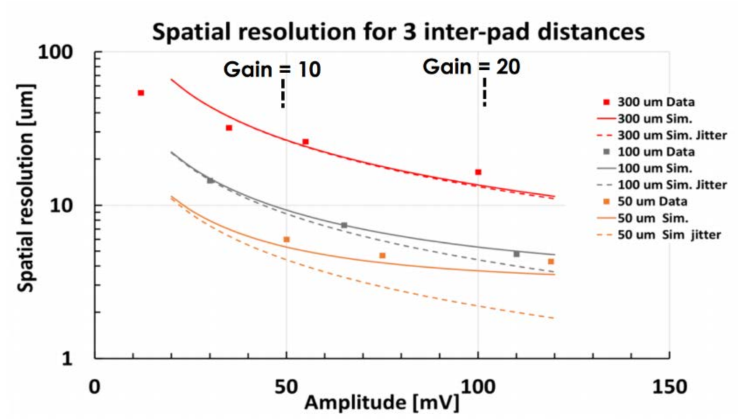


- LGADs, Internal gain, thin sensors of 50-30um
  - Can reach 20-30ps of time resolution and a gain of ~50
  - Reasonable performance up to a few 1E15Neq
  - Granularity limited to ~mm scale (for now)

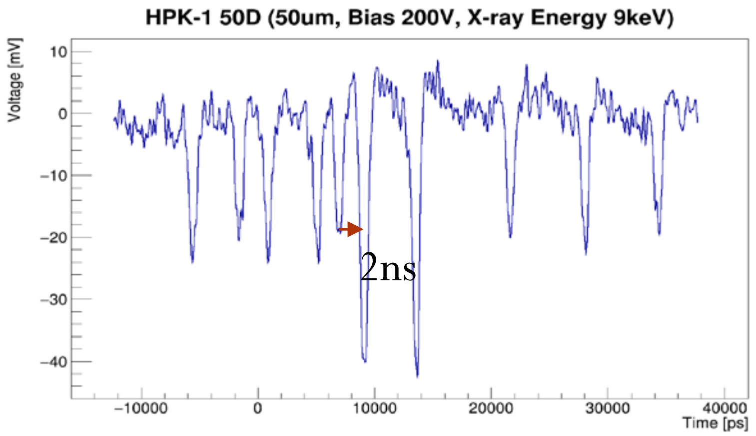


LGAD future development and applications

- In the future 15ps per hit is foreseeable with very thin LGADs
- Low granularity (10um) can be achieved with AC-LGADs
  - In a sparse environment low granularity (10um) with larger pitch (300um) is achievable
- Few mentions in the last years of Monolithic LGADs (lower cost and power)
  - https://indico.fnal.gov/event/44925/contributions/194082/attachments/132985/163760/Future_silicon_detectors_Aug13_2020.pdf
  - ttps://indico.cern.ch/event/669866/contributions/3234993/



- HL-LHC confirmed both ATLAS and CMS LGAD timing layers, ~2026
- Several Electron Ion Collider (BNL) LoI mention LGADs and AC-LGADs as possible technology for 4D tracking
- Application other than HEP are being pursued for LGADs, such as fast beam monitoring



- LGADs are also mentioned in several snowmass LoI
- A new "LGAD consortium" was formed across US universities and national laboratories to tackle LGAD R&D in the next years

Many thanks to the SCIPP group students and technicians!

This work was supported by the United States Department of Energy, grant DE-FG02-04ER41286

This project was supported in part by a Launchpad Grant awarded by the Industry Alliances & Technology Commercialization office from the University of California, Santa Cruz.

This work was partially performed within the CERN RD50 collaboration.

Part of this work has been financed by the European Union's Horizon 2020 Research and Innovation funding program, under Grant Agreement no. 654168 (AIDA-2020) and Grant Agreement no. 669529 (ERC UFSD669529), and by the Italian Ministero degli Affari Esteri and INFN Gruppo V.

Backup

Irradiation campaigns on LGADs

- Irradiation campaign on LGADs
- Sensors were irradiated at
  - JSI (Lubiana) with ~1 MeV neutrons
  - PS-IRRAD (CERN) with 23 GeV protons
  - Los Alamos (US) with 800 MeV protons
  - CYRIC (KEK, Japan) with 70 MeV protons
  - X-rays at IHEP (China)
- Neutron irradiation for fluence
  - From 1E13 Neq/cm^2 → 1E16 Neq/cm^2
- Proton irradiation for fluence and ionizing dose
  - Up to 4MGy
- X-ray irradiation for ionizing dose

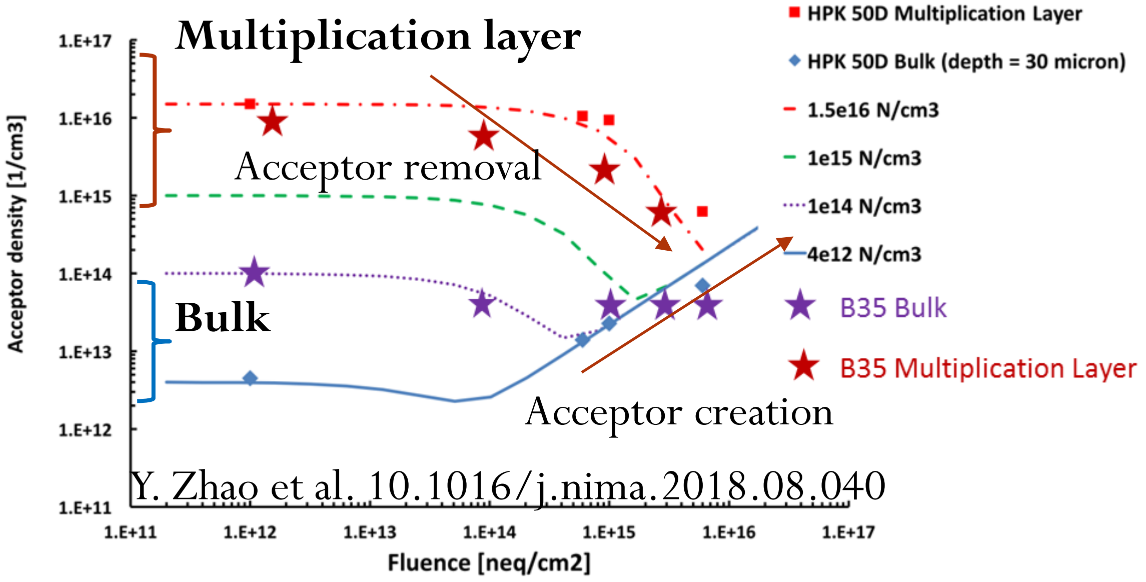
Jožef Stefan Institute

CERN IRRAD Proton Facility

Los Alamos NATIONAL LABORATORY

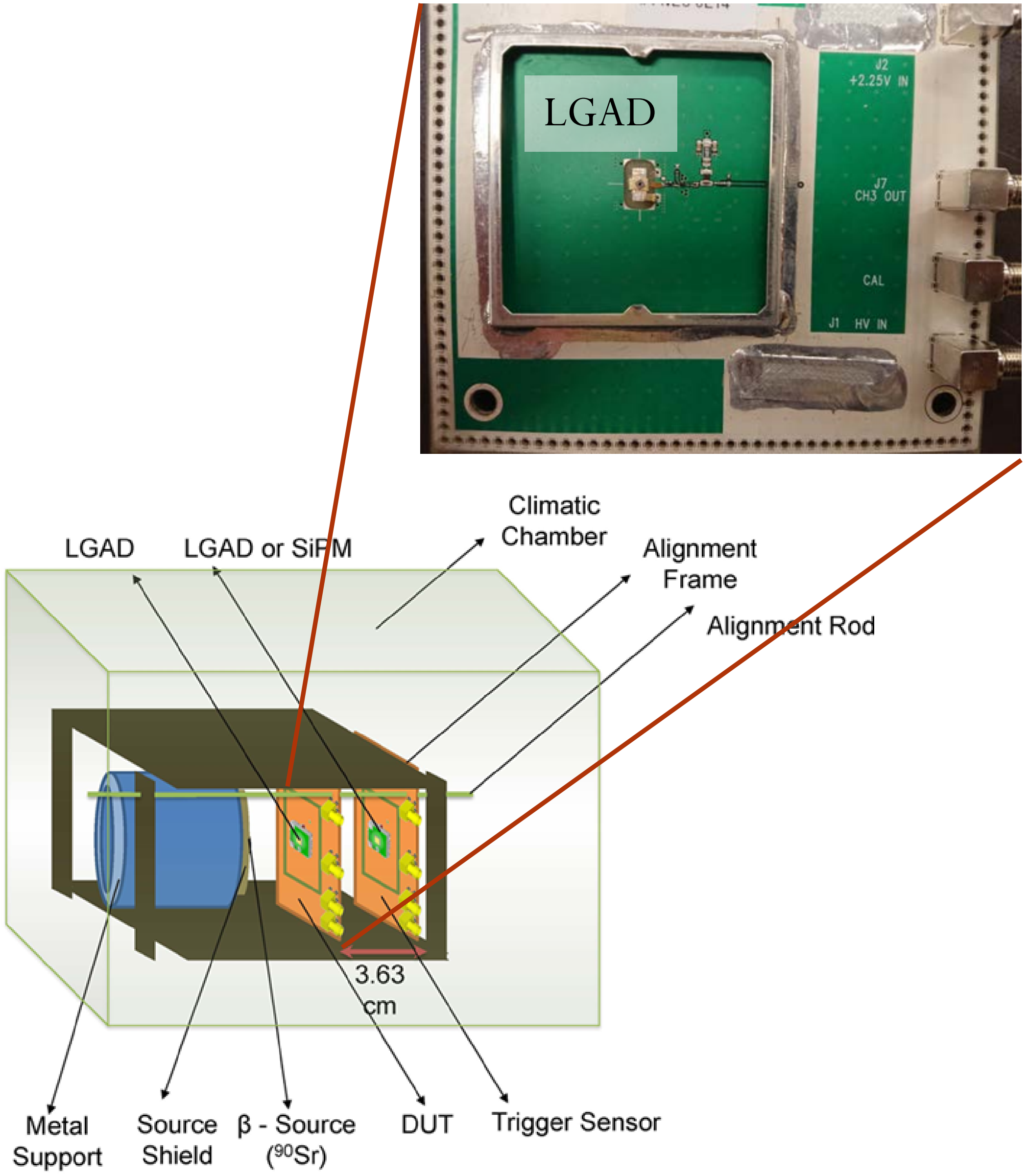
KEK

Acceptor removal mechanism



- Most widely accepted radiation damage explanation for LGADs is **acceptor removal**
  - M. Ferrero et al. arXiv:1802.01745, G. Kramberger et al. JINST **10** (2015) P07006
- Radiation damage for LGADs can be parameterized
  - $N_A(\phi) = g_{eff}\phi + N_A(\phi{=}0)e^{-c\phi}$
  - ϕ is radiation fluence in Neq/cm^2
- Acceptor creation: $g_{eff}\phi$
  - By creation of deep traps
- Initial acceptor removal mechanism: $N_A(\phi{=}0)e^{-c\phi}$
  - Ionizing radiation produces interstitial Si atoms
  - Interstitials inactivate the doping elements (Boron) via kick-out reactions that produce ion-acceptor complexes

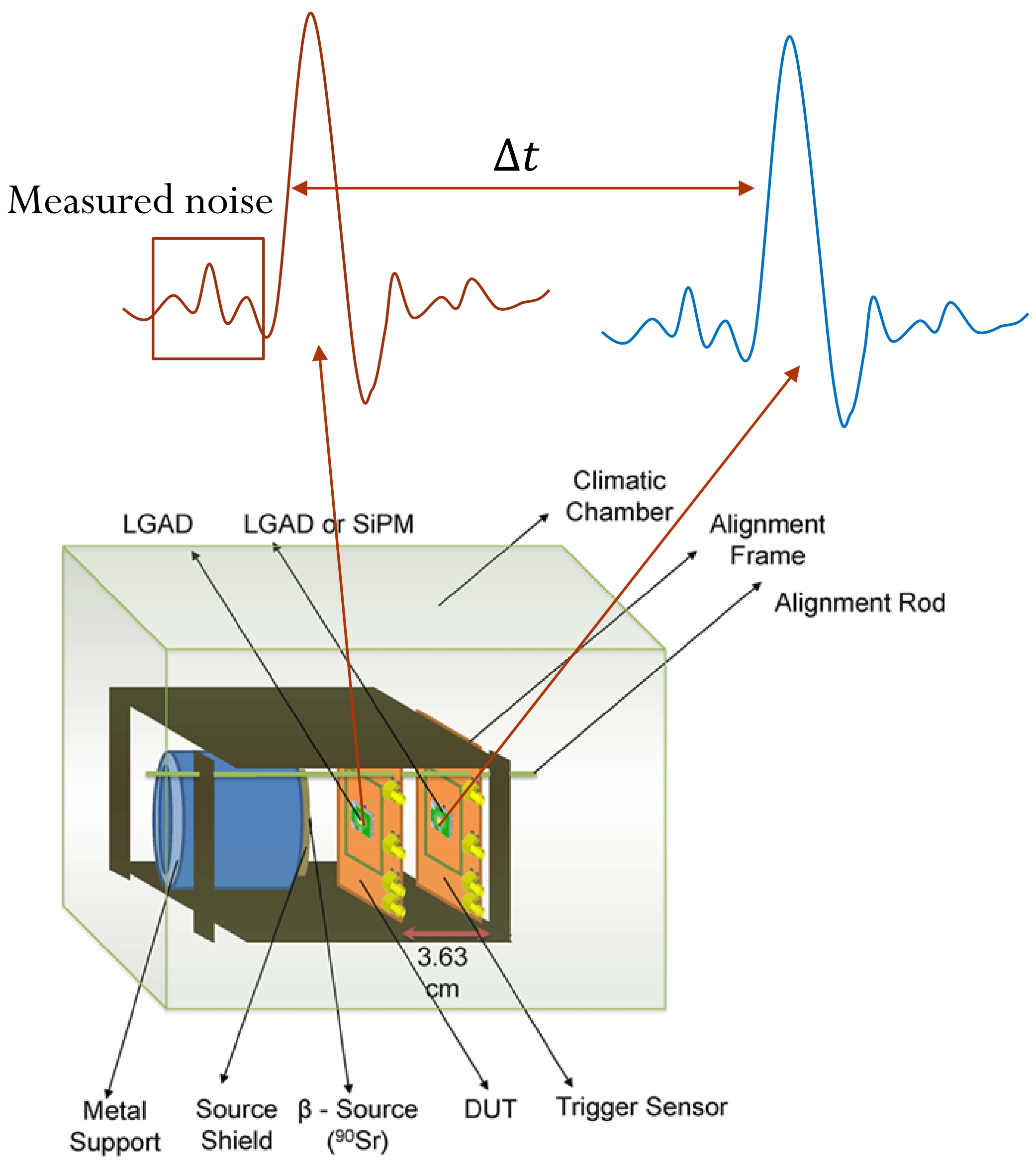
Sensor testing – Sr90 telescope



- Dynamic laboratory testing
  - Using MiP electrons Sr90 β-source
  - Signal shape, noise, collected charge, gain, **time resolution**
- β-telescope
  - Sensors mounted on analog readout board designed at UCSC (Ned Spencer, Max Wilder, Zach Galloway) with fast amplifier (22 ohm input impedance, bandwidth > 1GHz)
  - Trigger sensor (fast timing trigger) on the back
    - DUT (Device Under Test) is read in coincidence
  - Setup in climate chamber to run cold and dry
    - 20C/-20C/-30C
  - (however no position information)

S.M. Mazza et al. arXiv:1804.05449

Sensor testing – Sr90 telescope

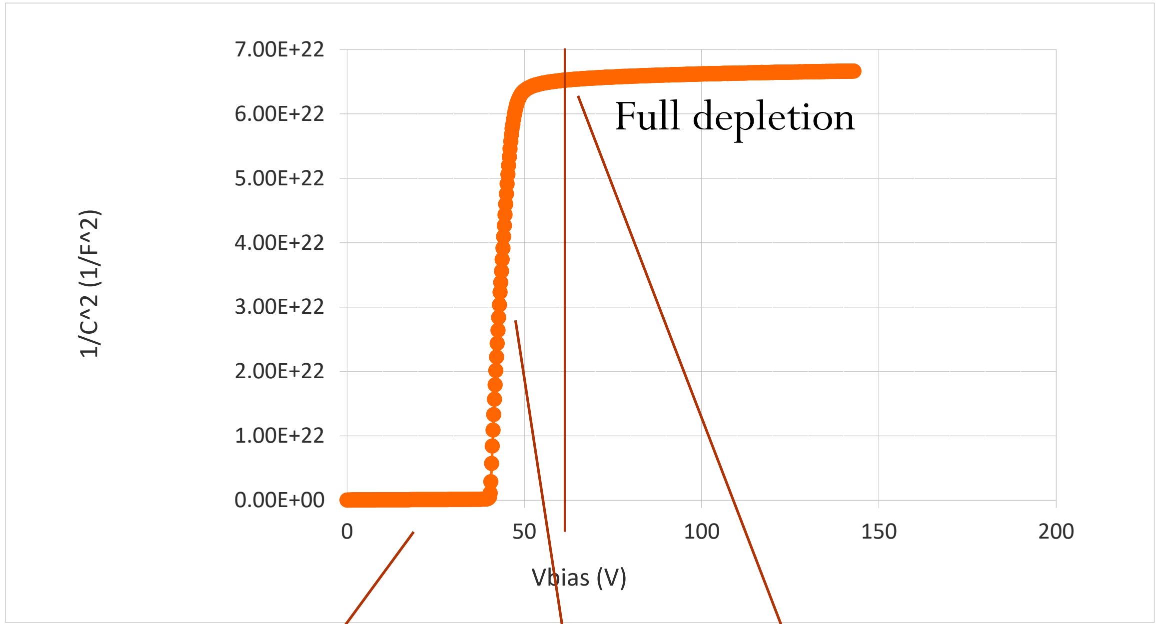


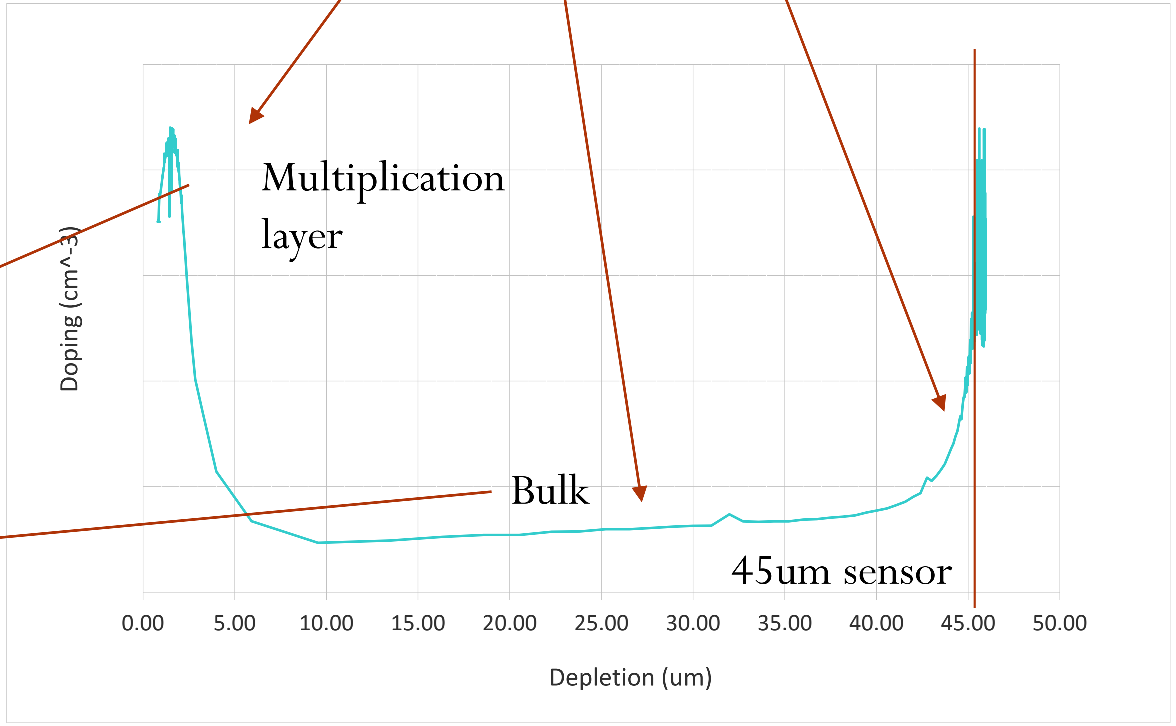
- Signal to Noise
  - Pulse maximum over noise
- 10-90% rise time
- Time resolution
  - Spread of time difference with trigger sensors and DUT
  - Trigger sensor time resolution measured by mounting two identical sensors
- Collected charge
  - Pulse area (minus undershoot) divided by trans impedance
- Gain
  - Collected charge divided by collected charge in same thickness PiN
  - Collected charge in PiN measured with the same β-telescope

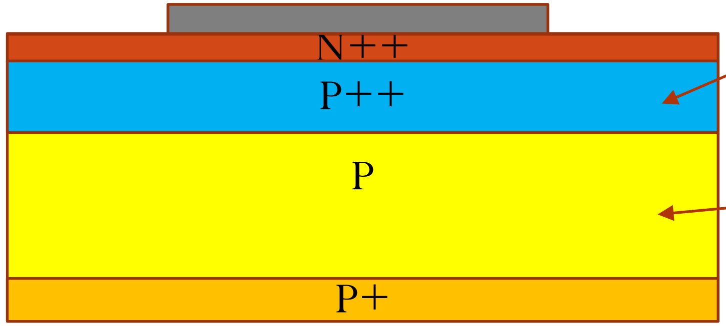
S.M. Mazza et al. arXiv:1804.05449

Sensor testing – IV/CV

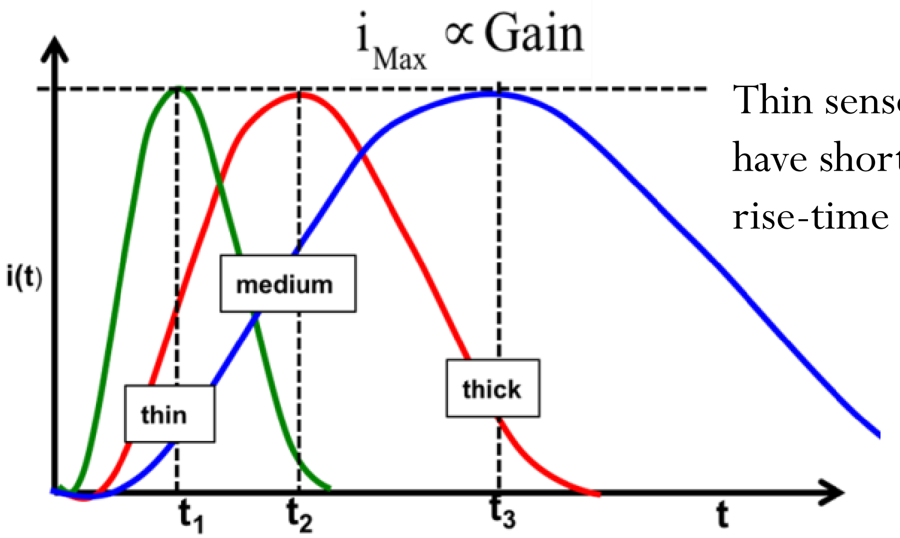
- Capacitance over voltage (CV)
  - Study doping concentration profile and full depletion of the sensor
- Study of the “foot” for LGADs on $1/C^2$
  - $1/C^2$ is flat until depletion of multiplication layer because of the high doping concentration
  - Proportional to gain layer active concentration
-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





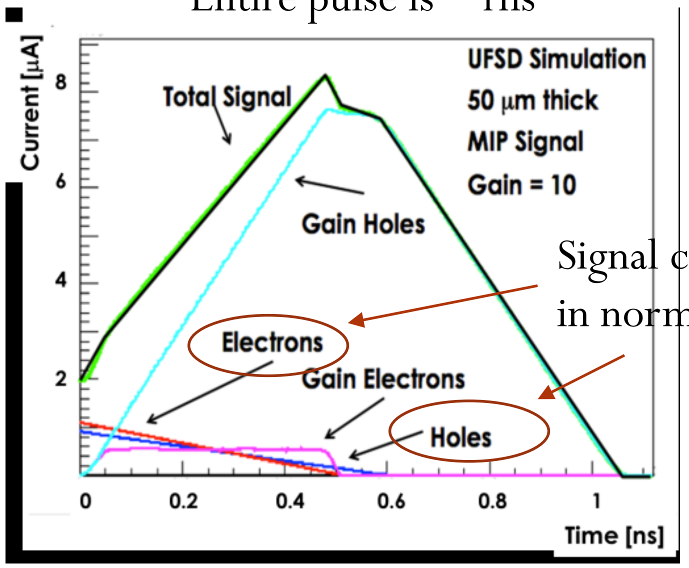


Low Gain Avalanche Detectors



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
- Thanks to gain LGADs can go thinner than normal silicon detectors
  - Down to 50um and 20um!
- Thinner detectors have shorter rise time and less Landau fluctuations
- Gain from multiplication layer
  - Better signal to noise ratio
- Better signal to noise ratio and thin detectors means improved timing resolution
  - **Time resolution < 30 ps**