Silicon Detectors

Time Resolution Comparison between LGADs and 3D-Detectors

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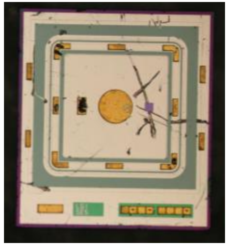
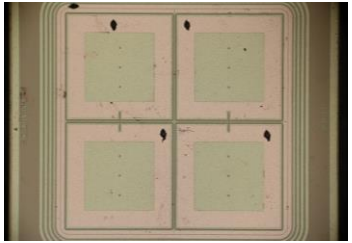
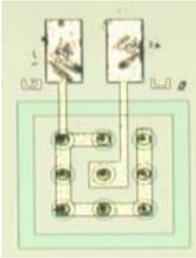
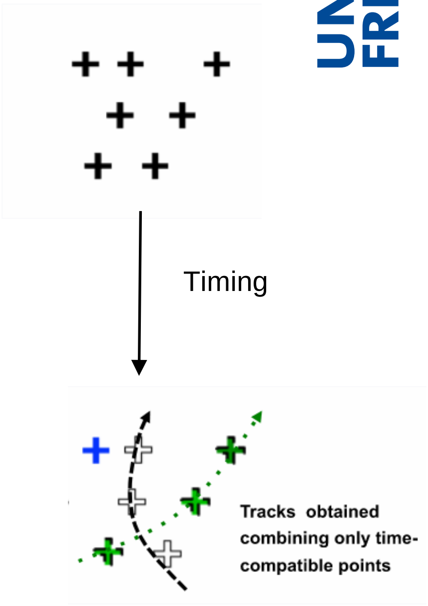
Introduction

- Hadron colliders challenge track reconstruction with increasingly high rates and pile-up
  - 4D Tracking
  - Time resolution measurements to compare sensors
- Measured sensors:
  - HPK Run 2 LGADs (50 µm active thickness, Cell size of 1.3 x 1.3 mm²)
  - FBK UFSD 3.2 W1 type 10 LGAD Array (45 µm active thickness, Cell size of 1.3 x 1.3 mm², 2 p-stops + bias grid, nominal no gain width of 49 µm)
  - CNM 3D Pixel Detector (235 µm active thickness, Cell size of 50 x 50 µm²)



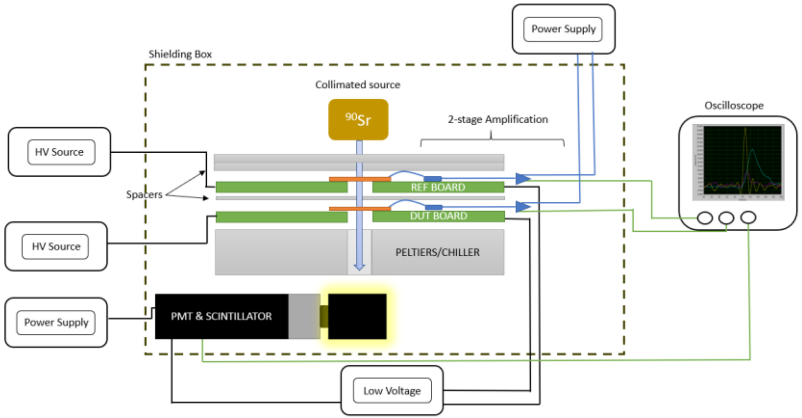






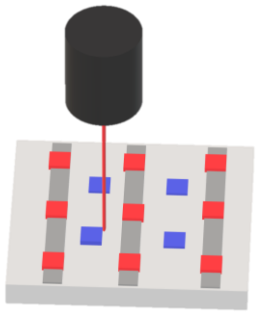
Timing Setups

Beta Setup:



- Sr-90 Source for MIP-like electrons
- Trigger on reference LGAD and PMT
- Waveforms from reference LGAD compared to **d**evice **u**nder **t**est (DUT)

Top - TCT Setup:

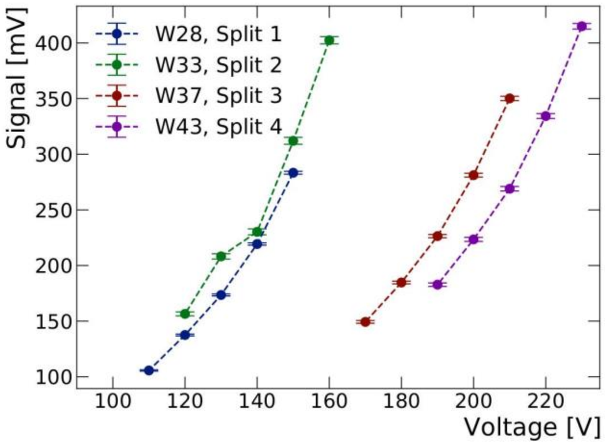


- Laser (1060 nm) beam splitted and one pulse delayed by ~ 25 ns
- Trigger on Laser
- Pulses compared to each other

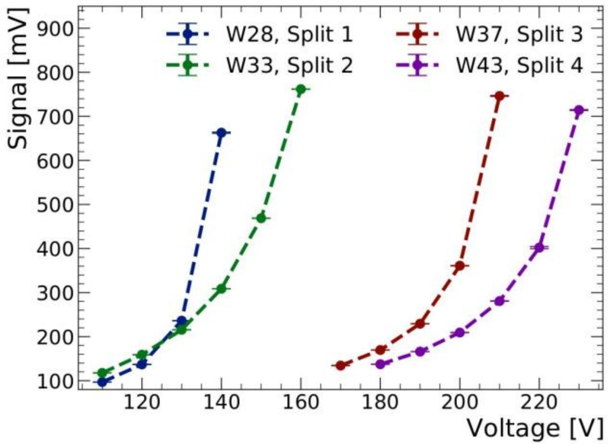
Unirradiated LGADs - HPK

- Gain layer doping from high (Split 1) to low (Split 4)
- Signal height similar for all sensors, albeit at different applied voltages
- TCT measurements show much higher signals for higher voltages
  - Gain Suppression (E.Curras et al. Gain suppression mechanism observed in LGADs)

Beta Measurements



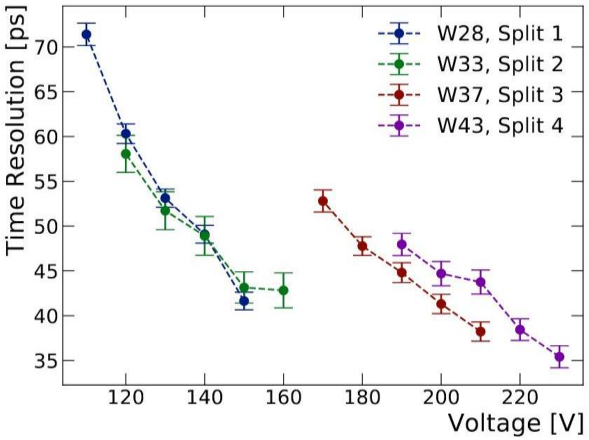
TCT Measurements



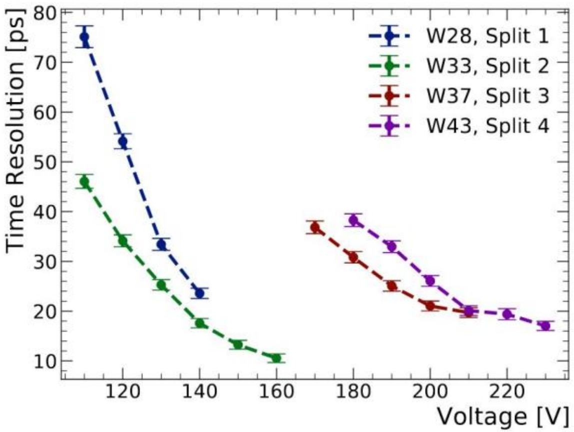
Unirradiated LGADs - HPK

- Gain layer doping from high (Split 1) to low (Split 4)
- Best resolution for lowest gain layer but also highest voltages needed
- TCT measurements show better time resolution
  - No Landau fluctuations, reduced jitter due to higher Signal

Beta Measurements



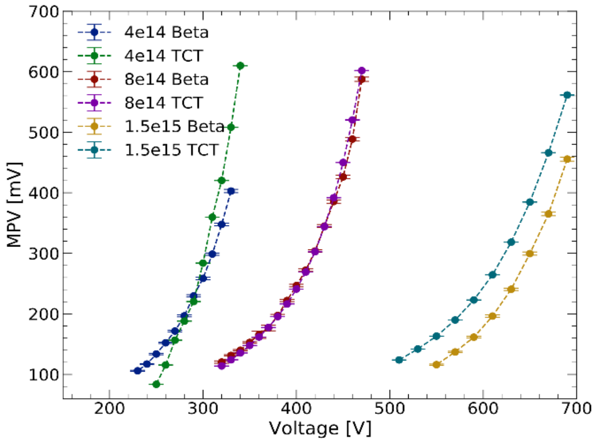
TCT Measurements



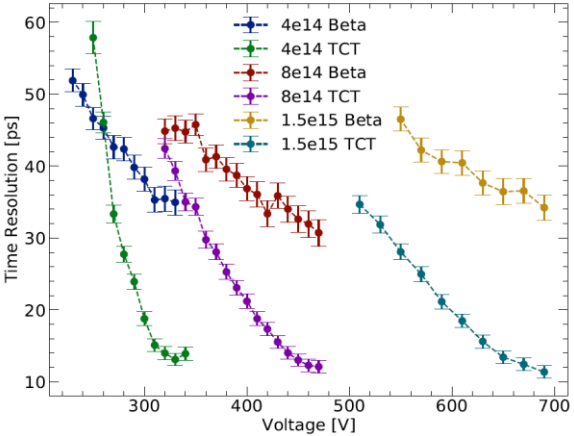
Irradiated LGADs – HPK Split 2

- Higher radiation leads to higher voltages which can/need to be applied
- Similar minimal time resolution achievable (at vastly higher voltages)
- Signal curves of beta and TCT become more similar for large fluences
  - Importance of Gain-Layer reduced

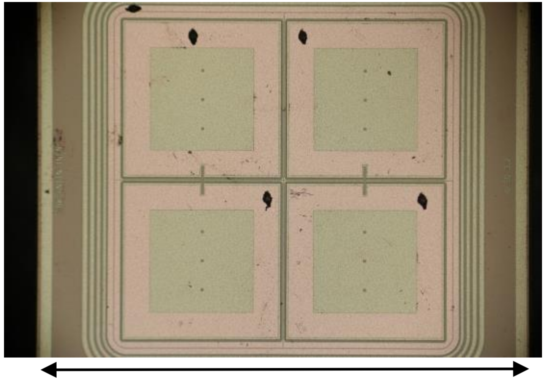
Signal

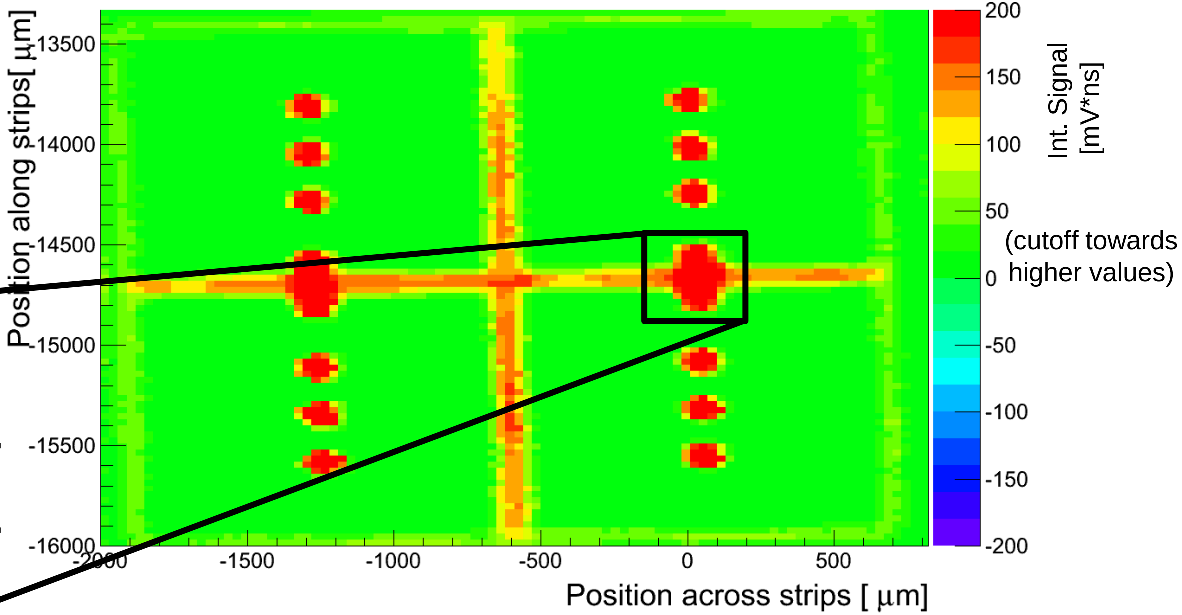


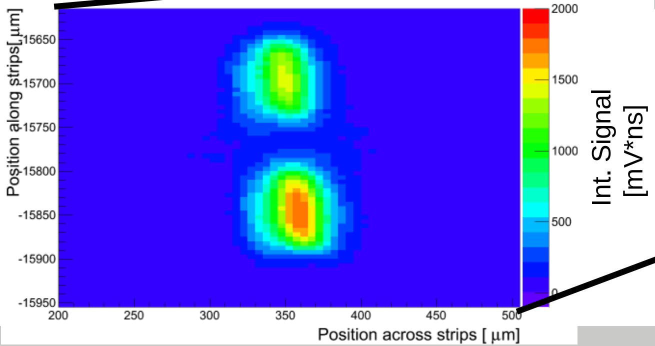
Timing Resolution



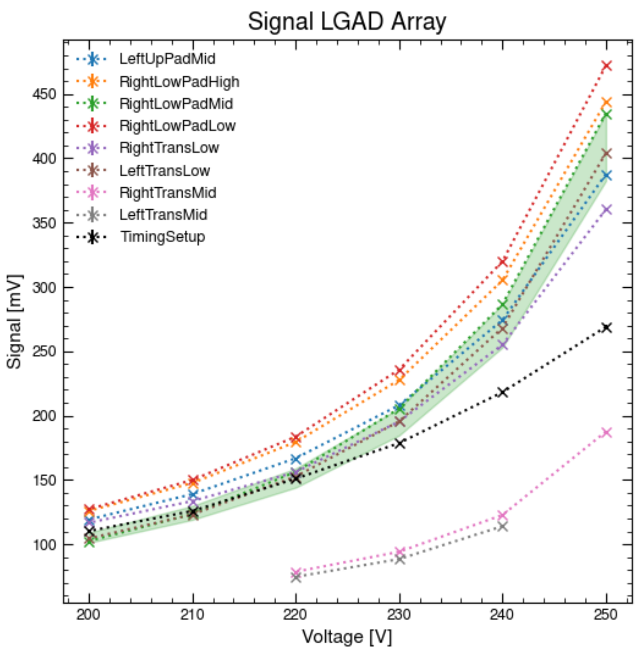
FBK LGAD Array - TCT

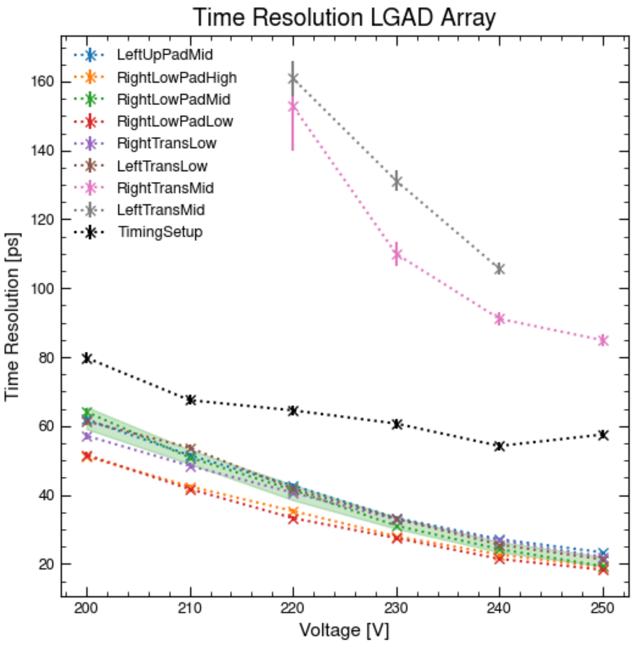


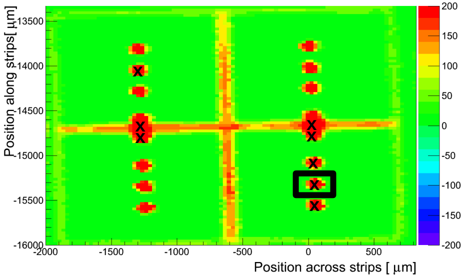




FBK LGAD Array

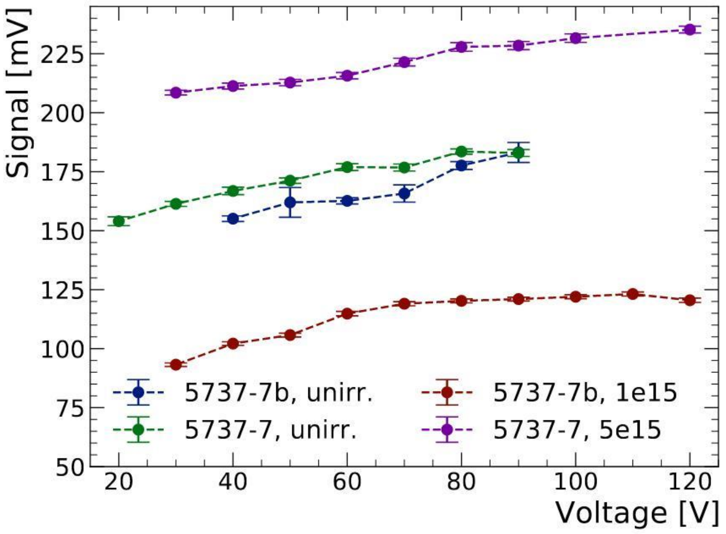


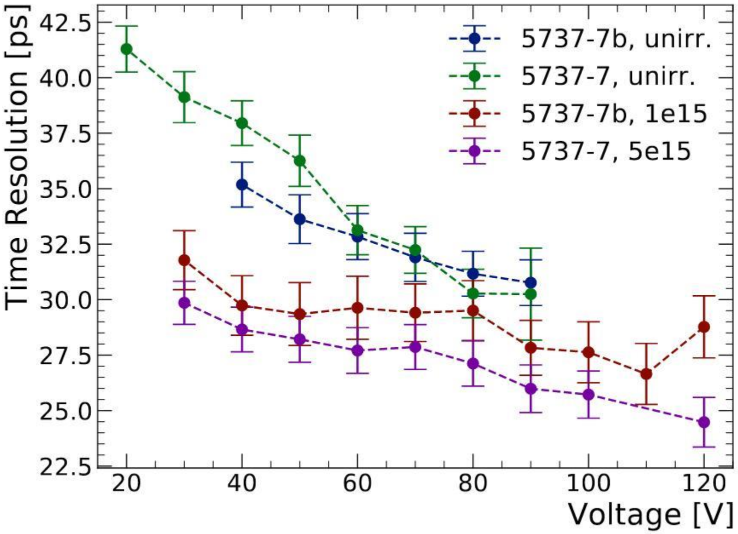




3Ds – Beta Setup, Single Cell Readout

- Irradiated sensors measured cold (-18.5 °C)
- Charge multiplication visible for highly irradiated sensor
- Time resolution becomes better for same voltages after irradiation

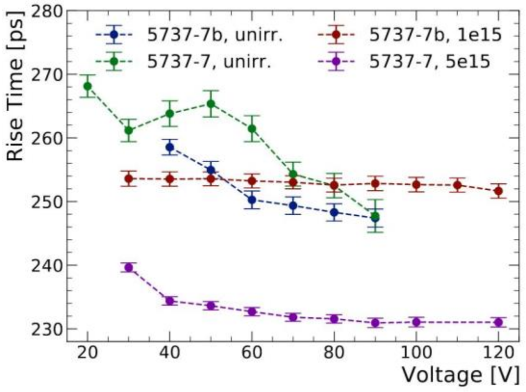


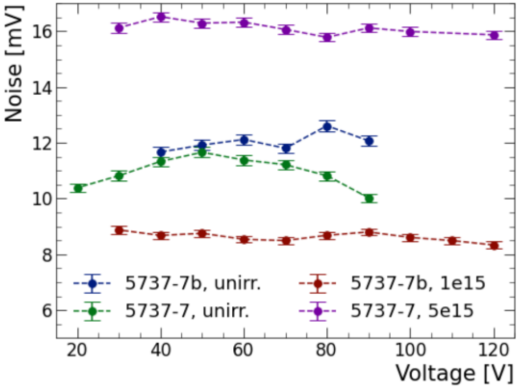


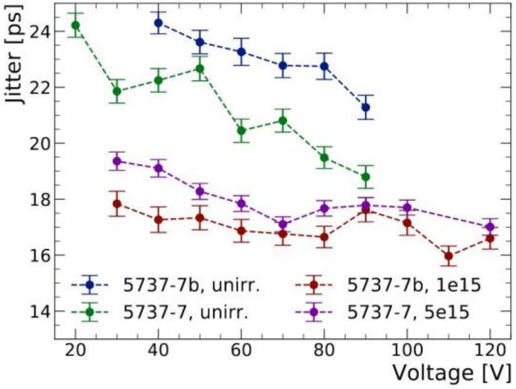
3Ds – Beta Setup, Single Cell Readout

- Risetime similar for all 3D, except for 5e15 sensor
  - Higher E-Field
- Noise lower for 1e15 sensor due to cooling
- Jitter lower for both irradiated 3D

$$\sigma_j = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} \approx \frac{\sigma_n}{\left|\frac{S}{\tau_p}\right|} = \frac{\tau_p}{S/N}$$







Conclusion and Outlook

- Single pixel LGADs, pre and post irradiation and LGAD array measured
  - Gain Suppression visible pre irradiation, less impactful post irradiation
  - Array shows similar timing response under all pads

- First 3Ds measured pre and post irradiation
  - Charge Multiplication results in better time resolution post irradiation
  - Voltage range stays same over fluence range
  - Time resolution comparable to that of LGADs

Outlook: Test further designs and fluences, esp. dedicated timing 3D Detectors

Thank you for your attention!

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Huge thanks also to Nicolo Cartiglia, Oscar Ferrer, Giulio Pellegrini and Valentina Sola for support and sensors!

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Backup

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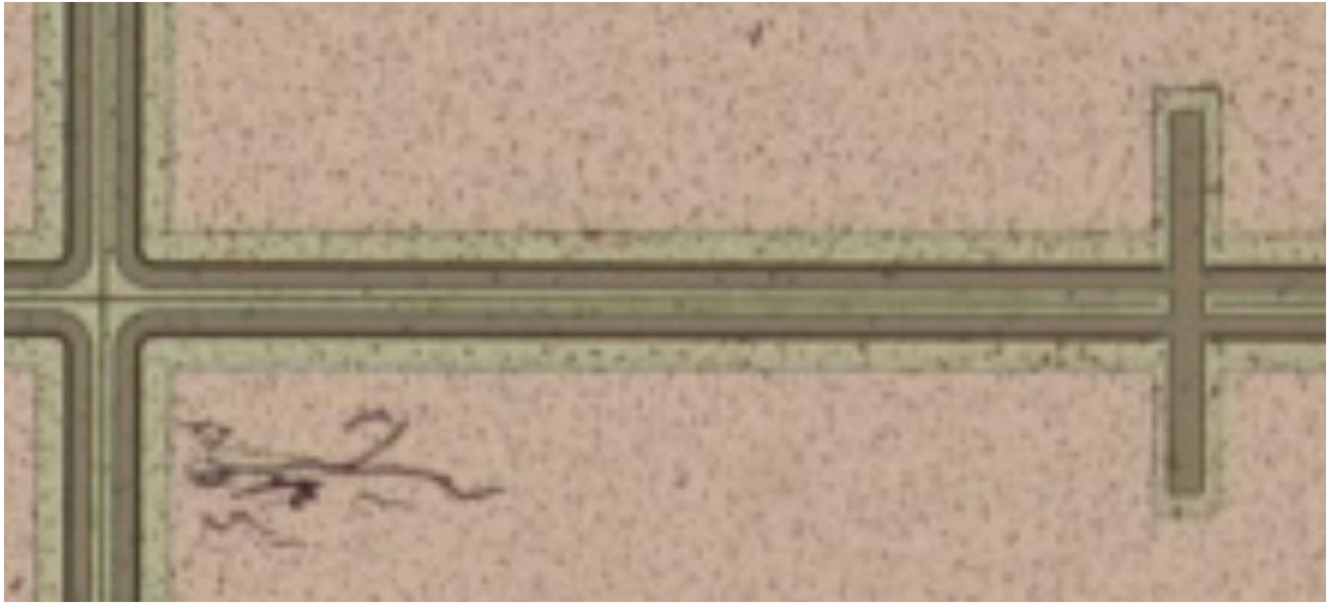
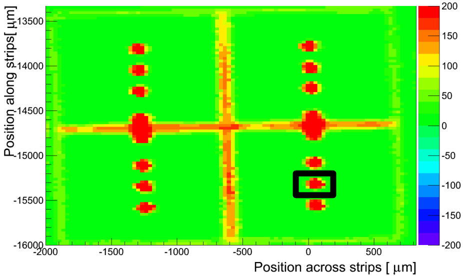
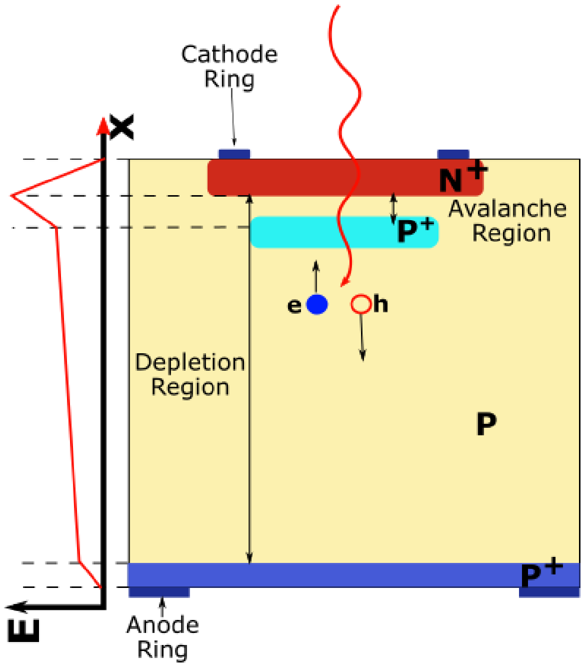
LGAD Array – Interpad Region





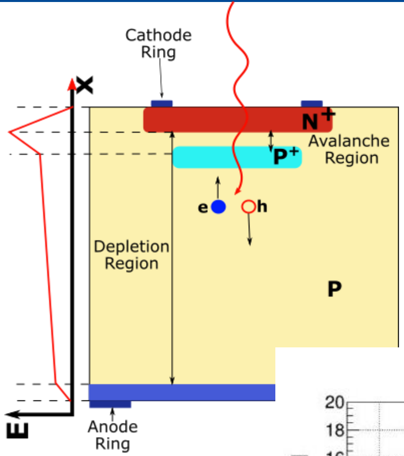
What are LGADs?

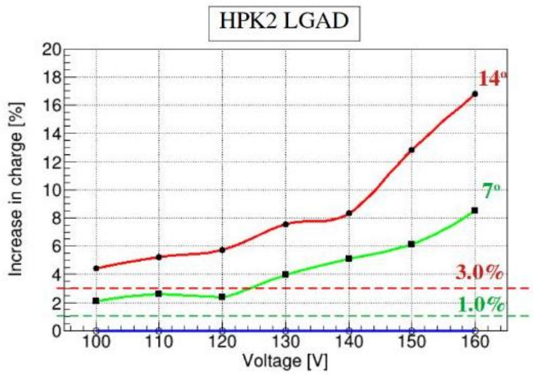
- Low Gain Avalanche Diodes
- Thin sensors to decrease impact of Landau fluctuations on timing
- Gain Layer at top of sensor needed for measurable signal above electronic noise
- Large pads to ensure homogeneous electric field over large volumes of the sensor to decrease weighting field contributions to timing resolution



Gain Suppression

- After multiple charge multiplications the created charge carriers locally reduce the effective electric field
- This reduces the amount of further charge multiplication
  - "Gain Suppression"
- If one induces the same charge over a broader area relative to the avalanche region (laser beam or MIPs under an angle) or reduces the effective doping of the avalanche region this effect is reduced and a higher signal created

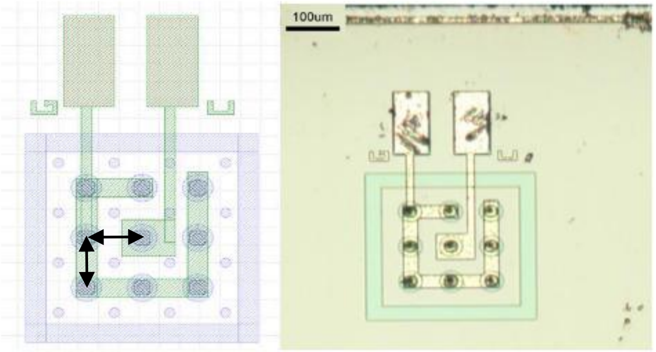




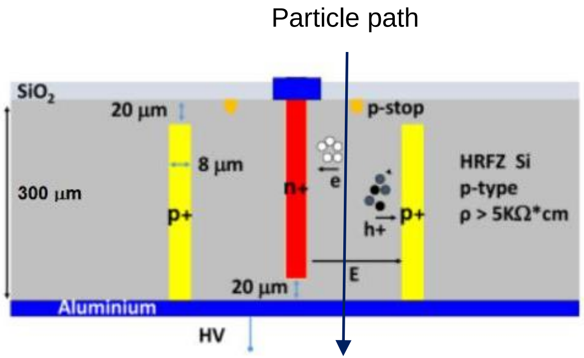
https://cds.cern.ch/record/2776521/files/2107.10022.pdf

What are 3Ds?

- 3D Sensors have electrodes going from surface to bottom of sensor, parallel to particle track instead of strips or pixels on the surface
- This allows for thick (235 – 300 µm) sensors without gain layer as impact of Landau fluctuations is minimised



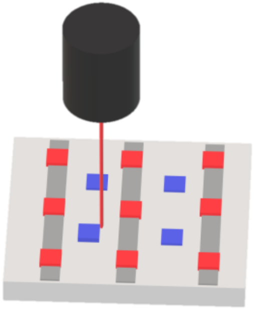
Cell size of 50 x 50 µm²



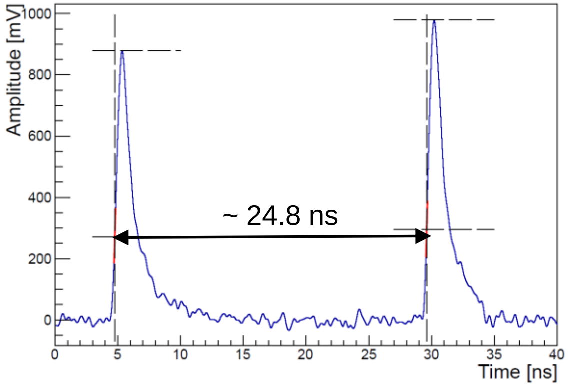
How can Timing be measured? - TCT

- Infrared laser source (1060 nm)
- Laser split into 2 pulses with one being delayed by ~24.8 ns
- 3000 waveforms taken for **D**evice **u**nder **T**est (DUT), **T**ime **o**f **A**rrival (ToA) differences determined, histogram populated and Gaussian fitted

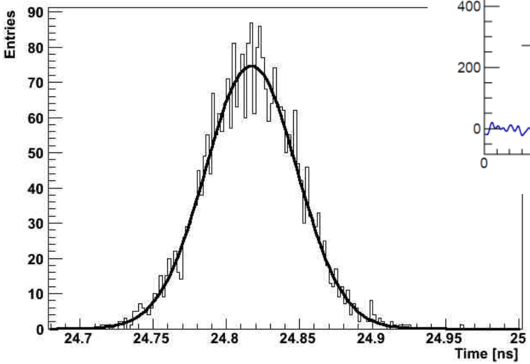
➢ Fitted standard deviation gives time resolution of system



Example Waveform



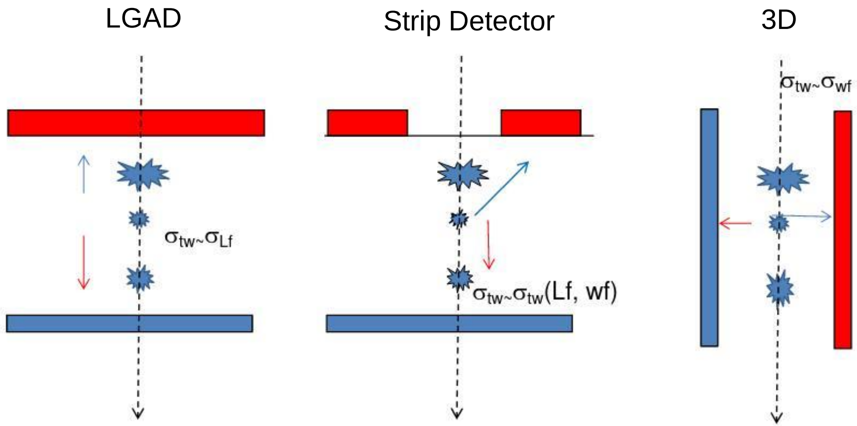
x 3000

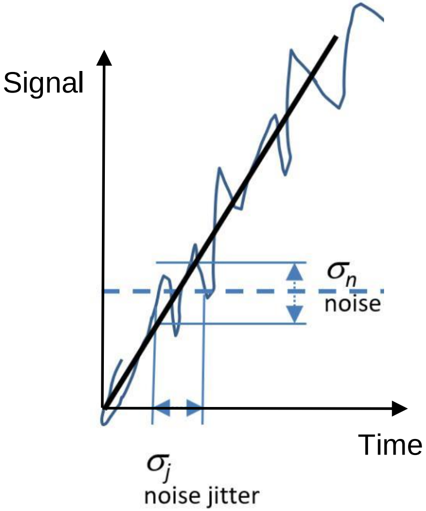


Time Difference Histogram

What can impact Time Resolution?

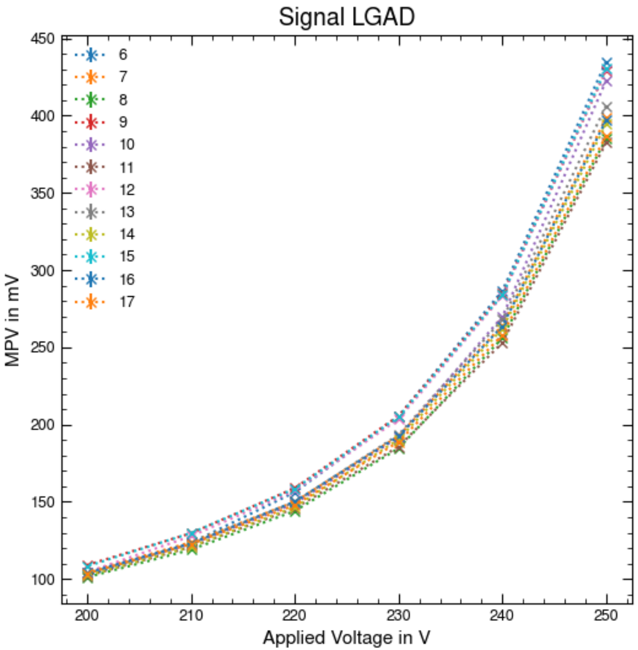
- Jitter
- Position of charge deposition
  (Landau Fluctuations, Weighting Field)

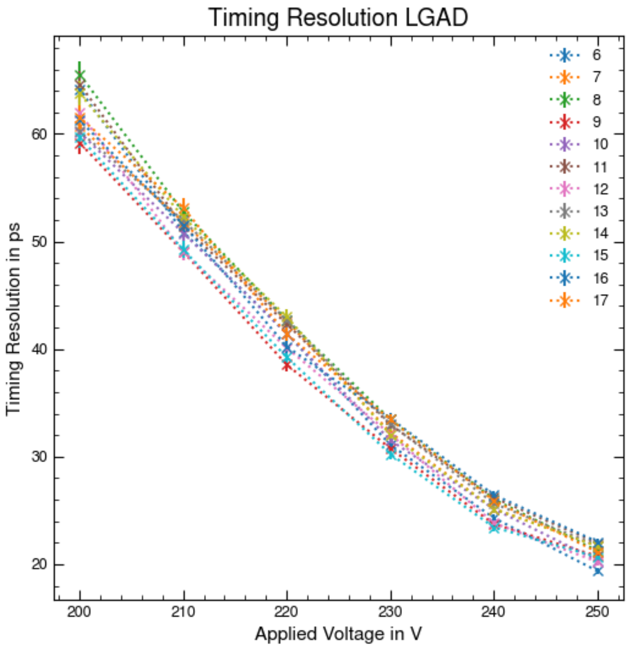


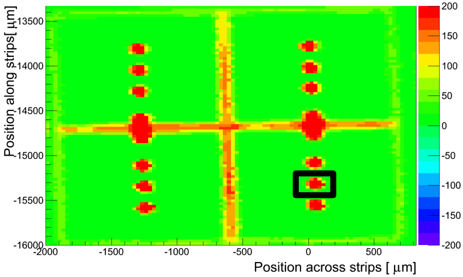


$$\sigma_j = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} \approx \frac{\sigma_n}{\left|\frac{S}{\tau_p}\right|} = \frac{\tau_p}{S/N}$$

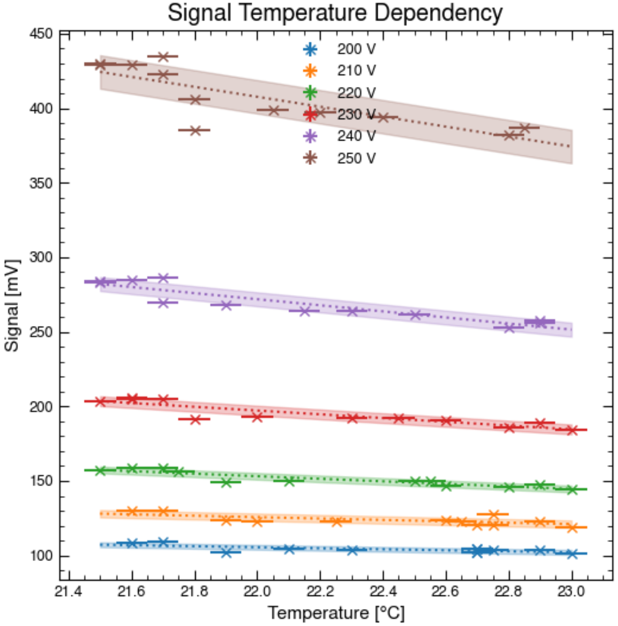
LGAD Arrays - TCT

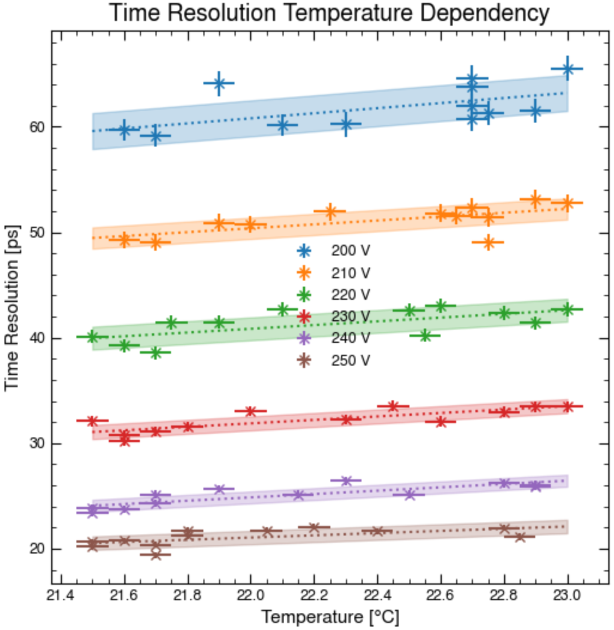




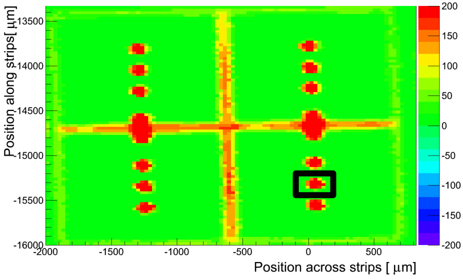


Temperature Dependence – TCT Setup

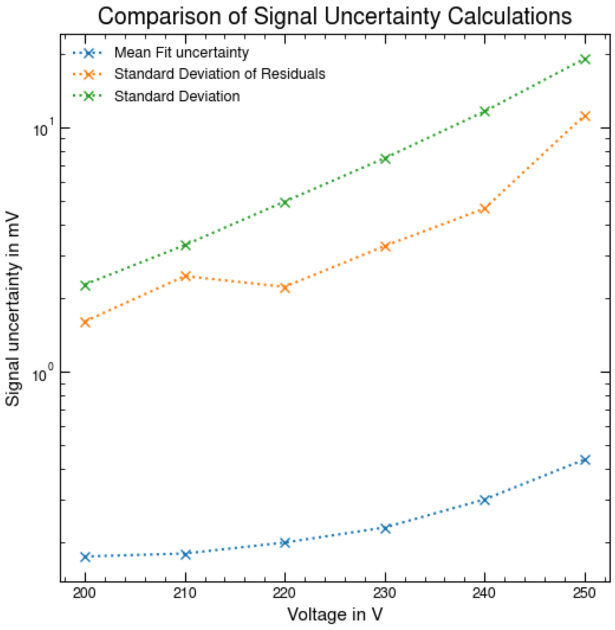


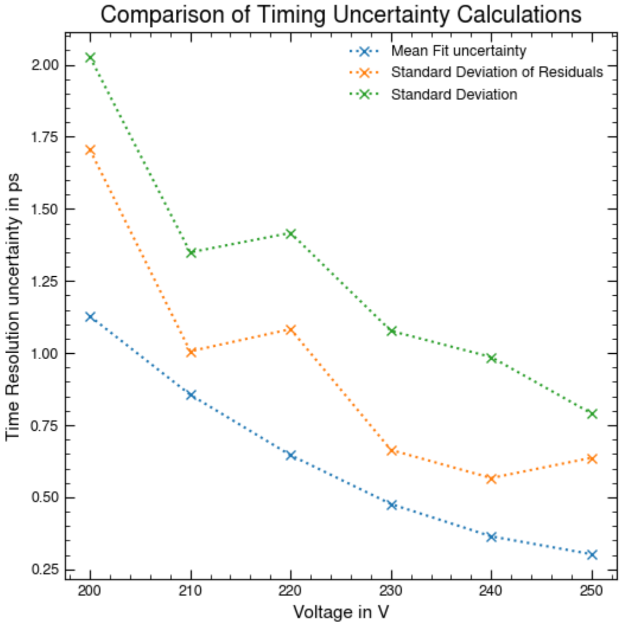


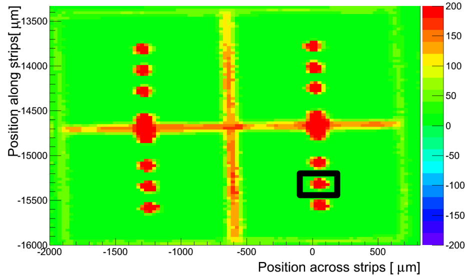
Coloured area represents the linear fit +- the standard deviation of the residuals



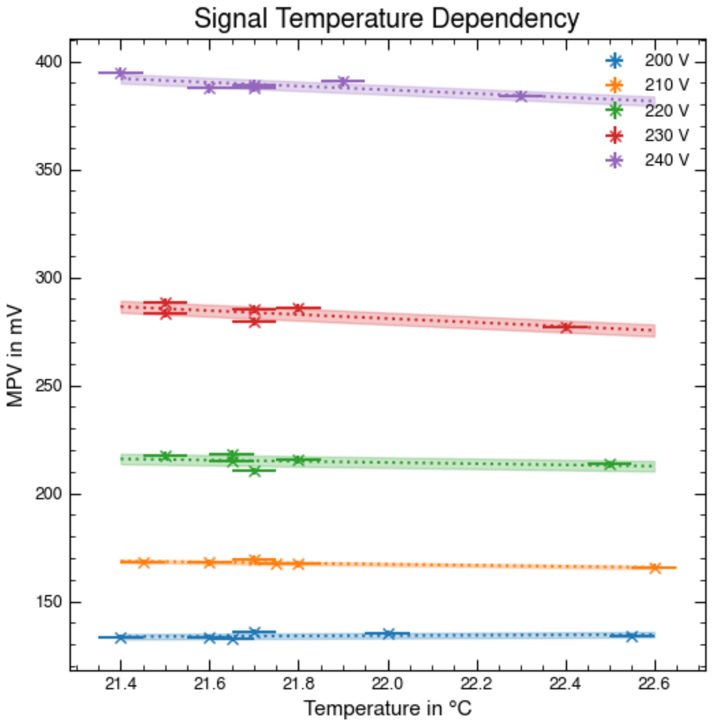
LGAD Arrays – TCT uncertainty

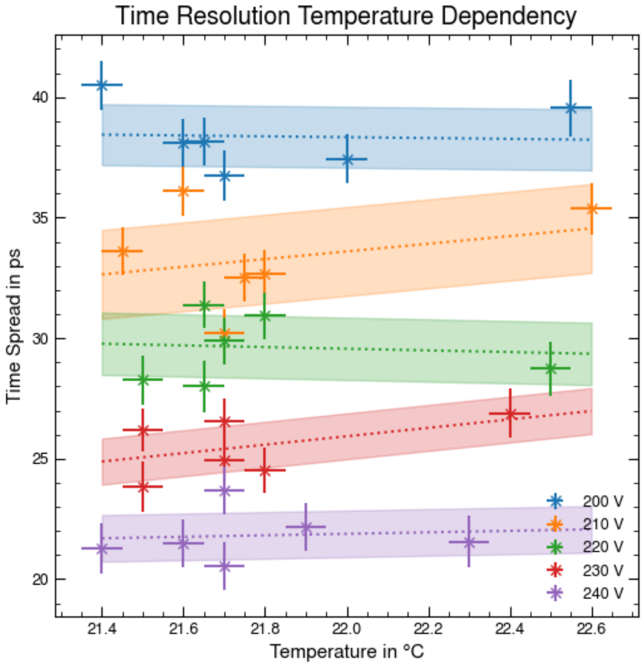




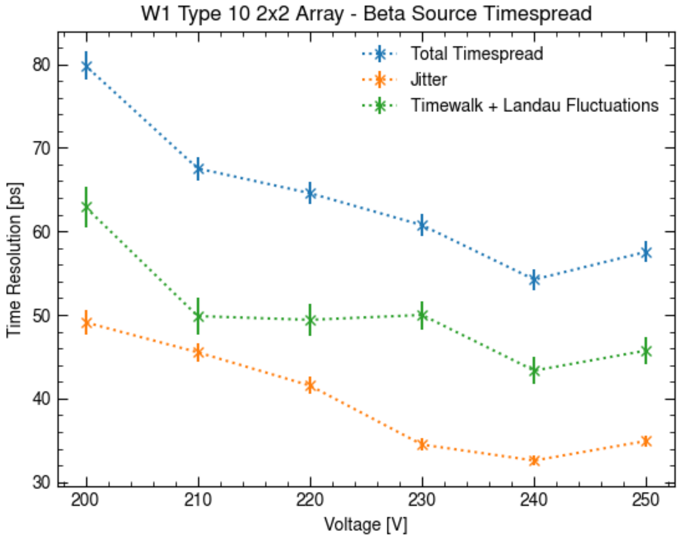


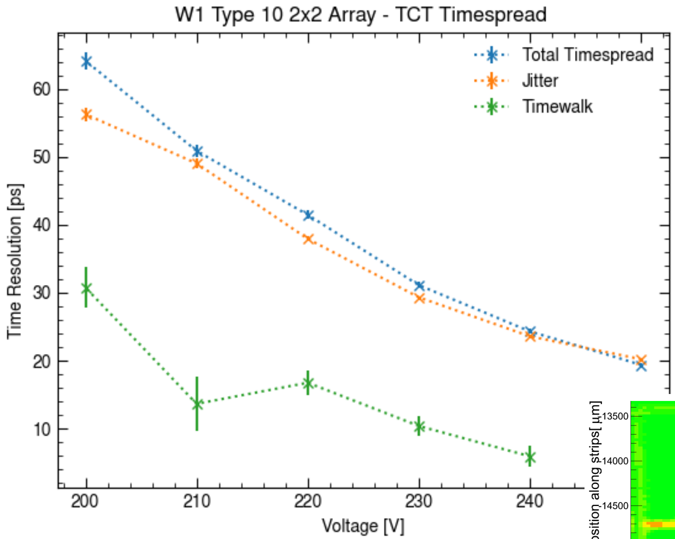
Temperature Dependence – Beta Setup

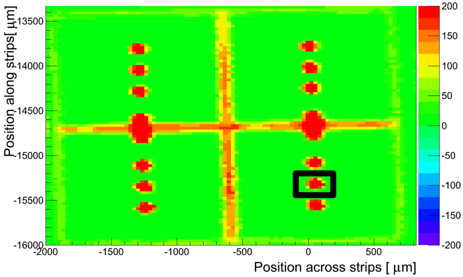




LGAD Arrays - Timing

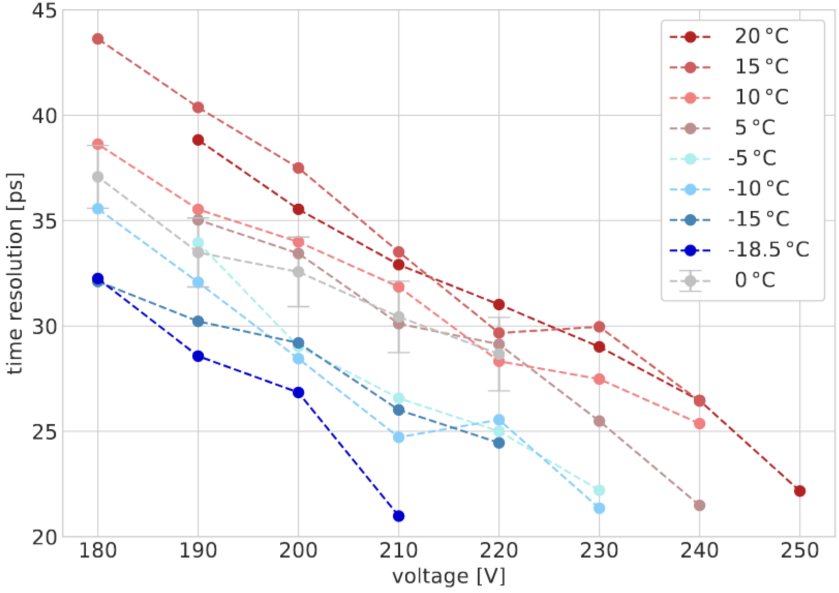




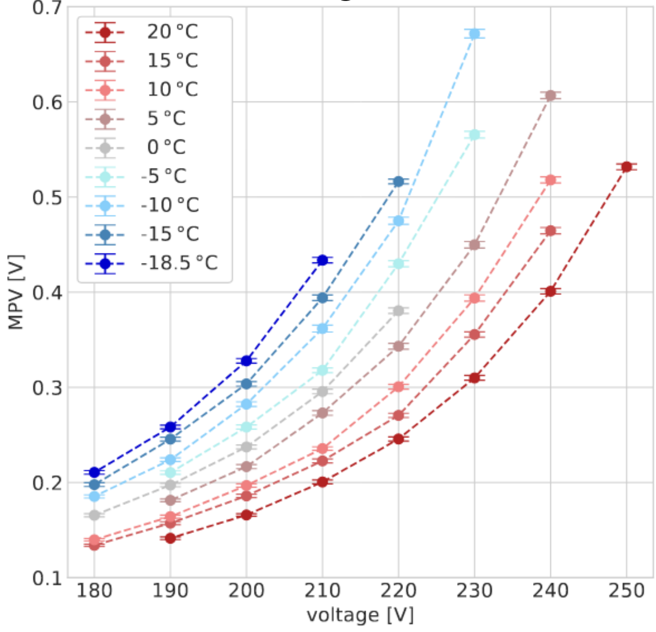


Temperature Dependence

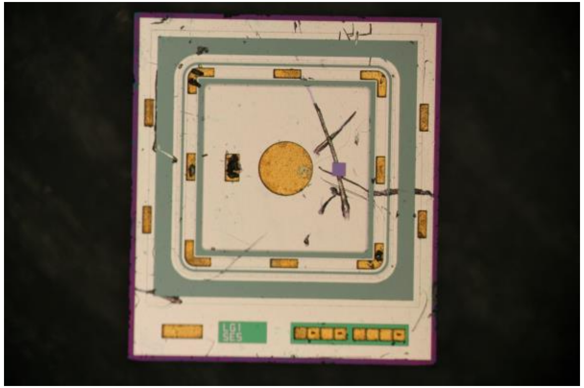
Time Resolution



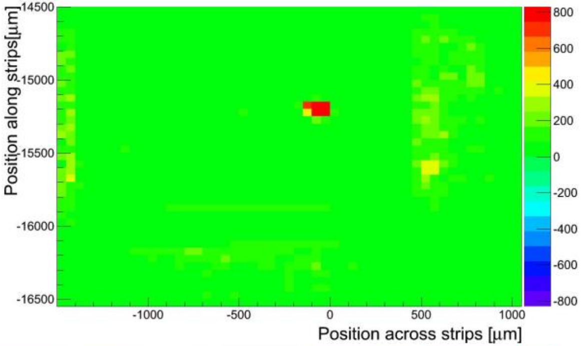
Signal



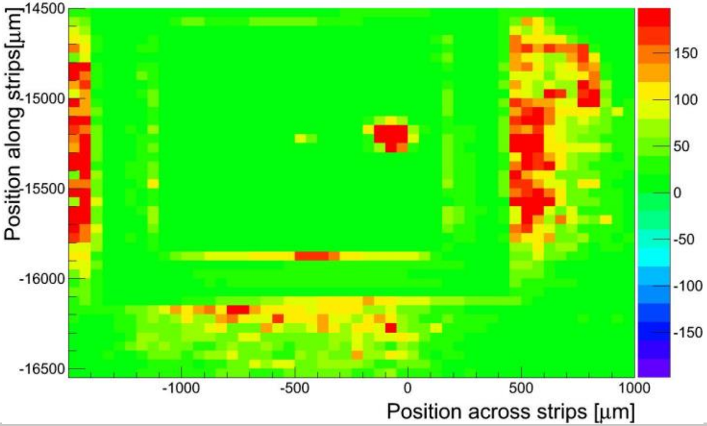
Single Pixel LGADs - TCT



~ 2.4 mm

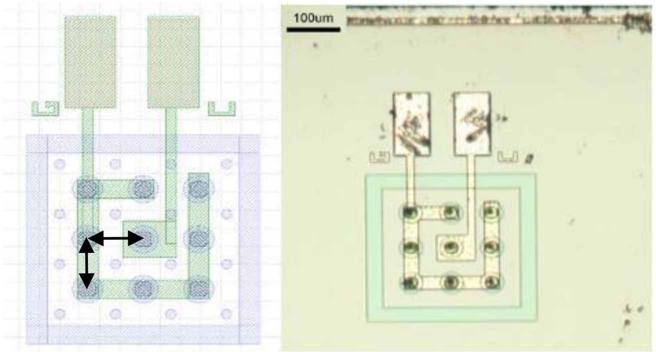


Max. Signal [mV]

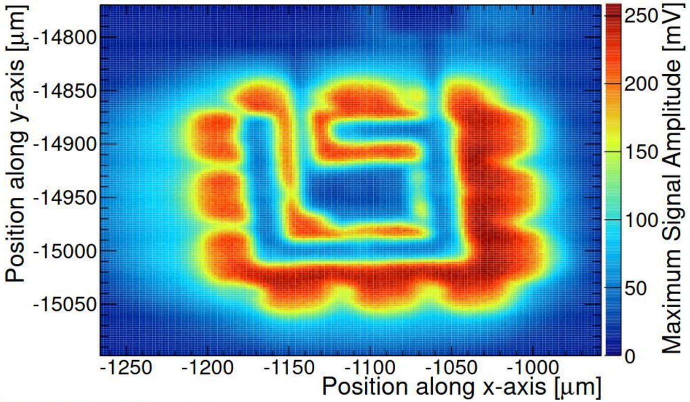


Max. Signal [mV] with cutoff towards higher values

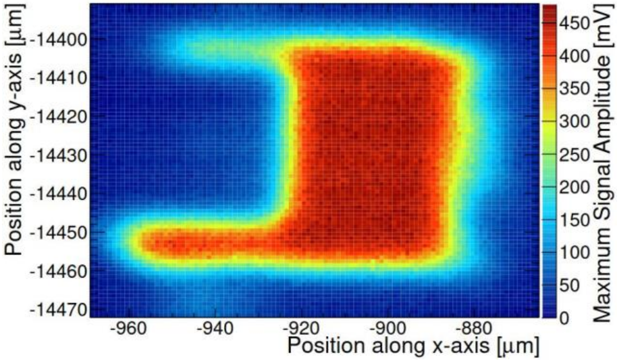
3Ds - TCT



Cell size of 50 x 50 µm²

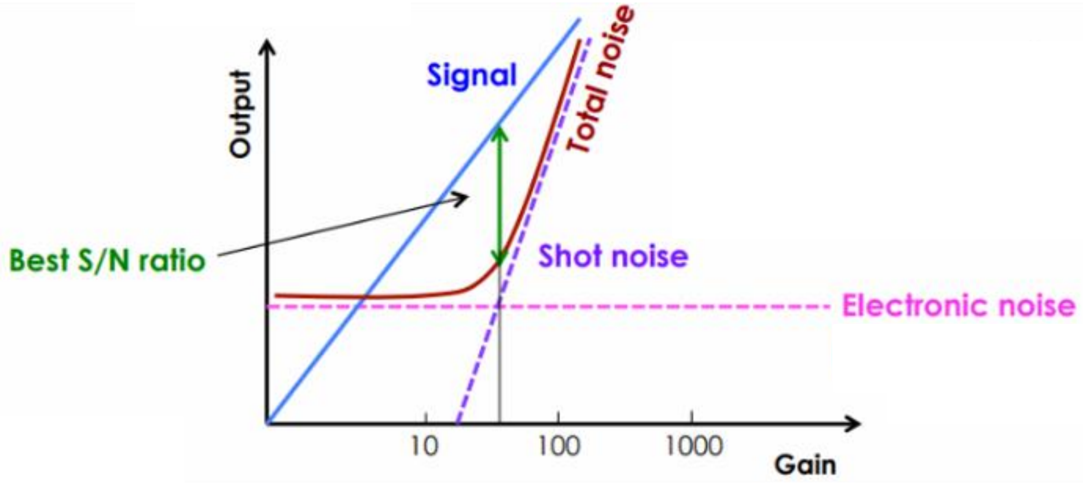


Outer cells connected to readout

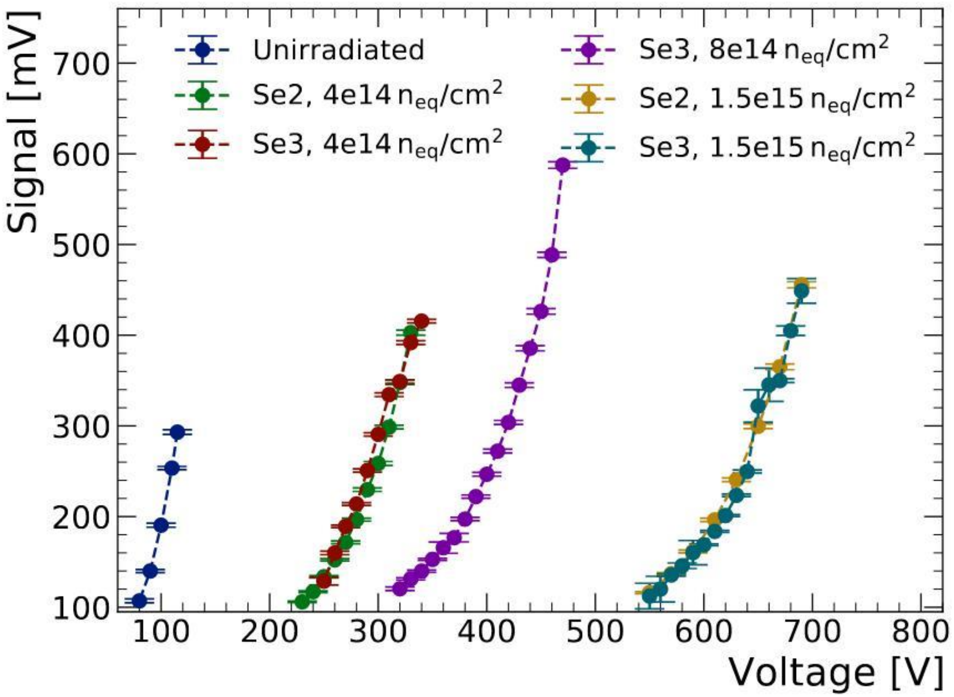


Single inner cell connected to readout

Signal/Noise vs Gain



LGAD – Beta Measurements

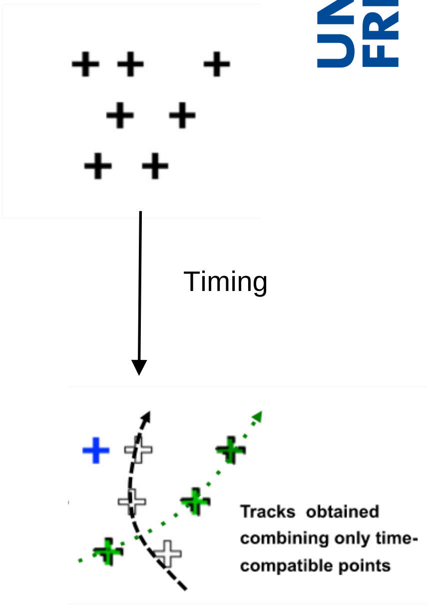


Why is Timing needed?

- Hadron colliders challenge track reconstruction with increasingly high rates and pile-up
- For timing distinction between measurement points:
  - ATLAS and CMS aim for time resolution of 30 – 40 ps for near future
  - FCC aims for 5 ps

- Highest resolving power needed in regions with highest fluences (I.e. near beam pipe)

➢ Sensors need to be able to withstand high amounts of radiation (e.g. for FCC ~ 10^{17} n_{eq}/cm^2)



Why is Timing needed?

- HL LHC upgrade phase II (2027 ->)