3D silicon sensors as timing detectors

Leena Diehl, Spyros Argryropoulos, Oscar Ferrer, Marc Hauser, Karl Jakobs, Montague King, Fabian Lex, Gregor Kramberger, Ulrich Parzefall, Giulio Pellegrini, Christina Schwemmbauer, Dennis Sperlich

05.12.2023

Albert-Ludwigs-Universität Freiburg

Introduction

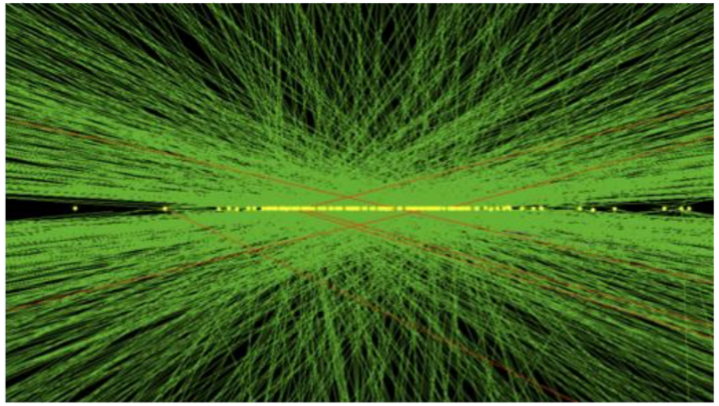
- Future hadron colliders challenge the tracking and reconstruction with high rates and huge pile-up

- ATLAS and CMS already aim for 30-40ps timing resolution, future trackers like FCC will demand timing of 5ps while still providing position resolution below 10 µm in high density environments

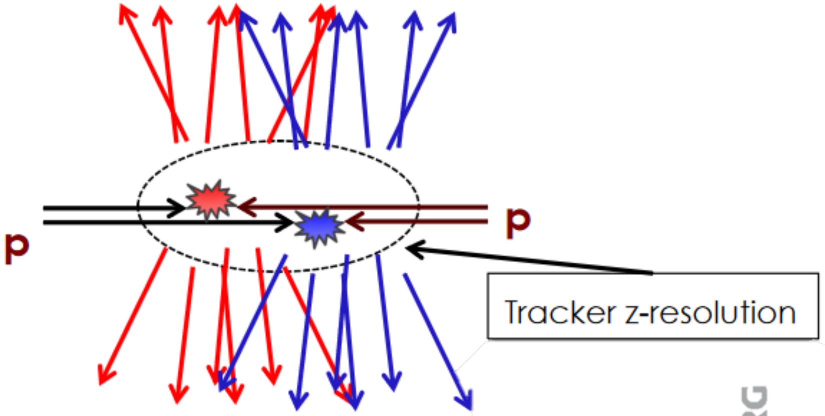
- Silicon sensors are proven to be very radiation hard and have a short charge collection time – current and future choice for tracking detectors

- Many collaborations working on improving time resolution, e.g.
  ➡Ultra Fast Silicon Detectors (UFSDs - LGADs)
    - Working on improving radiation hardness (gain layer degradation)

  ➡3D pixel sensors dedicated for timing: RD50 project
    - Potential alternative: proven radiation hardness, gain increase

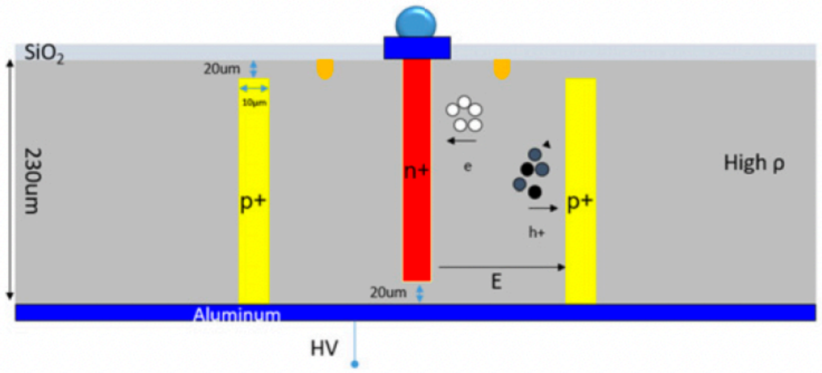


Tracking z-resolution larger than vertex-separation: Ambiguous Track-to-vertex association

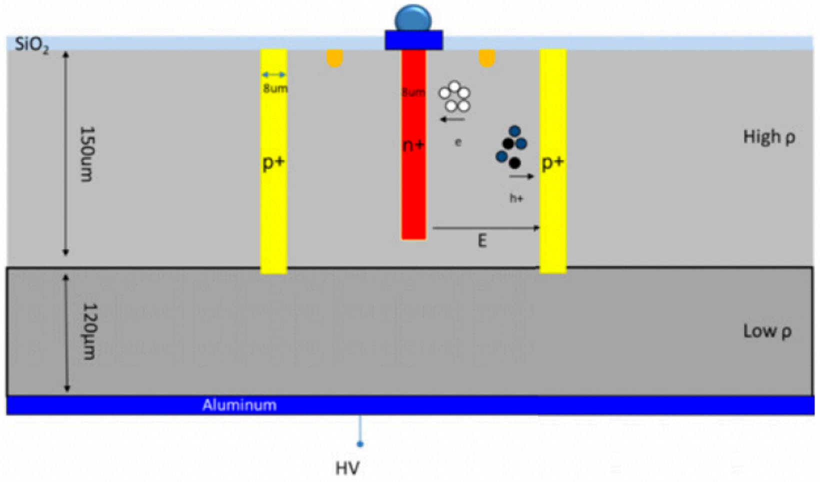


N. Cartiglia, INFN, Hiroshima Conference 2017

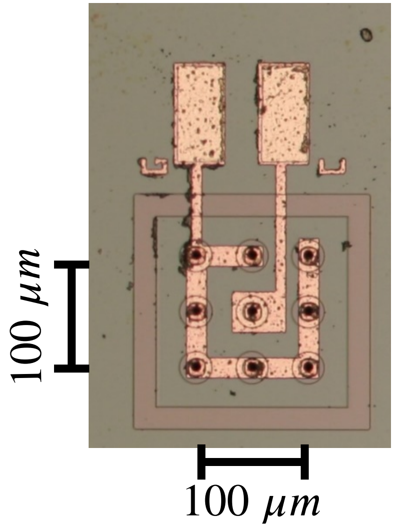
3D sensors



(a) IBL schematics



(b) ATLAS schematics



Insertable B-Layer production

- Double-sided
- 235 μm active thickness
- $50 \times 50\ \mu m^2$ unit cell size
- $100 \times 100\ \mu m^2$ active area
- Depletion voltage: 5-10 V

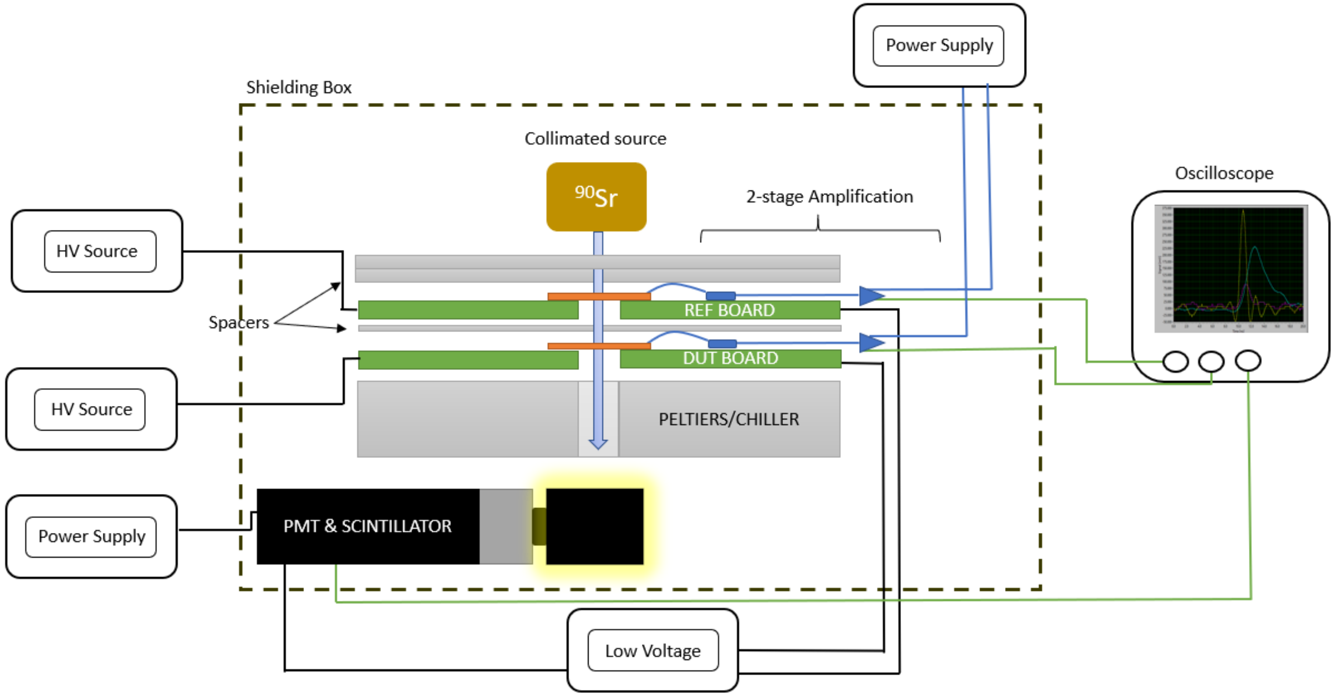
ATLAS Inner Tracker pre-production

- Single-sided
- 150 μm active thickness , 270 μm total thickness
- Unit cell size: $50 \times 50\ \mu m^2$ or $25 \times 100\ \mu m^2$
- Active area: $100 \times 100\ \mu m^2$ or $50 \times 200\ \mu m^2$
- Depletion voltage: 5-10 V

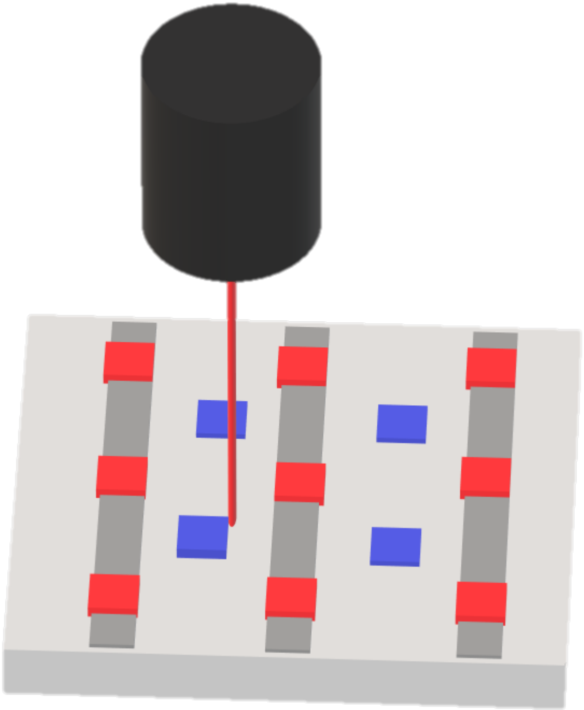
Experimental Setups

- Single pulses recorded of both reference and tested sensor
- About 3000 events with DUT signature for appropriate statistics

- Measurements with MIP-like particles and laser source
- If possible, only external triggers



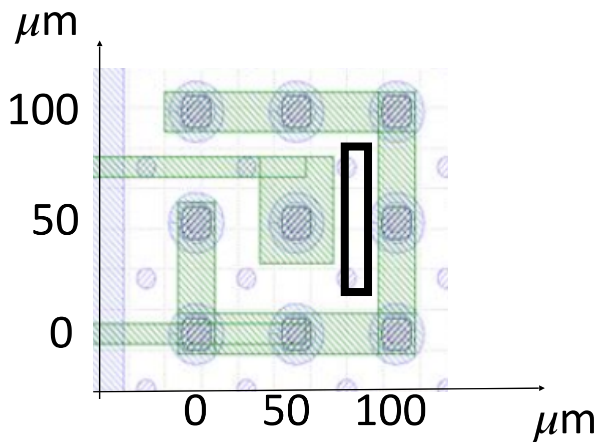
- ^{90}Sr-source
- LGAD reference, $\sigma_{Ref} = 25.18 \pm 0.35\ ps$
- PMT yes/no trigger



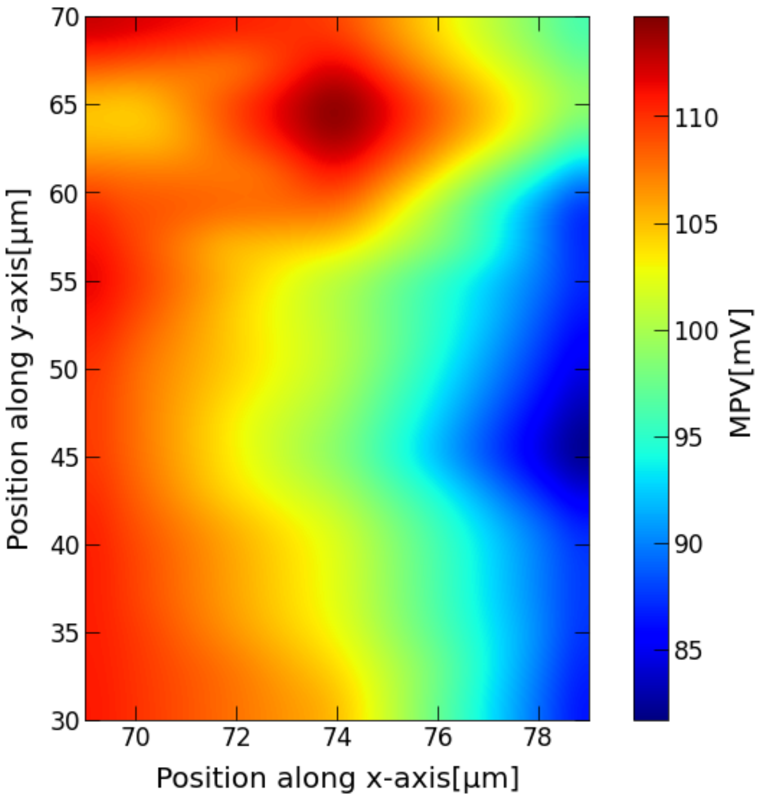
- Top-TCT, infrared laser (1060nm)
- 2 pulses recorded (fiber splitter)
- Intensity tunable

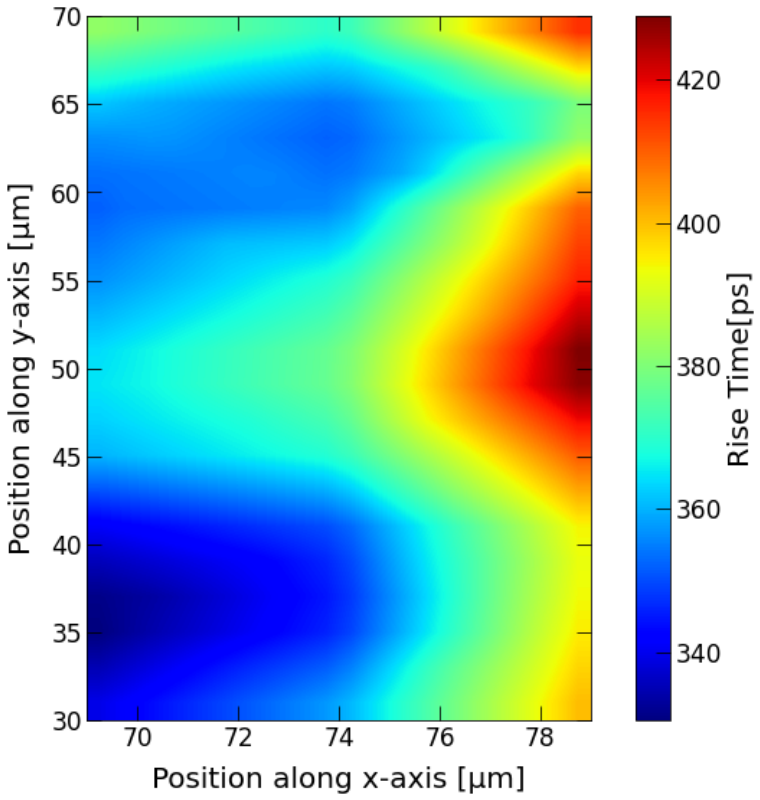
Time Resolution: Unirradiated 3D Pixel Sensors

- Low laser intensity – MPV around 80-110 mV, low compared to beta set-up (145 mV)
- Cell structure not as clear as for time resolution, but still fits the expectations
- Rise time between 340 and 420 ps, higher than measured in the beta set-up



MPV **5737-7b** **Rise Time**

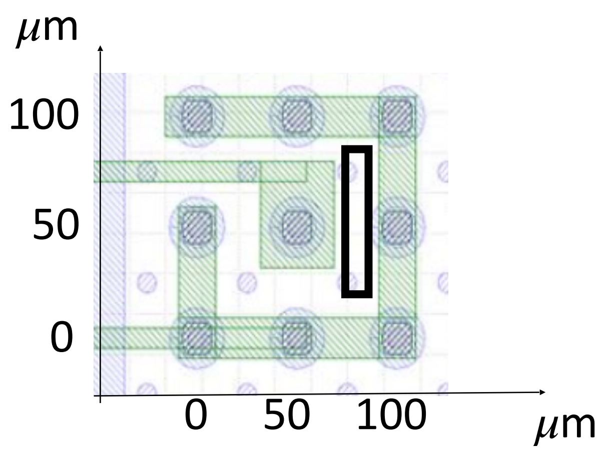




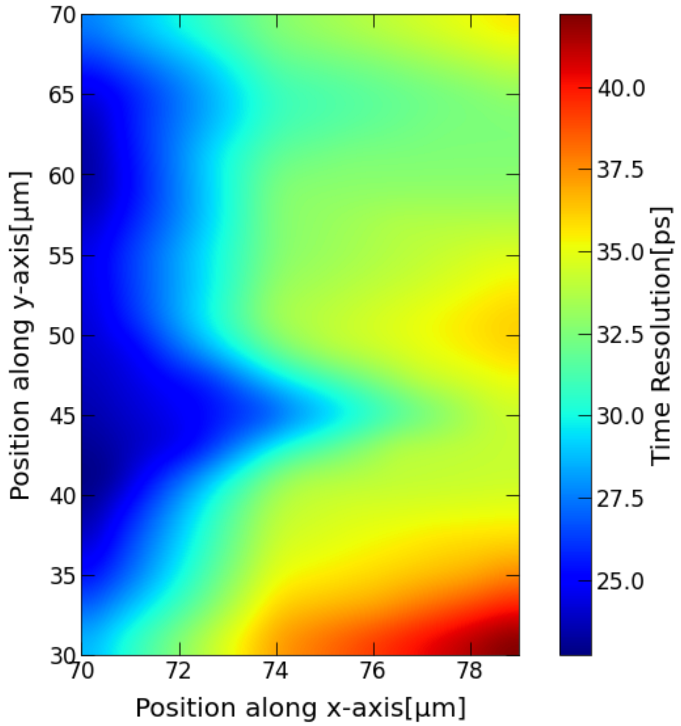
Time Resolution: Unirradiated 3D Pixel Sensors

- Time resolution measured at 60 V for a 10x40 μm area in 5 μm steps and interpolated
- Two sensors measured: Similar cell structure recognisable :
  - ➢ Better resolution closer to the readout column
  - ➢ Worse resolution closer to the other junction columns
  - ➢ Range from 23-43 ps/ 25-47 ps

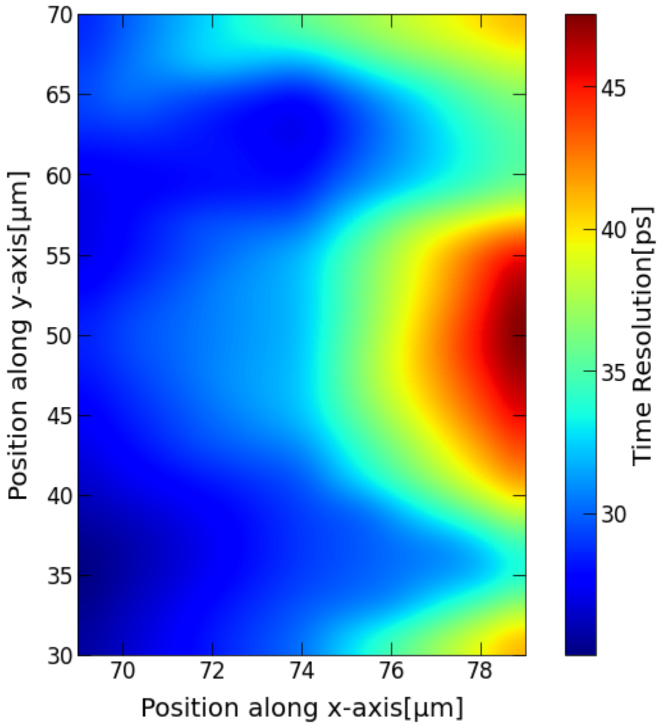
- Differences: Uncertainties in position, laser focus, laser intensity



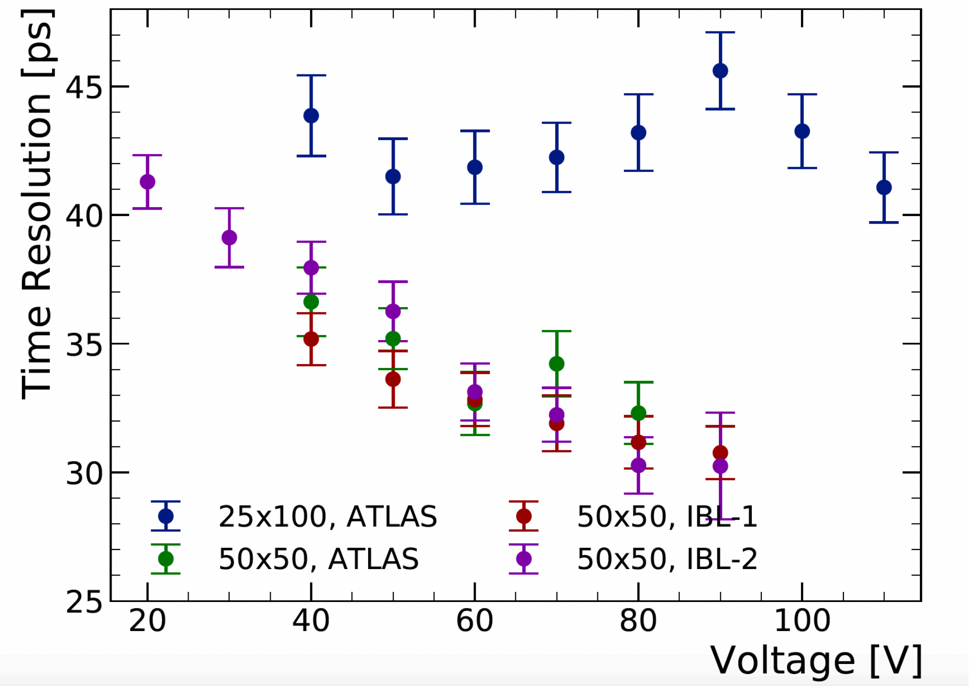
5737-7

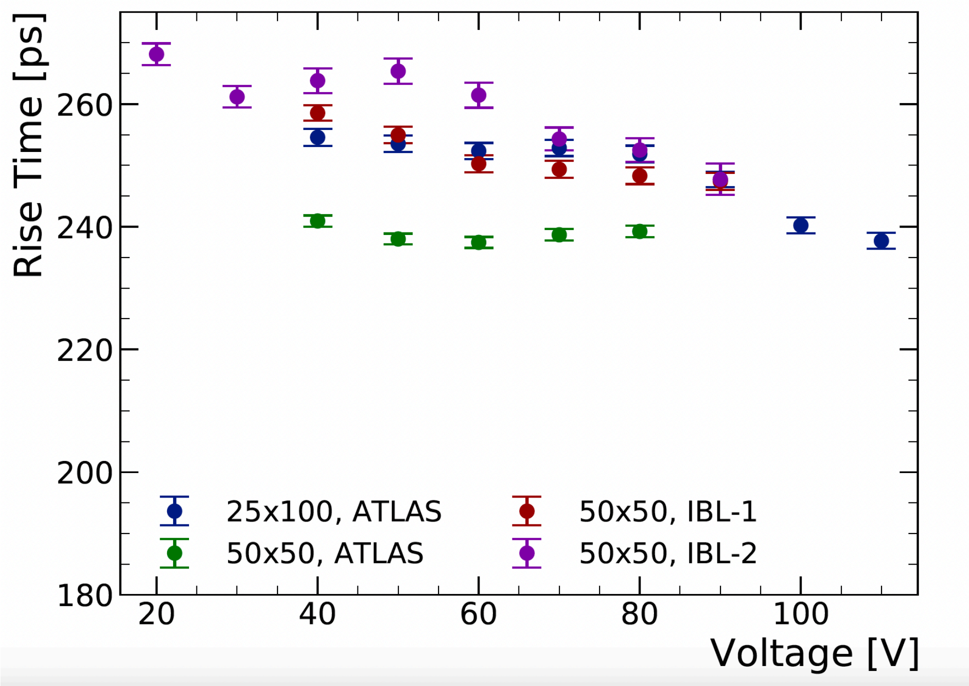


5737-7b



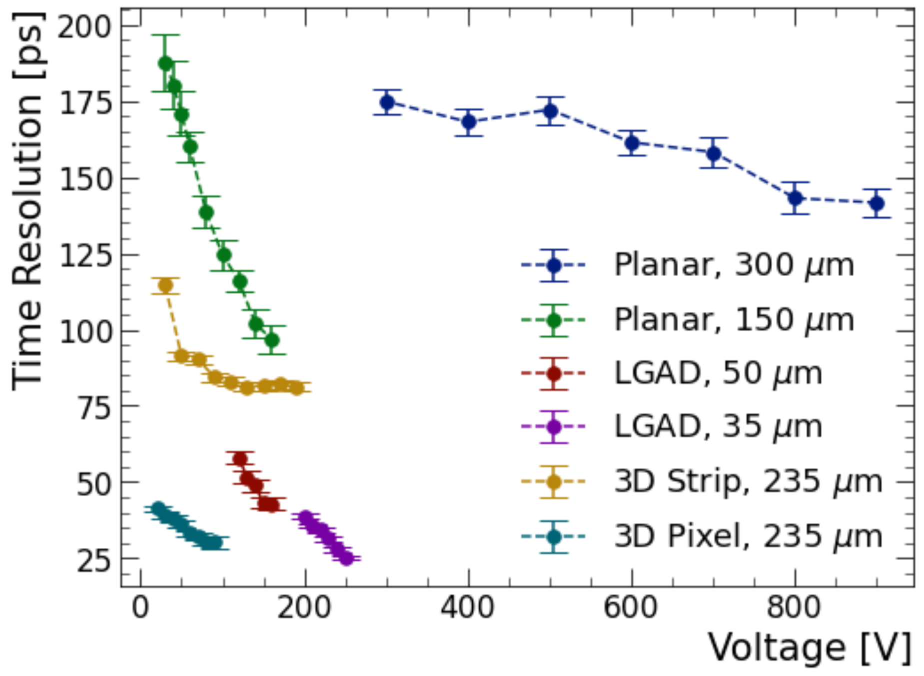
Time Resolution: Unirradiated 3D sensors

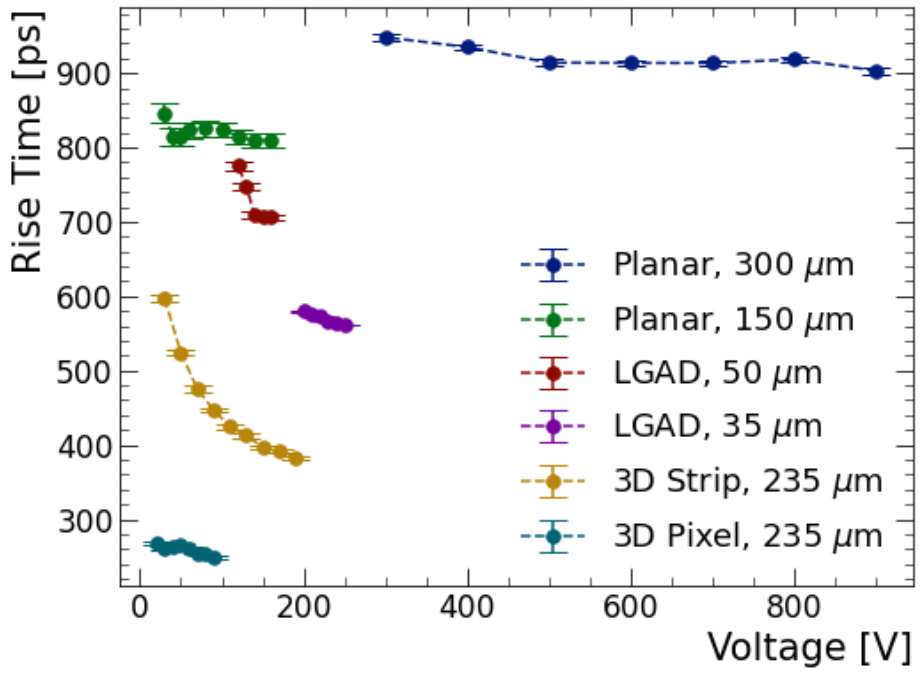




- Before irradiation, sensors reach about 30-31 ps time resolution at room temperature
- Quadratic geometry performs better
- ATLAS and IBL sensors perform very similar, slightly better rise time (240ps) for ATLAS sensor

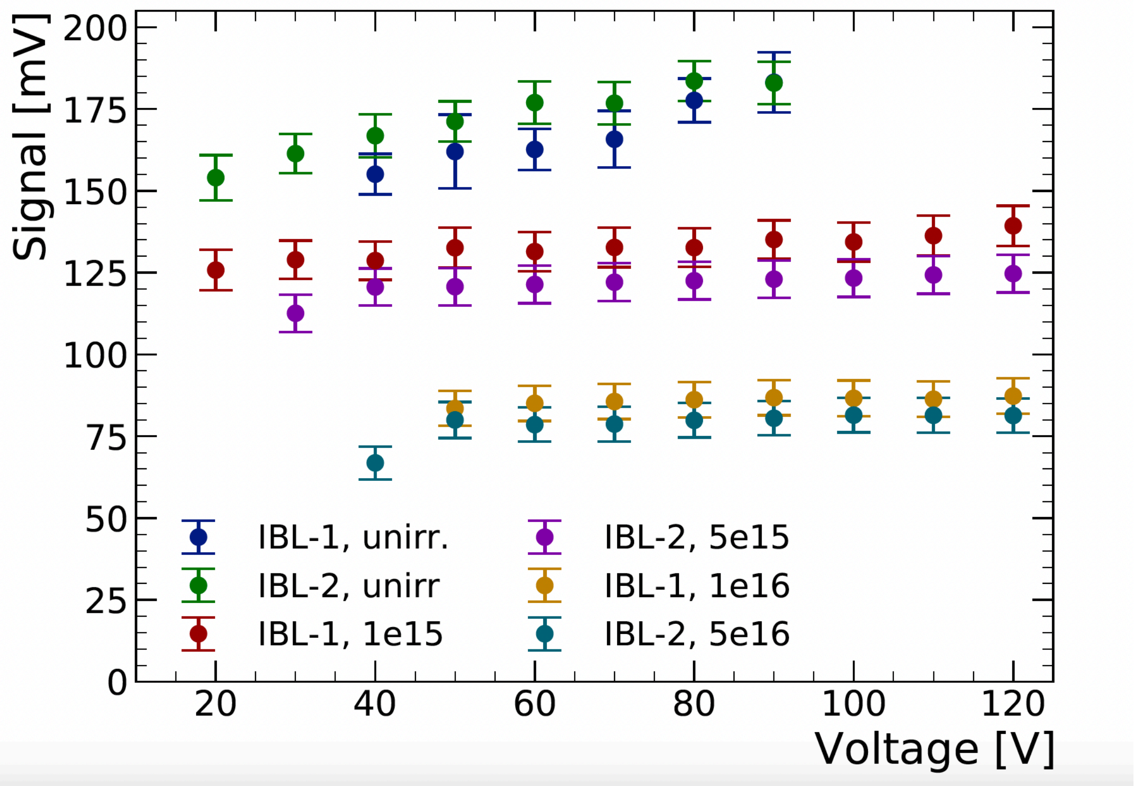
Time Resolution: 3D vs other sensors

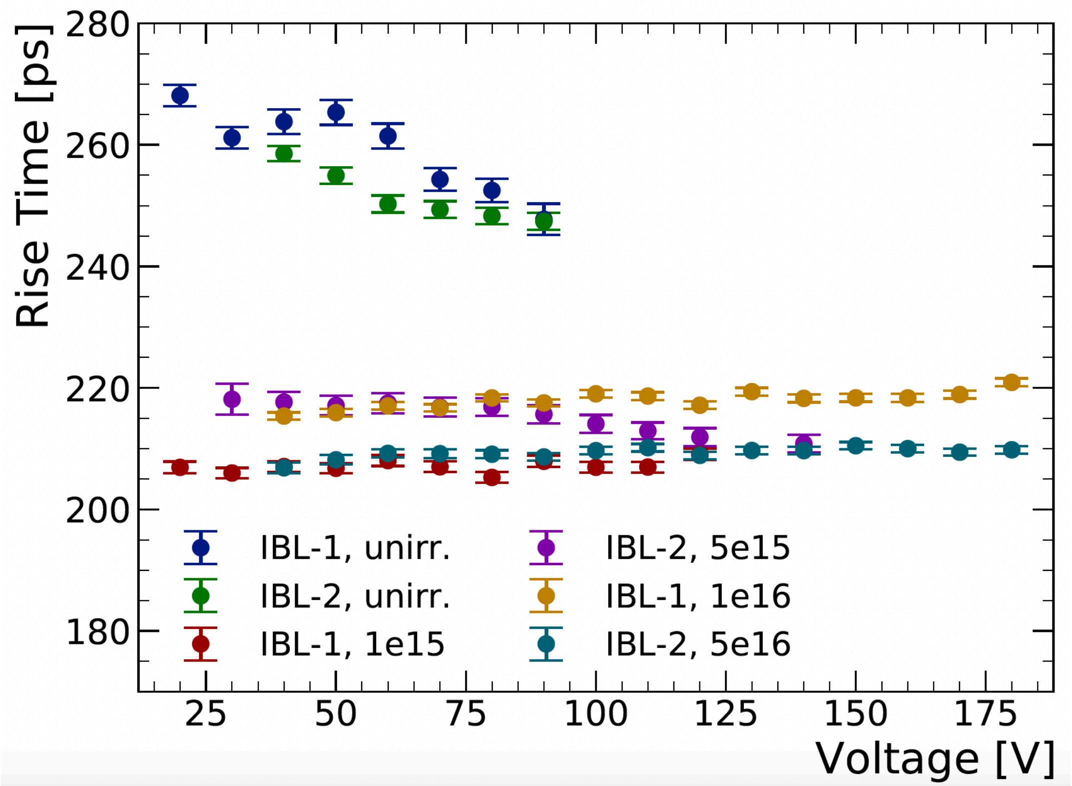




- Planar: Strips sensors - 300μm thickness (ATLAS, Hamamatsu) and $150\ \mu m$ thickness (CMOS, LFoundry)
- LGADs – Pad diodes: 50μm thickness, high gain layer doping and 35μm thickness, lower gain layer doping
- As expected, 3D strip sensors show better time resolutions than planar strip sensors, but only pixel sensors are competitive with LGADs
- Benefit: Lower voltage necessary for 3Ds than for LGADs

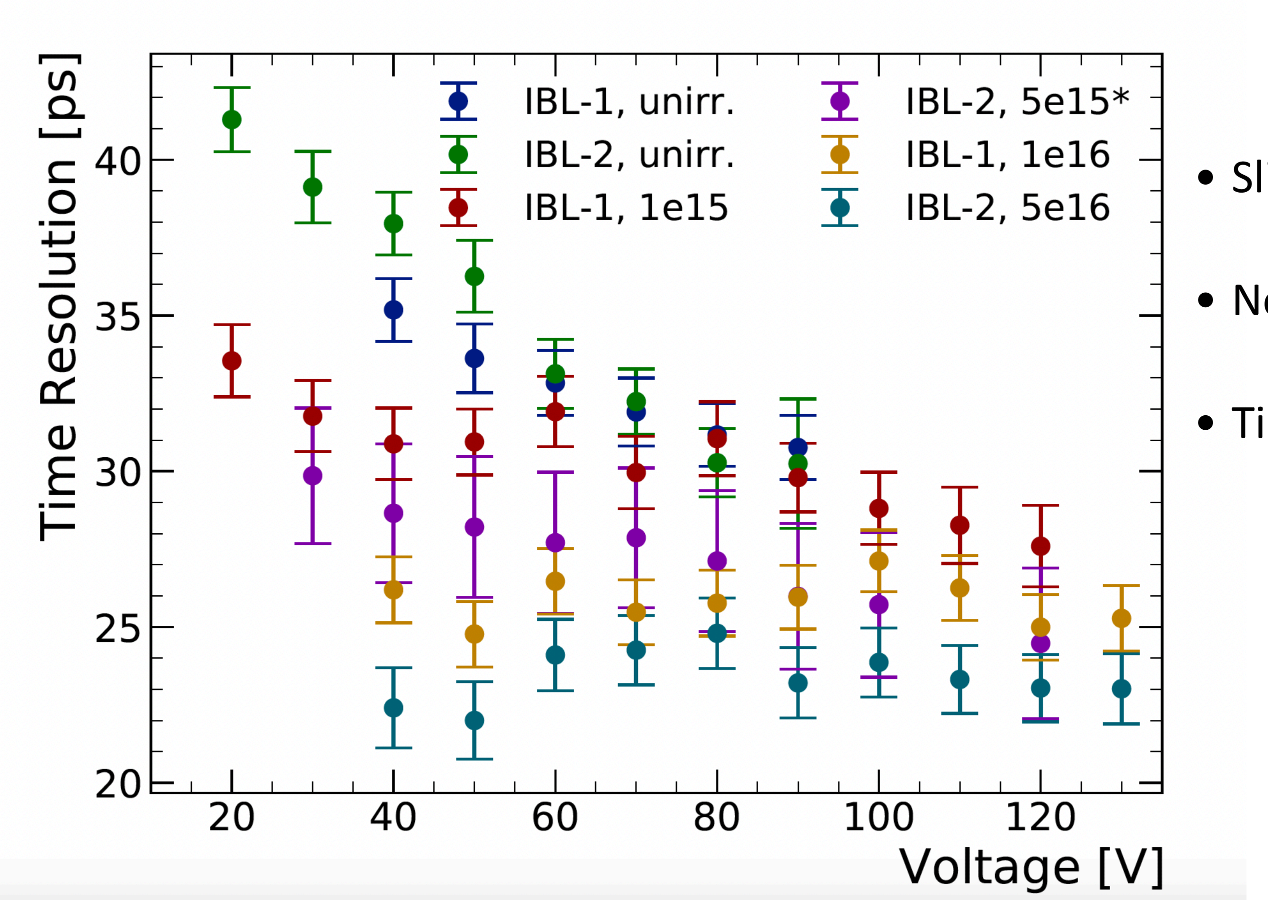
Time Resolution: Irradiated 3D sensors





- Signal decreases with fluence
- Rise time drop after irradiation
- No significant fluence dependence for rise time

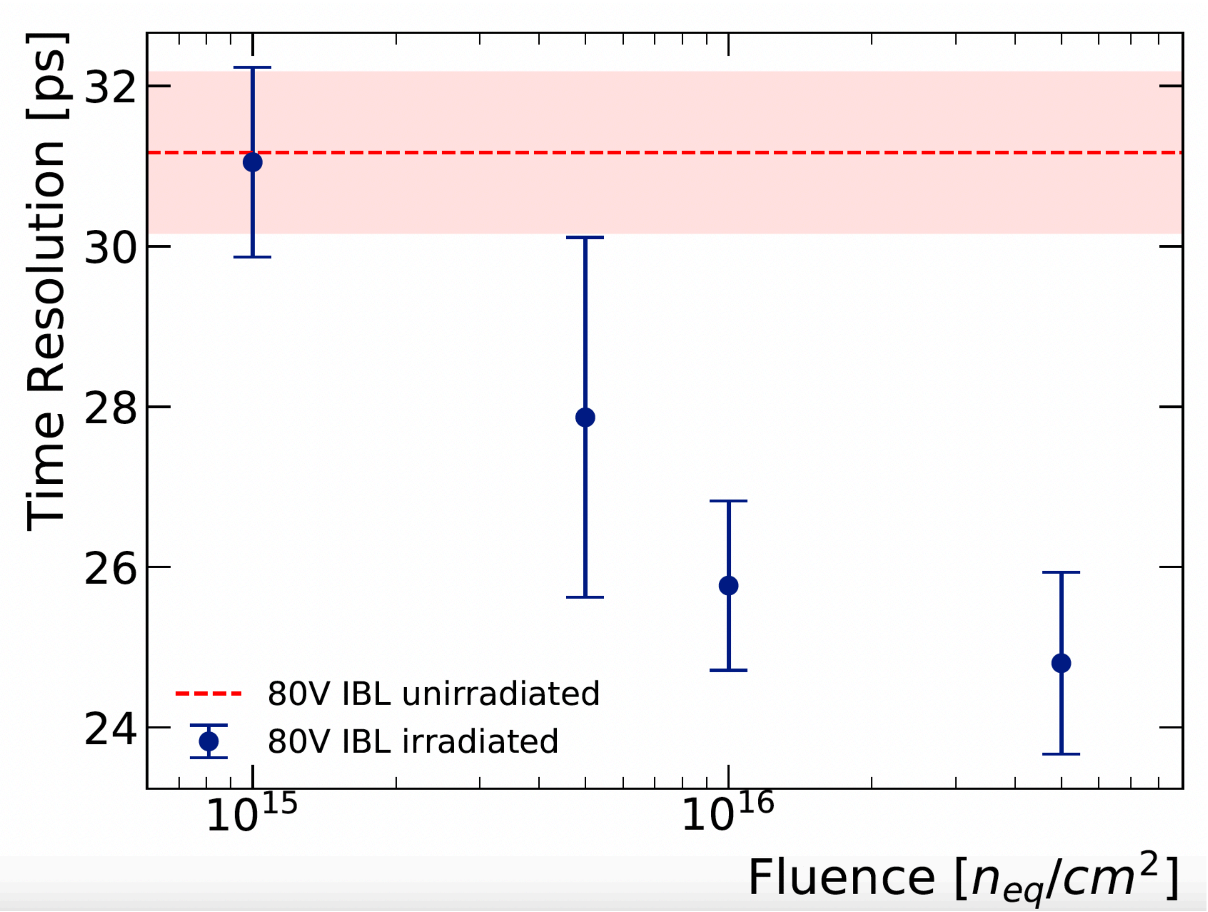
Time Resolution: Irradiated 3D sensors



- Slightly higher bias voltages necessary
- No clear voltage dependence for highest fluences
- Time resolution seems to be slightly improving with fluence

* *measured with different trigger setup*

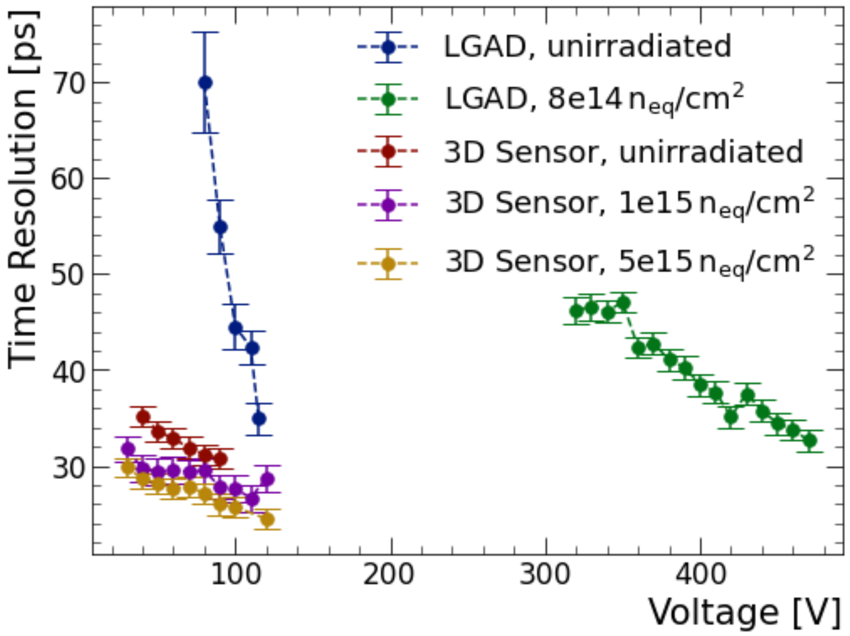
Time Resolution vs Fluence

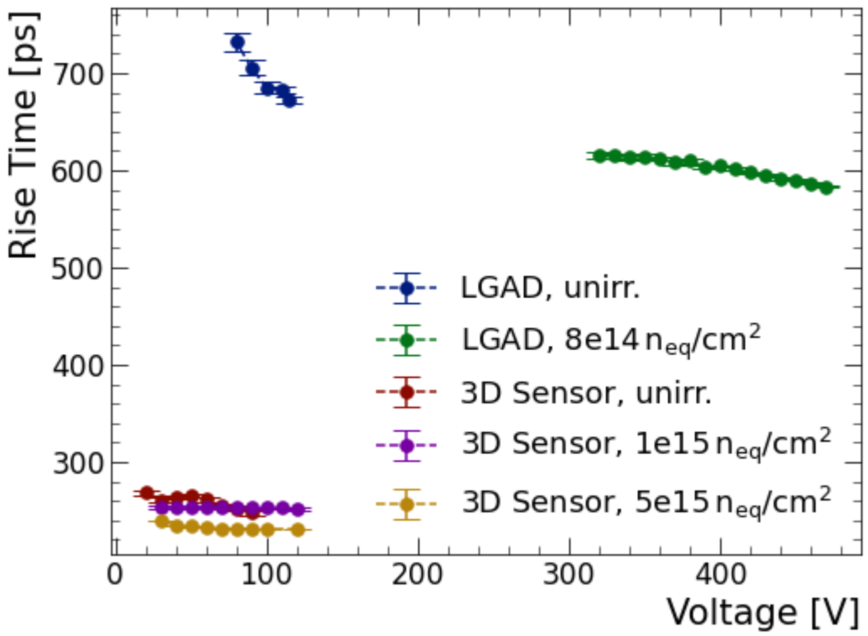


- Measured at 80V
- Time resolution improves with increasing fluence
- Higher electric field between columns improves timing

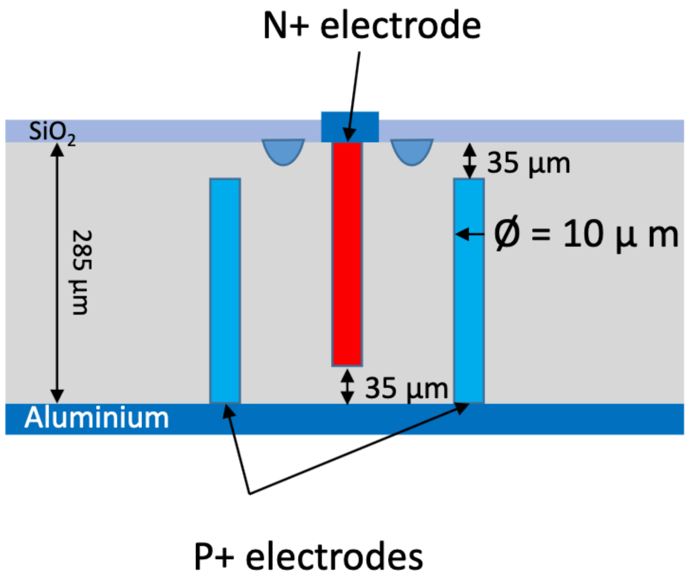
Comparison - LGAD vs 3D Pixel after irradiation

- Significantly lower rise time
- For these 3D pixel and LGAD types: 3D sensors perform better in timing measurements
- Note: This are not the latest/ fastest generation of LGADs – but the 3D sensors prove to be competitive

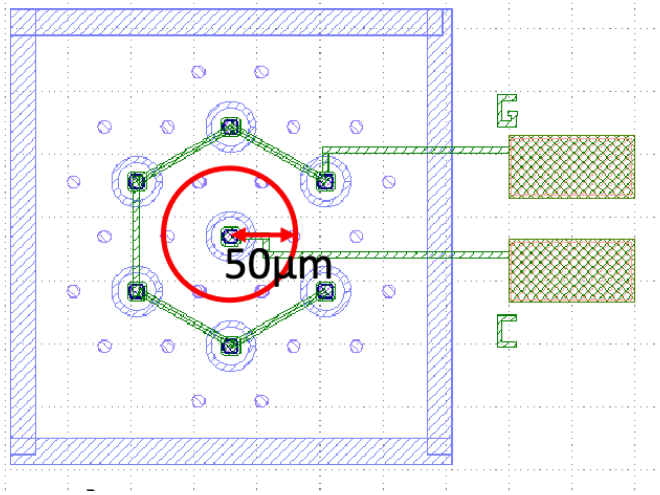


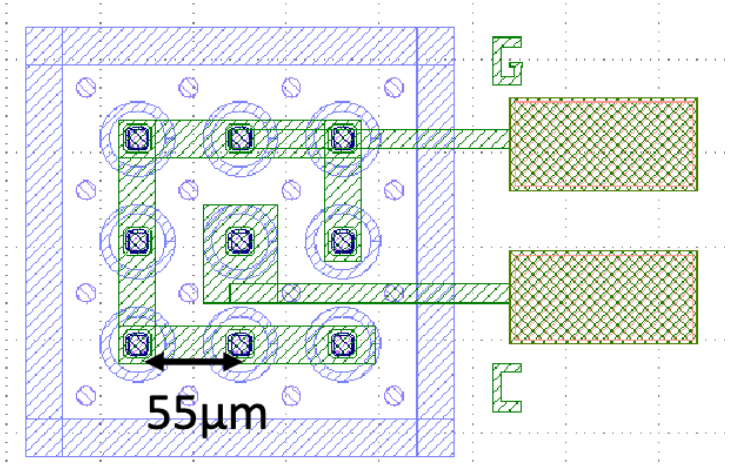


New Timing 3D sensors

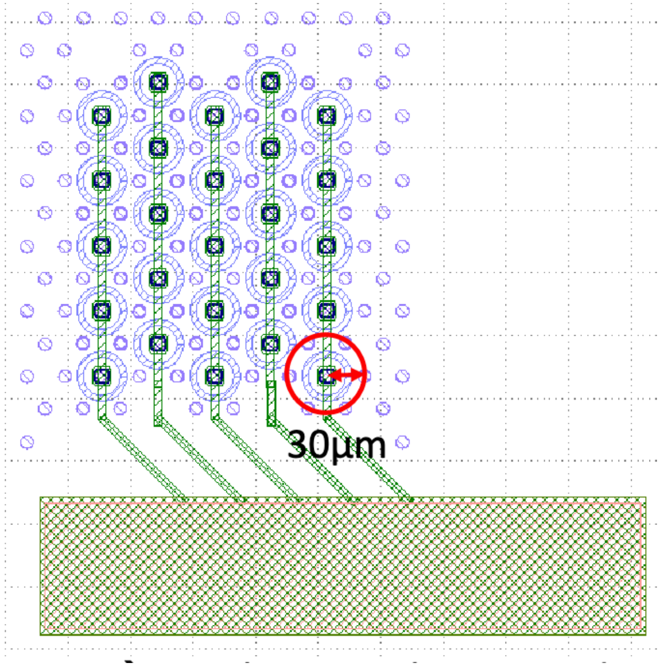


- 3D doublesided technology
- Hexagonal geometry, quadratic for comparison
- 285 μm active thickness
- 10 μm column diameter





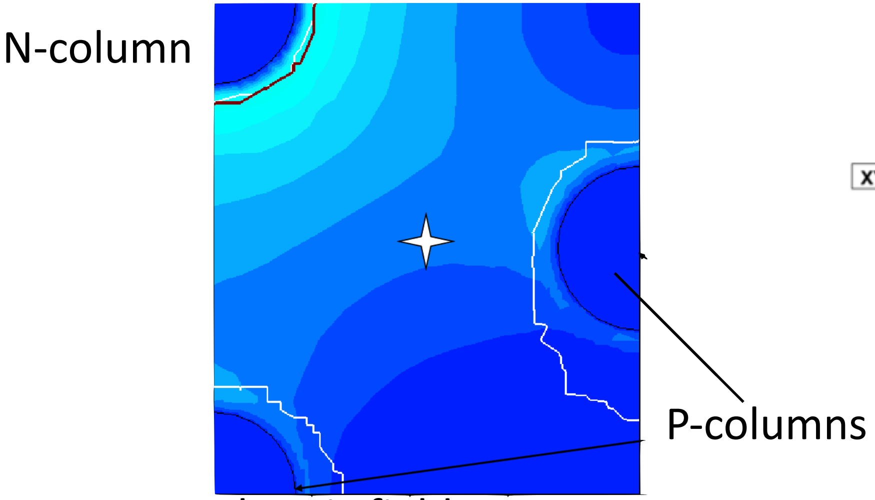
Designed and produced by CNM



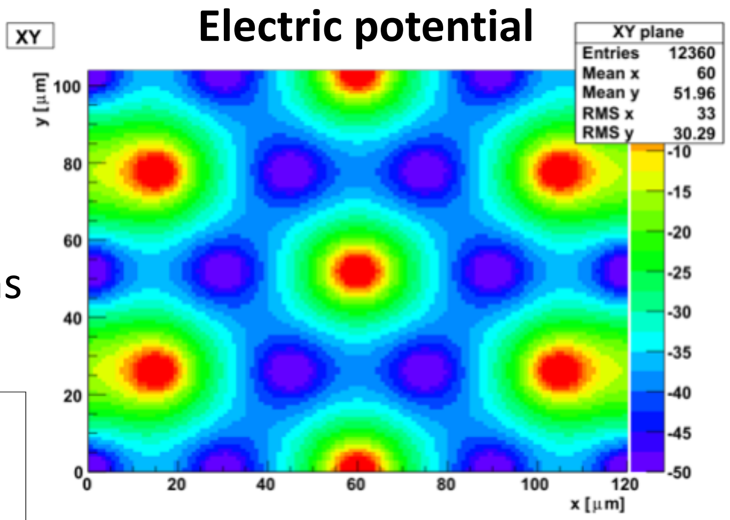
RD50 common fast timing project:

CNM, Uni Freiburg, JSI (Ljubljana), IFAE (Barcelona), NIKHEF (Amsterdam), UZH (Zurich)

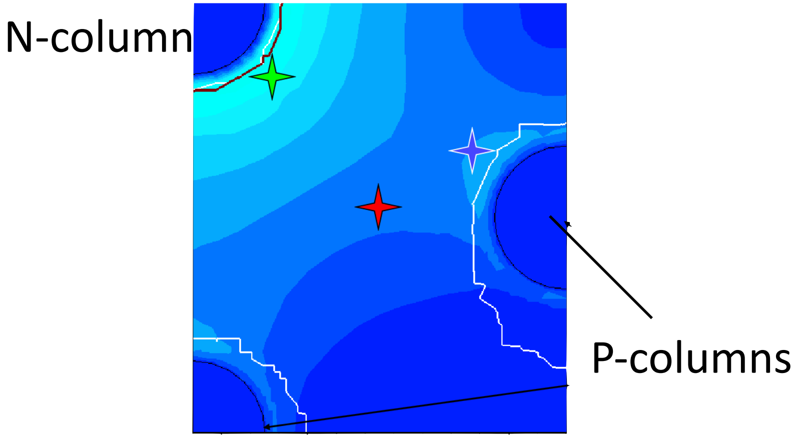
New Timing 3D sensors: Simulations

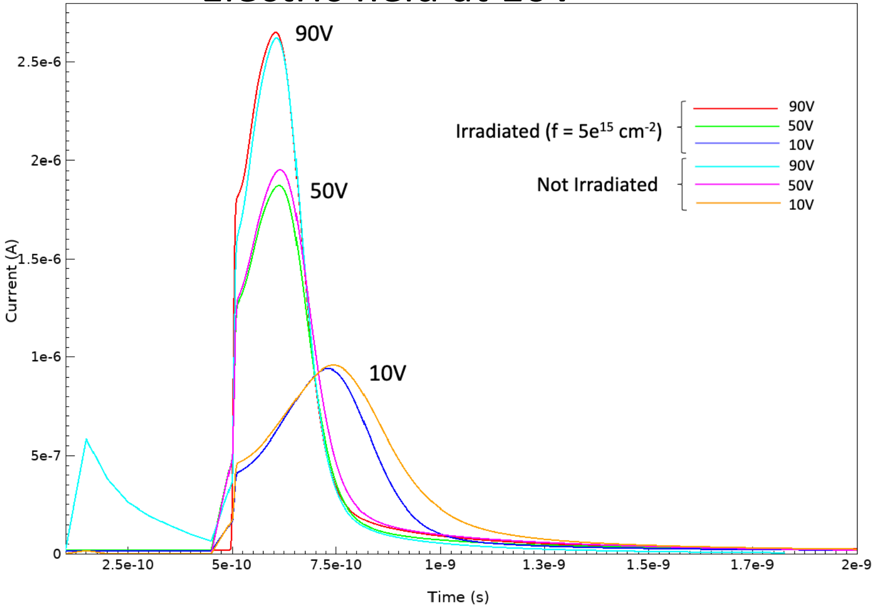


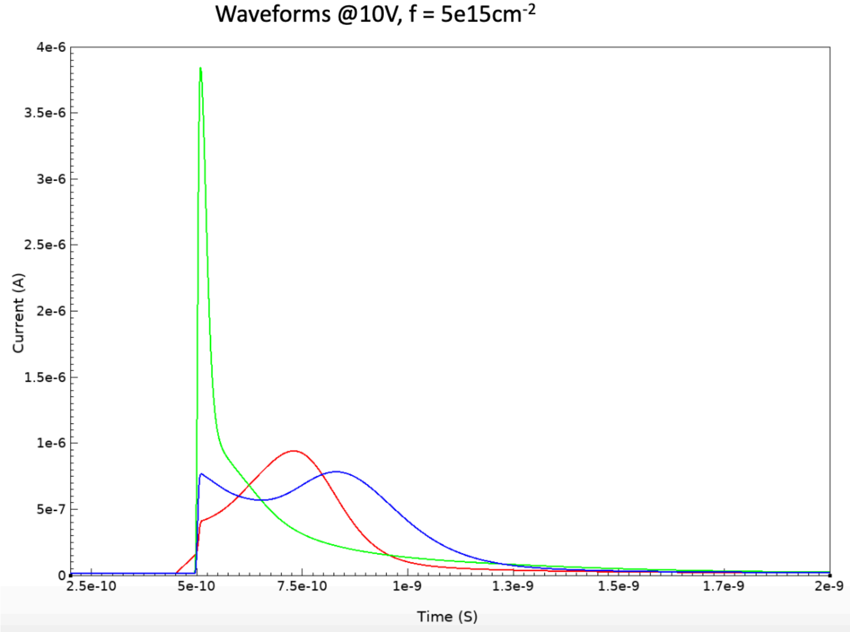
Electric field at 10V



No zero field spots

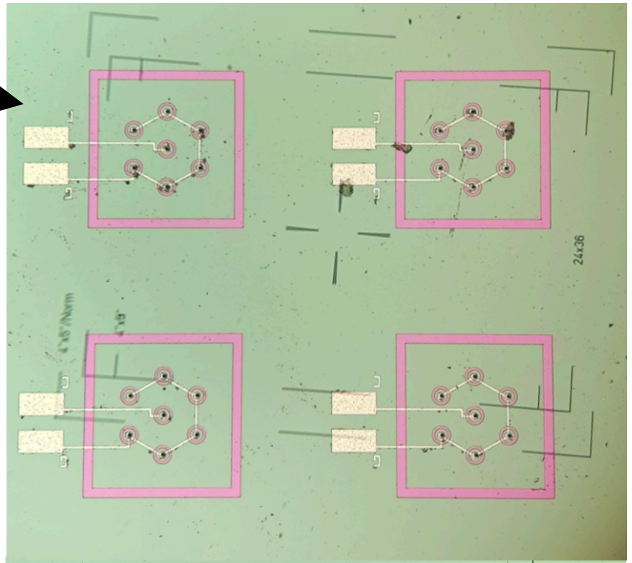




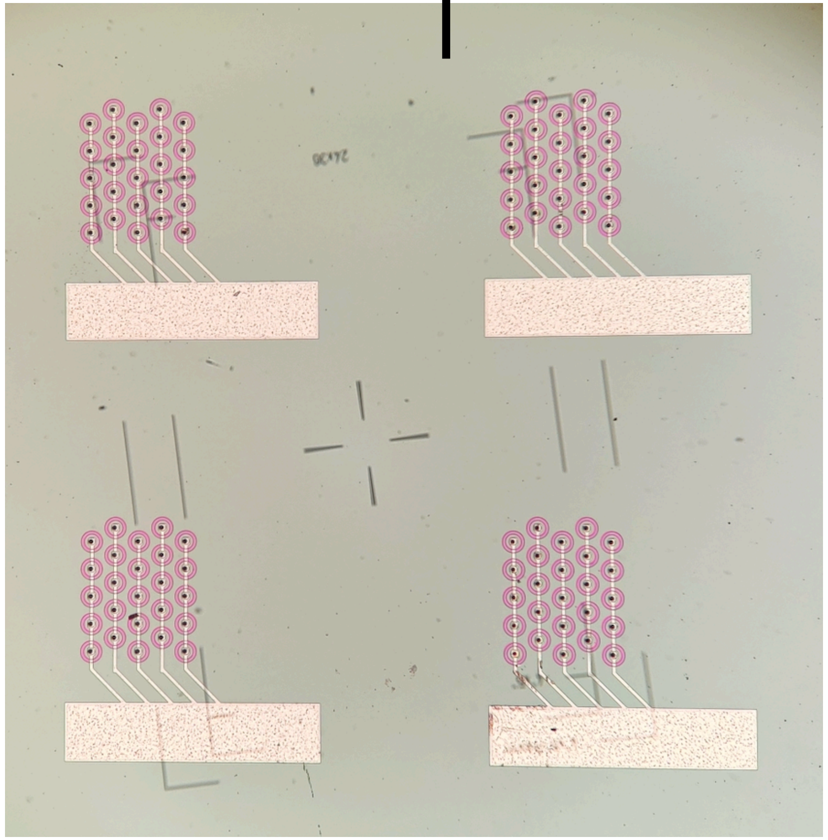


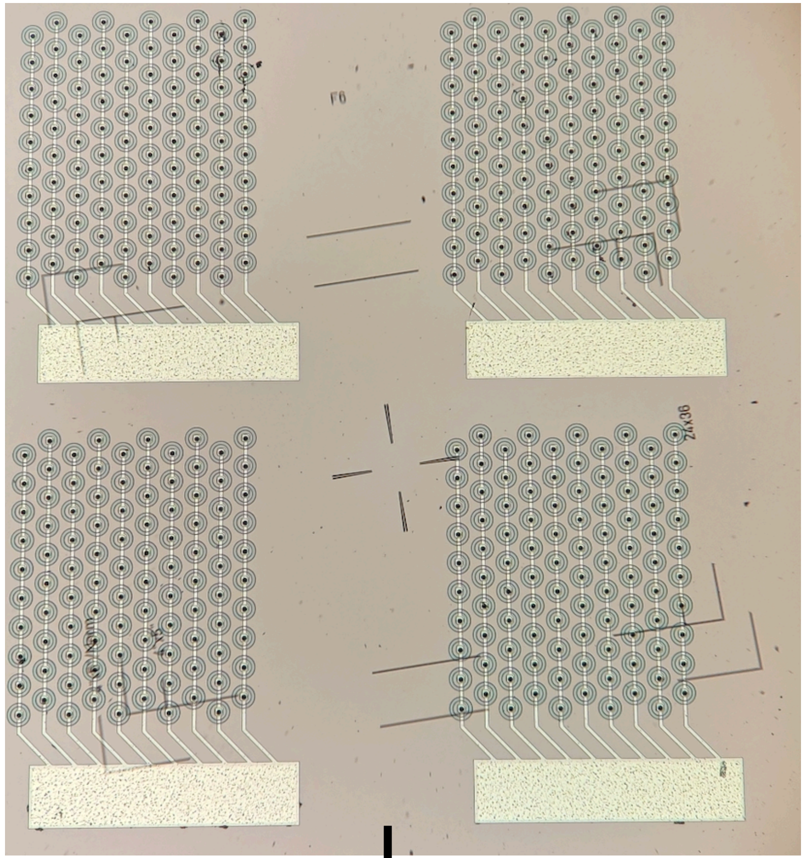
New Timing 3D sensors

2-x: SC, hexagonal, 50 μm rad

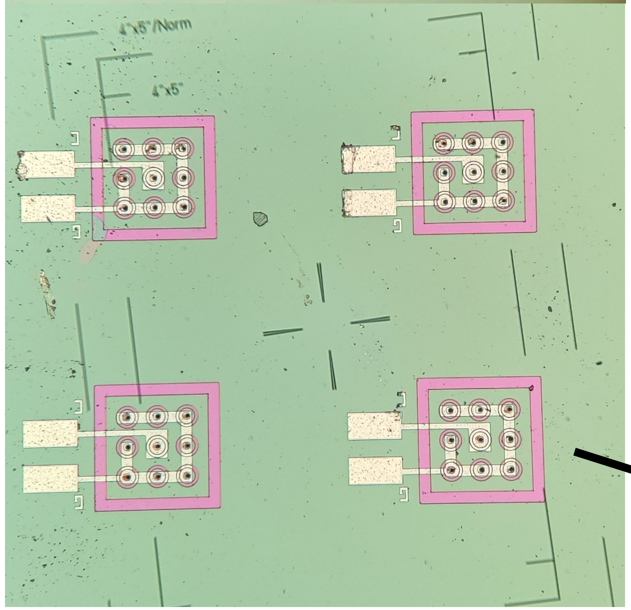


4-x: 5x5 array, Hexagonal, 30 μm rad



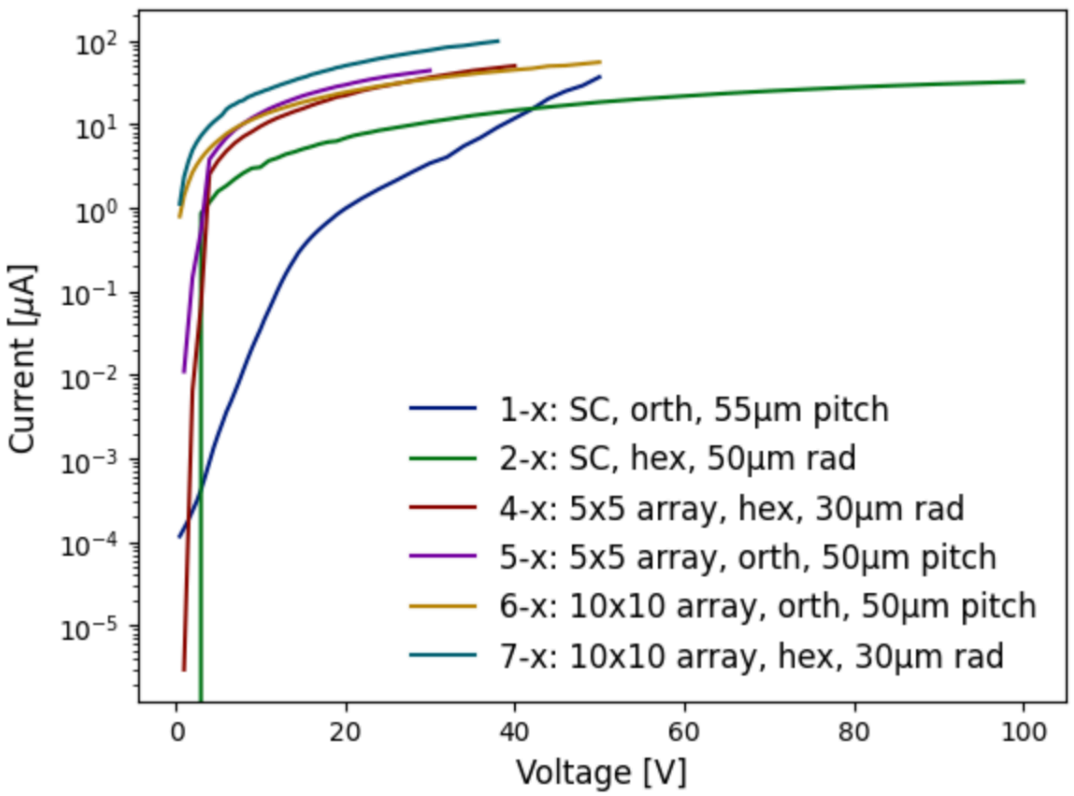


7-x: 10x10 array, Hexagonal, 30 μm rad

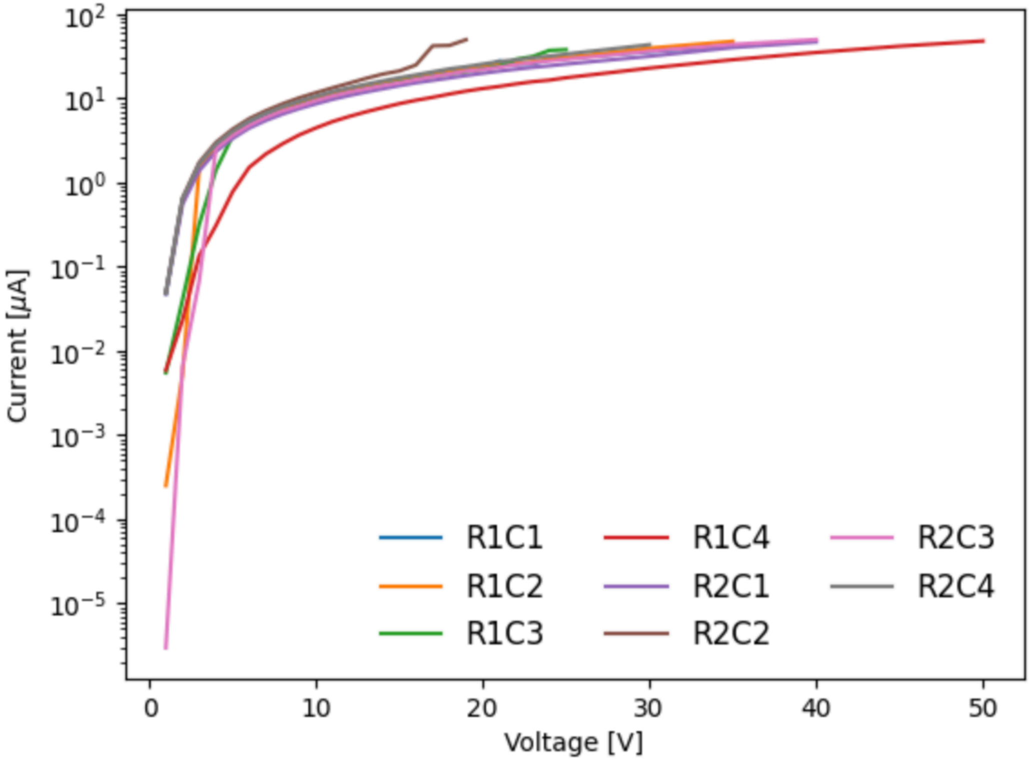


1-x: Single channel, orthogonal, 55 μm

New Timing 3D sensors: IVs



4-x Sensors: 5x5 array, hexagonal



- 7 different sensor types measured: Depletion voltages between 5-20V
- Several devices per type available: All functional, timing measurement campaign to be started

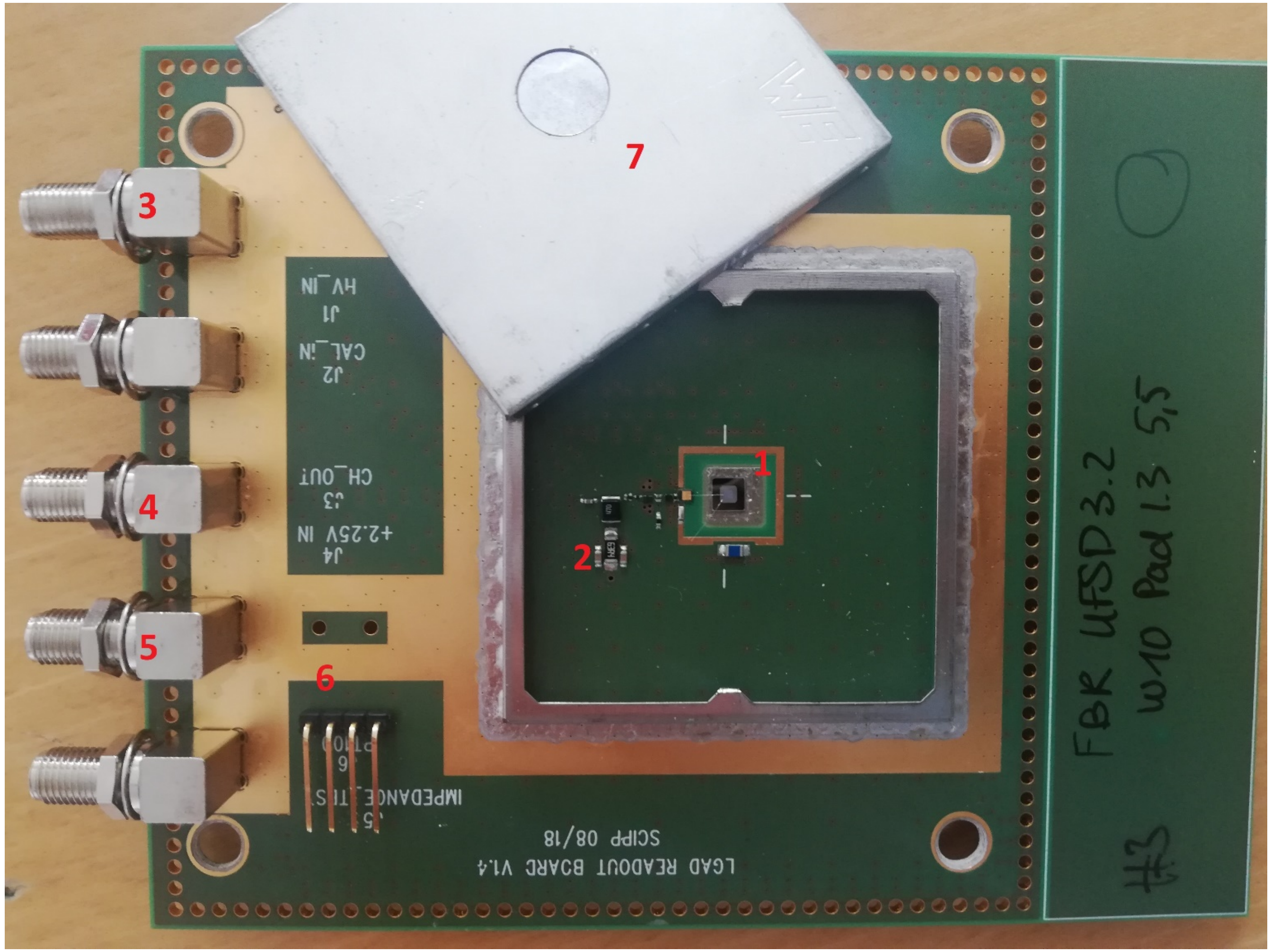
Conclusion and Outlook

- Time resolution of silicon sensors is an important research area for upcoming and future colliders
- Before irradiation, both 3D sensors reach time resolutions of 30-35 ps, comparable to LGADs
- 3D pixel sensors improve resolution after irradiation while the bias voltage range stays almost the same
- 3D pixels withstand $5 \times 10^{16} n_{eq}/cm^2$ while keeping their timing performance
- The position dependent time resolution measured correlates very well with the electric field distribution
- Dedicated timing sensors: Hexagonal geometry, IV measurements completed - timing measurements to be started soon
- Irradiation campaign to high fluences planned

Thank you for your attention!

BACKUP

LGAD Readout Board



1. Bonded LGAD
2. Amplifier
3. High voltage connector
4. Readout connector
5. Low voltage connector
6. PT100 connector
7. Lid

Time Resolution - Components

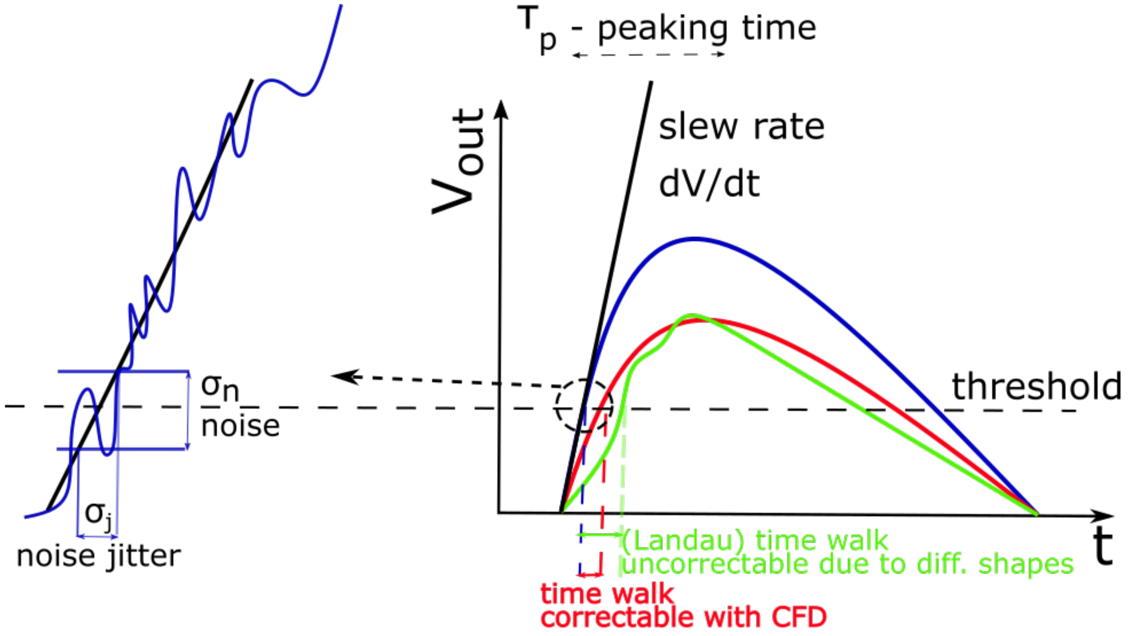
- Main components: Jitter and time walk: $\sigma_t^2 = \sigma_j^2 + \sigma_{TW}^2$

- Jitter component σ_j: Determined by the rise time at the amplifier output dV/dt and the noise level σ_n:

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

- Time walk component includes:
  - Weighting field/ el. Field contribution
  - Landau fluctuations in signal shape
  - Landau fluctuation in the amount of deposited charge (correctable)

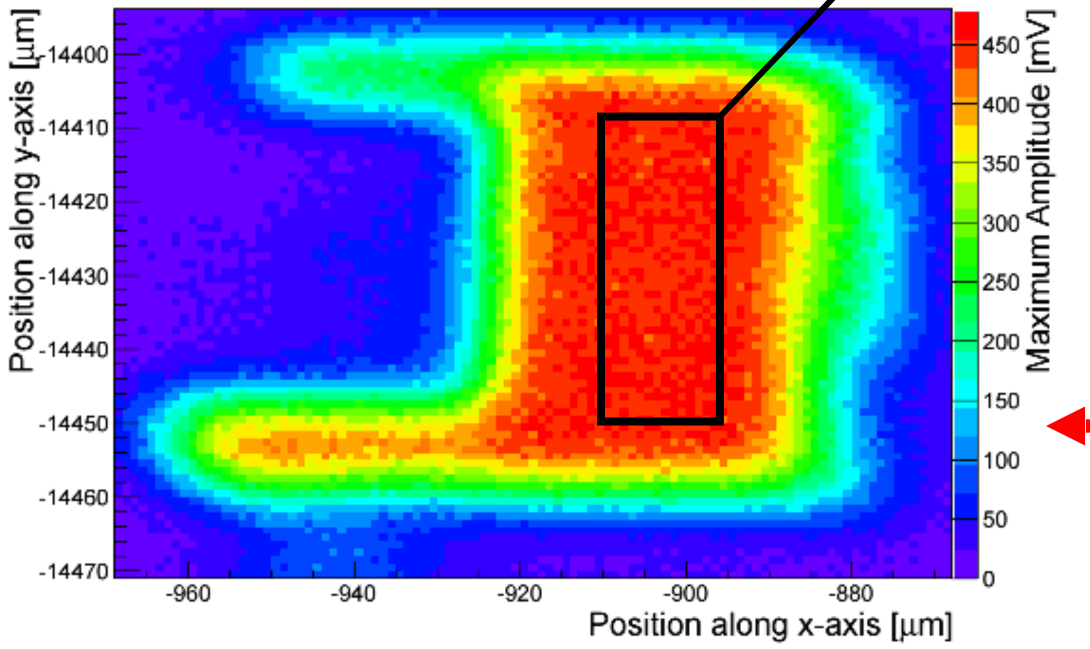
- Time Walk component depends strongly on the sensor design



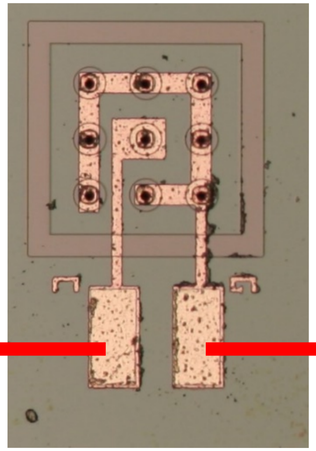
TCT area scans: 3D Pixel Sensors

- TCT scans show very small measurable area for Timing-TCT
- Outer columns connected – indefinite electric field outside the cell

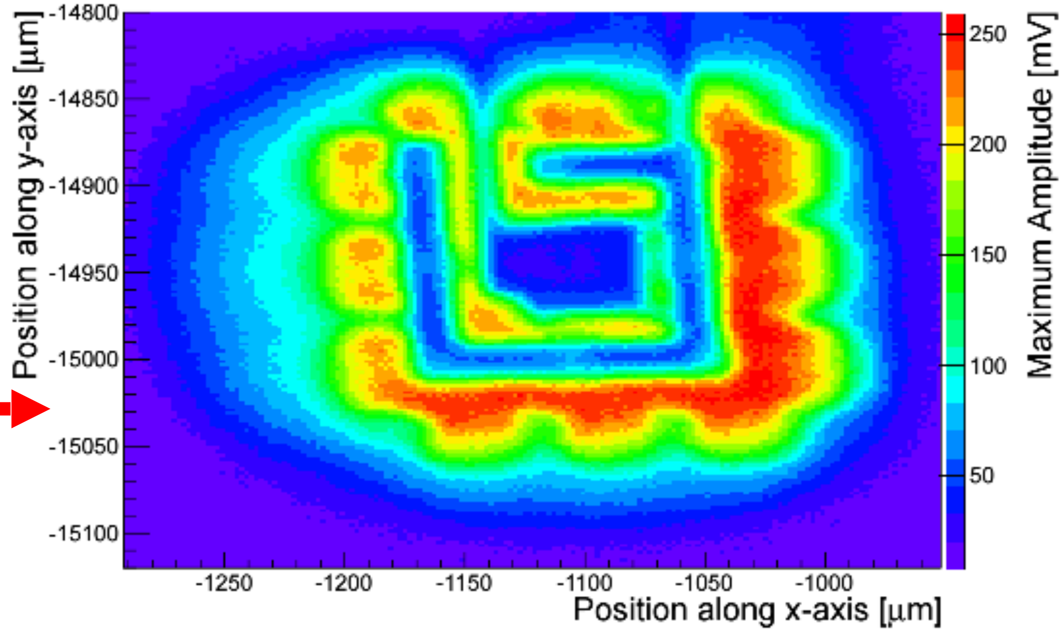
Measured area Timing-TCT



Single column



5737 -7b

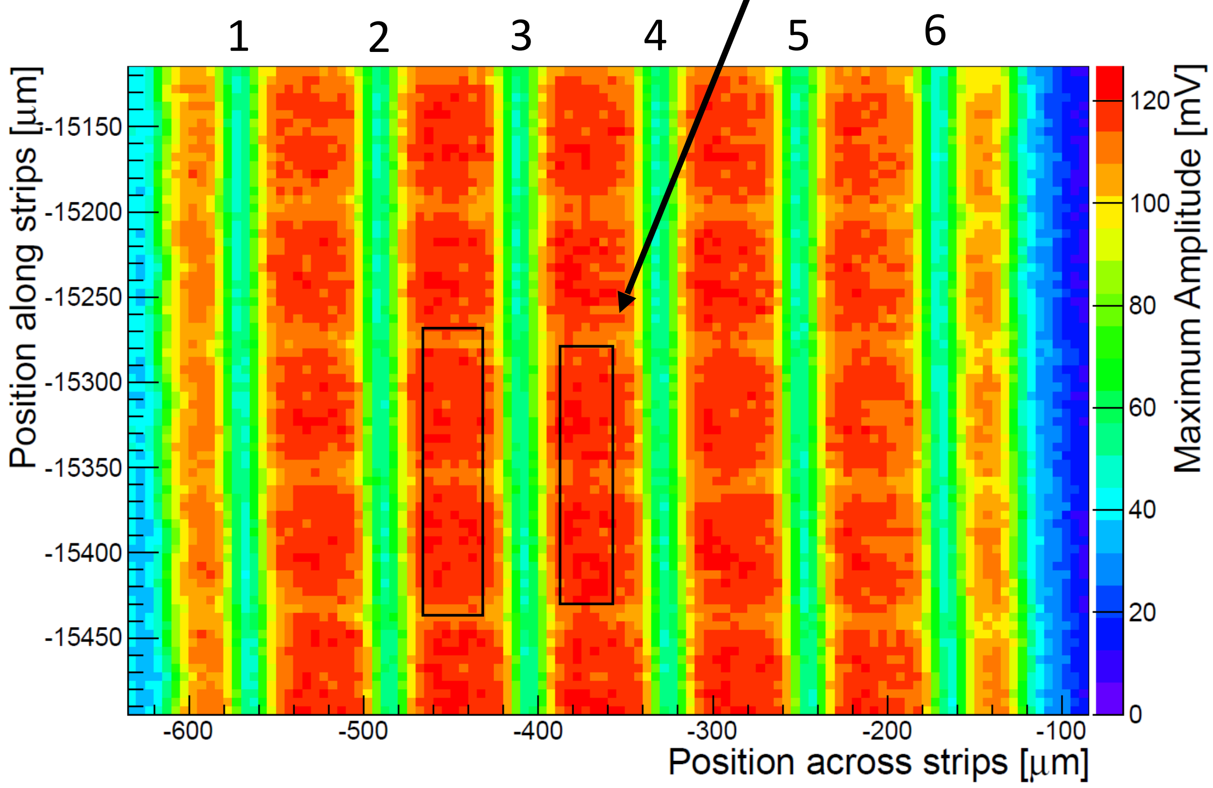


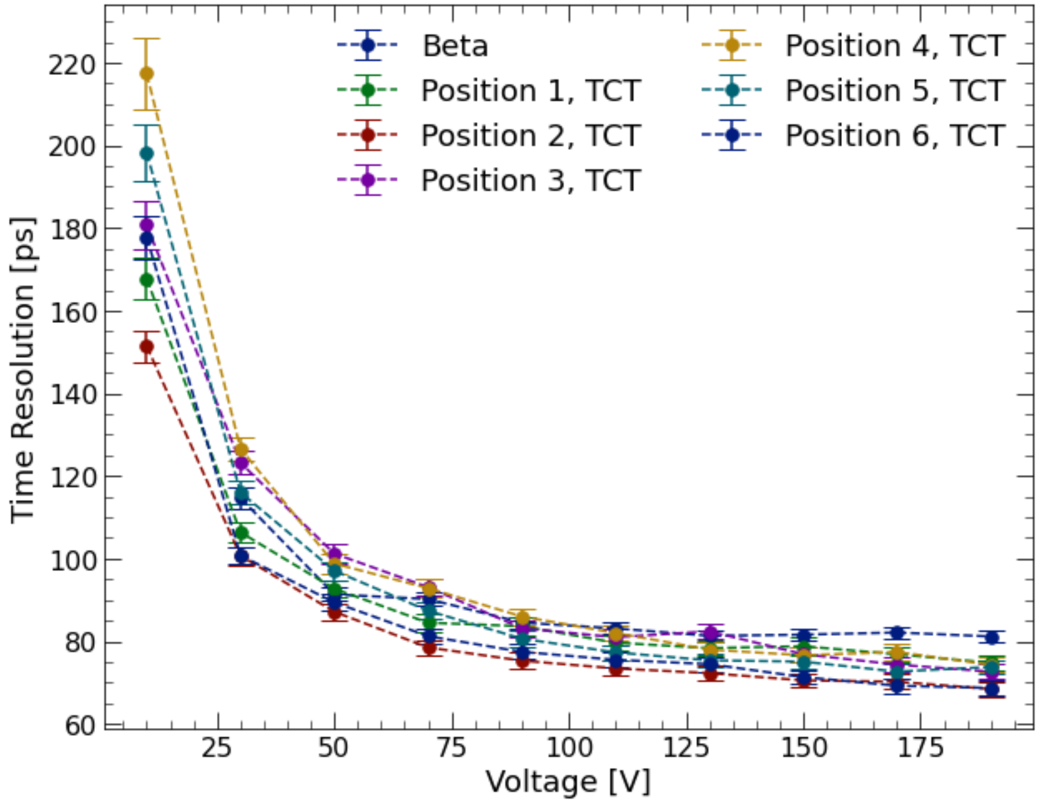
Outer columns

Time Resolution: 3D Strip Sensor

- 3D strip sensor: 235 µm thickness, 80x80μm^2 cell size, 6 channels connected to readout
- Measured with TCT and Timing Set-Up
- For high voltages: Time resolution of about 75 ps reached

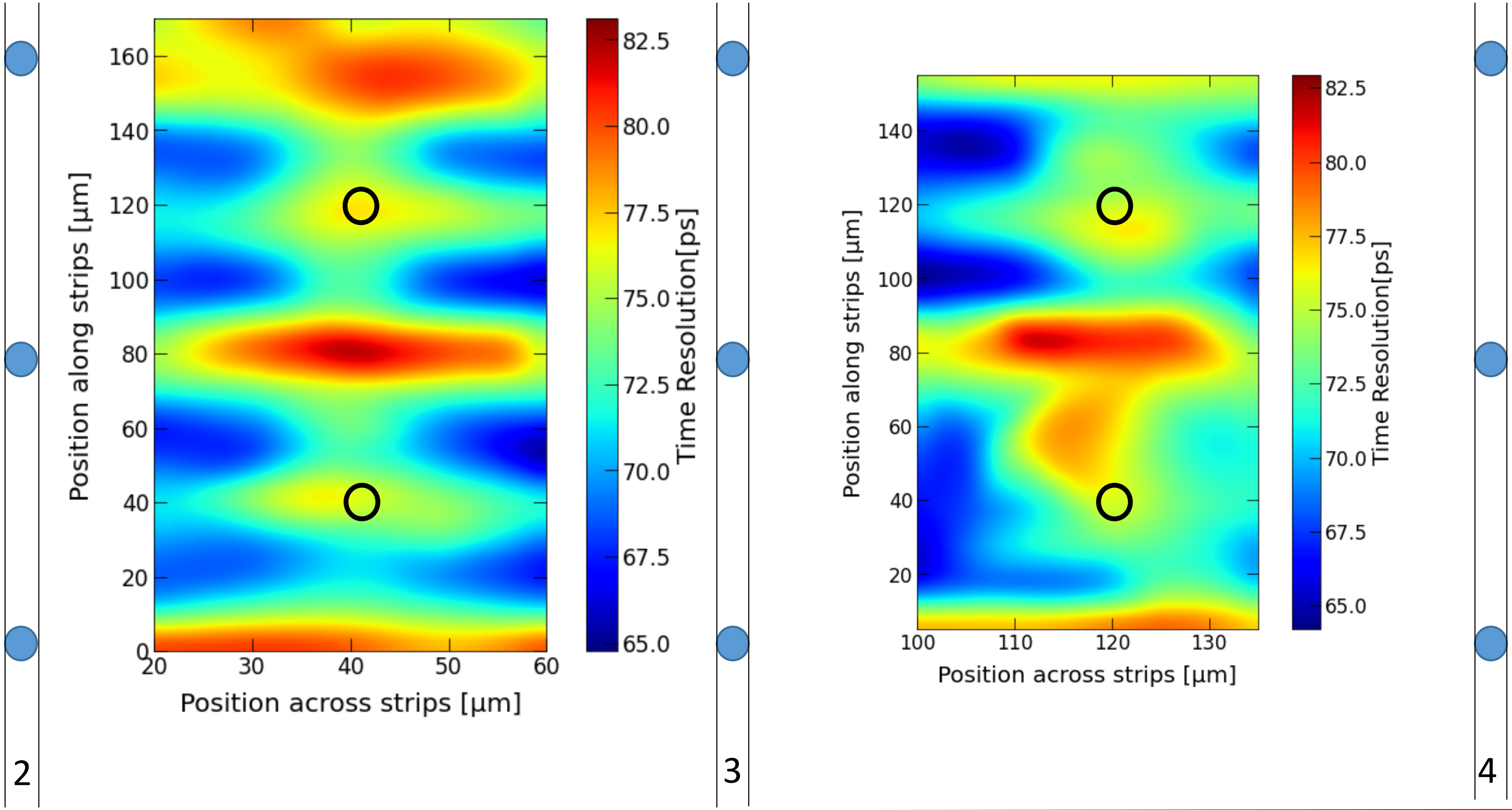
Measured areas for TCT-Timing





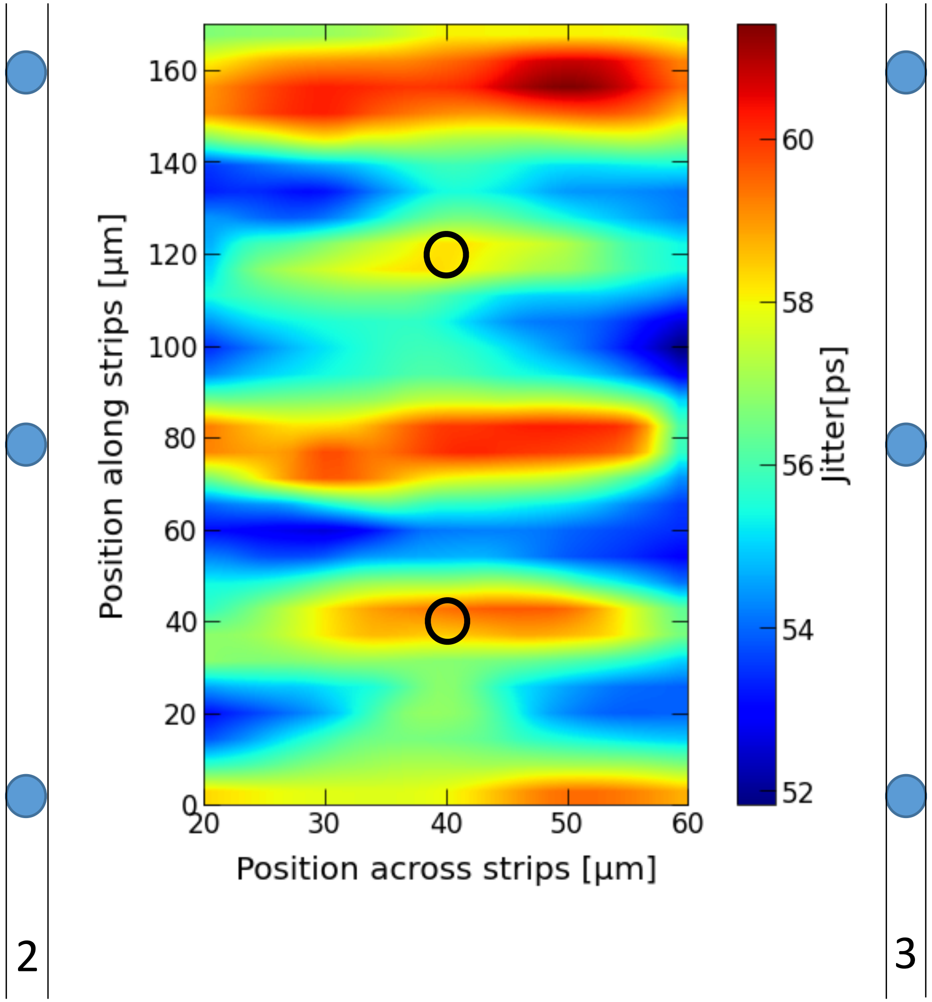
Time Resolution: 3D Strip Sensor

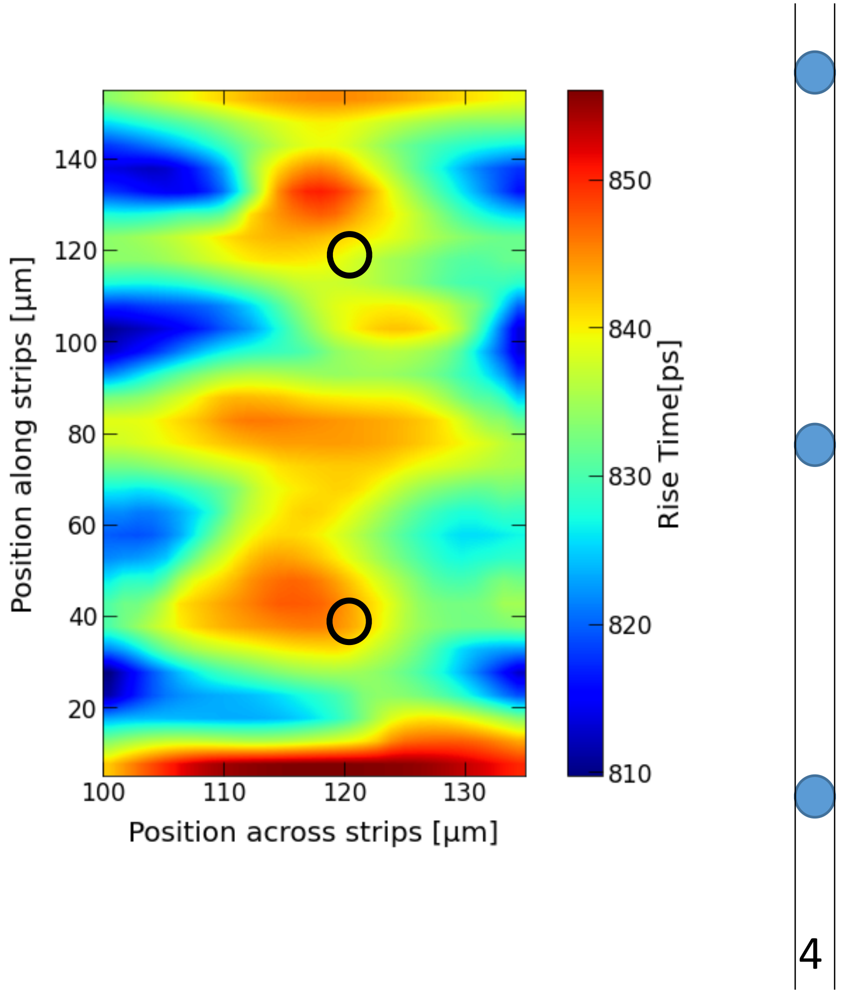
Position dependent measurement of the time resolution with the TCT, measured at 150 V



- Clear cell structure
- Worse resolution between junction columns
- Worse resolution around ohmic columns
- Resolution correlates to the expected el. Field
- Resolution between 65 and 83 ps

Time Resolution: 3D Strip Sensor

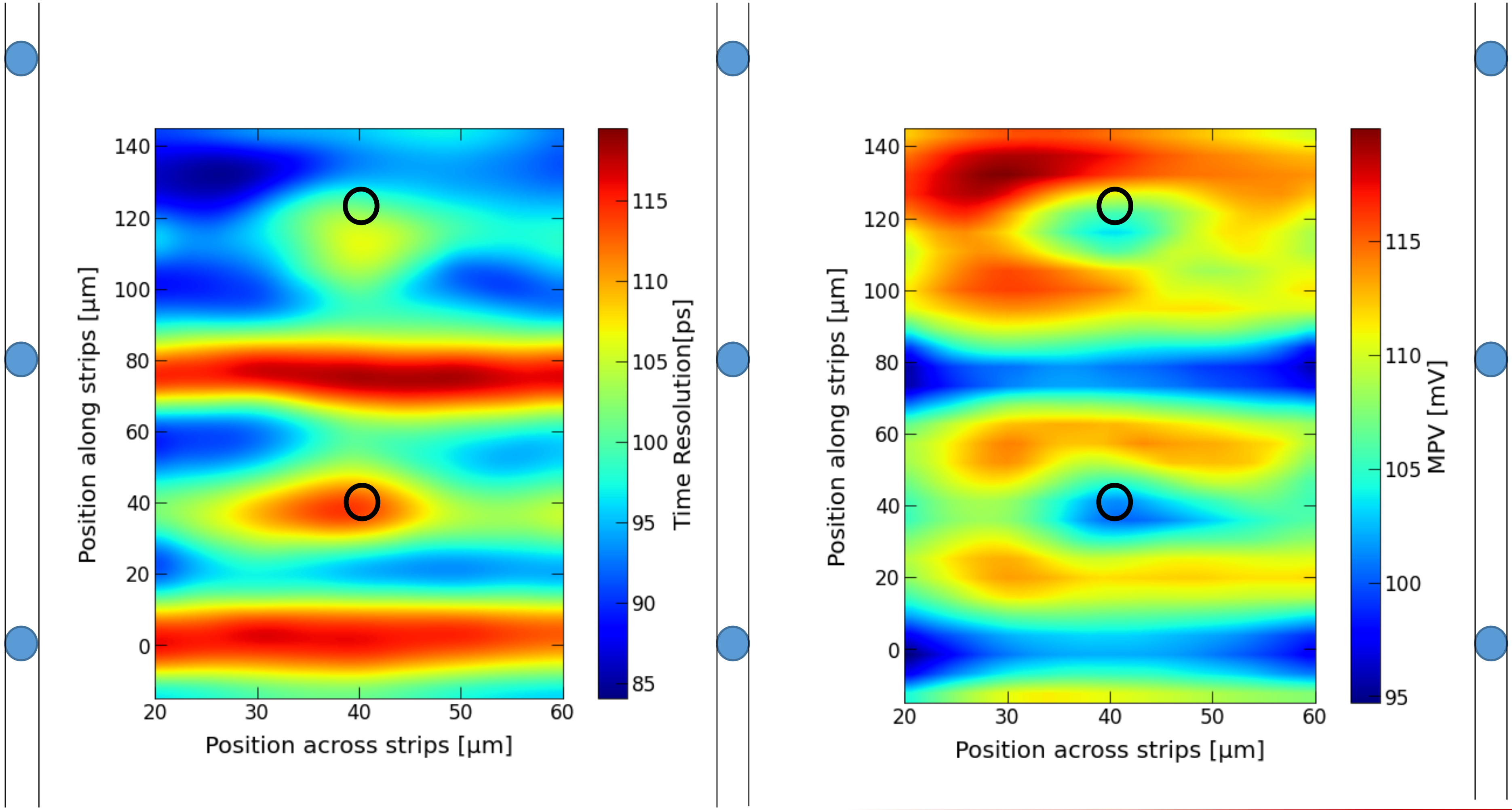




- Clear cell structure
- Similar patterns for jitter and rise time
- Both correlate to the expected el. Field
- Rise Time between 810 and 855 ps
- Jitter higher than in Beta Set-Up, 52-62 ps

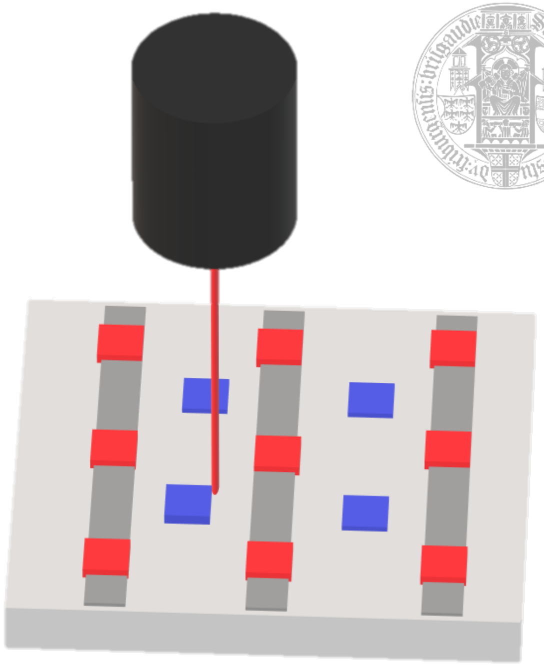
Time Resolution: 3D Strip Sensor 2

5936-4 Strip Sensor: 285 μm thick, high leakage current (sensor broken in half), measured at 40 V

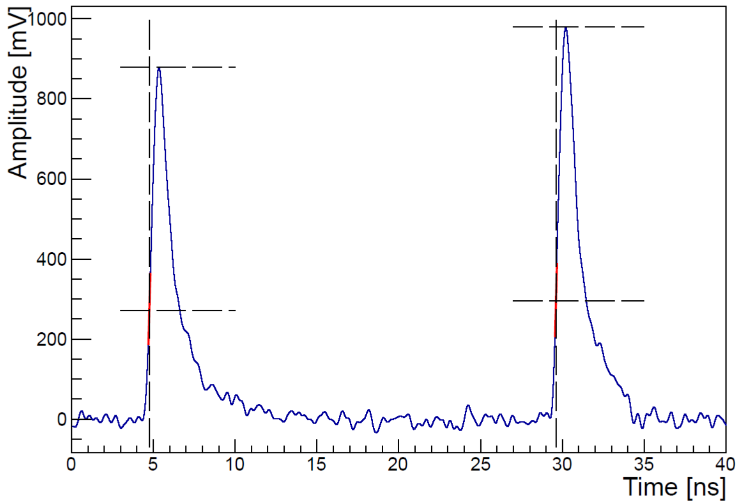


- Clear cell structure
- Worse resolution between junction columns
- Worse resolution around ohmic columns
- Resolution correlates to the expected el. Field
- Resolution between 85 and 115 ps -> lower voltage, higher noise
- Correlation also to MPV

TCT Set-Up for Timing

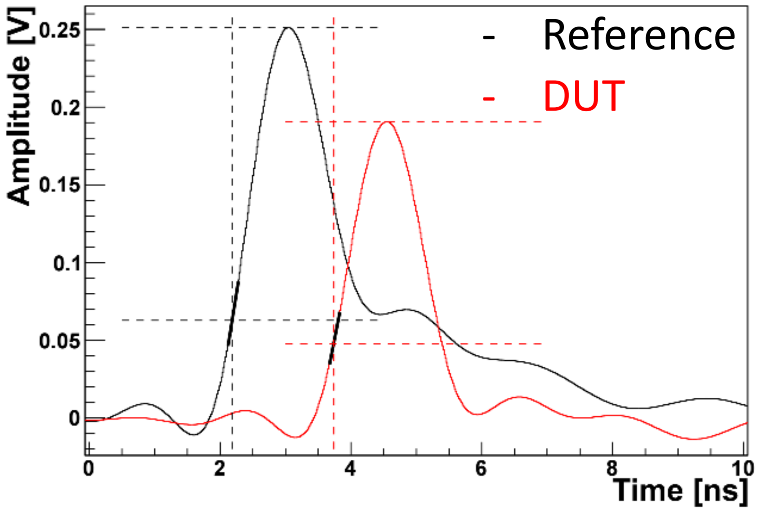


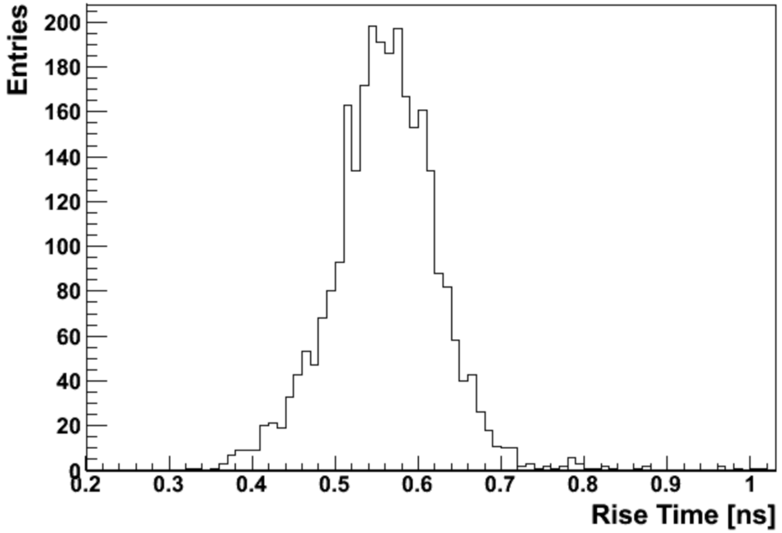
- **T**ransient **C**urrent **T**echnique: Charge created by a short laser pulse
- The current arising from the created e/h-pairs is amplified
  and then recorded with an oscilloscope
- Top-TCT: Laser on sensor surface, laser wavelength 1060 nm (infrared)
- First: Scanning the sensor area to determine the position of the columns
- For each specific position on the sensor: 3000 single events recorded
- Two pulses recorded per event: Using a fiber splitter and a cable (25 ns delay)



Time Resolution: Analysis

- Maximum amplitude for each event filled into histogram – MPV of the sensor is extracted with a Landau-Gauss-Fit
- If the maximum signal is above a threshold, events used for further analysis
- **T**ime **o**f **A**rrival determined with **C**onstant **F**raction **D**iscrimination
- Linear fit around this point to extract the slope
- Determination of the rise time for each event by diving the maximum amplitude by the slope – mean of the distribution defines rise time





Time Resolution: Analysis

- Noise level: Determined in a time span in the recorded waveform before the pulse
- Jitter: Sigma of a Gauss fit to the distribution of noise divided by slope
- Time Spread: Sigma of a Gauss fit to the distribution of the time difference between the two signals
- Time resolution can then be calculated

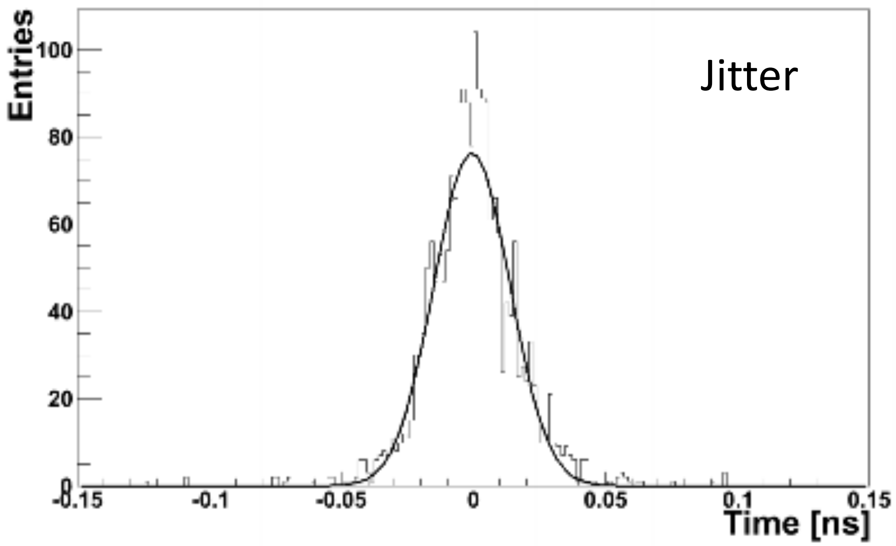
Beta Set-Up:

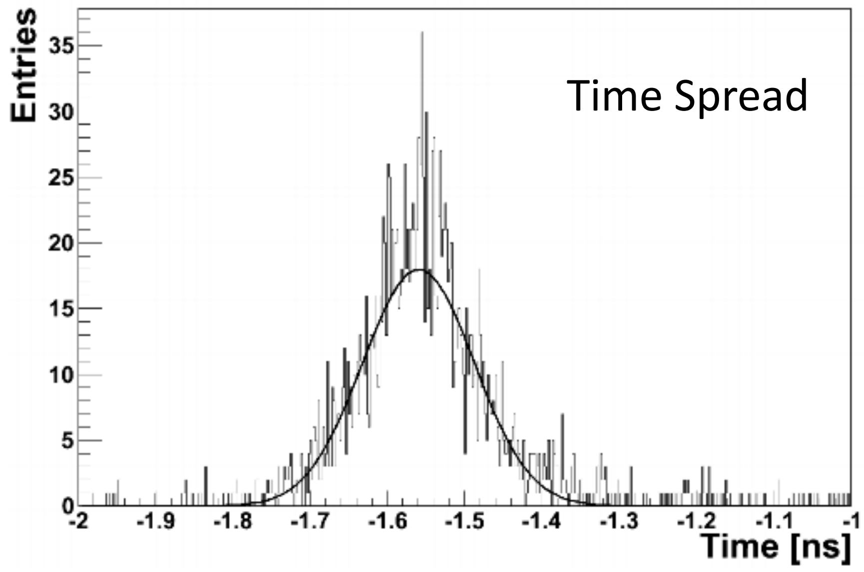
$$\sigma_{DUT} = \sqrt{\sigma_{TS}^2 - \sigma_{Ref}^2}$$

TCT Set-Up:

$$\sigma_{DUT} = \frac{\sigma_{TS}^2}{\sqrt{2}}$$

$$\sigma_{Ref} = 25.18 \pm 0.35\ ps$$

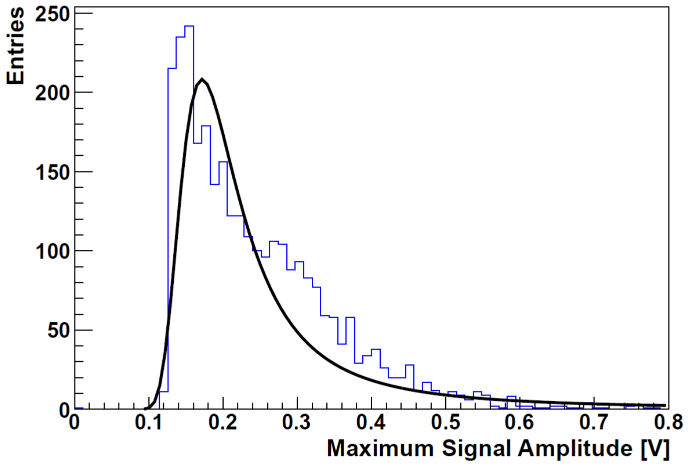


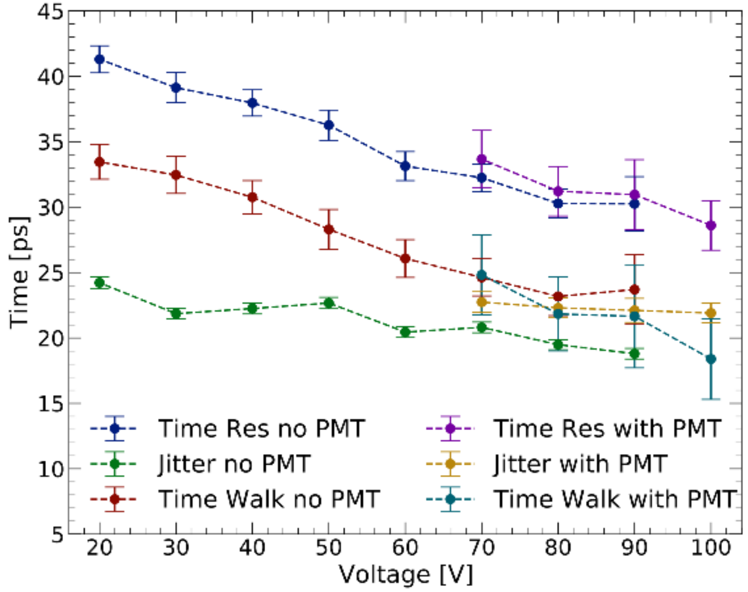


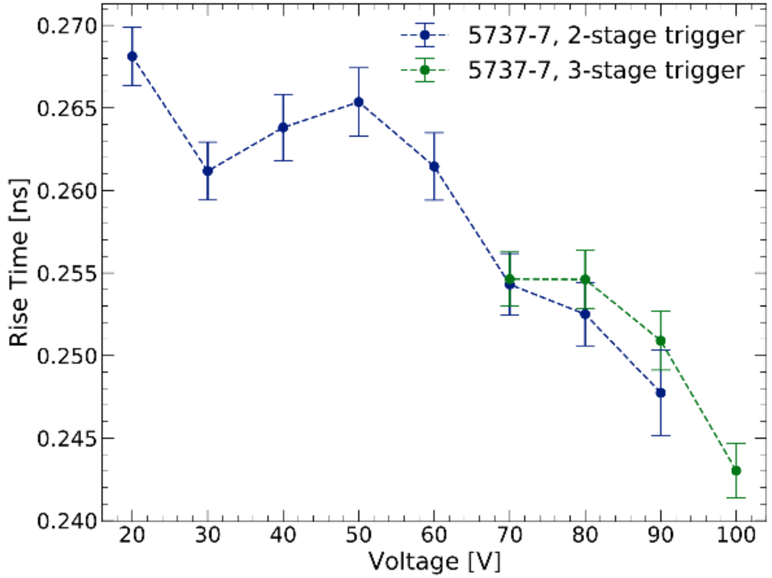
Time Resolution: 3D Pixel sensors

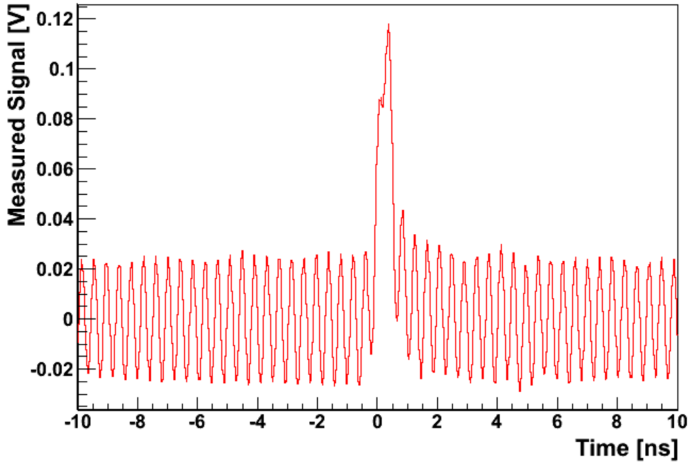
- Sanity Check: Comparison with/without additional PMT trigger
- With PMT: Very low rate – pick-up noise problems
- Without PMT: overestimation of MPV
- Otherwise: Very comparable results

➢ All further measurements without PMT – improved statistics and measurement time, while time resolution characteristics are maintained





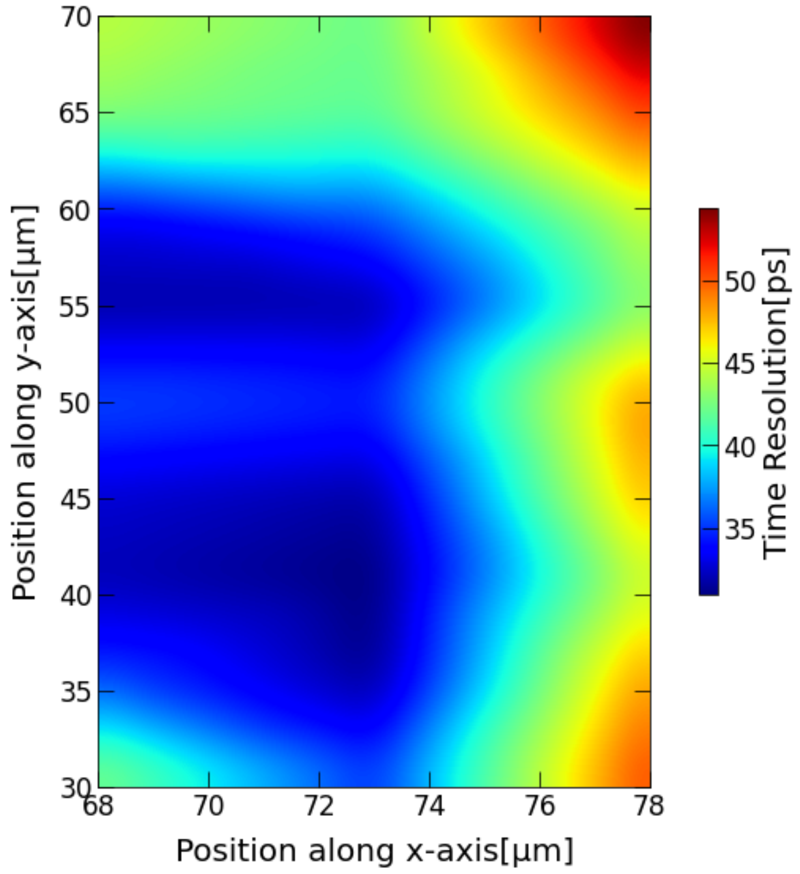


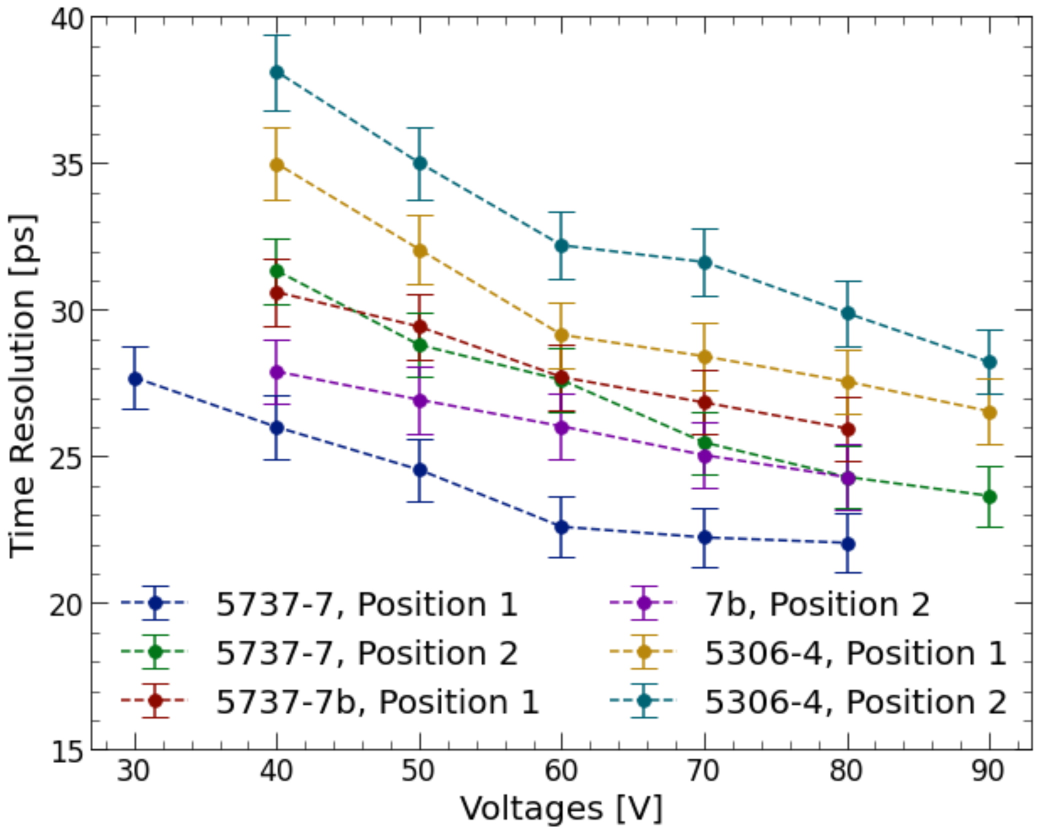


Average waveform with PMT trigger

3D Pixel sensors

5306-4





Expected voltage dependence