Investigation of the Time Resolution of LGADs and 3D sensors using a beta source and a laser system

Leena Diehl, Marc Hauser, Karl Jakobs, Montague King, Ulrich Parzefall, Christina Schwemmbauer, Dennis Sperlich

Albert-Ludwigs-Universität Freiburg

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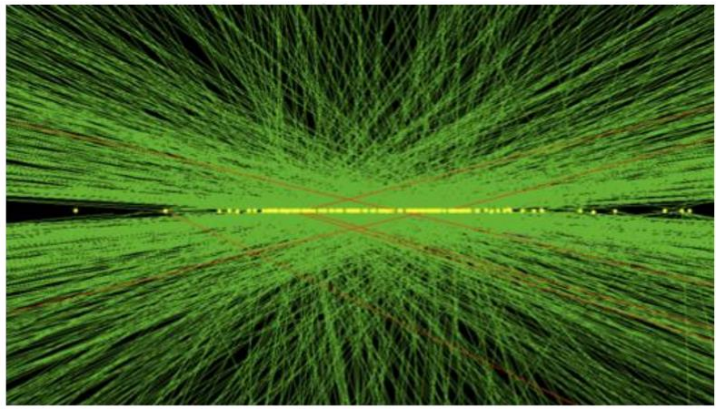
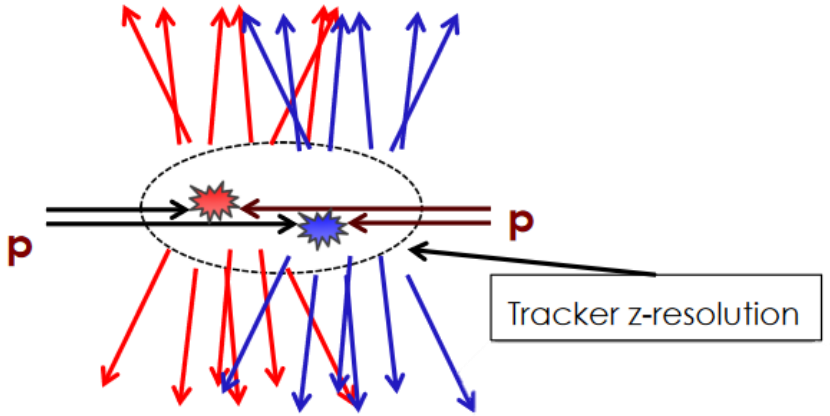
Introduction – Why do we need timing?

- 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
- High radiation doses challenge the sensors additionally
  - Fluences up to $1 \cdot 10^{17} n_{eq}/cm^2$

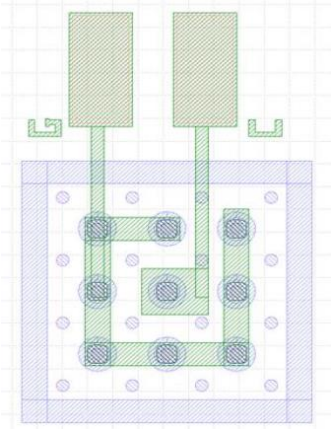


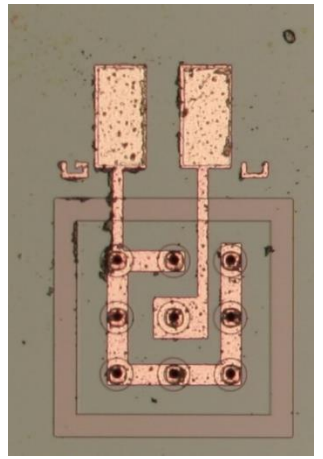


Tracking z-resolution larger than vertex-separation: Ambiguous Track-to-vertex association

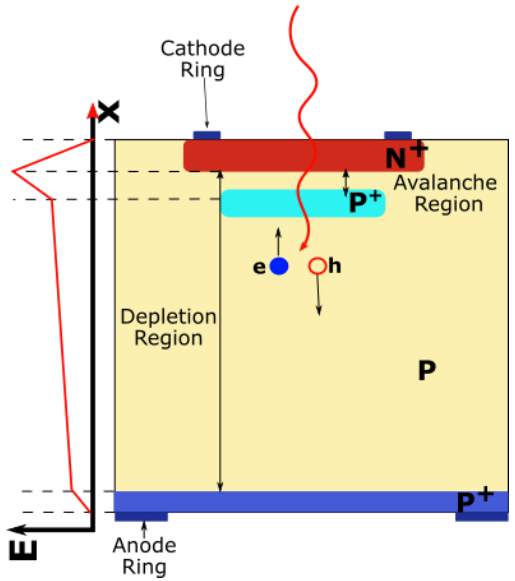
Investigated Sensors

- 3D sensors: strip and single pixel sensors tested, 235 (285) μm thickness, 215 (265) μm column depth.
- Single pixel size 100x100 μm^2
- Strip cell size 80x80 μm^2, strip length 1 mm



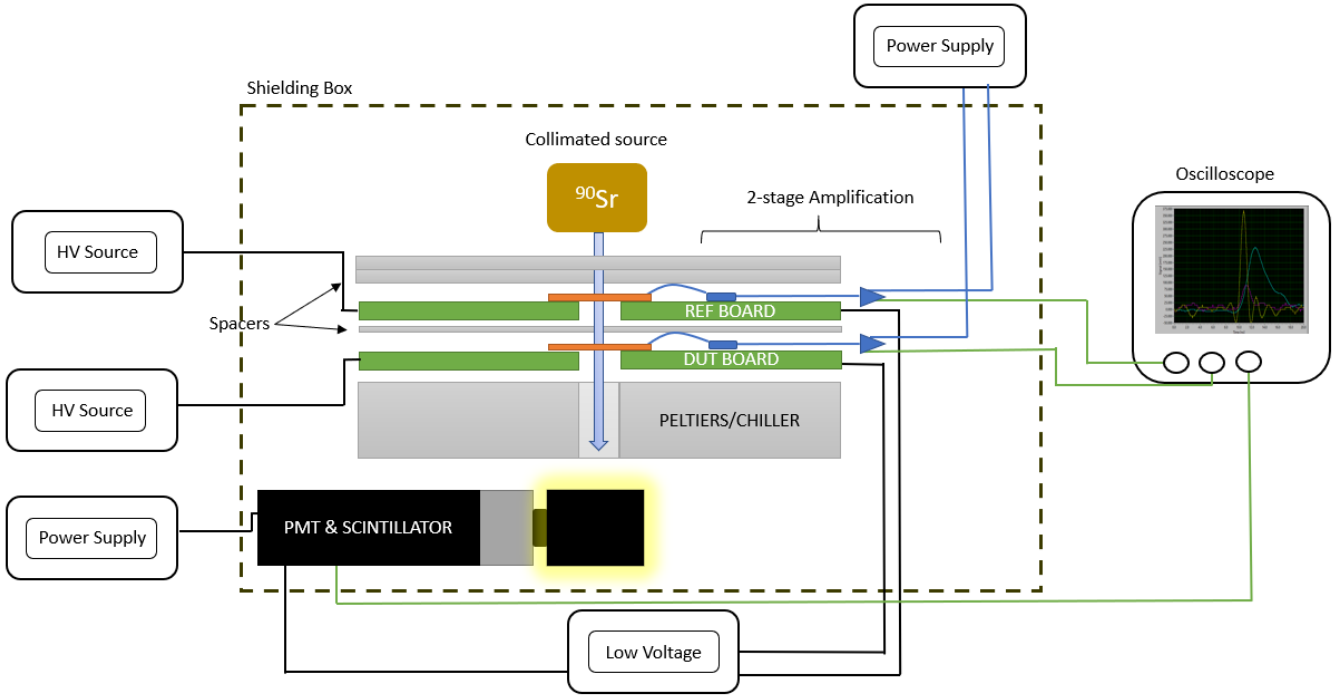


- HPK LGADs: 50 μm active thickness
- Varying gain layer doping concentration

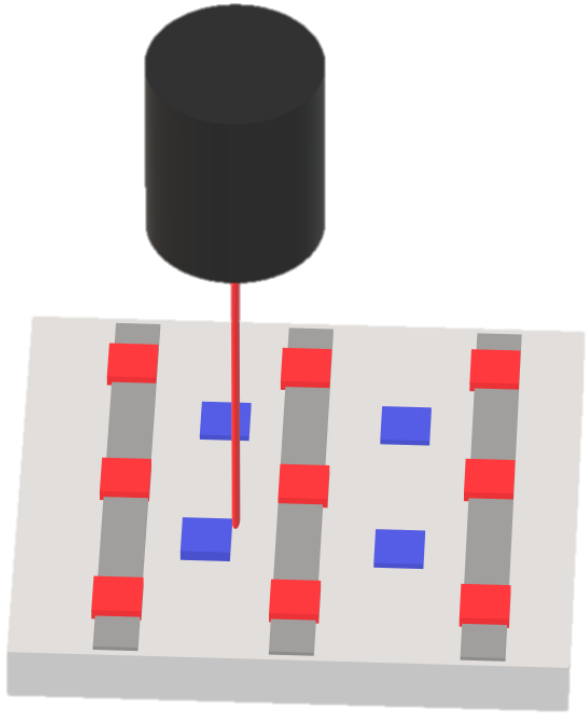


Set-Ups

- Single pulses recorded, if possible external triggers
- About 3000 events with DUT signature for appropriate statistics
- Offline analysis using Constant Fraction Discrimination (CFD)



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

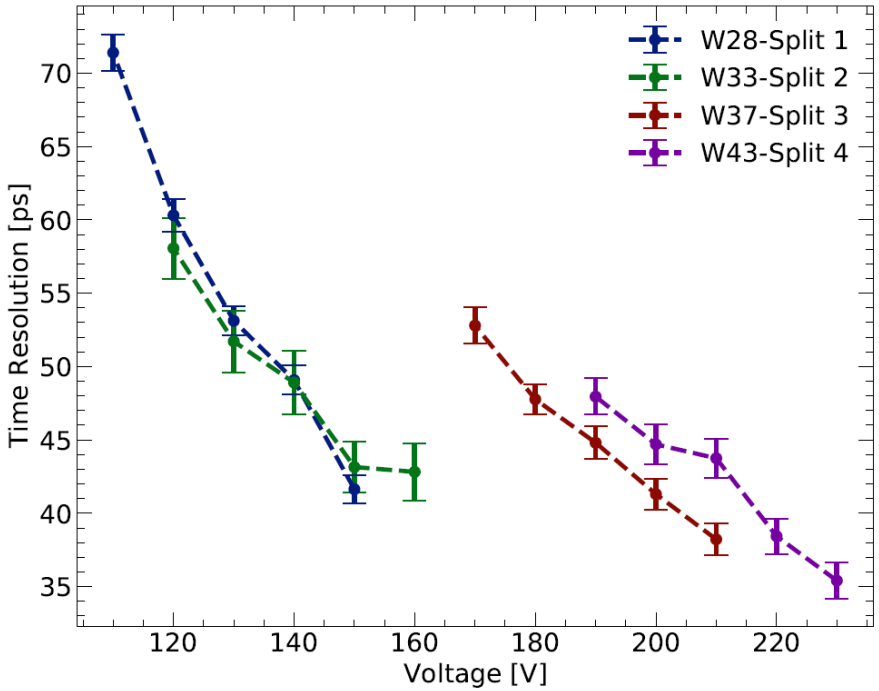


- Top - TCT, infrared laser (1060nm)
- 2 pulses recorded (fiber splitter)
- Intensity tunable

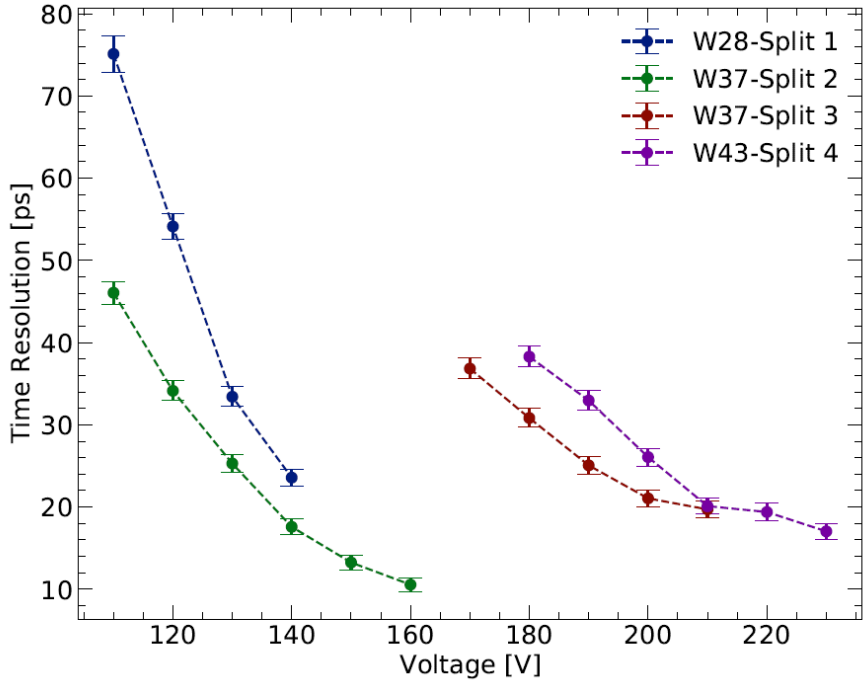
Time Resolution: LGADs - Unirradiated

- Different gain layer doping: High (Split 1) to low (Split 4)
- Better resolution (35ps) for low doping concentration, but higher voltages
- TCT results better than beta measurements – no contribution from Landau fluctuations

Beta measurements

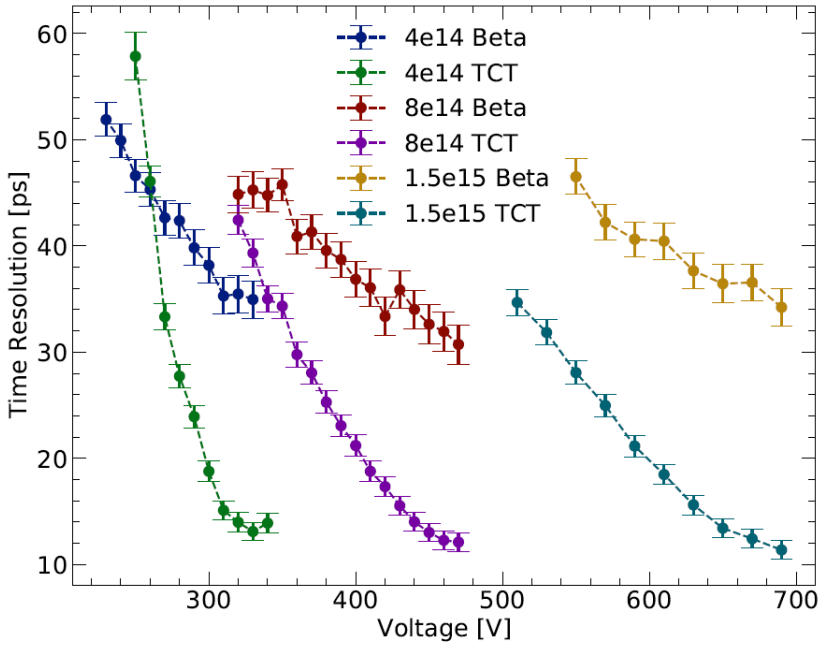


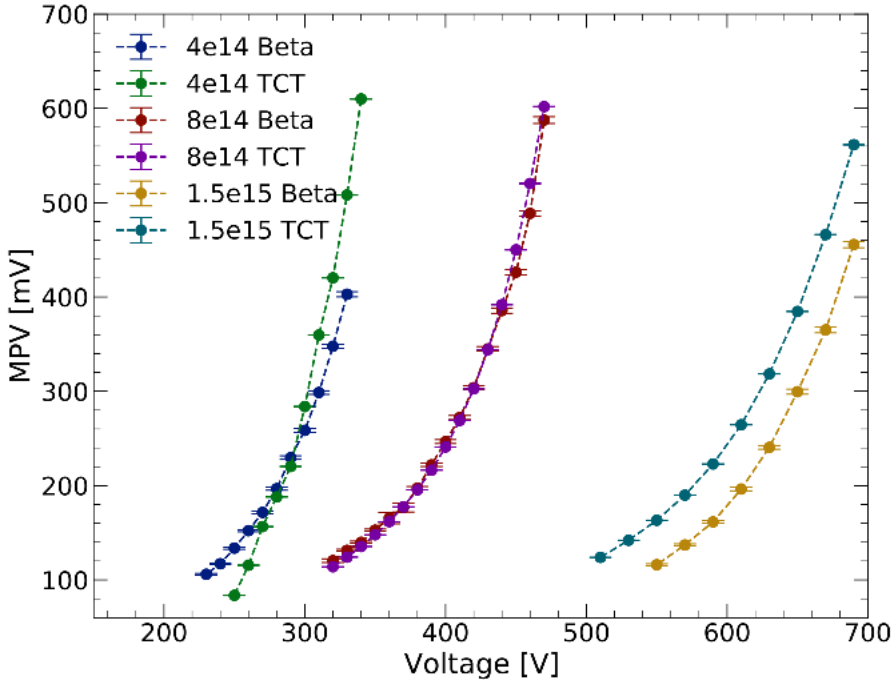
TCT measurements



Time Resolution: LGADs - Irradiated

- Irradiated HPK LGADs from Split 2 (high doping concentration)
- Increase in voltage as expected
- Steeper improvement of resolution for TCT at low fluence – no gain layer suppression (wide opened lens)
- More equal at high fluences – less influence of the gain layer after degredation (total high velocity)
- With beta source: time resolution between 31 and 35 ps achieved for all fluences

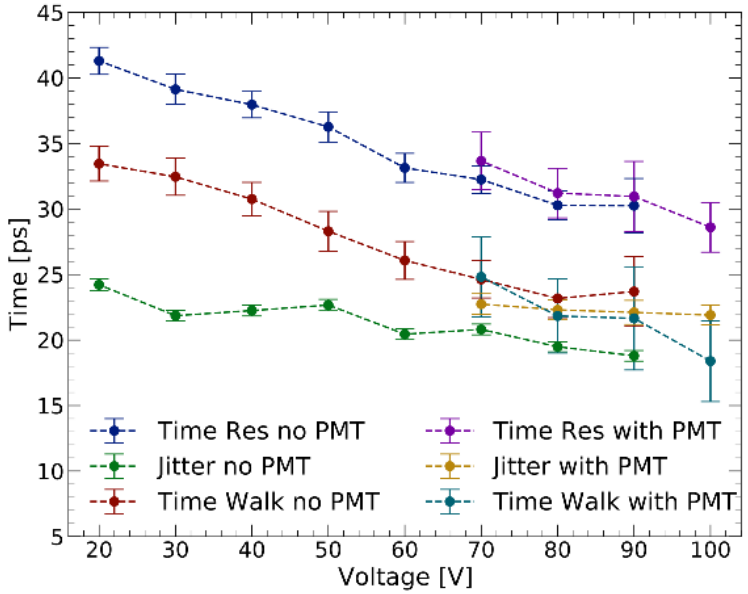


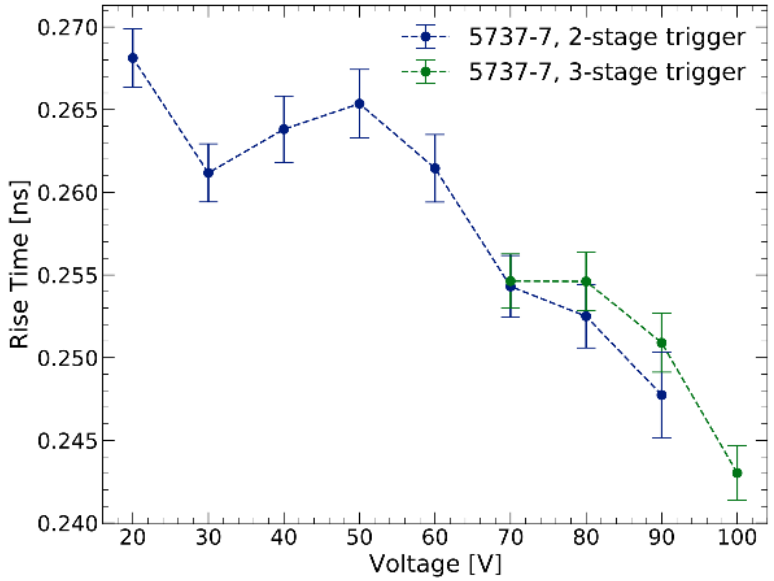


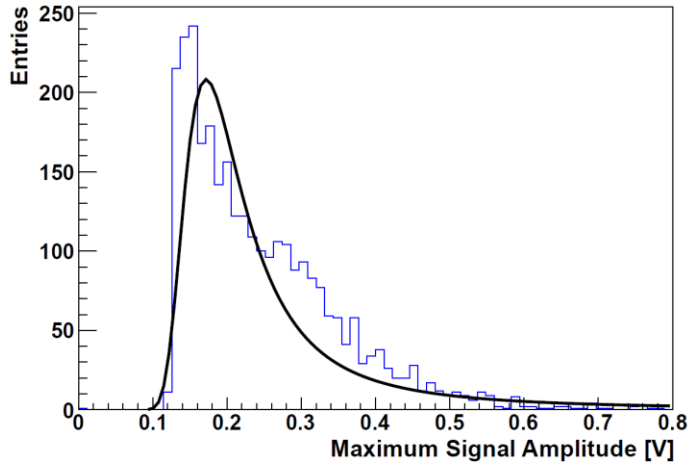
Time Resolution: 3D Pixel sensors

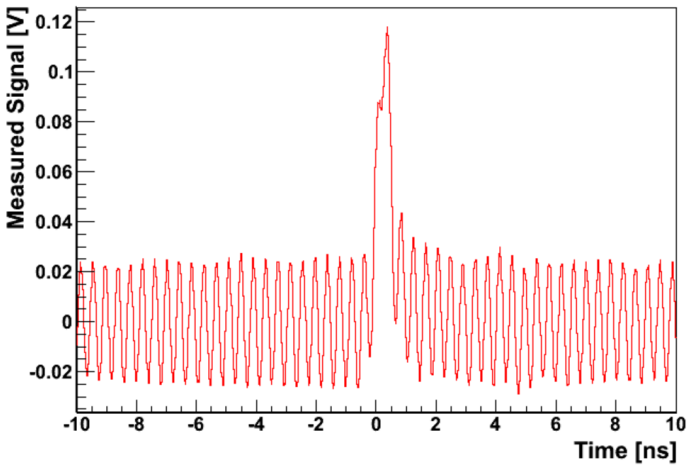
- Sanity Check: Comparison with/without additional PMT trigger
- With PMT: Very low rate – pick-up noise problems
- Without PMT: overestimation of MPV
- Otherwise: Very comparable results

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





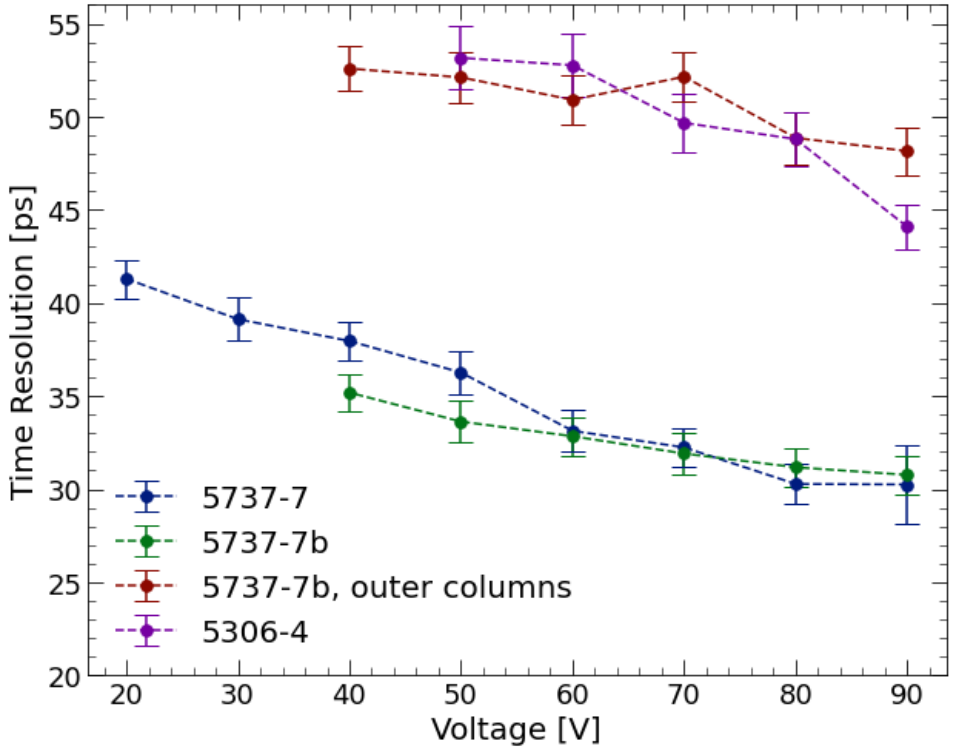


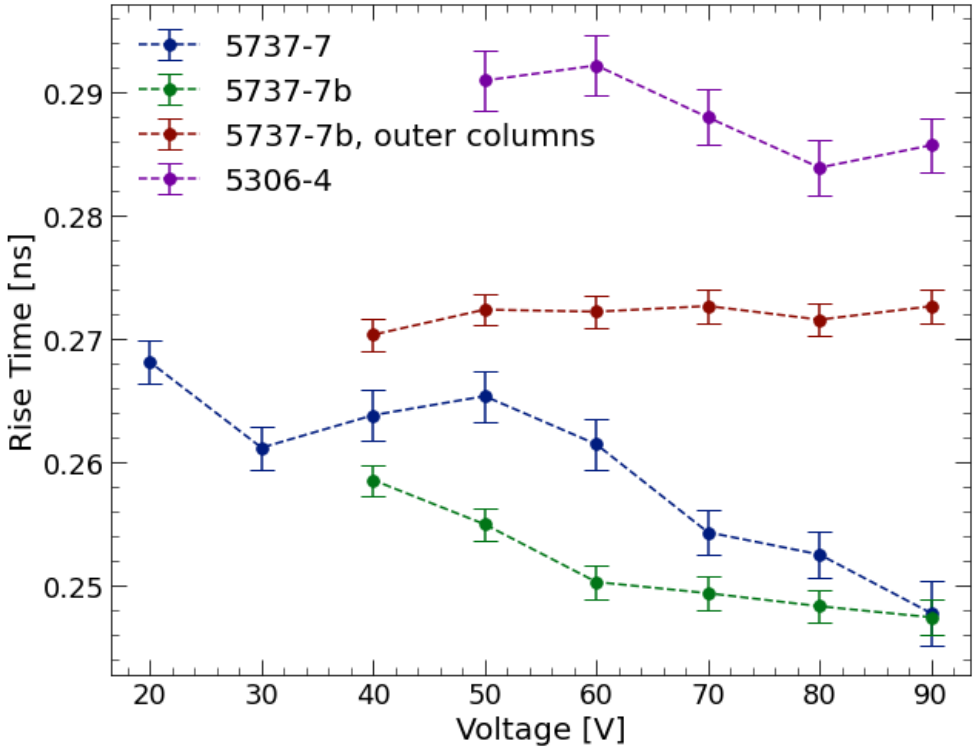


Average waveform with PMT trigger

Time Resolution: 3D Pixel Sensors

- The 5737 sensors reach about 30-31 ps time resolution while the thicker 5306 only reaches 44 ps
- Outer columns: no well defined electric field – time resolution worse, reaching only 50 ps
- Excellent rise time below 300 ps for all sensors – the reference LGAD has ~550 ps

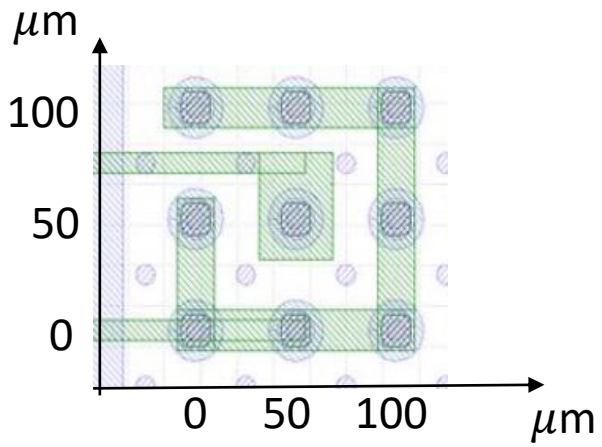




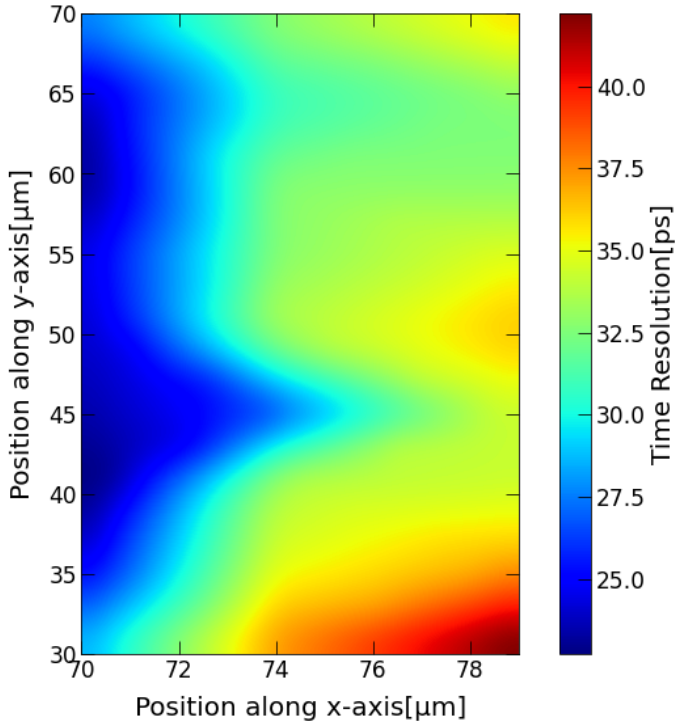
Time Resolution: 3D Pixel Sensors

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

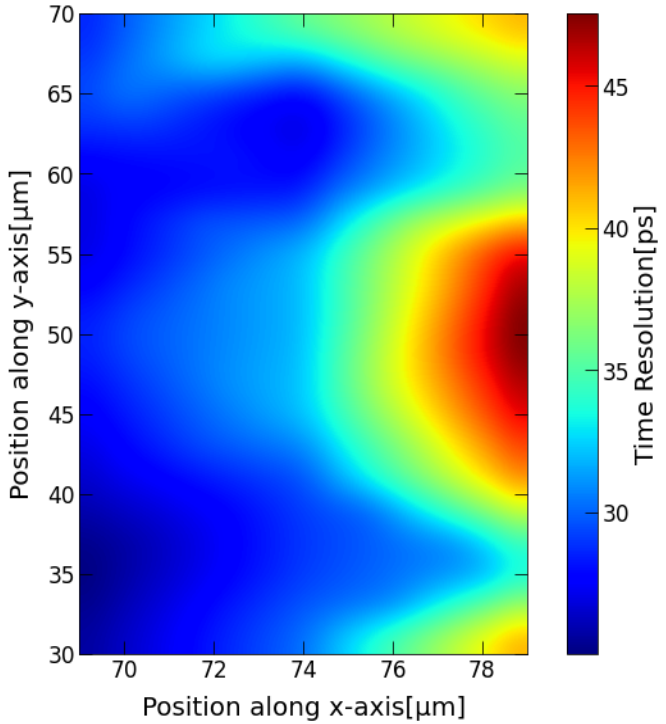
- Differences: Uncertainties in position, laser focus, laser intensity



5737-7

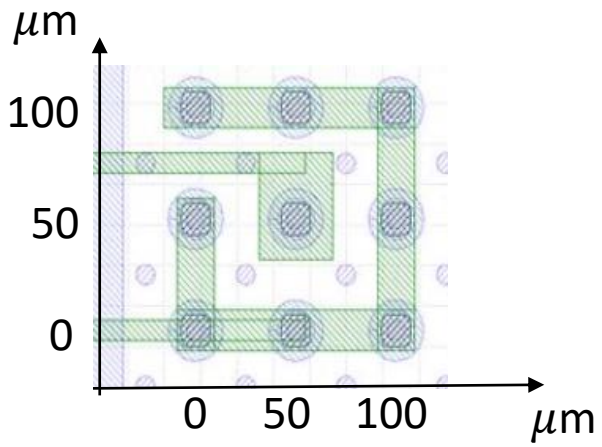


5737-7b

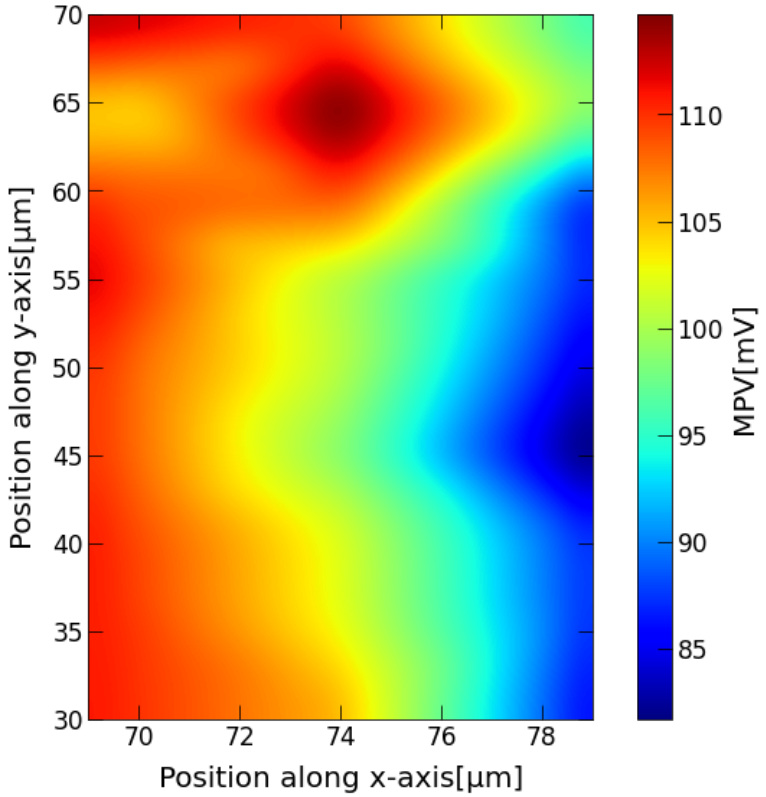


Time Resolution: 3D Pixel Sensors

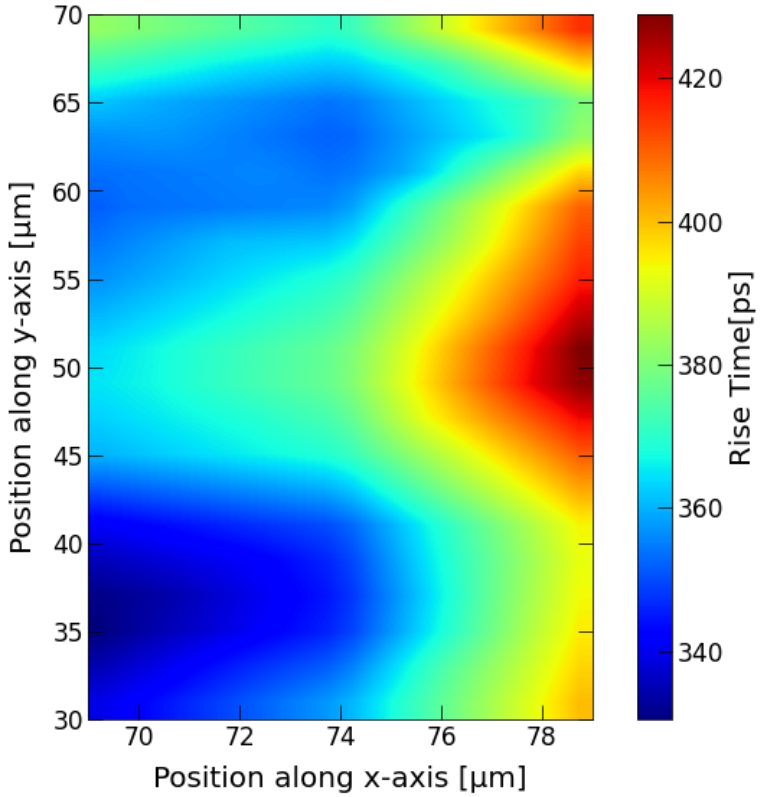
- Low laser intensity – MPV around 80-110 mV, low compared to beta set-up (145 mV)
- Cell structure not as clear as for time resolution, but still fits the expectations
- Rise time between 340 and 420 ps, higher than measured in the beta set-up



MPV **5737-7b**

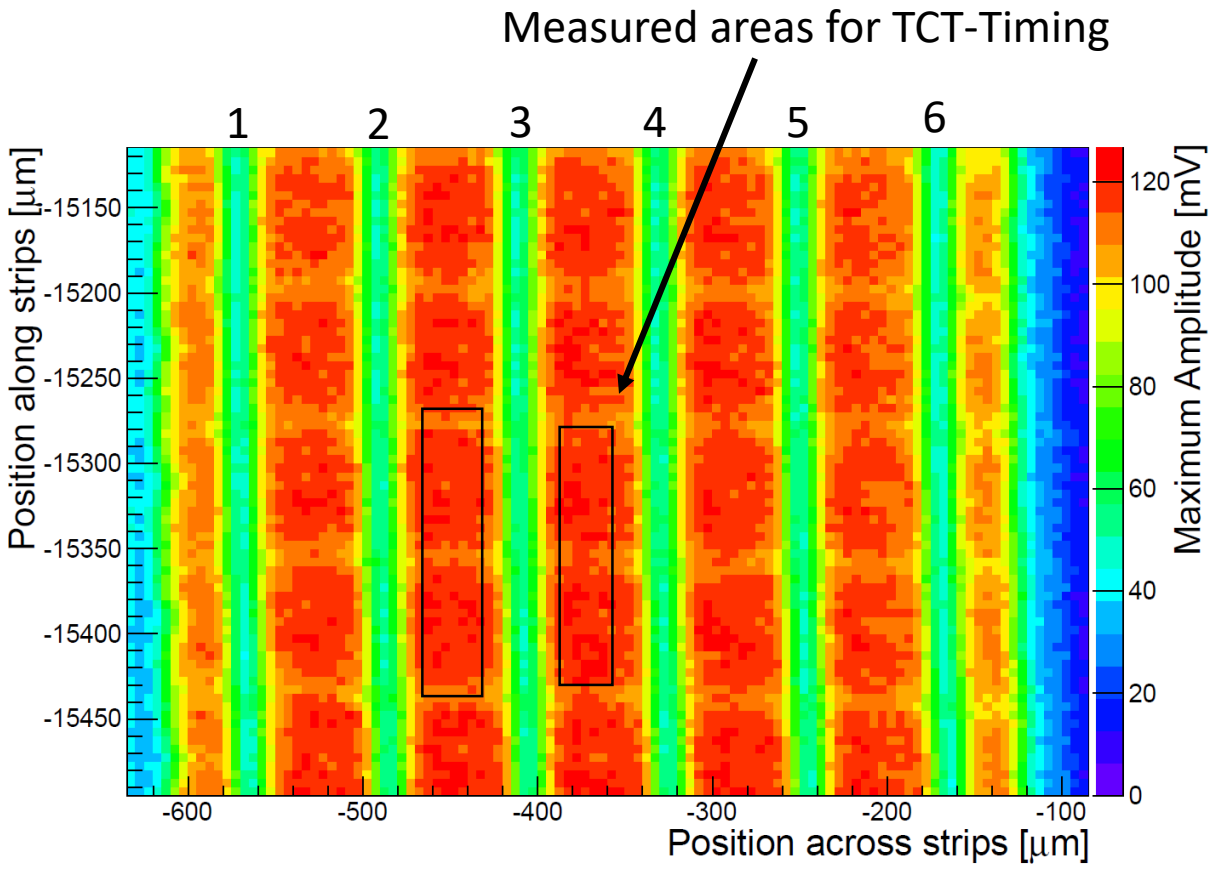


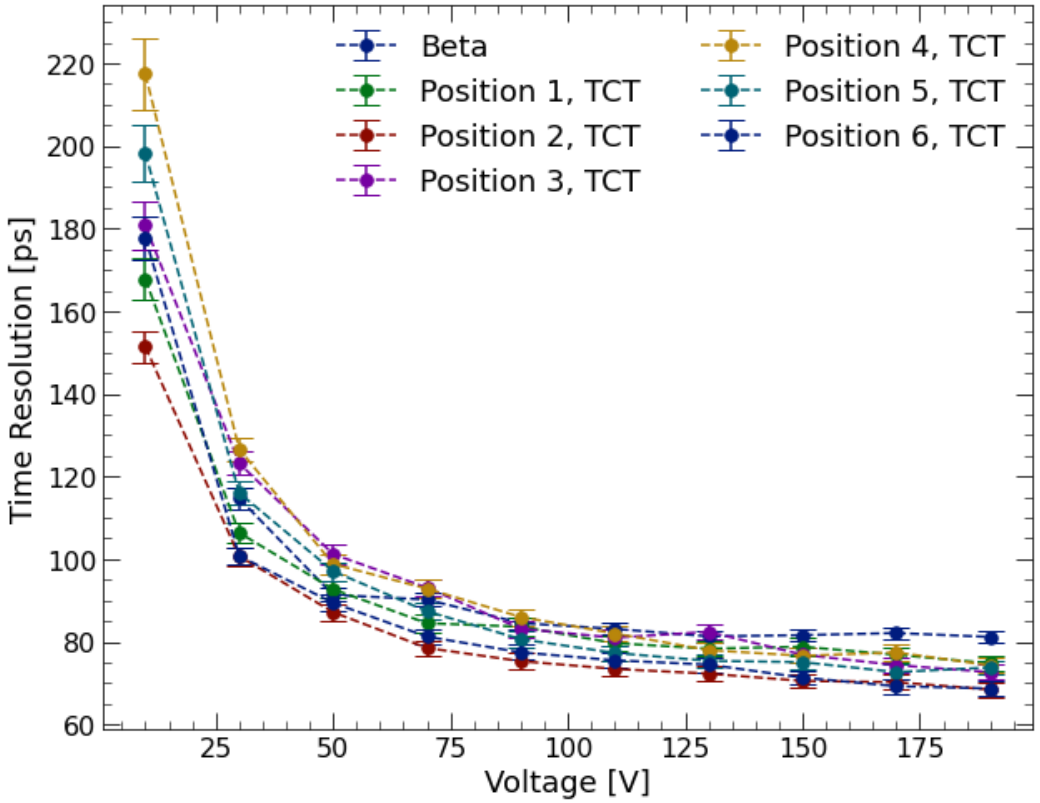
Rise Time



Time Resolution: 3D Strip Sensor

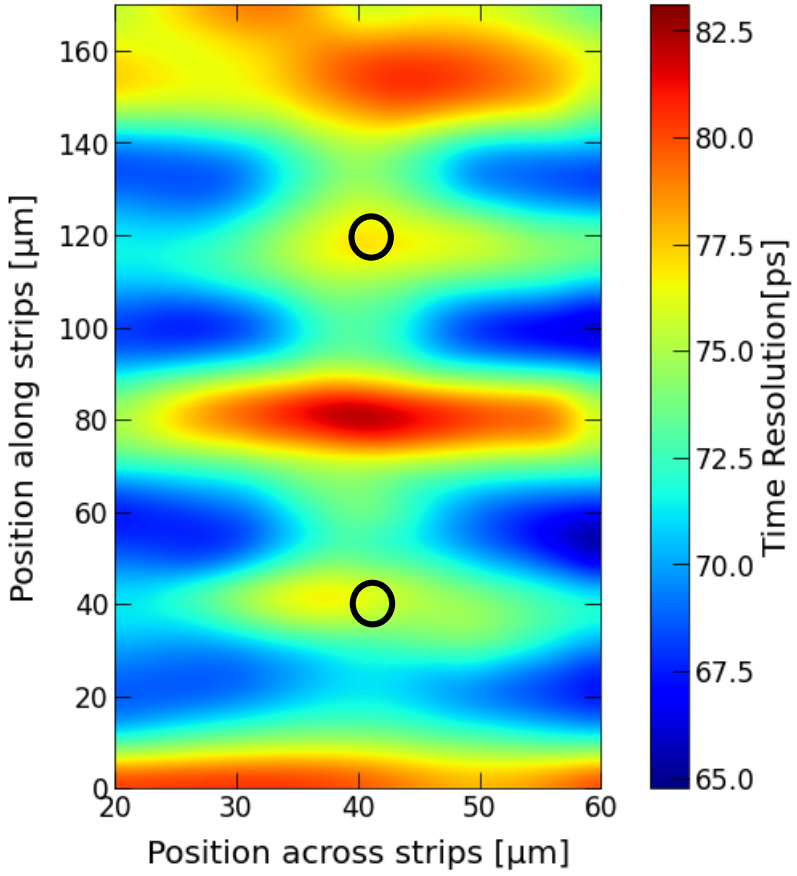
- 3D strip sensor: 235 µm thickness, 80x80µm^2 cell size, 6 channels connected to readout
- Measured with TCT and Timing Set-Up
- For high voltages: Time resolution of about 75 ps reached

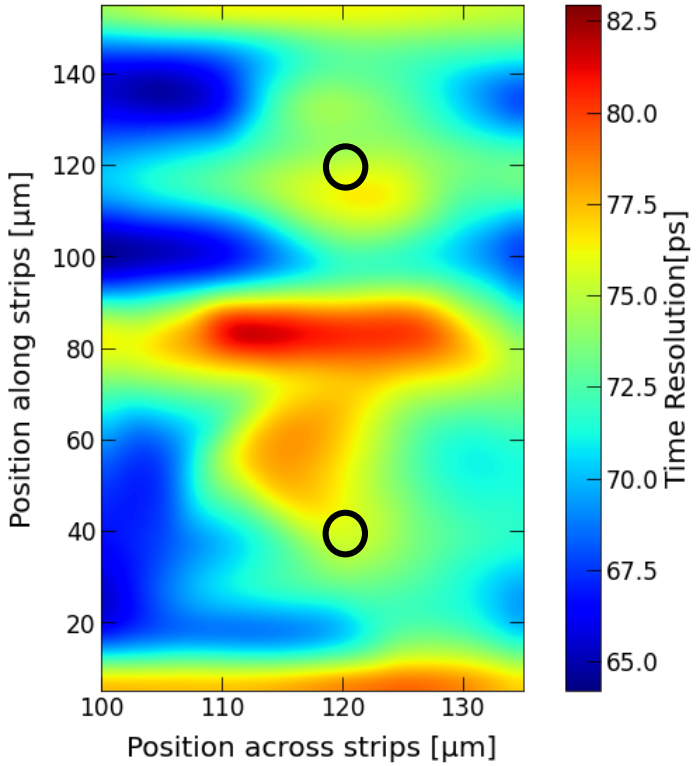




Time Resolution: 3D Strip Sensor

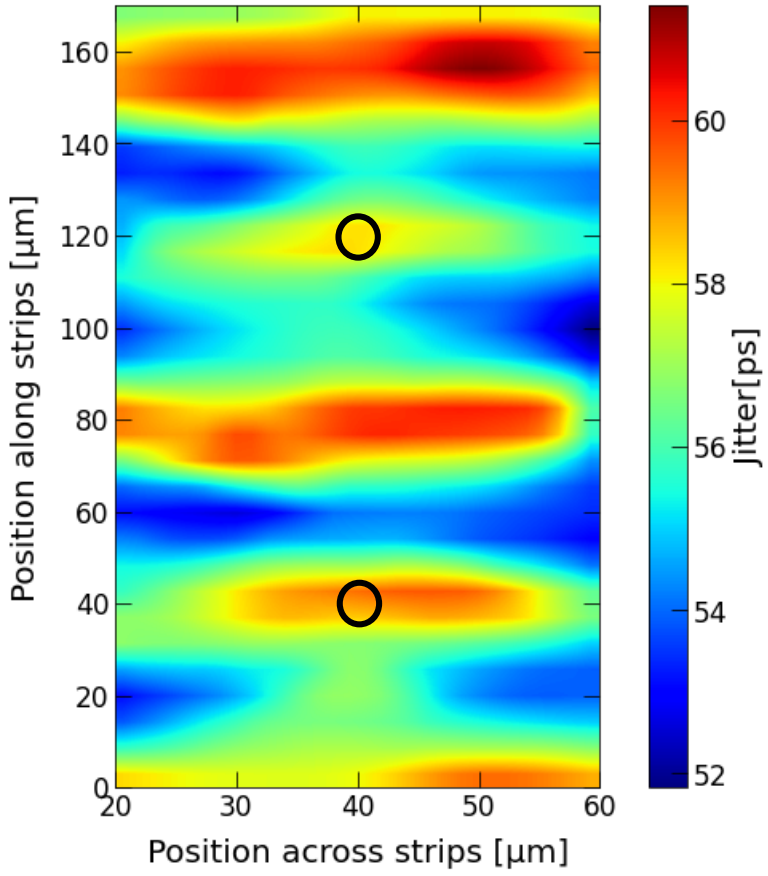
Position dependent measurement of the time resolution with the TCT, measured at 150 V

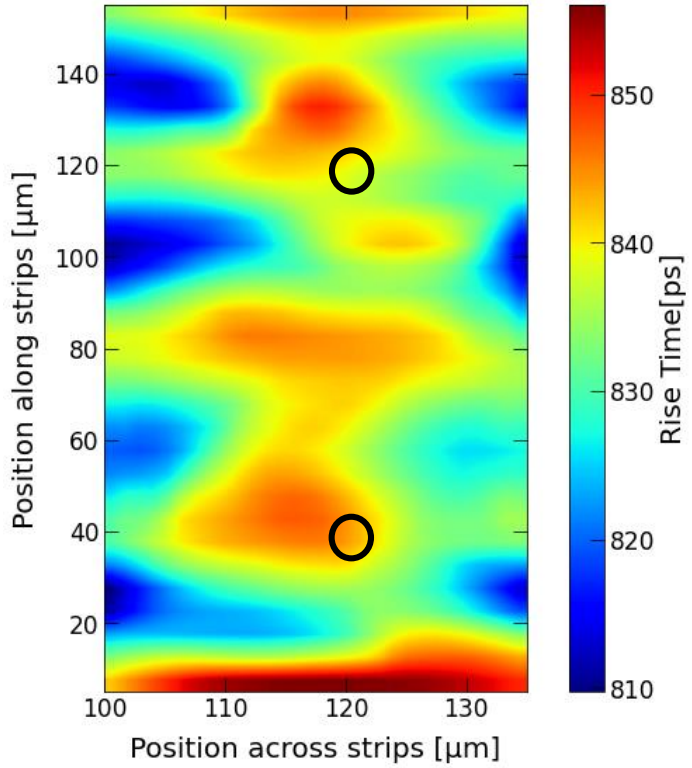




- Clear cell structure
- Worse resolution between junction columns
- Worse resolution around ohmic columns
- Resolution correlates to the expected el. Field
- Resolution between 65 and 83 ps

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

Conclusion and Outlook

- Time resolution of silicon sensors is an important research area for upcoming and future colliders
- LGADs with high doping gain layers withstand fluences up to $1.5 \times 10^{15} n_{eq}/cm^2$
- Unirradiated 3D pixel sensors reach a time resolution competitive with LGADs
- The position dependent time resolution measured correlates very well with the electric field distribution

- Upcoming: Measurements of 3D sensors after irradiation
- Future: 3D sensors designed specifically for timing purposes

Thank you for your attention!

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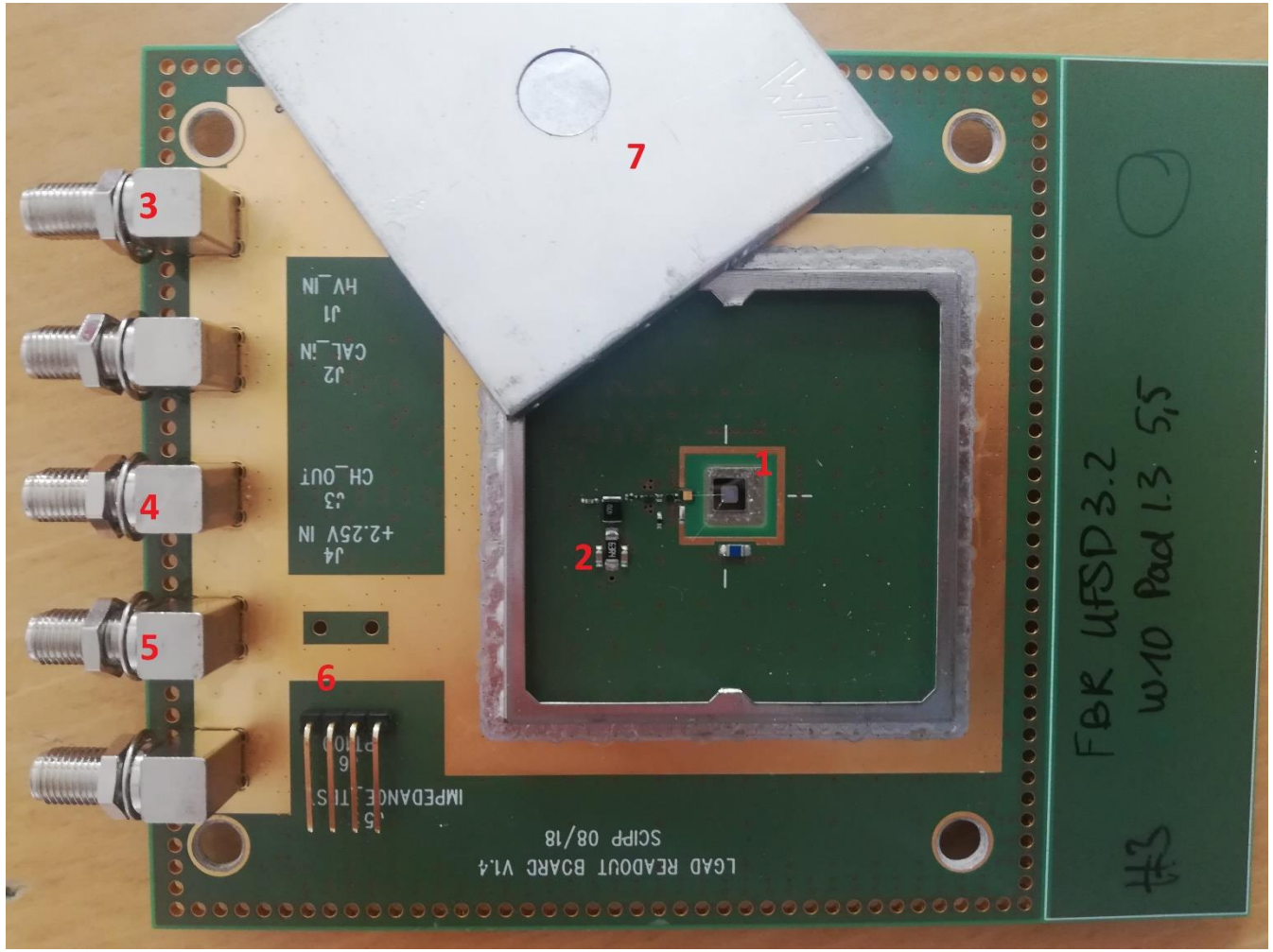
BACKUP

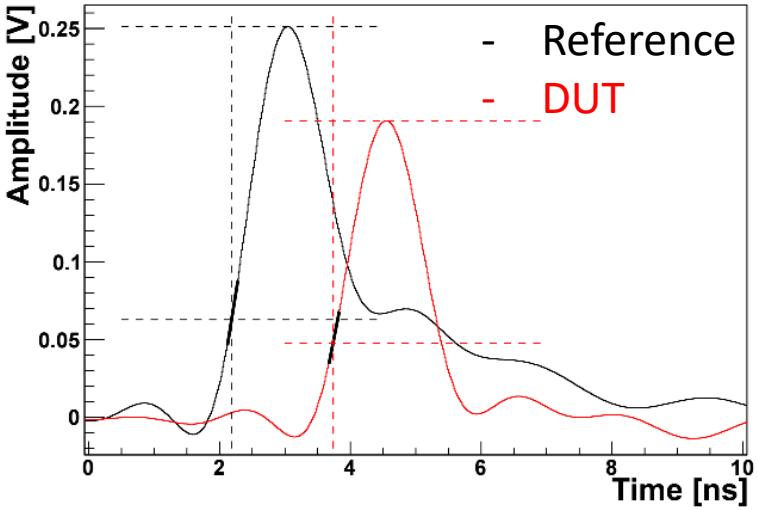
LGAD Readout Board

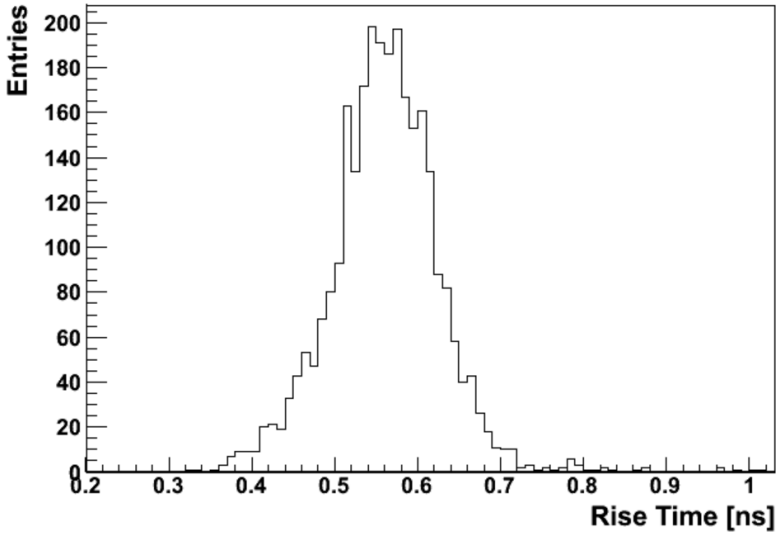


1. Bonded LGAD
2. Amplifier
3. High voltage connector
4. Readout connector
5. Low voltage connector
6. PT100 connector
7. Lid

Time Resolution: Analysis

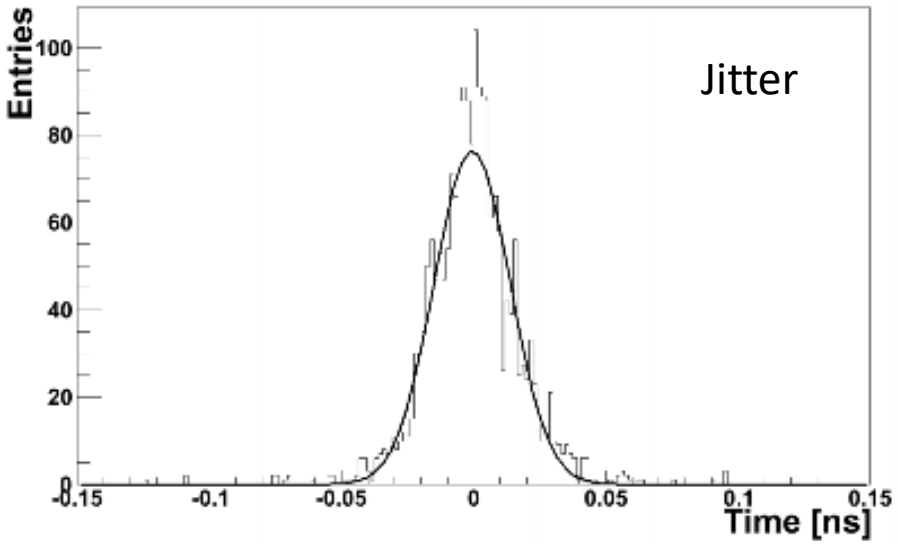
- Maximum amplitude for each event filled into histogram – MPV of the sensor is extracted with a Landau-Gauss-Fit
- If the maximum signal is above a threshold, events used for further analysis
- **T**ime **o**f **A**rrival determined with **C**onstant **F**raction **D**iscrimination
- Linear fit around 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

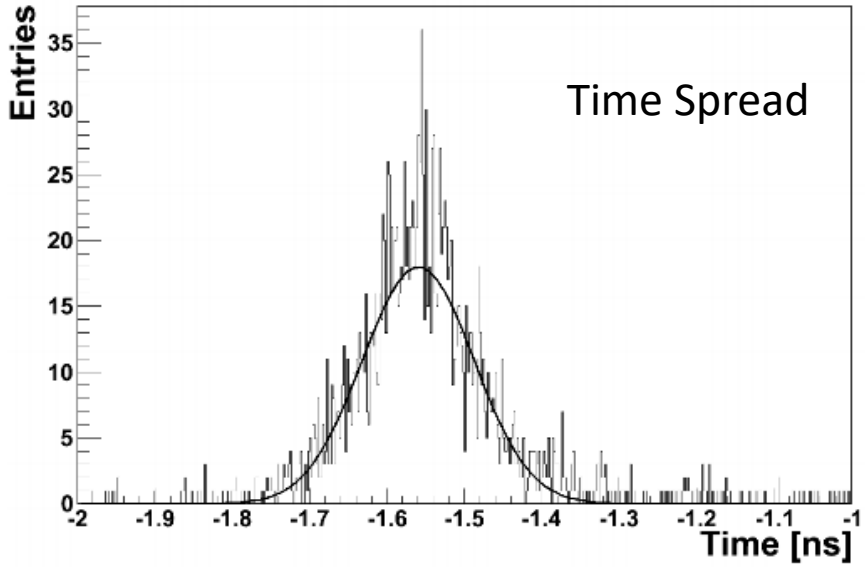




Time Resolution: Analysis

- 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:

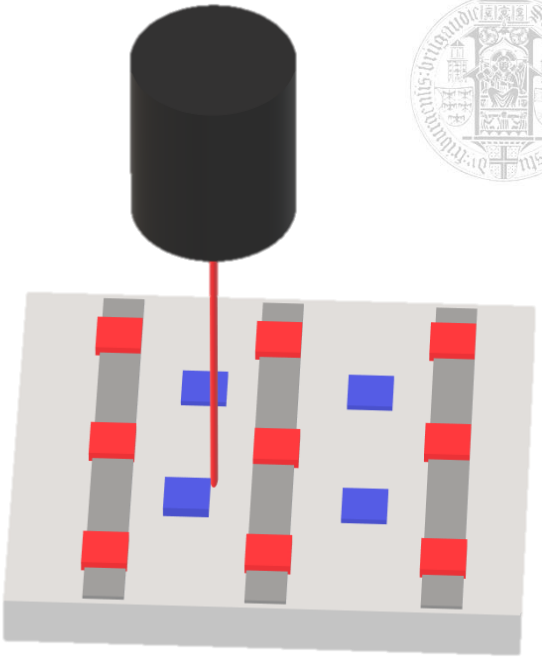
$$\sigma_{DUT} = \sqrt{\sigma_{TS}^2 - \sigma_{Ref}^2}$$

TCT Set-Up:

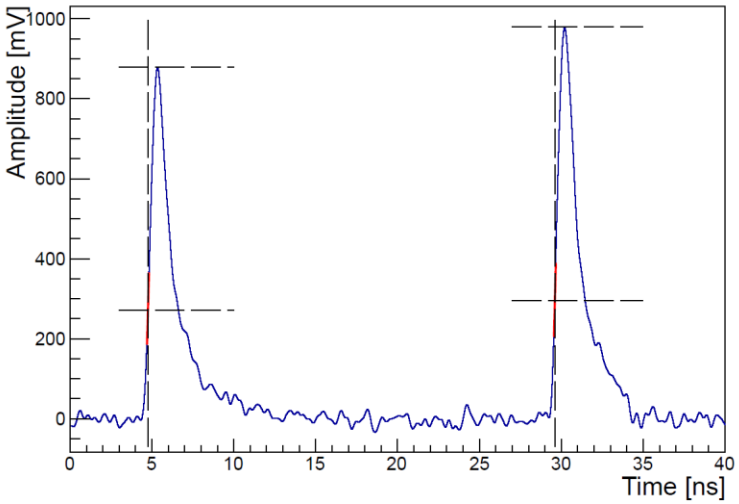
$$\sigma_{DUT} = \sigma_{TS}^2 \Big/ \sqrt{2}$$

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

TCT Set-Up for Timing

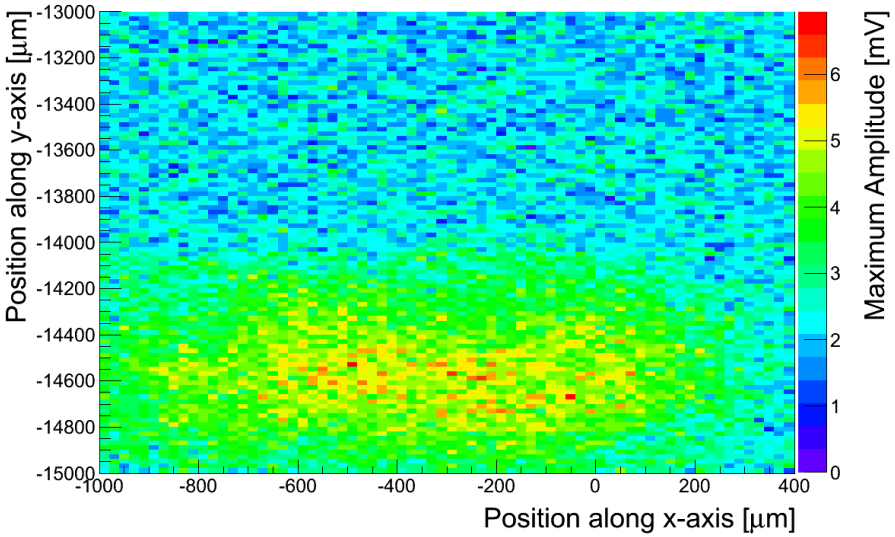


- **T**ransient **C**urrent **T**echnique: Charge created by a short laser pulse
- The current arising from the created e/h-pairs is amplified and then recorded with an oscilloscope
- Top-TCT: Laser on sensor surface, laser wavelength 1060 nm (infrared)
- First: Scanning the sensor area to determine 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)



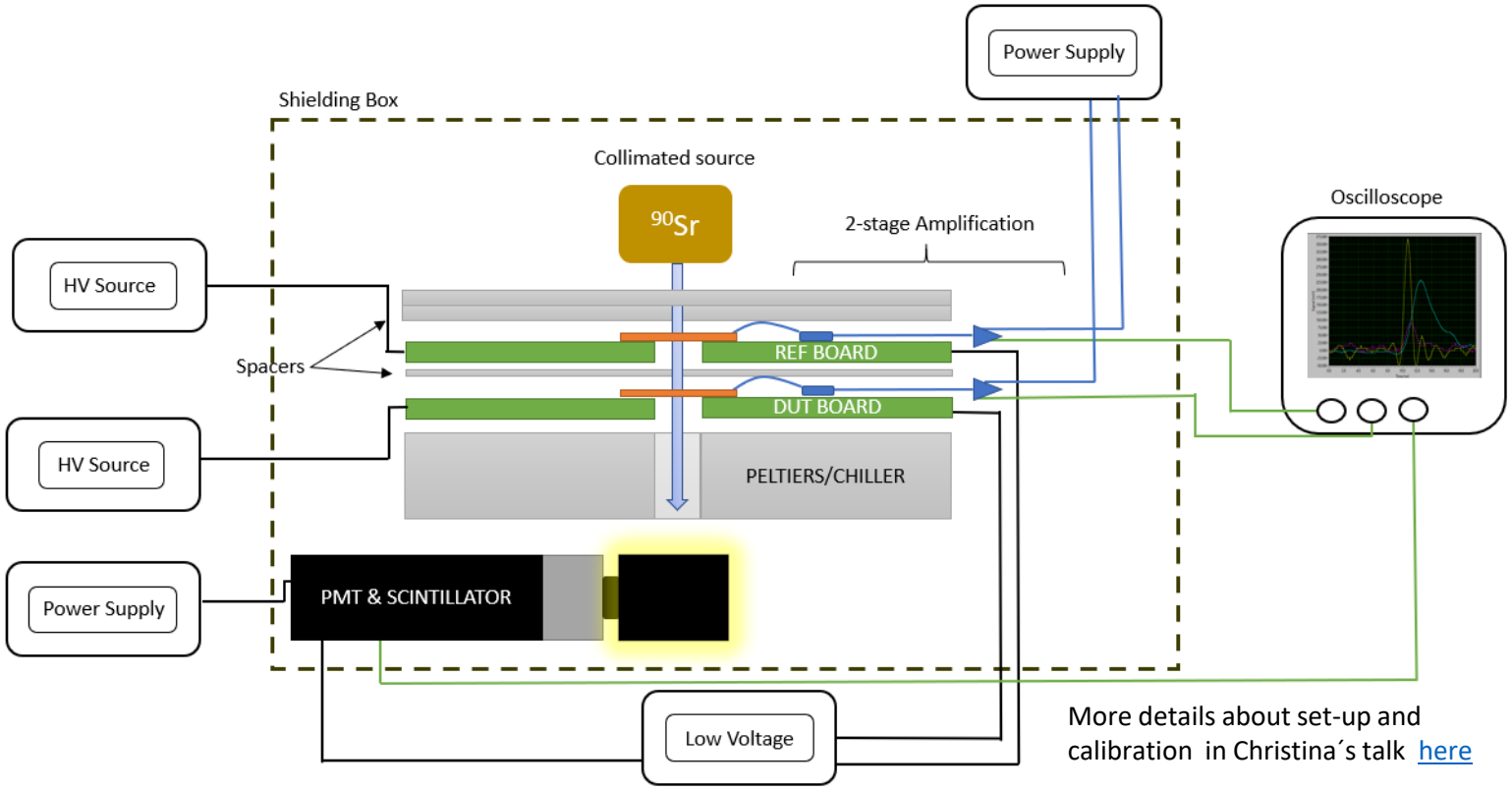
TCT Set-Up for Timing

- Intensity regulation: **N**eutral **D**ensity **F**ilter transmitting only 25% of light
- TCT-Timing measurements have several difficulties:
  - ➢ Finding the focus on tiny devices such as the 3D pixels is tedious
  - ➢ Without focus, problematic to find the metal opening at all
  - ➢ During the timing measurements: Position insecurities, as the laser has to be moved by hand with another software for each step (automated software still in development)
  - ➢ Gaussian laser beam and reflections back into the sensor from backside decrease position resolution further



Beta Set-Up for Timing

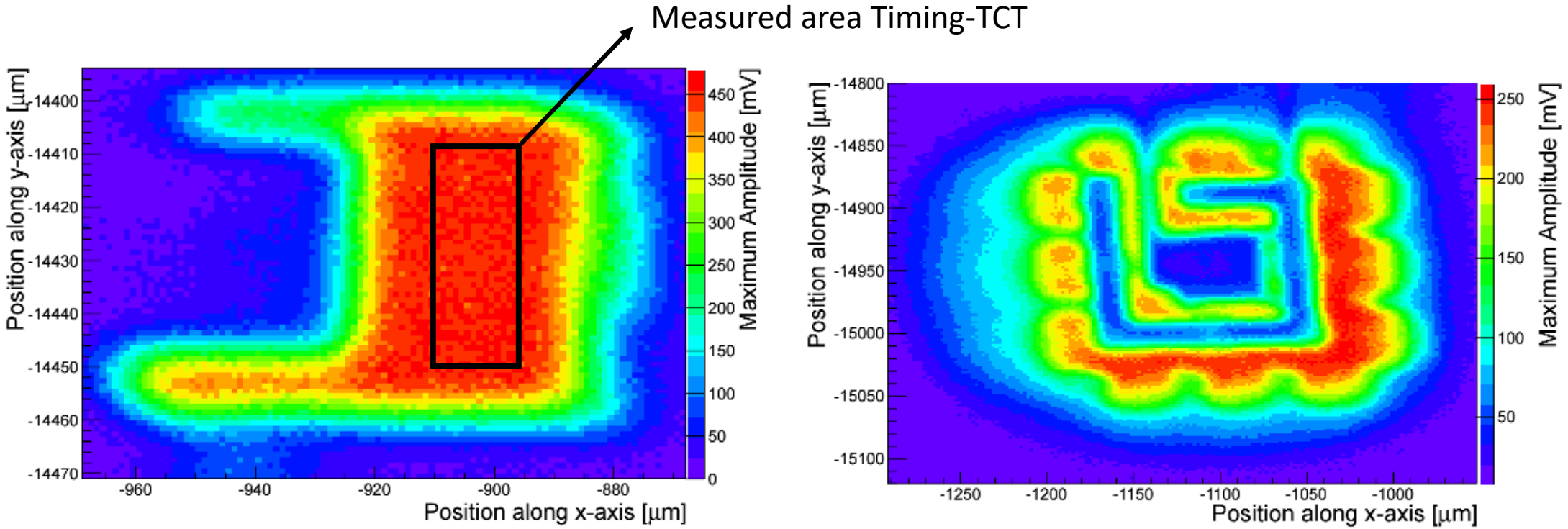
- ^{90}Sr-source for MIP-like electrons
- LGAD as reference sensor
- Scintillator & PMT as Yes/No trigger
- Reference and DUT signal recorded for each event



- Trigger on LGAD and PMT: 10000 events recorded, about 1/3 show a DUT signature
- Trigger on LGAD and DUT: 3000 events recorded, necessary for thicker devices or extremely small sensors

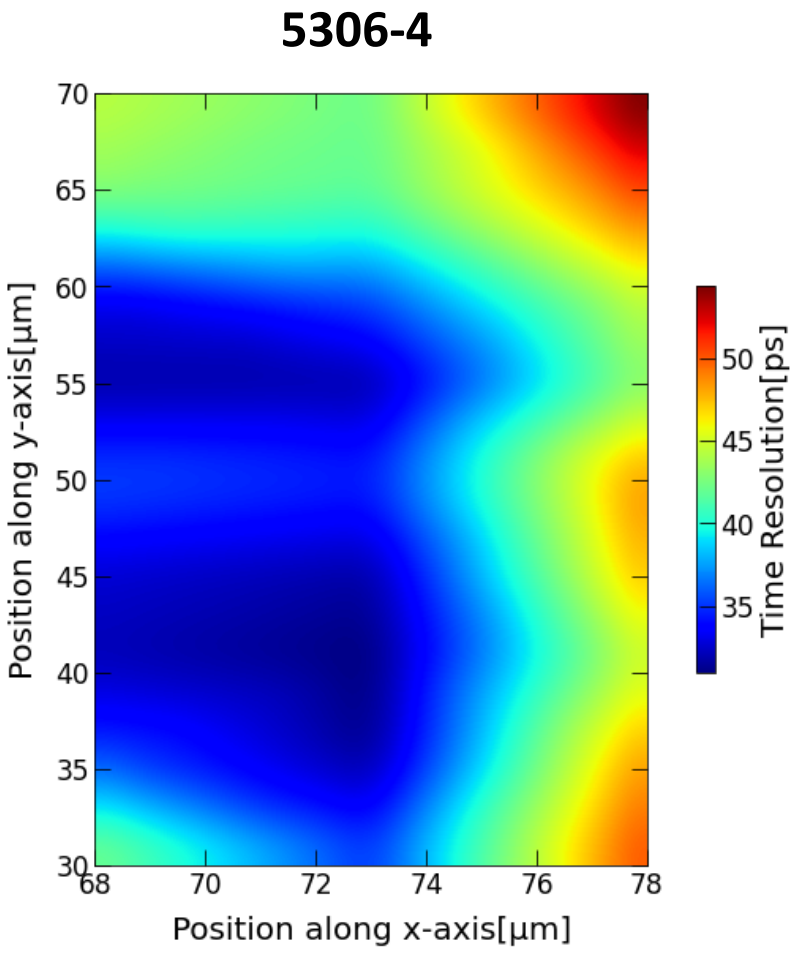
Time Resolution: 3D Pixel Sensors

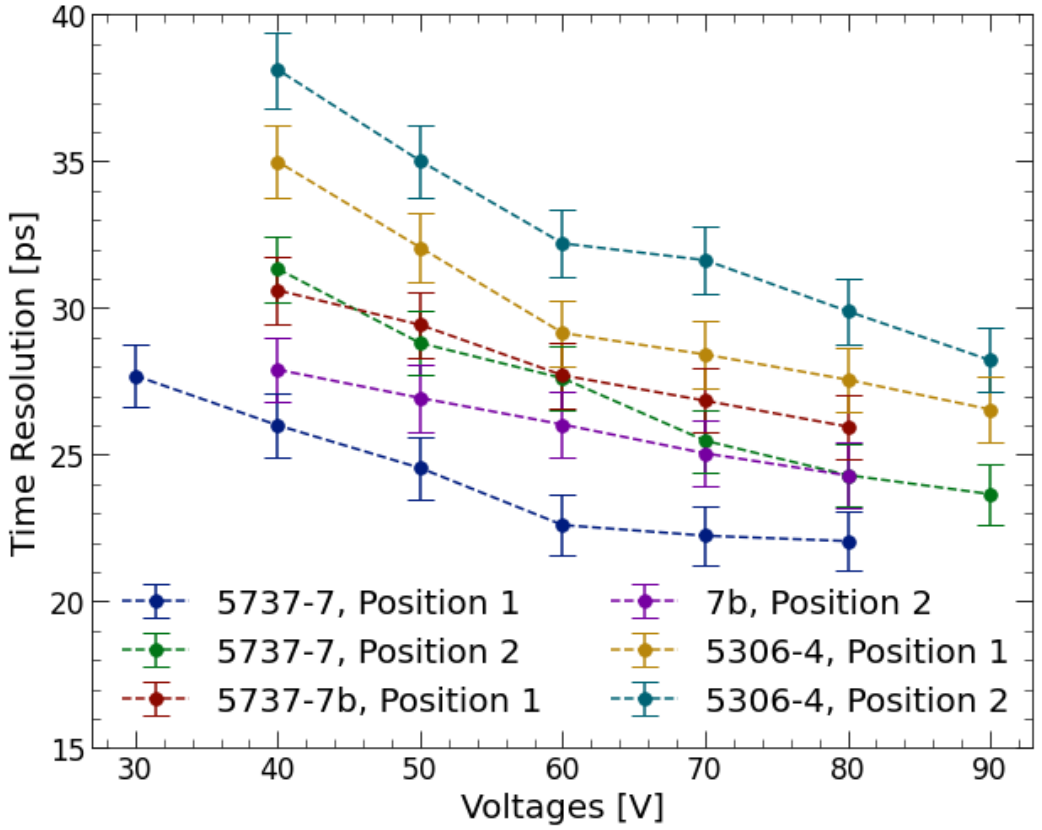
- TCT scans show very small measurable area for Timing-TCT
- Outer columns connected – indefinite electric field outside the cell explains the higher time resolution
- For Timing-TCT: Measured with laser intensity similar to one MIP-equivalent



Single column **5737 -7b** Outer columns

3D Pixel sensors

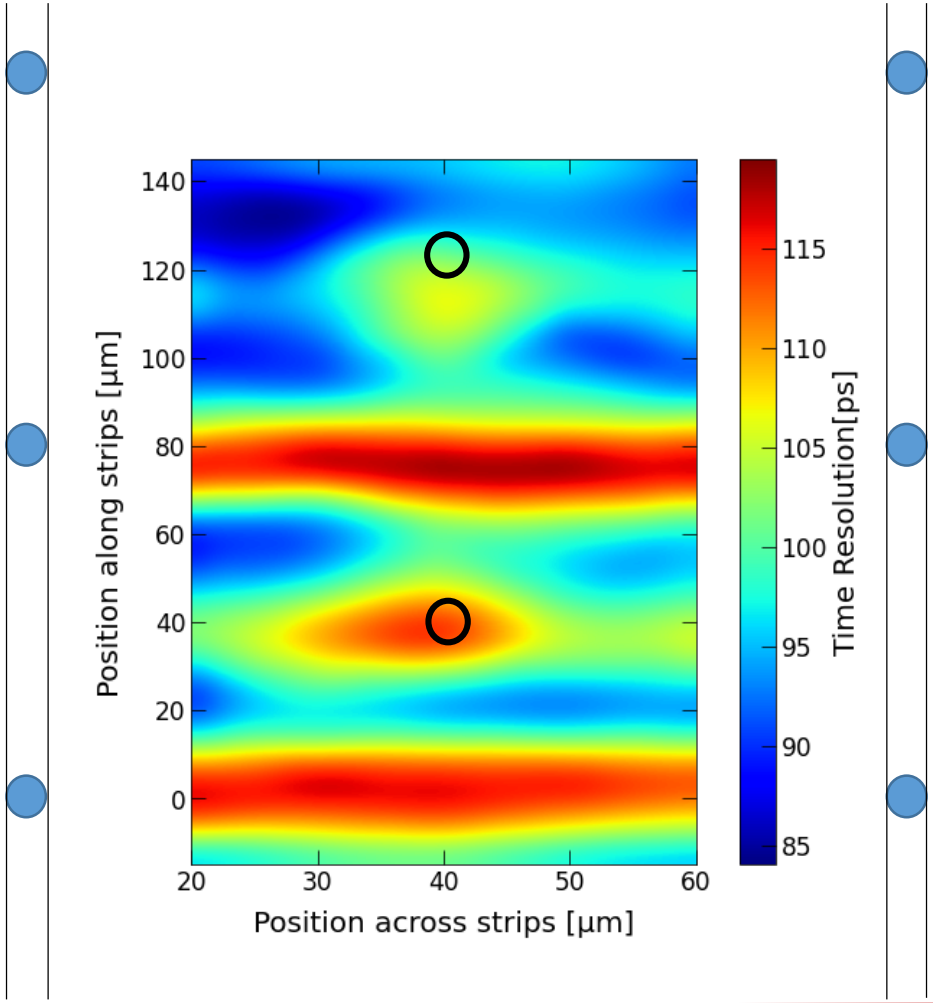


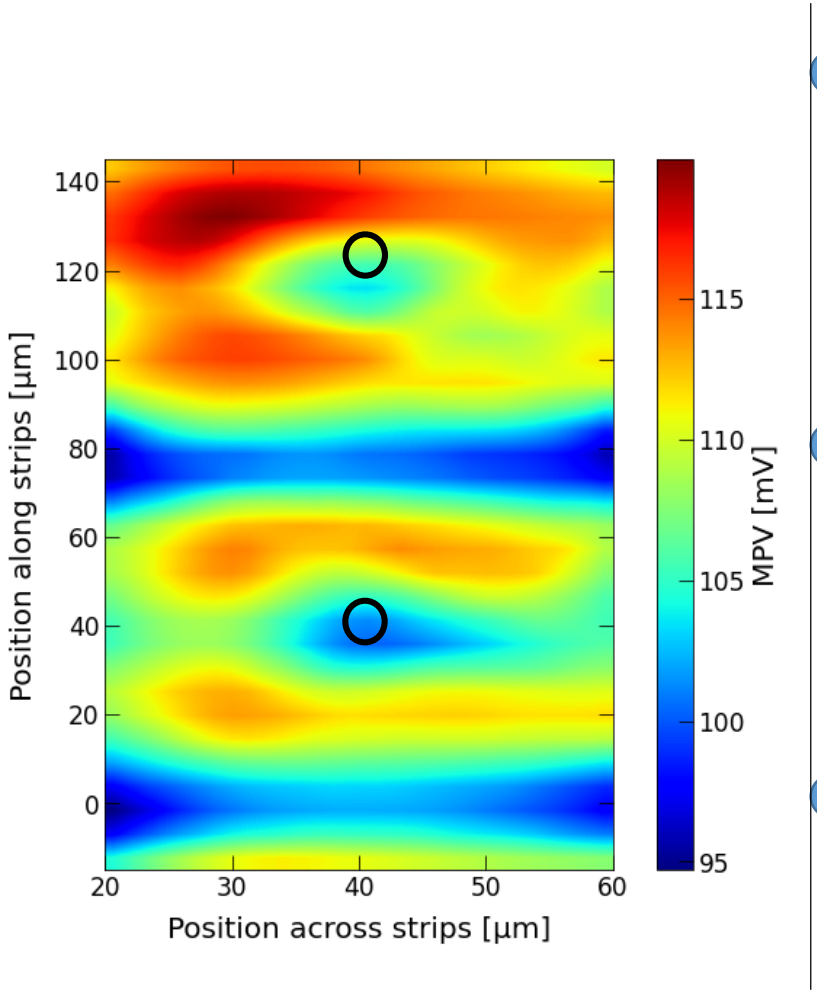


Expected voltage dependence

Time Resolution: 3D Strip Sensor 2

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

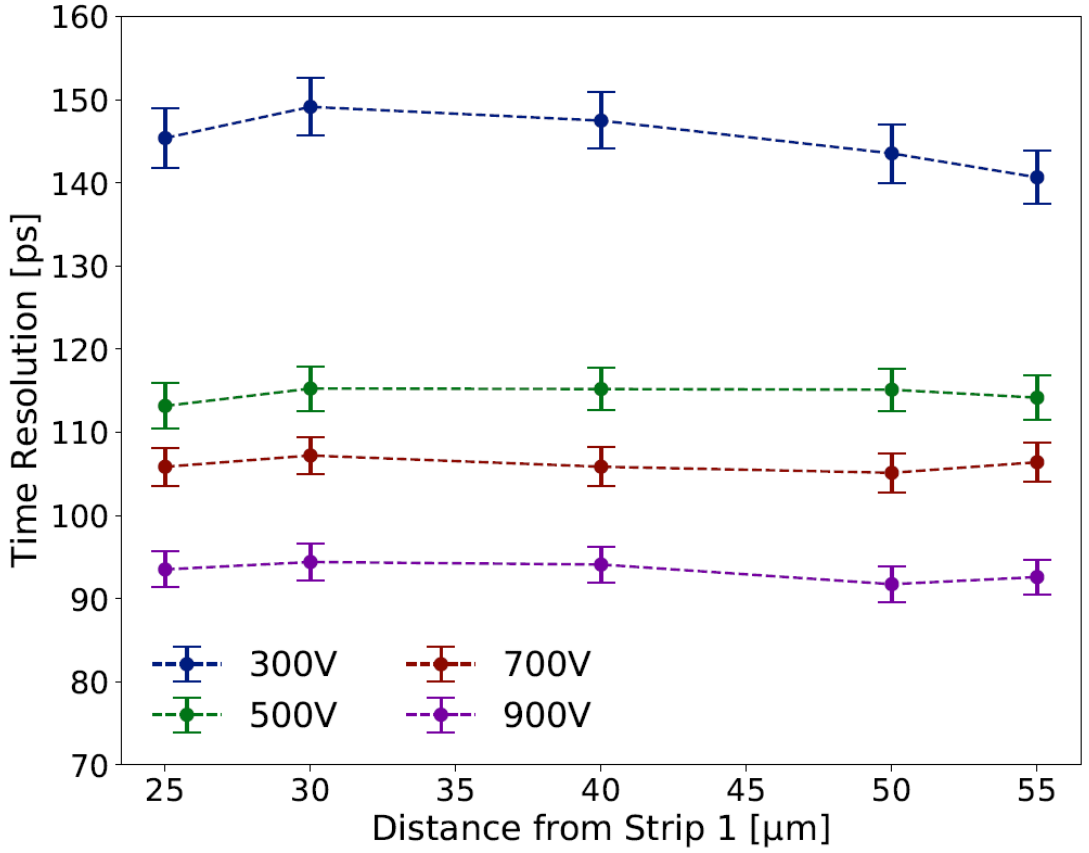


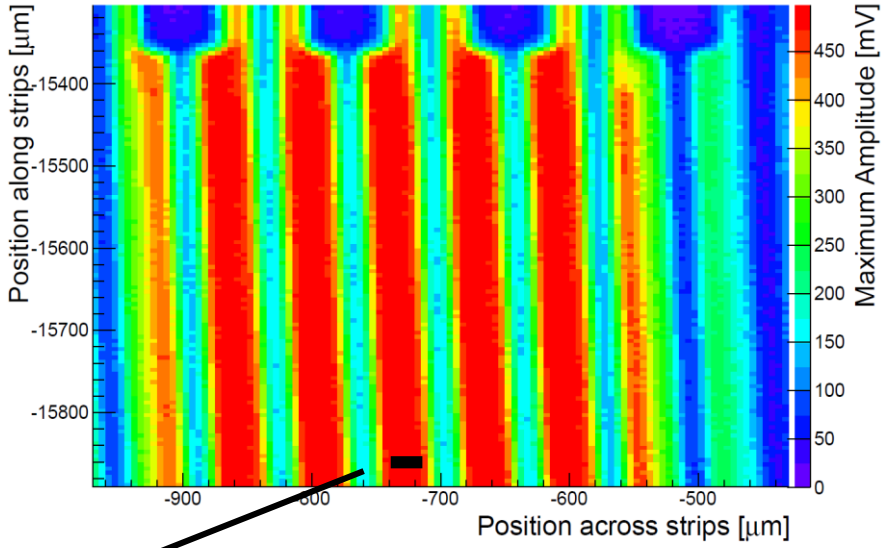


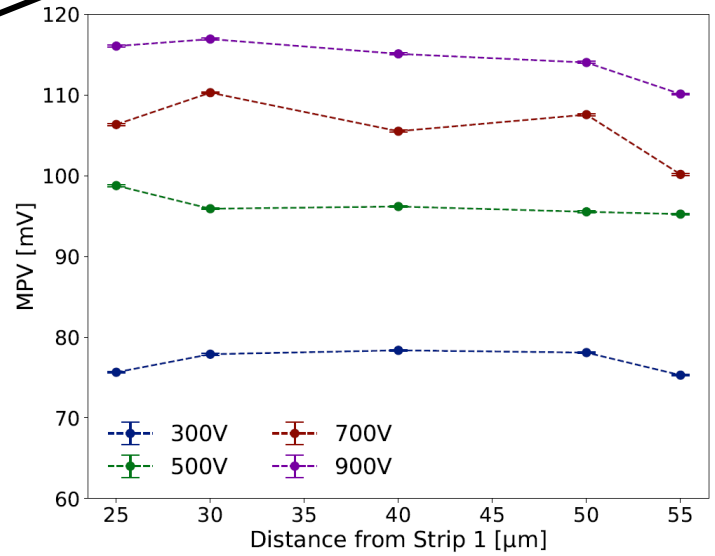
- Clear cell structure
- Worse resolution between junction columns
- Worse resolution around ohmic columns
- Resolution correlates to the expected el. Field
- Resolution between 85 and 115 ps -> lower voltage, higher noise
- Correlation also to MPV

Planar Strip Sensor

- Unirradiated ATLAS12 EC sensor
- The position dependence is minimal
- Time resolution: 92 ps for high voltage with TCT





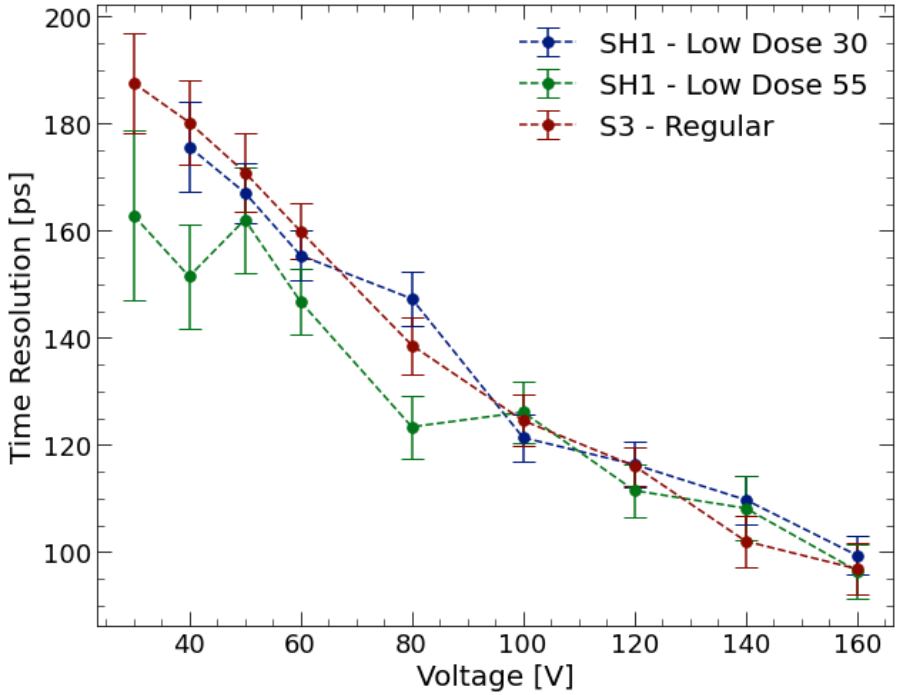


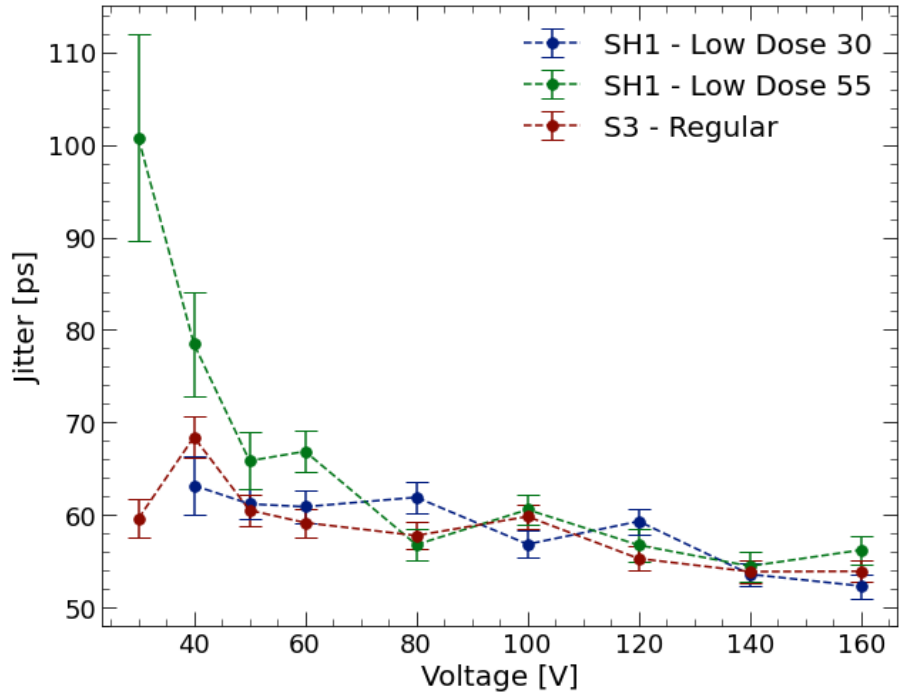
Time Resolution

- Similar time resolution for all designs, expected dependence on voltage
  - ➢ Values within the expected range for a 150μm thick planar sensor
- Jitter in the range of 60ps
- High capacitance: sensors are noisier -> negative effect on jitter &resolution

At 160V

Design	Resolution [ps]
Low Dose 30	99.4 ± 3.6
Low Dose 55	96.5 ± 5.1
Regular	96.9 ± 4.7





Planar Strip Sensor

Time resolution reached with MIP-like electrons: about 145 ps