Investigation of the time resolution of unirradiated and irradiated 3D sensors

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Introduction

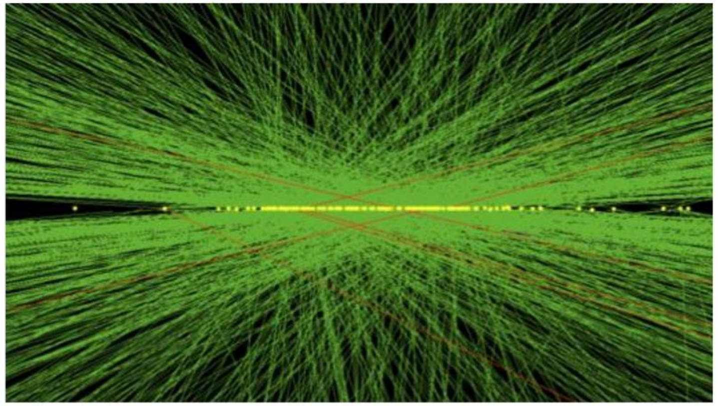
- Future hadron colliders challenge the tracking and reconstruction with high rates and huge pile-up

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

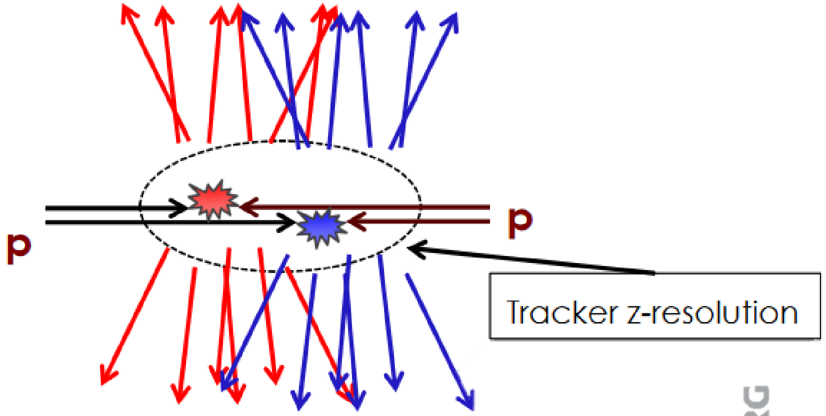
- High radiation doses challenge the sensors additionally

- 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)
  - ➢ 3D pixel sensors dedicated for timing

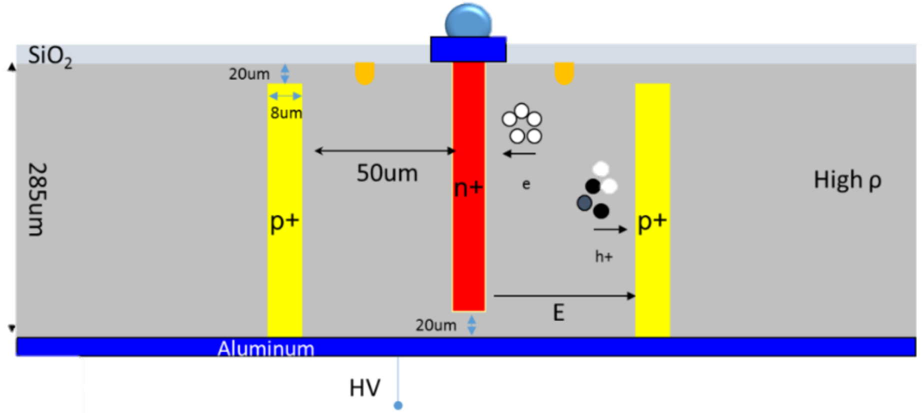


Tracking z-resolution larger than vertex-separation: Ambiguous Track-to-vertex association



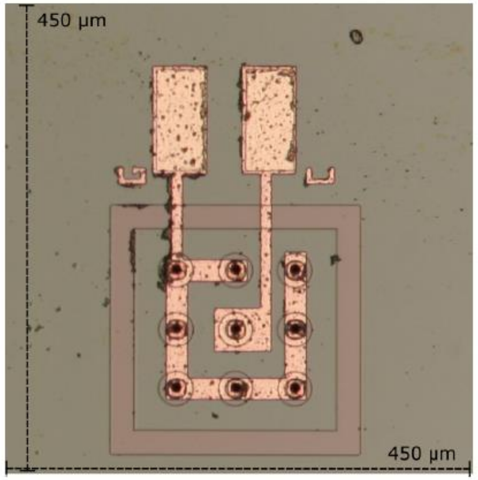
N. Cartiglia, INFN, Hiroshima Conference 2017

3D sensors



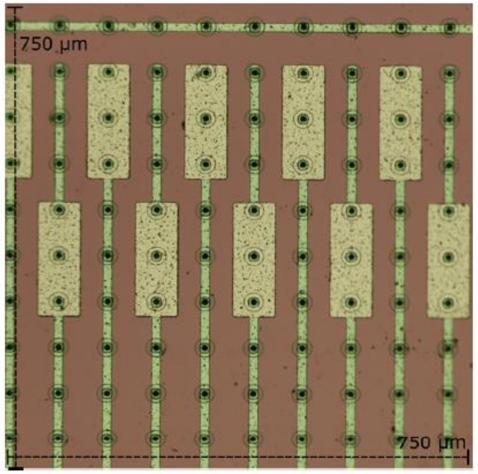
- Junction columns etched into the sensor bulk
- 235 μm or 285 μm active thickness
- Columns etched 215 μm and 265 μm
- Produced by CNM Barcelona

Pixel sensor



- Pixels: $50 \times 50\ \mu m^2$ unit cell size
- Total pixel size: $100 \times 100\ \mu m^2$
- 16 pixels per test structure

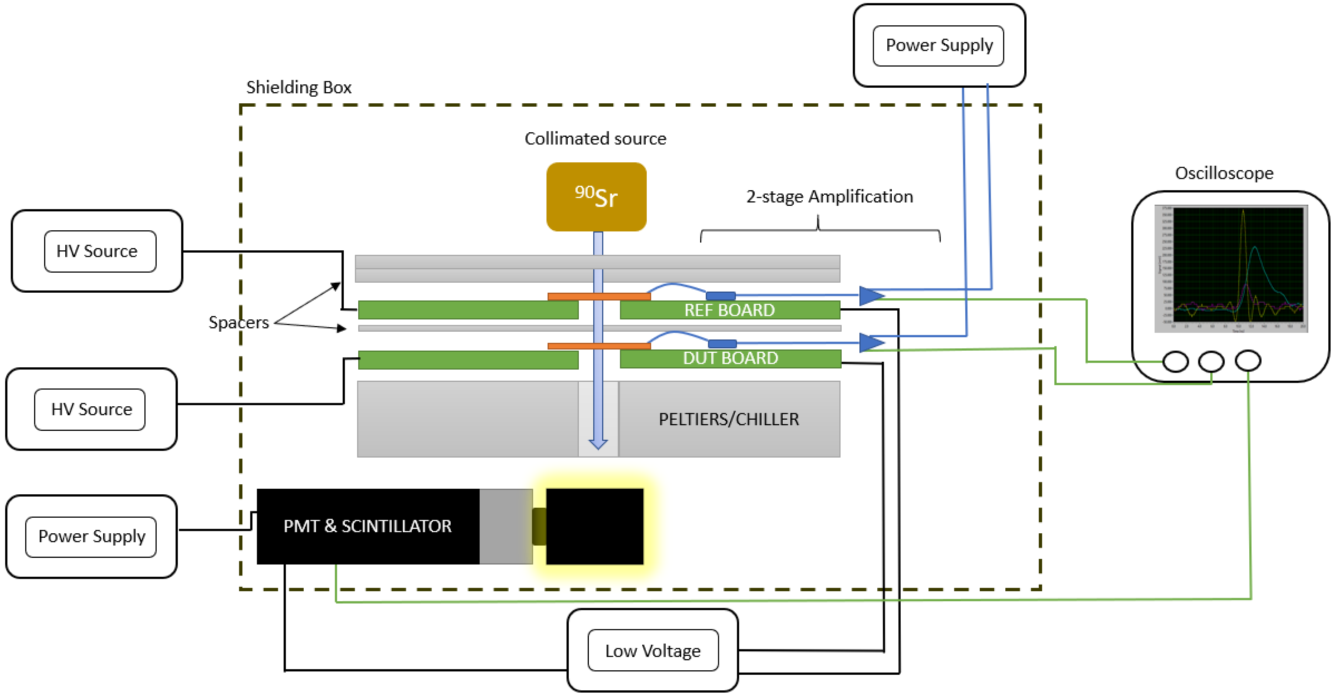
Strip sensor

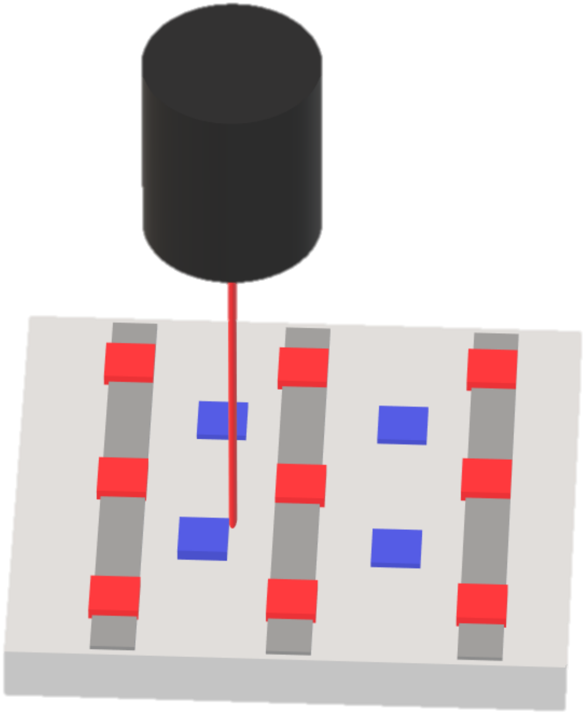


- Strips: $80 \times 80 \mu m^2$ unit cell size
- Total sensor size: $10 \times 10\ mm^2$

Experimental Setups

- Single pulses recorded of both reference and tested sensor
- About 3000 events with DUT signature for appropriate statistics
- If possible, only external triggers



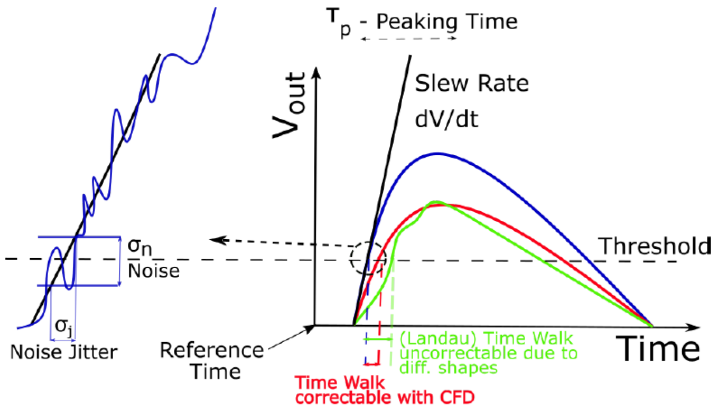


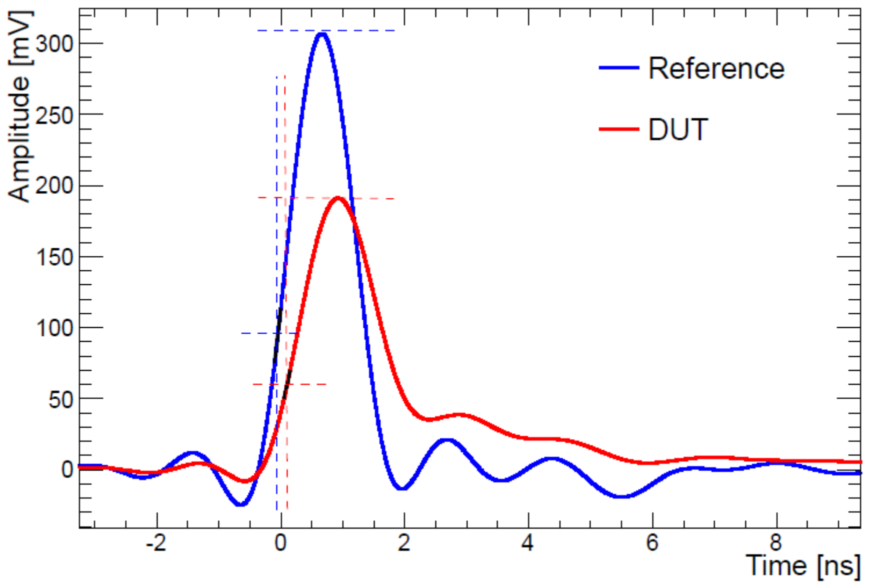
- ^{90}Sr-source
- LGAD reference, $\sigma_{Ref} = 25.18 \pm 0.35\ ps$
- PMT yes/no trigger

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

Time Resolution - Analysis

- Time resolution is determined using a Constant Fraction Discrimination (CFD, usually 30%)
- Full rise time is calculated (max. amplitude /slope), mean of distribution = rise time of sensor
- Jitter: Sigma of a Gauss fit to the distribution of the noise divided by the slope - $\sigma_j = N/(\frac{dV}{dt}) \sim t_p/(\frac{S}{N})$
- Note: The measured timing characteristics are setup-dependent
  - Readout electronics and noise level influence timing
  - Results within this (or an equivalent) setup are comparable
  - However, giving a good estimation for real-life use





Beta Set-Up:

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

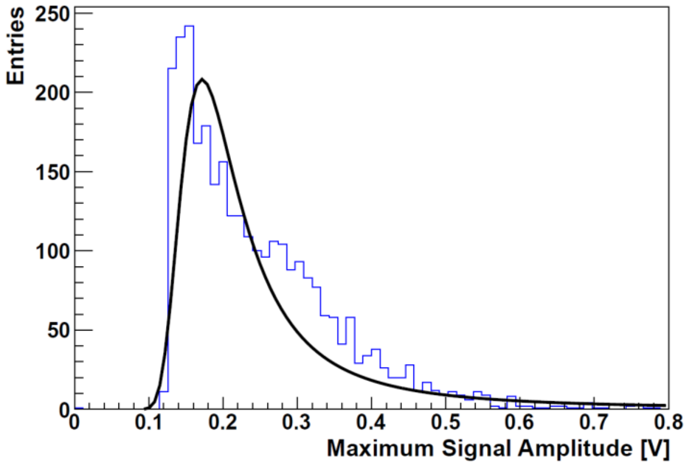
TCT Set-Up:

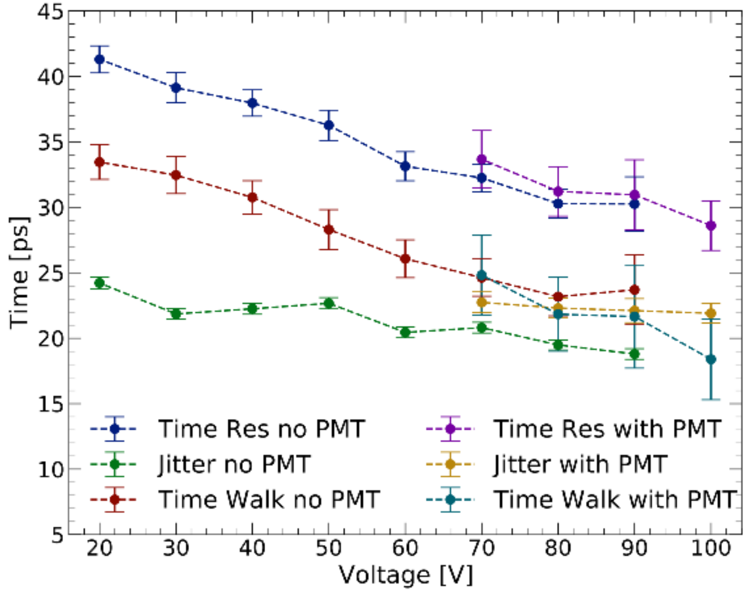
$$\sigma_{DUT} = \sigma_{TS}/\sqrt{2}$$

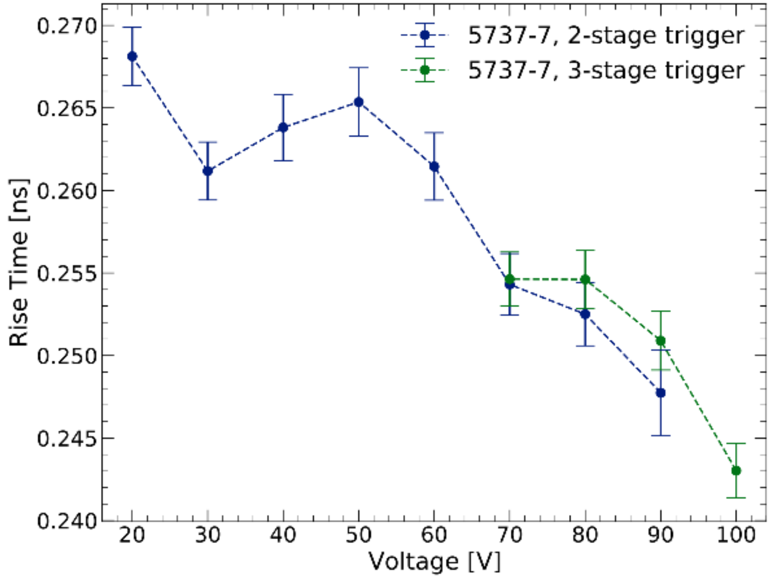
Time Resolution: 3D Pixel sensors

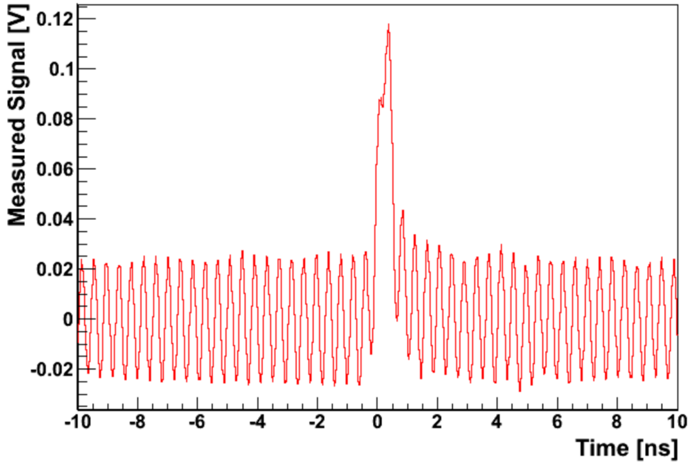
- Sanity Check: Comparison with/without additional PMT trigger
- With PMT: Very low rate – pick-up noise problems
- Without PMT: overestimation of MPV
- Otherwise: Very comparable results

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





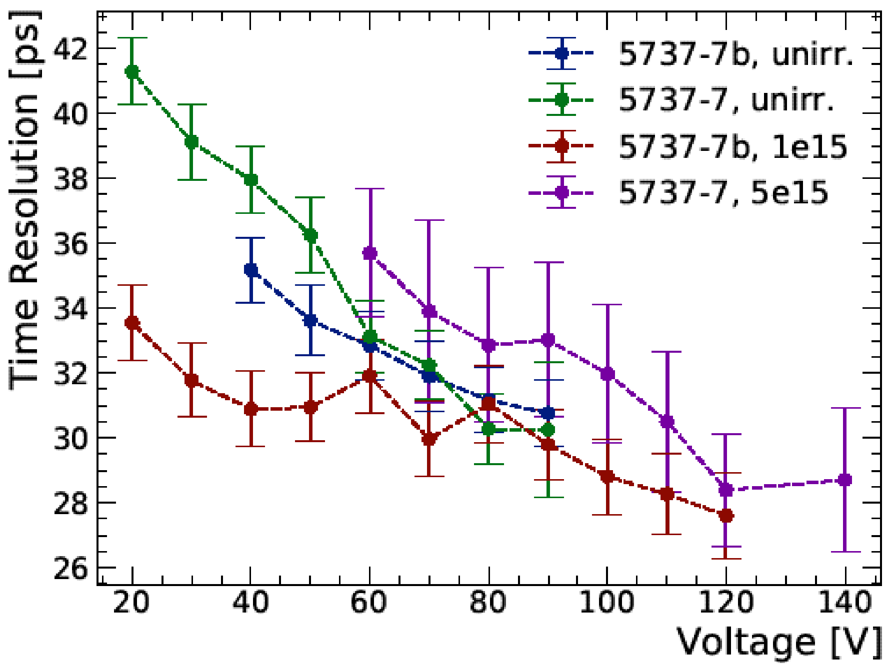


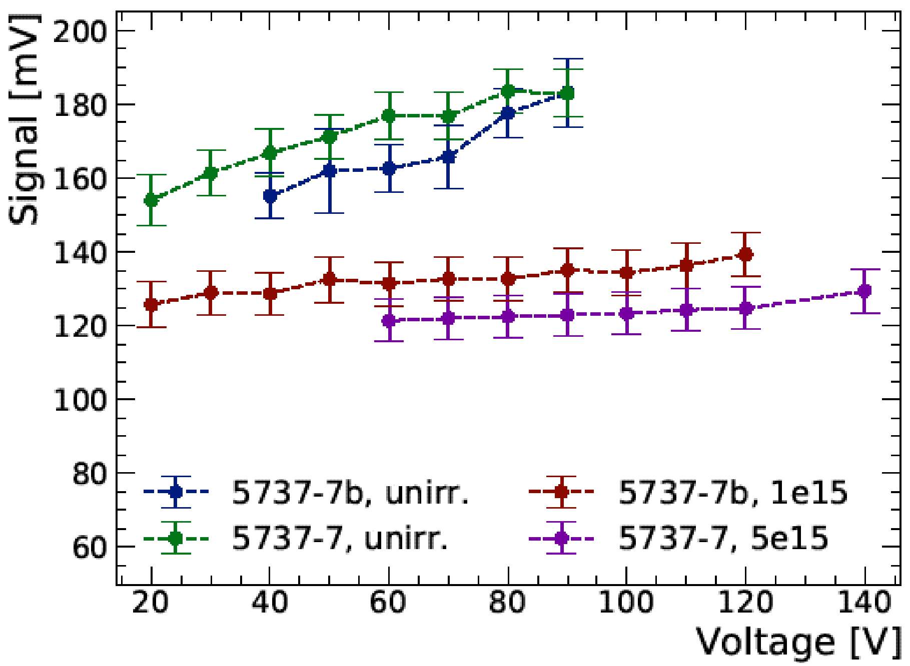


Average waveform with PMT trigger

Time Resolution: 3D Pixel Sensors

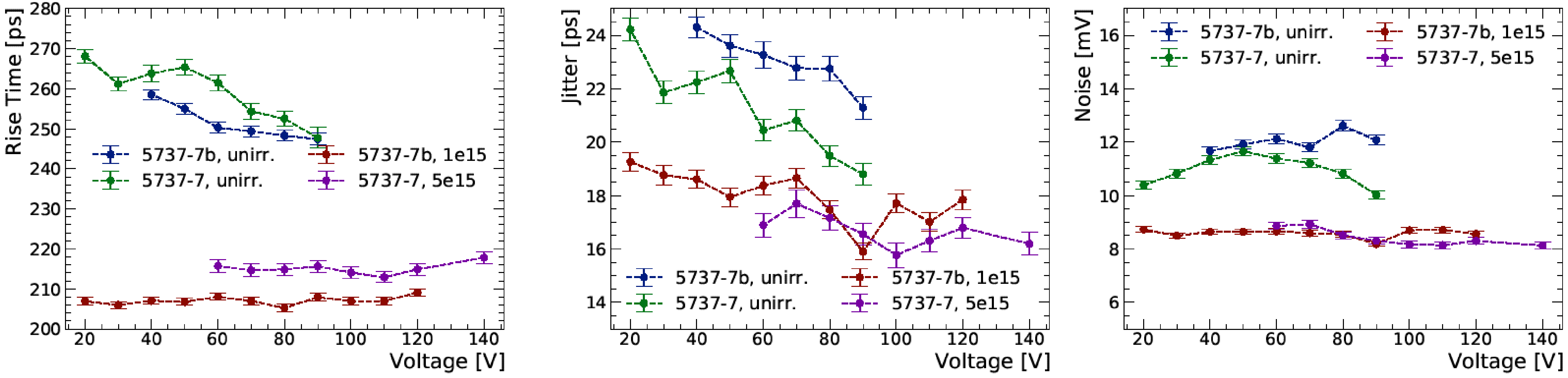
- Before irradiation, sensors reach about 30-31 ps time resolution at room temperature
- After irradiation the sensors reach 28 ps at -18°C, but are consistent with unirradiated
- Signal decrease with irradiation





Time Resolution: 3D Pixel Sensors

- Rise time significantly lower for 1e15 and 5e15
- Jitter for irradiated sensors slightly lower (measured cold)
- Lower noise for 1e15 and 5e15 (cold measurement)
- Smaller voltage dependence for rise time and jitter of the irradiated sensors



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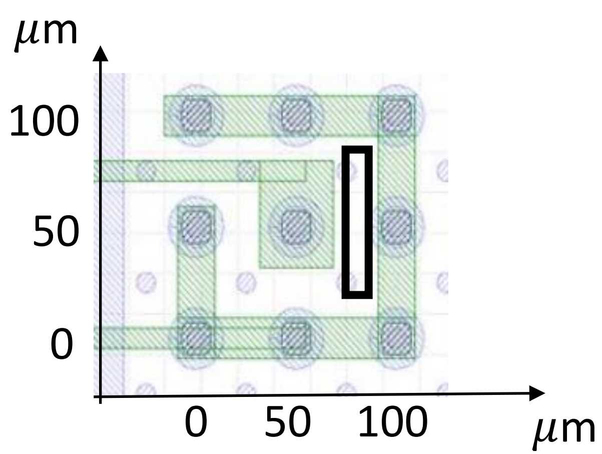
Time Resolution: Unirradiated 3D Pixel Sensors

- 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



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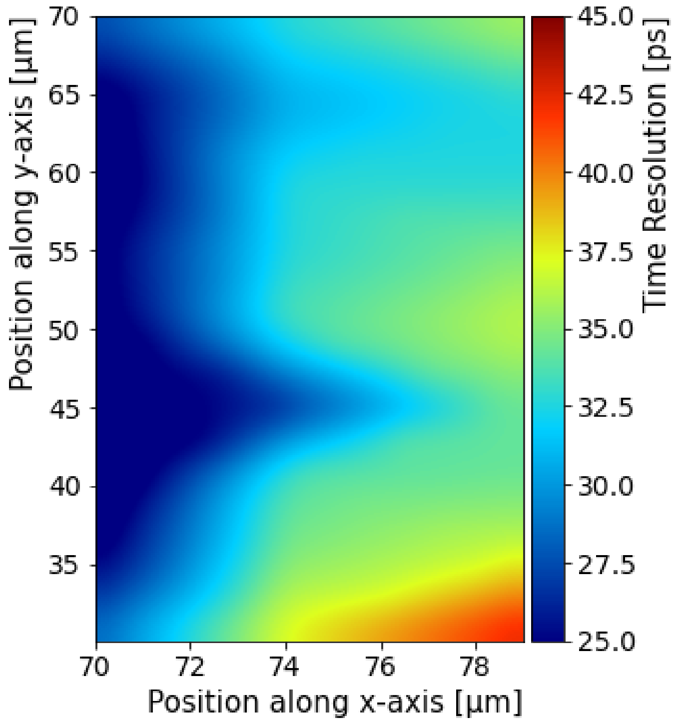

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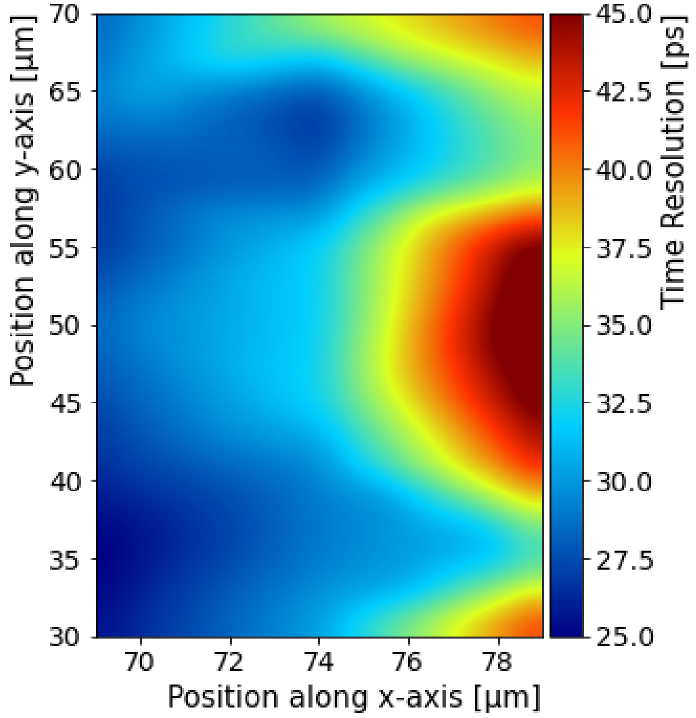
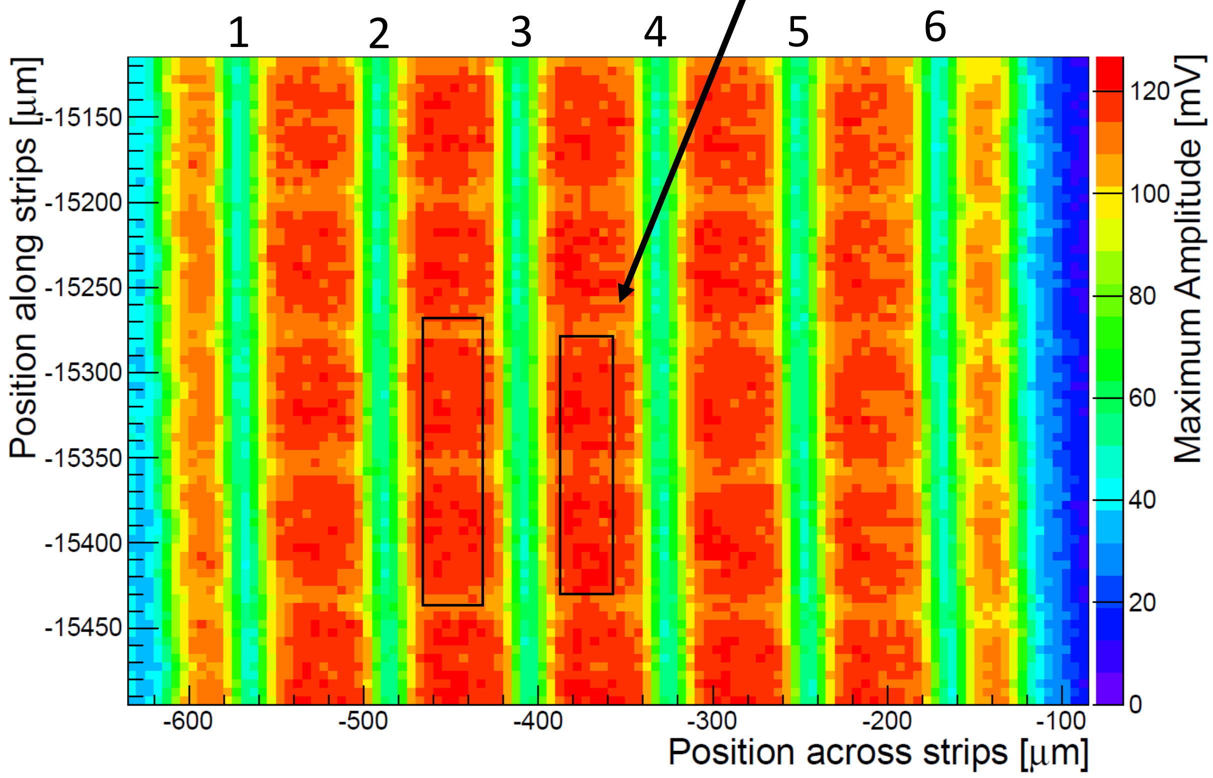
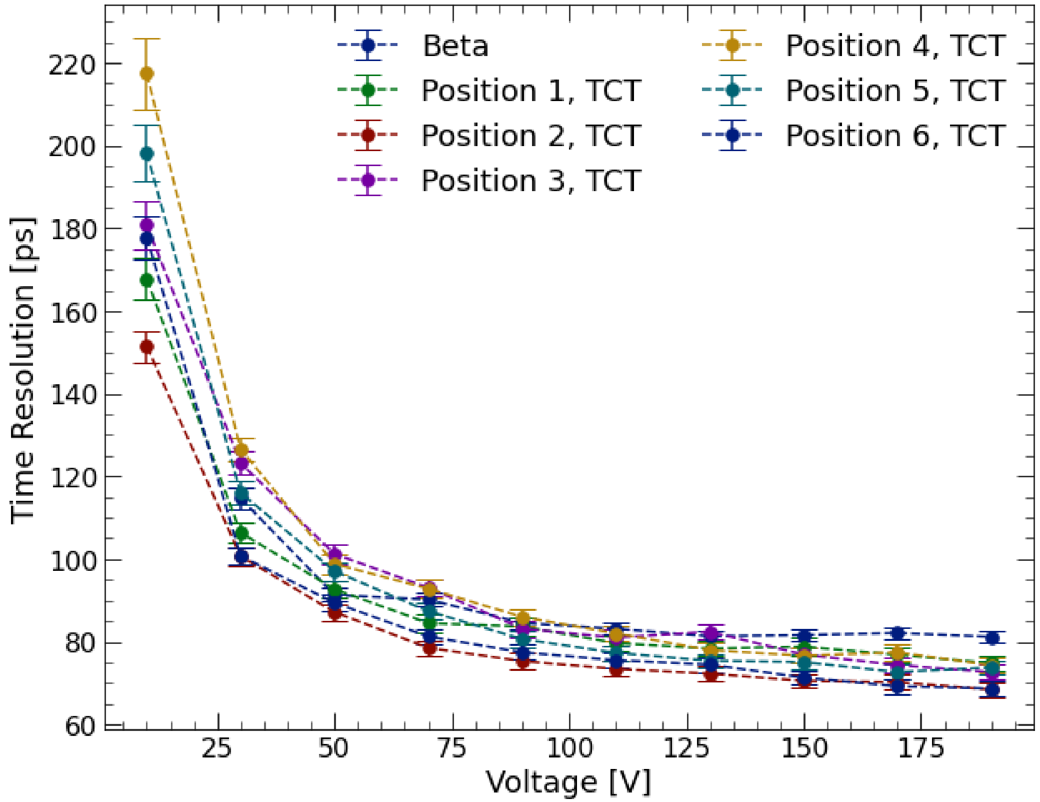


Time Resolution: 3D Strip Sensor

- 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

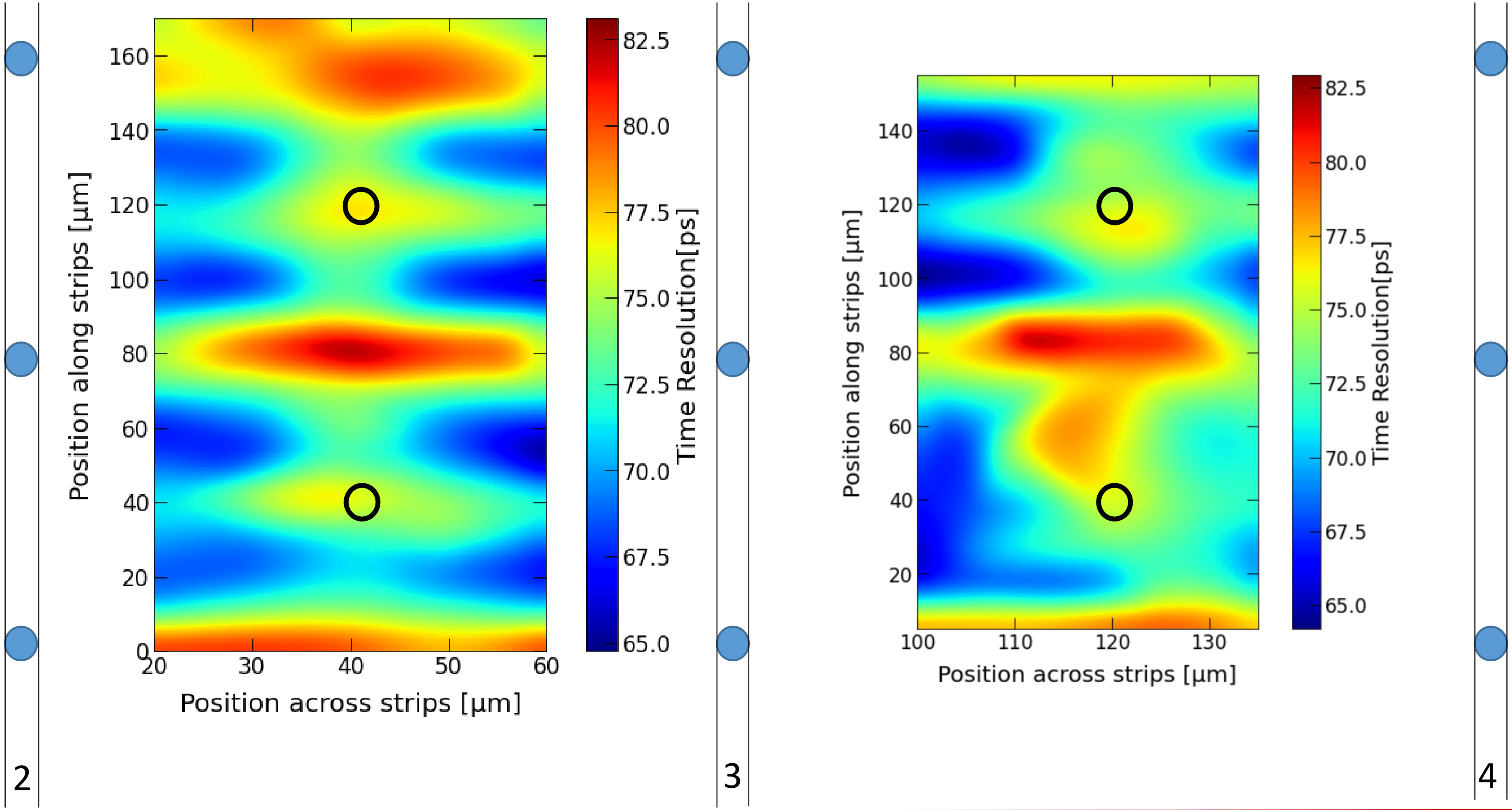
Measured areas for TCT-Timing





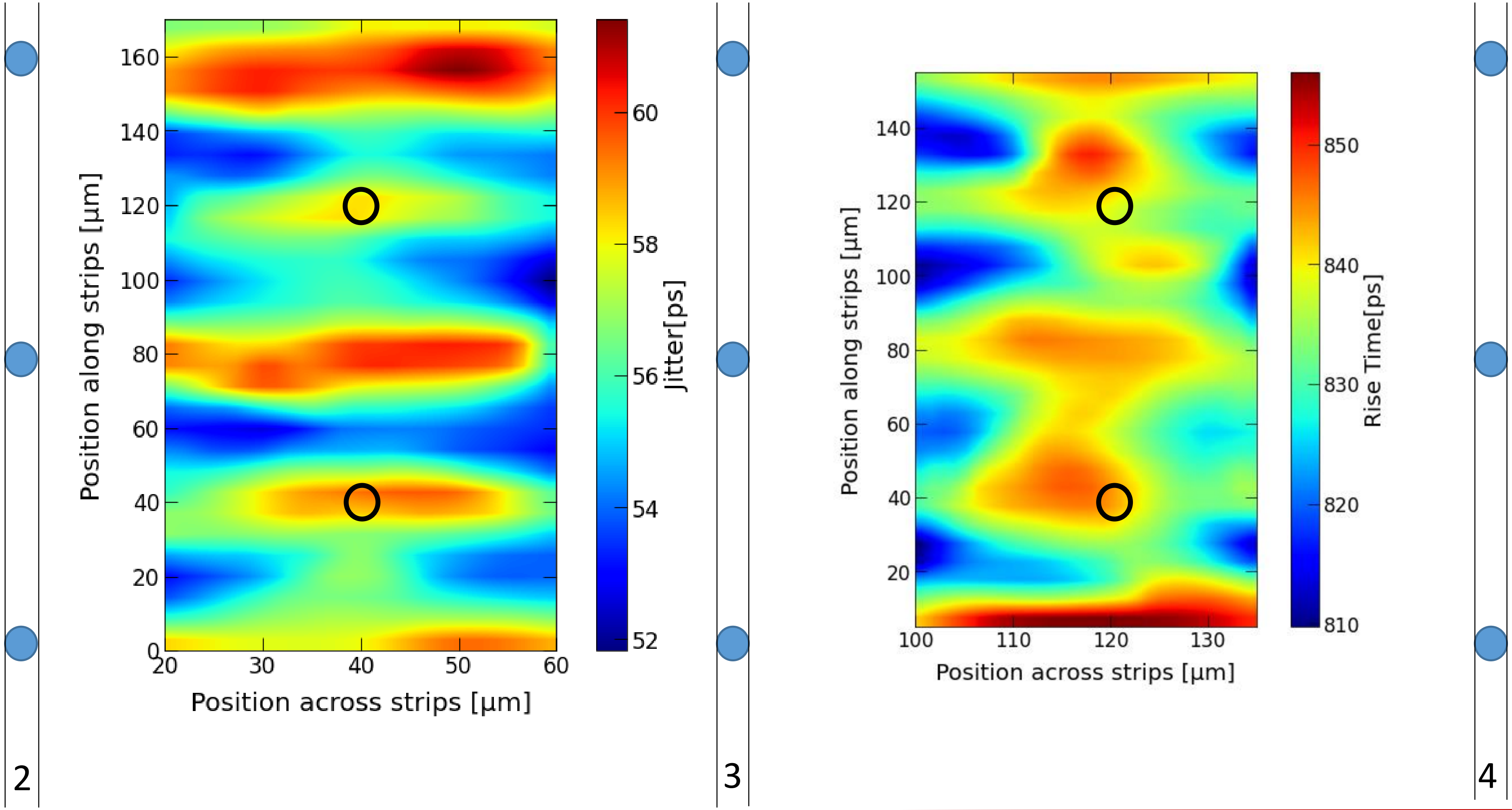
Time Resolution: 3D Strip Sensor

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

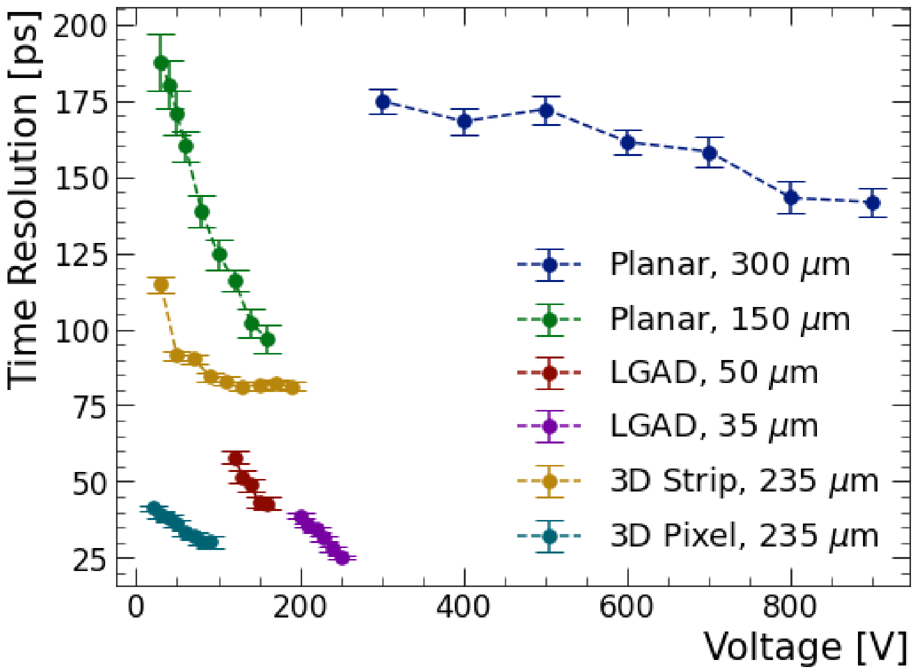
Time Resolution: 3D Strip Sensor

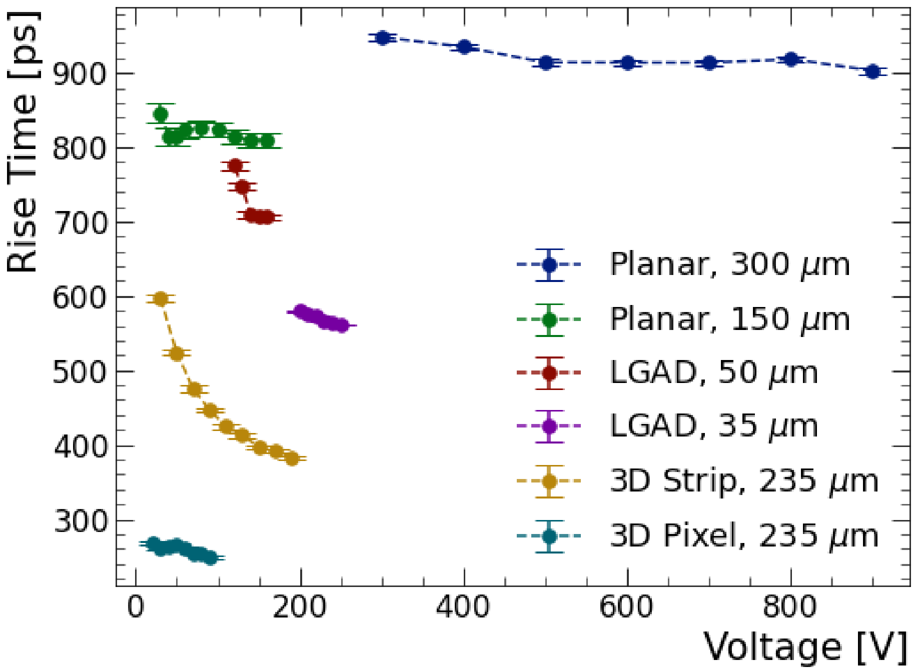


- Clear cell structure
- Similar patterns for jitter and rise time
- Both correlate to the expected el. Field
- Rise Time between 810 and 855 ps
- Jitter higher than in Beta Set-Up, 52-62 ps

Comparison – 3D vs other designs

- 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
- 3D Sensors: Strip Sensor and Pixel Sensor - 235μm thickness





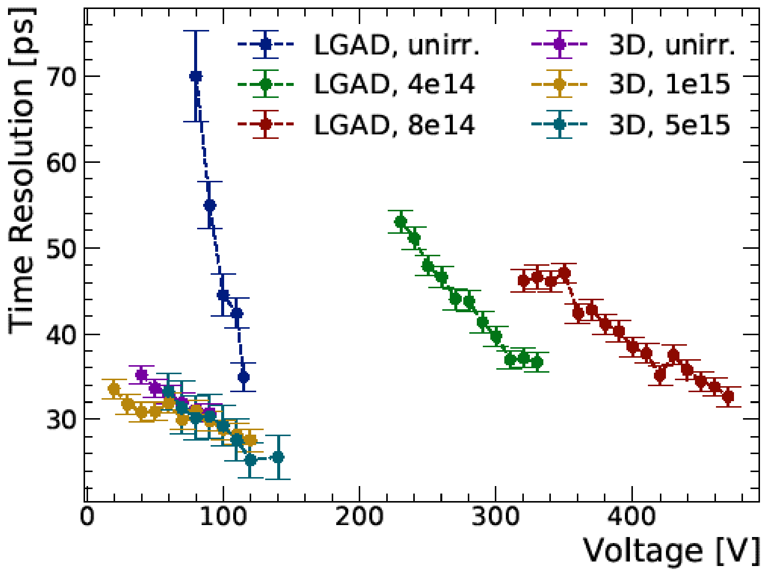
- 3D Sensors have the overall fastest rise times, especially the pixels – significantly shorter than LGADs
- As expected, 3D strip sensors show better time resolutions than planar strip sensors, but only pixel sensors are competitive with LGADs
- Benefit: Lower voltage necessary for 3Ds than for LGADs

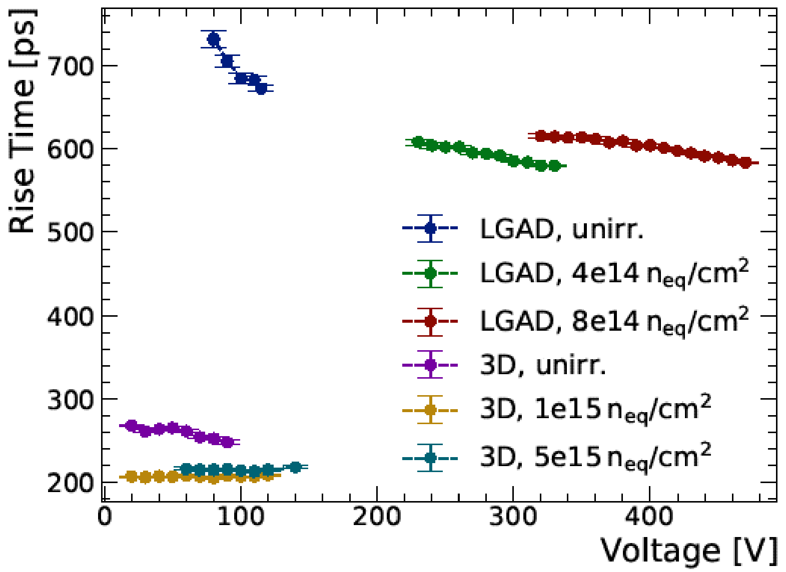
Comparison – LGAD vs 3D Pixel

- Compared LGADs: 50 μm, high gain layer doping (HPK run 2)

- LGADs need significant voltage increase to reach same time resolution (gain layer degradation)
- Improved time resolution for 3D pixels after irradiation – at the same voltage
- Significantly lower rise time – improving after irradiation for both LGADs and 3Ds

- Note: This are not the latest/ fastest generation of LGADs – but the 3D sensors prove to be competitive





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Conclusion and Outlook

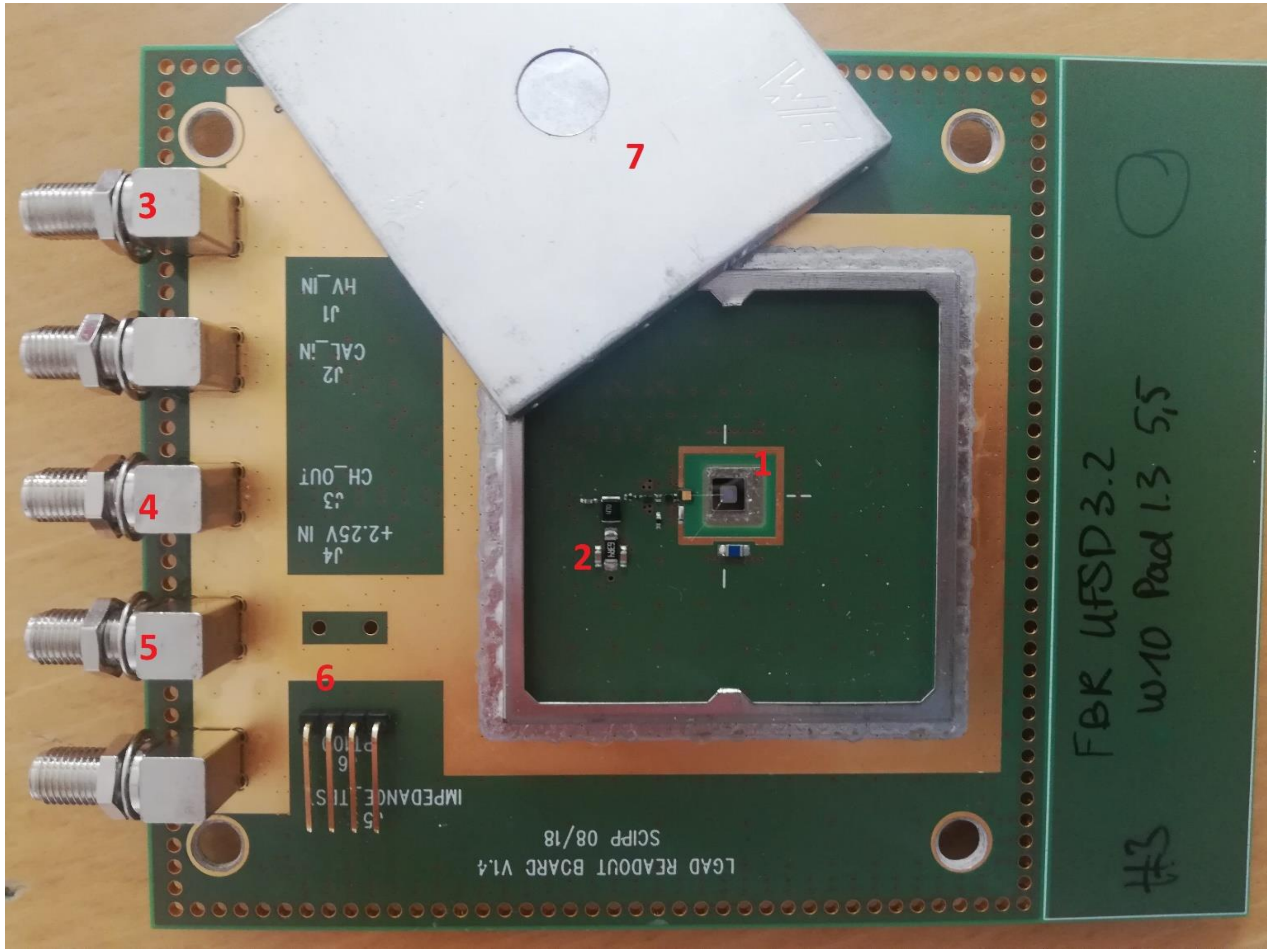
- Time resolution of silicon sensors is an important research area for upcoming and future colliders
- 3D sensors reach a time resolution competitive with LGADs (around 30 ps)
- 3D pixel sensors slightly improve resolution after irradiation to $5 \times 10^{15} n_{eq}/cm^2$ while the bias voltage range stays the same (up to 28 ps are reached)
- The position dependent time resolution measured correlates very well with the electric field distribution
- **Outlook**: Test of higher irradiation doses and different 3D sensor geometries, including sensors designed specifically for timing purposes (dedicated 3D timing project)

Thank you for your attention!

Acknowledgments: Big thanks to Gregor Kramberger, Alissa Howard, Giulio Pelligrini, Dario di Simone, Oscar Ferrer, Neil Moffat, Pablo Fernandez-Martinez, Sebastian Grinstein, Christopher Betancourt for the collaboration, help and support.

BACKUP

LGAD Readout Board



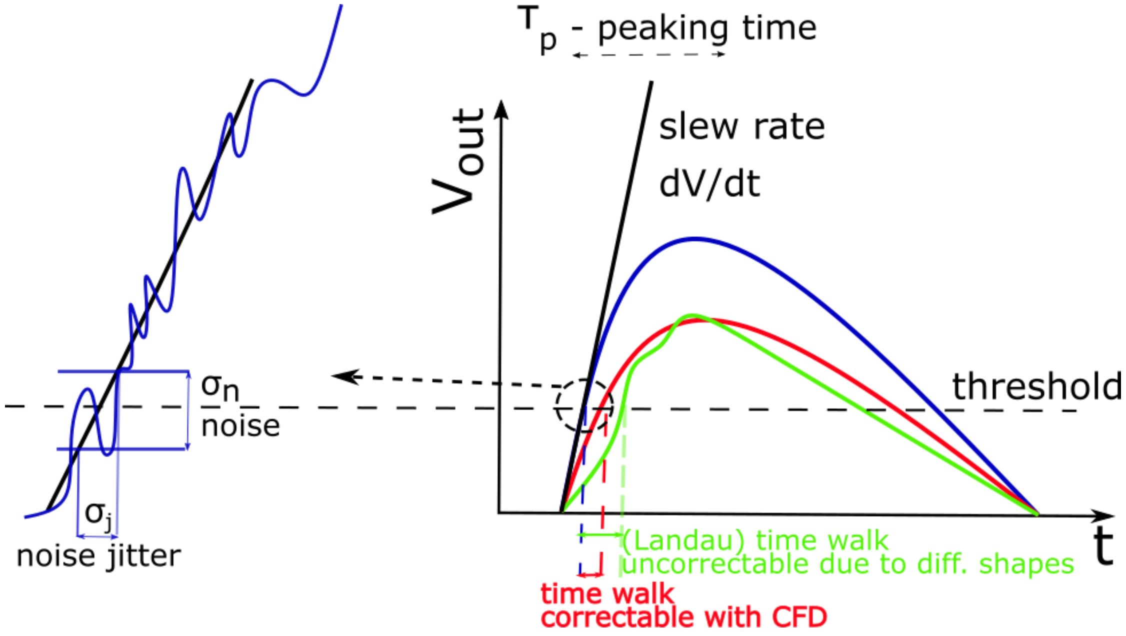
1. Bonded LGAD
2. Amplifier
3. High voltage connector
4. Readout connector
5. Low voltage connector
6. PT100 connector
7. Lid

Time Resolution - Components

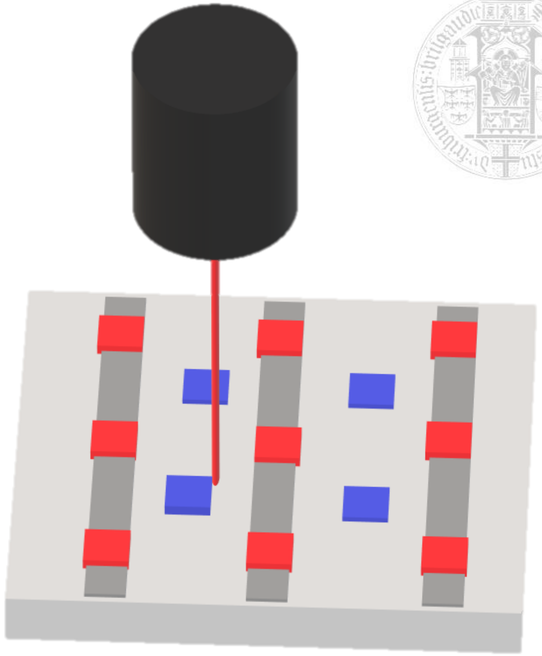
- Main components: Jitter and time walk: $\sigma_t^2 = \sigma_j^2 + \sigma_{TW}^2$
- Jitter component σ_j: Determined by the rise time at the amplifier output dV/dt and the noise level σ_n:

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

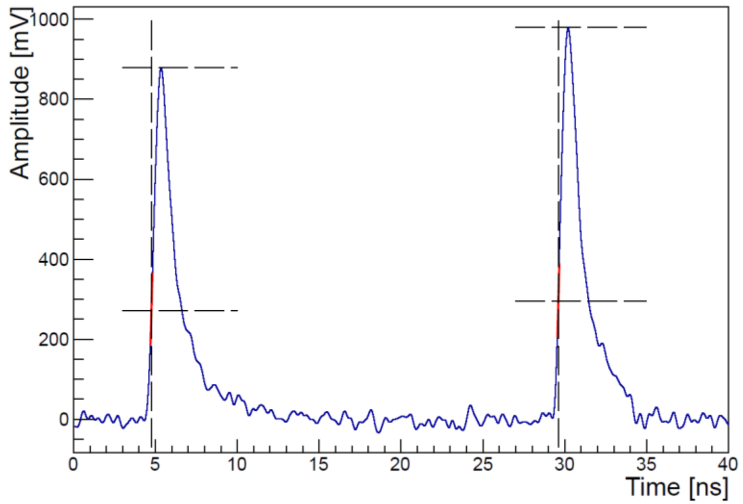
- Time walk component includes:
  - Weighting field/ el. Field contribution
  - Landau fluctuations in signal shape
  - Landau fluctuation in the amount of deposited charge (correctable)
- Time Walk component depends strongly on the sensor design



TCT 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

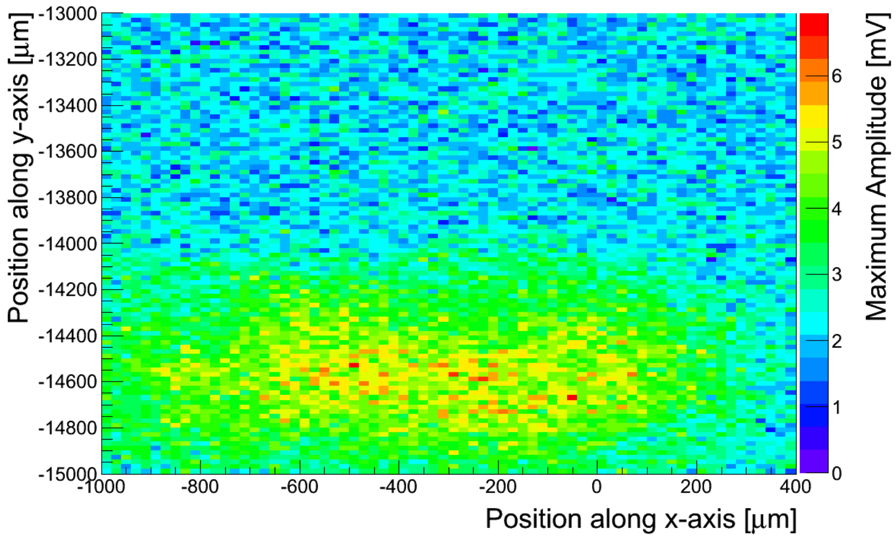
- TCT-Timing measurements have several difficulties:

  - 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)

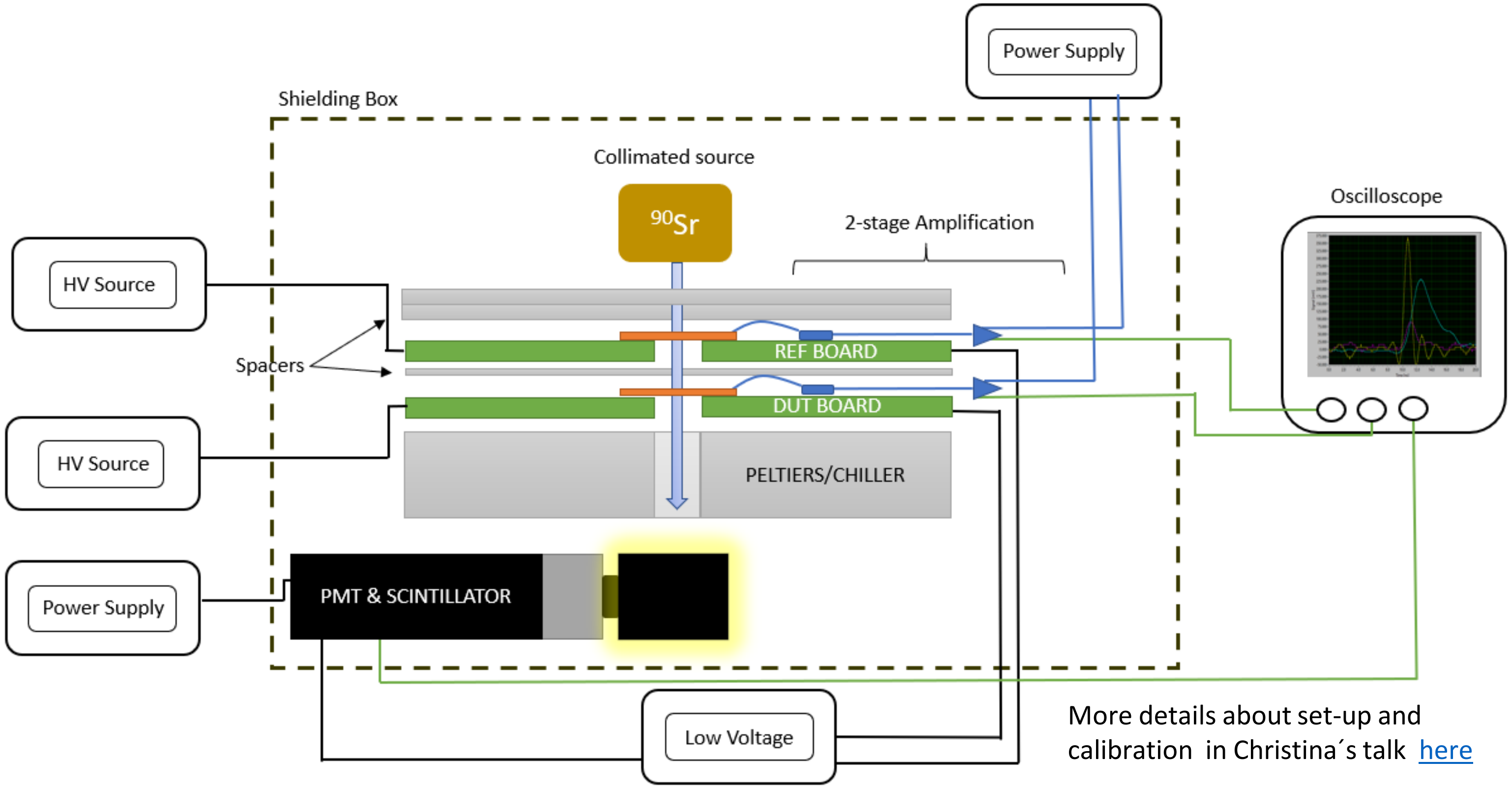
  - Gaussian laser beam and reflections back into the sensor from backside decrease position resolution further



- Freiburg is one of very few institutes able to successfully perform TCT-Timing measurements - so far the only one testing 3D-sensors with it

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

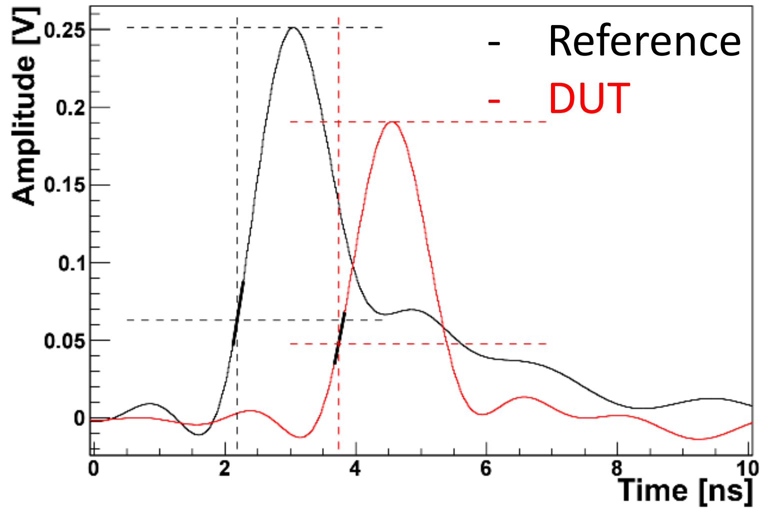


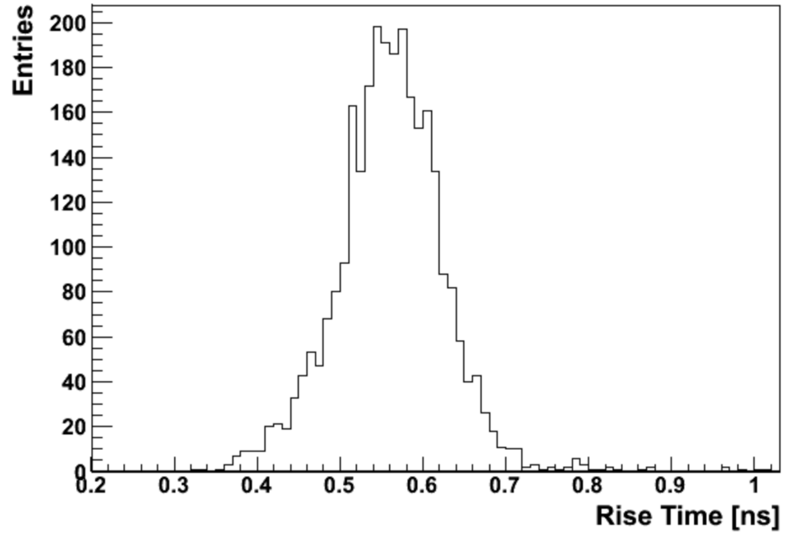
More details about set-up and calibration in Christina´s talk here

- 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: Analysis

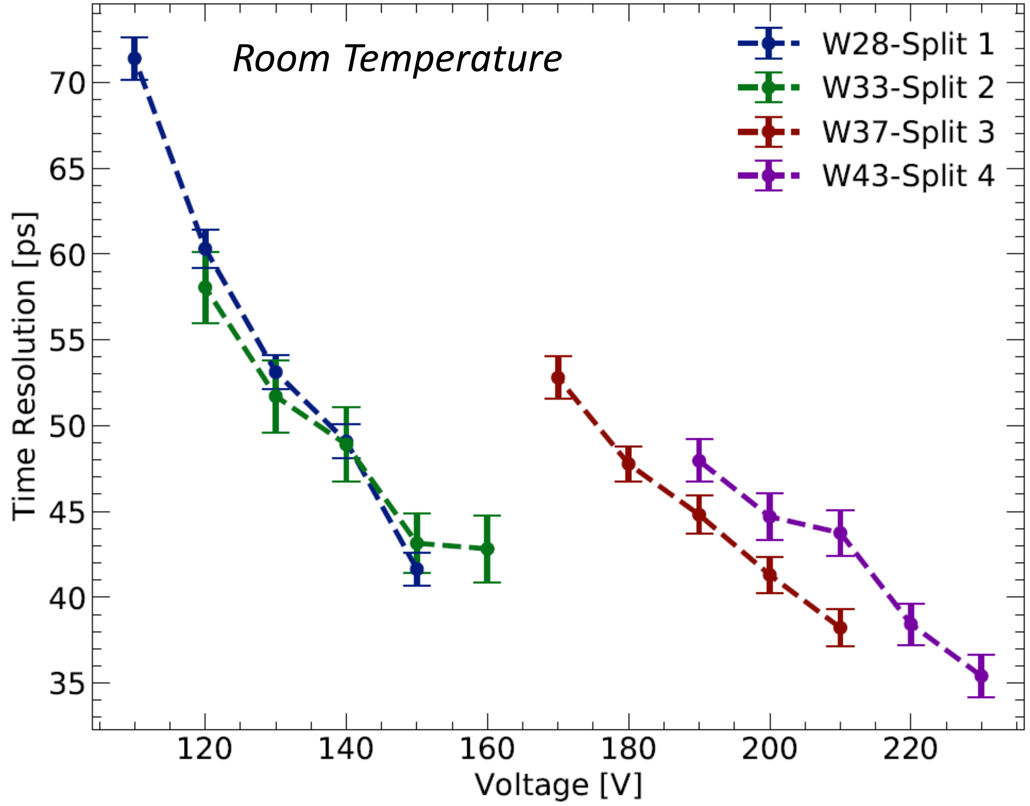
- Maximum amplitude for each event filled into histogram – MPV of the sensor is extracted with a Landau-Gauss-Fit
- If the maximum signal is above a threshold, events used for further analysis
- **T**ime **o**f **A**rrival determined with **C**onstant **F**raction **D**iscrimination
- Linear fit around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



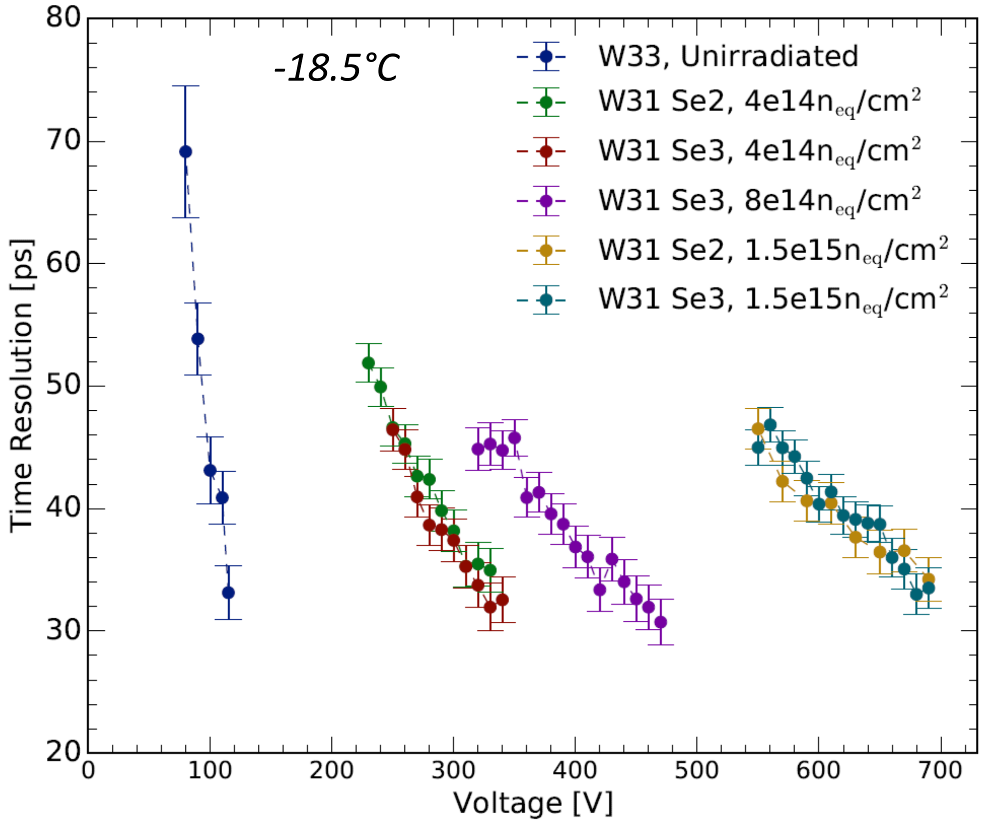


Time Resolution: LGADs -Beta

LGADs with different gain layer doping



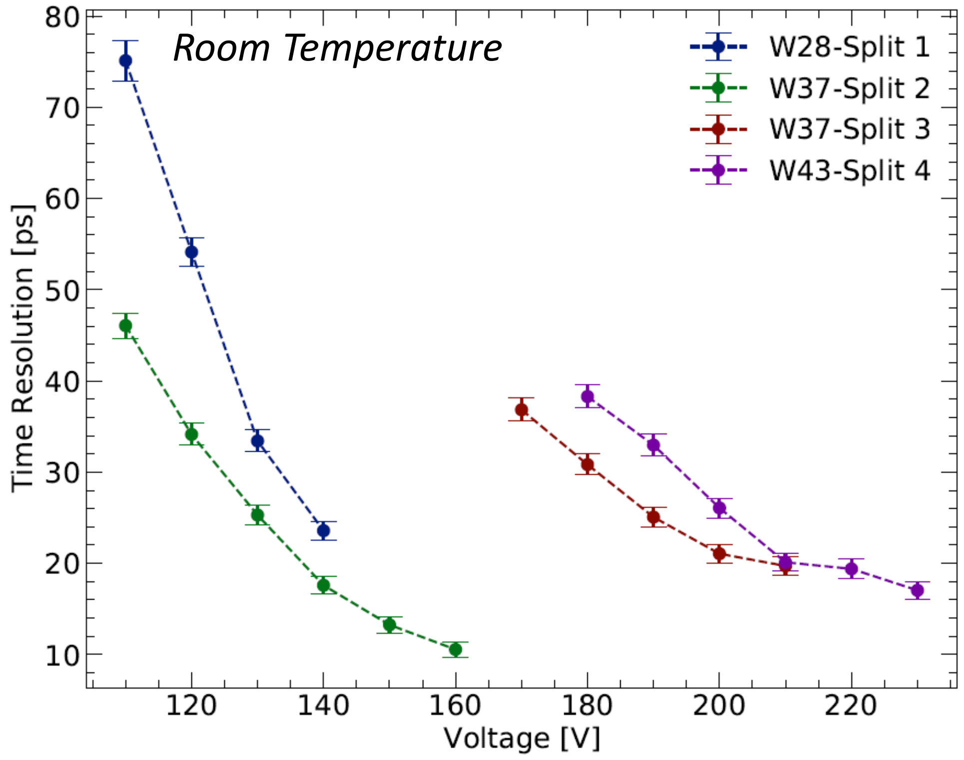
Irradiated LGADs from Split 2



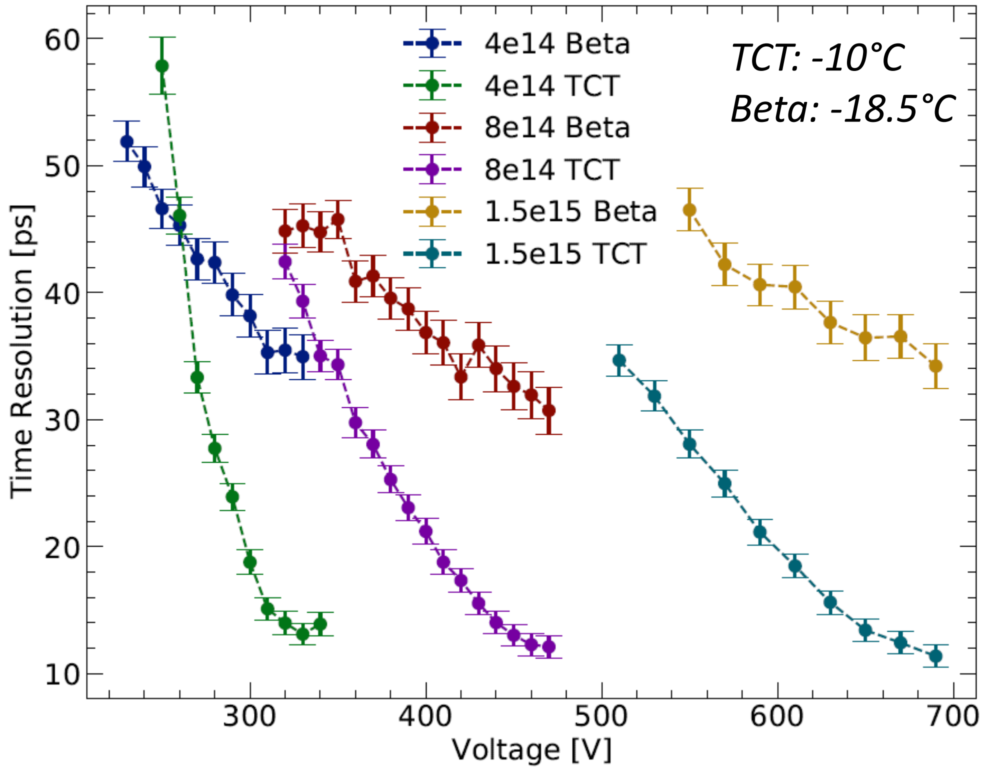
- From high (Split 1) to low (Split 4) gain layer doping – increase in voltage necessary
- Lower doping reaches in total better resolution at highest voltages
- Irradiated sensors still working, reaching approximately the same resolution as an unirradiated sensor

Time Resolution: LGADs - TCT

LGADs with different gain layer doping



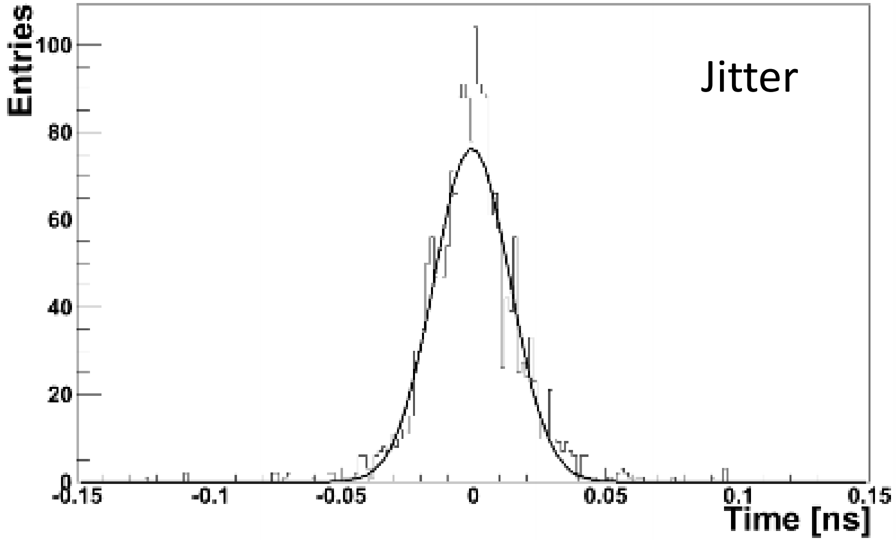
Irradiated LGADs from Split 2

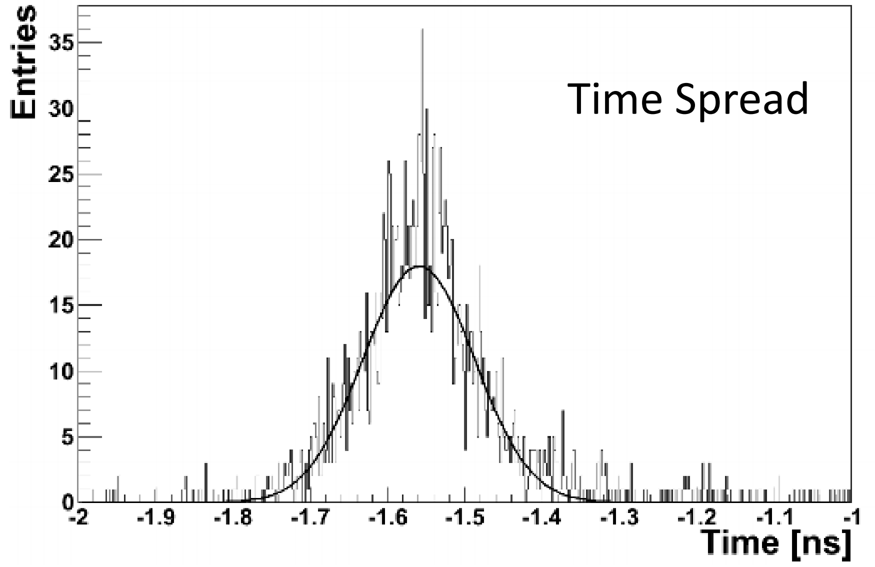


- No Landau fluctuation in TCT setup – significantly smaller time walk contribution
- No gain layer suppression (broad laser beam): Steeper improvement of the time resolution (stronger increase in signal)

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:

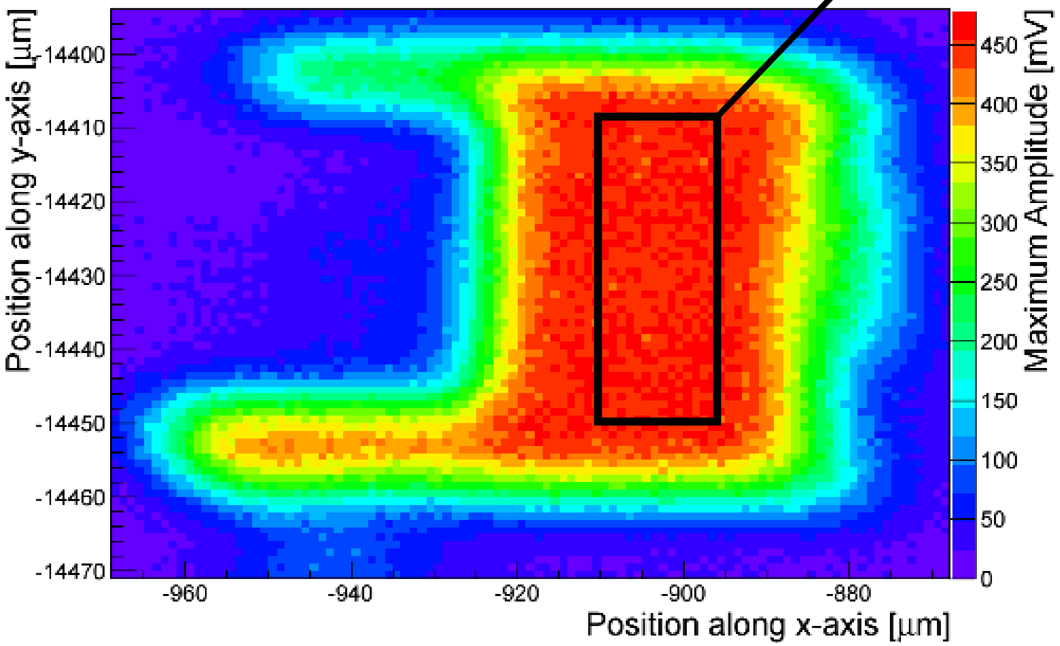
$$\sigma_{DUT} = \sigma_{TS}^2 / \sqrt{2}$$

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

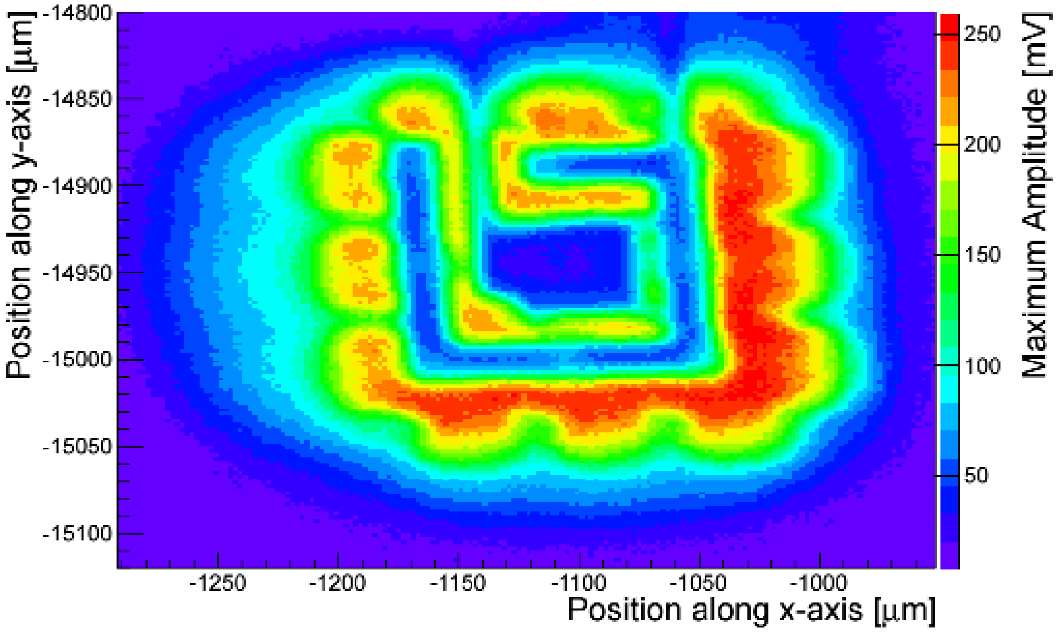
Time Resolution: 3D Pixel Sensors

- 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

Measured area Timing-TCT



Single column



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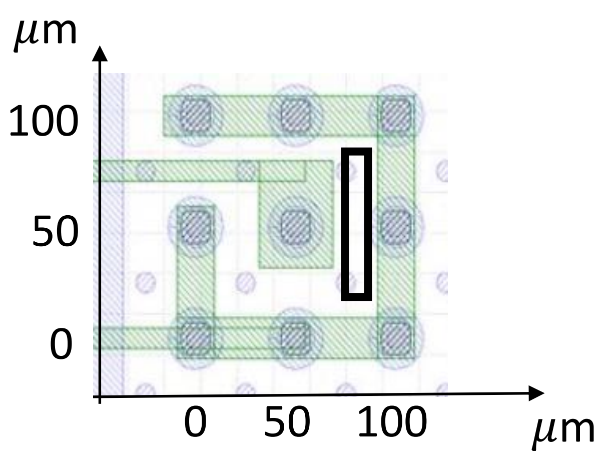
Outer columns

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



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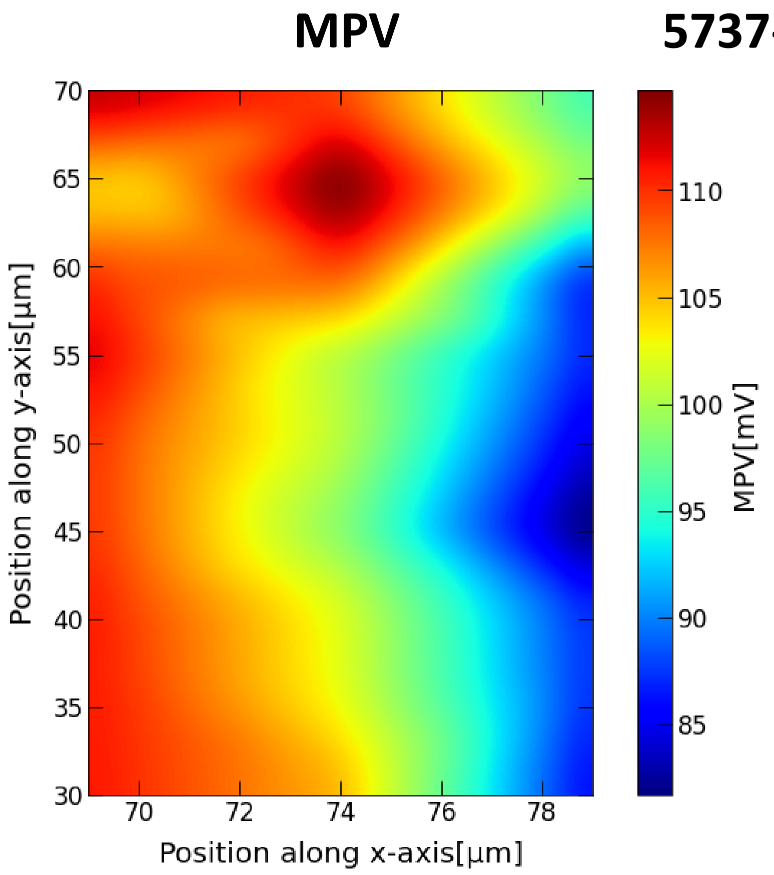
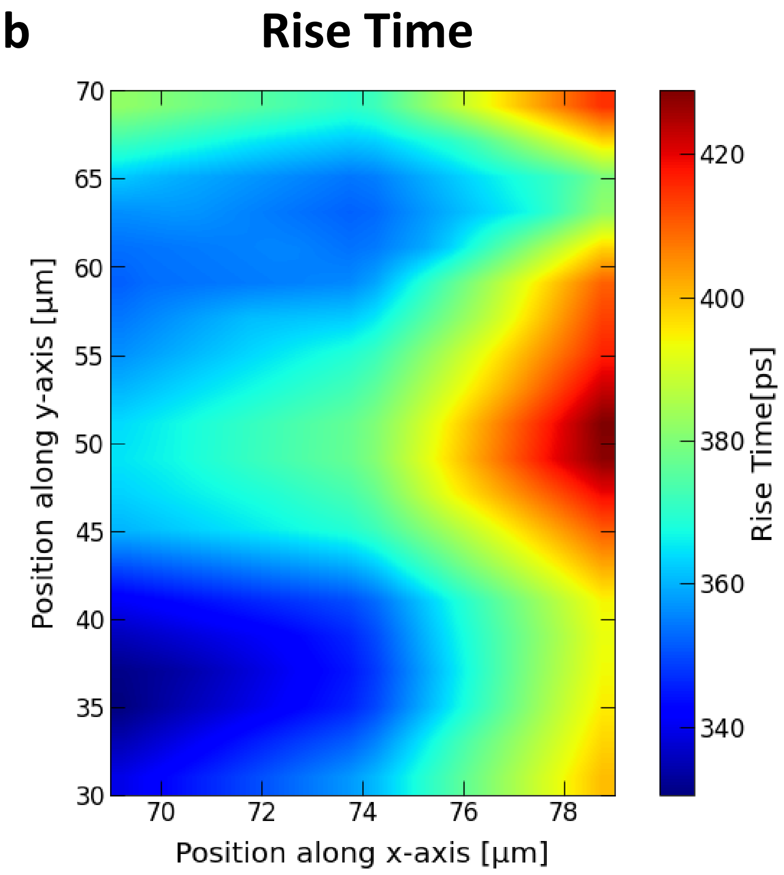
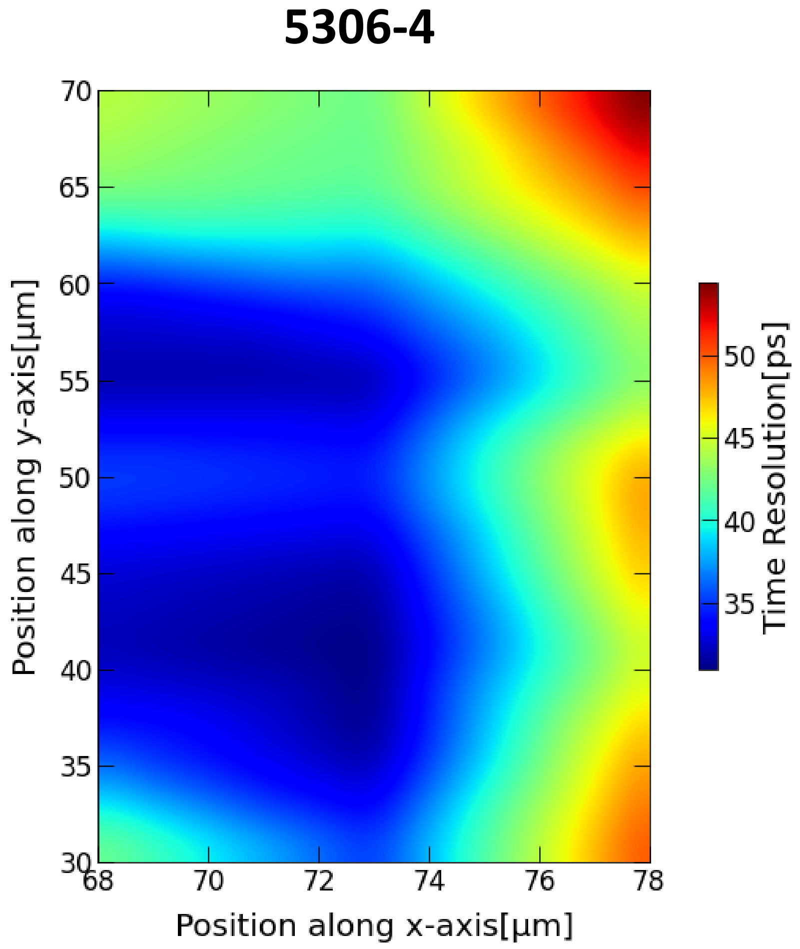
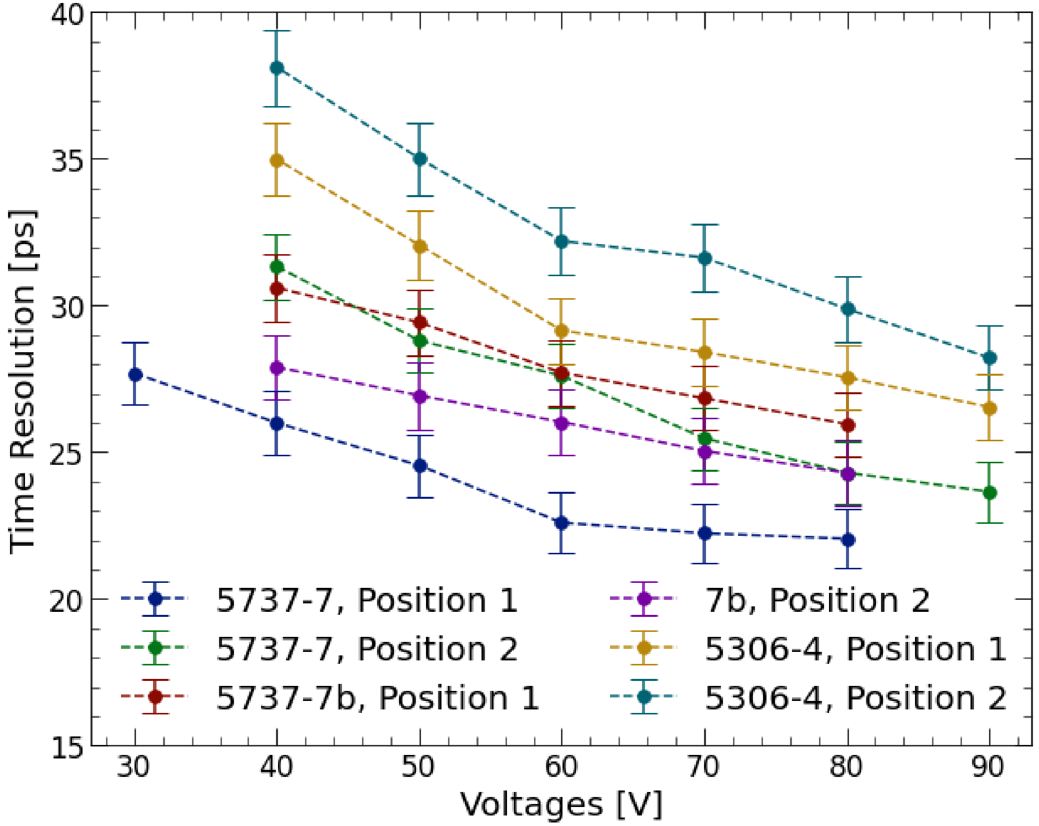




3D Pixel sensors

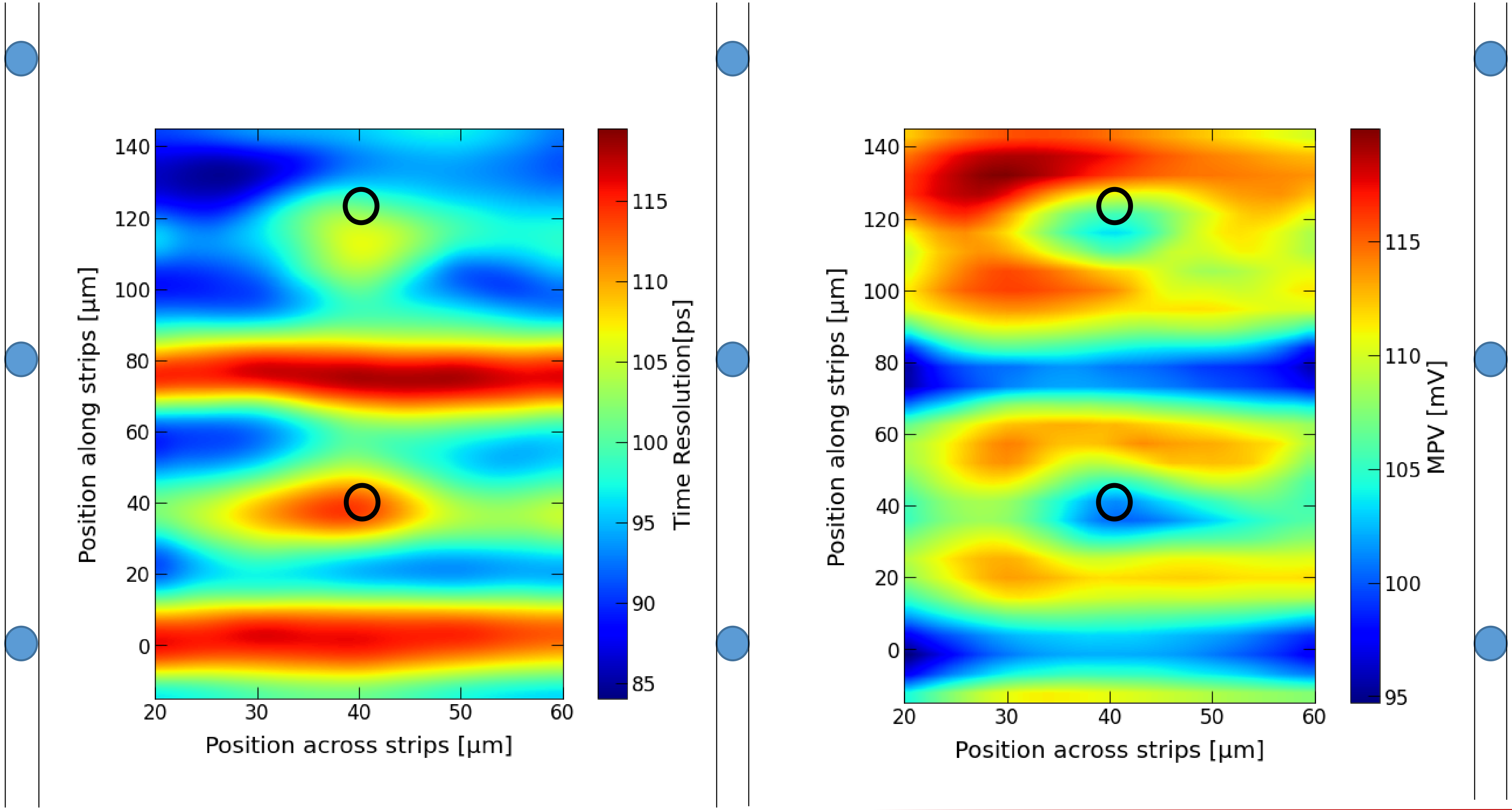




Expected voltage dependence

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

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