Comparison of the time resolution of unirradiated and irradiated LGADs and 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 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
Low Gain Avalanche Diodes (LGADs)

- Avalanche region creates fast and high signals
- LGADs with different gain layer doping tested
- 50 $\mu m$ active thickness
- $1.3 \times 1.3 \ mm^2$ area
- Produced by Hamamatsu (HPK Run 2)

3D Sensors

- Junction columns etched into the sensor bulk
- Strip and pixel sensors tested
- 235 $\mu m$ active thickness
- Strips: $80 \times 80 \mu m^2$ cell size
- Pixels: $50 \times 50 \mu m^2$ cell size
- Produced by CNM
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

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

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

- 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: 3D Pixel Sensors

- Before irradiation, sensors reach about 30-31 ps time resolution at room temperature

- After irradiation the sensors reach 26.7 ps (1e15) and 24.5 ps (5e15) at -18.5°C

- Signal decrease for sensor at 1e15, but increase at 5e15 – hints to charge multiplication
Time Resolution: 3D Pixel Sensors

- Rise time significantly lower for 5e15, similar to unirradiated for 1e15
- Jitter for irradiated sensors slightly lower (measured cold)
- Smaller voltage dependence for rise time and jitter of the irradiated sensors
- Lower noise for 1e15 (cold measurement), but significantly higher for 5e15 – hint for charge multiplication
Comparison – LGAD vs 3D Pixel

- No large voltage increase after irradiation for the 3D sensors
- Significantly lower rise time
- For this 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
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
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
Time Resolution: 3D Strip Sensor

- 3D strip sensor: 235 μm thickness, 80x80μm² 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

![Graph showing time resolution vs voltage for different positions and channels.](image-url)
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
- Before irradiation, both LGADs and 3D sensors reach a comparable time resolution of 30-35 ps
- After irradiation, the LGADs need significantly higher bias to maintain a similar resolution
- 3D pixel sensors improve resolution after irradiation while the bias voltage range stays the same
- At a fluence of $5 \times 10^{15} \text{neq/cm}^2$ the 3D pixel sensors show signs of charge multiplication
- 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!

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BACKUP
Comparison of the time resolution of unirradiated and irradiated LGADs and 3D sensors

- Bonded LGAD
- Amplifier
- High voltage connector
- Readout connector
- Low voltage connector
- PT100 connector
- Lid
Time Resolution - Components

• Main components: Jitter and time walk: \( \sigma_t^2 = \sigma_j^2 + \sigma_{TW}^2 \)

• Jitter component \( \sigma_j \): Determined by the rise time at the amplifier output \( \frac{dV}{dt} \) and the noise level \( \sigma_n \):
  \[
  \sigma_j = \frac{\sigma_n}{|\frac{dV}{dt}|} \approx \frac{\sigma_n}{S/\tau_p} = \frac{\tau_p}{S/N}
  \]

• 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

- **Transient Current Technique**: 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: **Neutral Density Filter** 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

- 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

More details about set-up and calibration in Christina’s talk [here](#)
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

• Time of Arrival determined with Constant Fraction Discrimination

• 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

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

\[
\sigma_{DUT} = \frac{\sigma_{TS}^2}{\sqrt{2}}
\]

\[
\sigma_{Ref} = 25.18 \pm 0.35 \text{ ps}
\]
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
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](image)

- Single column
  - 5737 -7b
- Outer columns
3D Pixel sensors

5306-4

Expected voltage dependence
Comparison of the time resolution of unirradiated and irradiated LGADs and 3D sensors

5936-4 Strip Sensor: 285 $\mu$m 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

Leena Diehl - Comparison of the time resolution of unirradiated and irradiated LGADs and 3D sensors