Gain and time resolution of 50 µm LGADs before and after irradiation

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Samples from 50 μm LGAD Run

- Studied small LGAD pad diodes LGA from 50 μm SOI CNM run 9088
  - LGA: active area 1.3x1.3 mm², multiplication area 1.0x1.0 mm², active thickness ~45 μm
  - 3 different CM-layer implantation doses: 1.8 (low), 1.9 (med) and 2.0 (high) x 10^{13} cm^{-2}
  - Before and after irradiation with neutrons at JSI Ljubljana to 3e14 and 1e15 n_{eq}/cm²
  - Performed gain measurements with Sr90 (Ljubljana) and test beam measurements (CERN SPS, 120 GeV pion) for time resolution

<table>
<thead>
<tr>
<th>Sample</th>
<th>Dose [1e13 cm^{-2}]</th>
<th>Fluence [n_{eq}/cm²]</th>
<th>Measurements</th>
<th>Short Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>W3-LGA-61</td>
<td>1.8</td>
<td>0</td>
<td>IV,CV, Beam</td>
<td>low,unirr,L1</td>
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<td>0</td>
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<td>IV,CV,Sr90,Beam</td>
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<td>3e14</td>
<td>IV,Sr90,Beam</td>
<td>med,3e14,L1</td>
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<td>W7-LGA-45</td>
<td>1.9</td>
<td>3e14</td>
<td>IV,Sr90,Beam</td>
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<td>W7-LGA-35</td>
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<td>1e15</td>
<td>IV,Sr90,Beam</td>
<td>med,1e15,L2</td>
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</table>
IV and Charge/Gain

- IV
  - Good behaviour before irradiation
    - $V_{BD}(\text{low}) \sim 320$ V, $V_{BD}(\text{med}) \sim 240$ V
    - Low current $\sim nA$ at $20^\circ C$
  - ... and after irradiation
    - $V_{BD}$ shifts higher with fluence:
      - $V_{BD}(3e14) \sim 420$ V, $V_{BD}(1e15) \sim 550$ V
    - Radiation-induced current $\sim \mu A$ at $-10^\circ C$

- Sr90 Beta
  - Setup at Ljubljana
  - Measurements performed on LGAD + reference without CM ($Q_{ref} = 2880$ e$^-$)
    - Gain as ratio
  - Gain at same V lower, but $V_{BD}$ higher for lower dose and higher fluence
    - Probably same origin: less doping in CM layer (initially or due to acceptor removal)
  - Measurements limited by noise and micro discharge increase after breakdown

See G. Kramberger’s talk
LGADs in AFP Beam Tests

- First timing measurements of 50 µm LGADs before and after irradiation in AFP beam tests 2016
  - June/July -> med dose, unirradiated
  - September -> med + low dose, unirradiated
    -> med dose, 3e14 + 1e15 n$_{eq}$/cm$^2$

- AFP: ATLAS Forward Proton detector
  - Precision 3D tracking and timing
  - Trackers already (half) installed in 2016
  - Need 10-20 ps timing detectors for 2017
  - Baseline: L-shaped Cherenkov-radiating Quartz LQbars + MCP-PMT
    - 14 ps resolution achieved (w/o TDC)
    - Installation now in winter shutdown
  - LGADs very interesting alternative technology for upgrade
    - Higher segmentation: advantage for very high pile-up conditions
    - But need radiation hardness:
      non-uniform irradiation with peak of 1e15 n$_{eq}$/cm$^2$
      for 35 fb$^{-1}$ (1 year)
  - Long experience with ps timing, infrastructure available
    - Amplifiers, CFDs, HPTDC, tracker, scopes, read out system
    - 2x Quartz+SiPM reference detectors with 10 ps resolution

J. Lange et al., JINST 11 (2016) P09005
AFP Beam Test Setup

3D FEI4 Pixel Tracker
LQbar ToF
SiPMs
LGADs
Movable table 1
Movable table 2
TB Setup – SiPMs and LGADs

- Movable Stage
- SiPM1
- SiPM2
- Amps
- LGADs

- Base plate in styro-foam box (dry ice cooling possible)
- TCT PCB developed by DESY/Hamburg
- Advantage: one mount for both measurements
- Disadvantage: long wirebond + SMA connector before amplifier
  -> sensitive to pick-up noise, reflection

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• Scopes:
  • Agilent infiniium DSA91204A, 12 GHz, 40GS/s
    -> default shown here
    • Typically down-tuned to 1 GHz (optimum)
  • LeCroy 2GHz 20GS/s (2ch)
    -> only in June/July, not shown here

• Pre-amps:
  • CIVIDEC C2 TCT broadband 10 kHz-2 GHz, 40 dB
    -> default shown here
    • Particulars TCT (broadband)
    • AFP PAa+Pab (broadband)
    • CIVIDEC CSA C6 4 ns shaping
    • Uni Geneva CSA 1 ns shaping
    -> See talk by L. Paolozzi

• 10 ps timing reference: Quartz + SiPM + CFD, 3x3x30 mm³

• With and without CFD in electronics chain
  • 1a) Direct raw/analog waveform recorded
    -> main topic of this talk
  • 1b) Optional Constant Fraction Discriminator (CFD)
    • SiPMs always measured with CFDs
    • LGADs only tested in June/July with CFDs
      (not shown here, only few ps worse)

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Thanks to M.Moll, M.Fernandez, E.Curras, E.Griesmayer, L.Paolozzi

See talk by L. Paolozzi
Waveforms

- LGADs: Raw analog waveform
  - Rise time ~500 ps (10-90%)

- SiPMs: CFD digital steep signal

W5-LGA-81, V=200.0

SiPM2, V=30.7
Waveform Properties (unirr)

- **Amplitudes increase with V as expected**
- **Noise 3-4 mV**, consistent within run-to-run variations, no V dependence before irradiation seen
- **Similar SNRs achievable** (at different V)
- **Strong decrease of jitter=noise/slew rate**, 10-15 ps achievable at high V

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![Waveform Amplitudes vs Voltage](image1)

**Unirradiated, Medium + Low Dose**

- **150 V MPV=45 mV**
- **200 V MPV=58 mV**
- **230 V MPV=105 mV**

![Waveform Noise vs Voltage](image2)

- **Noise**
  - **med, unirr, L1**
  - **med, unirr, L2**
  - **low, unirr, L1**
  - **low, unirr, L2**

![Waveform SNR vs Voltage](image3)

- **Signal-to-Noise Ratio**
  - **med, unirr, L1**
  - **med, unirr, L2**
  - **low, unirr, L1**
  - **low, unirr, L2**

![Waveform Jitter vs Voltage](image4)

- **Jitter Time Resolution 10-90%**
  - **med, unirr, L1**
  - **med, unirr, L2**
  - **low, unirr, L1**
  - **low, unirr, L2**

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21/02/2017

Jörn Lange - 50 µm LGAD Gain+Resolution
Time Difference Distributions

- $\Delta t(\text{LGAD} - \text{SiPM})$
  - ToA from CFD algorithm: % of max. amplitude (optimised at each V)
  - Gaussian
  - Some runs with 2 LGADs + 2 SiPMs
    -> $\sigma_{\text{SiPM,1/2}}$ from combined analysis of all 4 ch.
      - 13 ps for SiPM1
      - 7 ps for SiPM2
    - In the following $\sigma_{\text{LGAD}}$ from $\Delta t(\text{LGAD} - \text{SiPM2})$ after subtracting $\sigma_{\text{SiPM2}}$

- $\Delta t(\text{LGAD1} - \text{LGAD2})$
  - ToA from CFD algorithm: % of max. amplitude (optimised at each V)
  - Gaussian
  - $\sigma_{\text{LGAD}}$ (average) from $\sqrt{2}$ division
    - In the following only used as a cross check and in case no SiPM available
    - Good agreement with measurements using SiPM
As a function of $V$
- Medium dose $\sim$15 ps better at same $V$
- Both reach similar end point at 235 V (medium) or 320 V (low)
  - **28 ps achieved!**
- Similar results as HGTD and UCSC/Torino (N. Cartiglia et al., arXiv:1608.08681)

As a function of Gain
- Decreasing slope, need increasingly higher gain for resolution improvement
- Similar **universal behaviour** for both doses
• Most measurements done in same setup as for unirradiated devices ("DO box")
  • Cooled with dry ice, closed styrofoam box
  • Temperature on-sensor extracted from IV (comparing to lab measurements)
    • 3e14: ~ -6°C
    • 1e15: ~ -15°C

• One measurement for 3e14 also in climate chamber ("MPI cooling box")
  • T set to -20°C
    • On-sensor T similar (cross-check with IVs)
    • Only the 2 LGADs measured (SiPM needed in other setup)

• Issues at 1e15
  • Sensors became instable at ~620 V
  • Both broke at that V after 1h of no beam (heating? Thermal runaway?)
  -> now breakdown V < 1V
Waveform Properties (irr)

- Level of noise after irradiation covered by run-to-run variations; but increasing with V
- **SNR** higher at -20°C than -6°C for 3e14, similar values as before irradiation achievable; but very low at 1e15

- Similar jitter values as before irradiation achievable at 3e14 (15-20 ps), but much worse at 1e15
- **∆t**: Good Gaussian behaviour also after irradiation
At 3e14 similar time resolution achieved as before irradiation (at higher V)
- -6°C: 34 ps at 445 V
- -20°C: 28 ps at 430 V
At 1e15 gain is highly reduced and voltage stability not high enough to compensate for it
- ~60 ps at 620 V
Gain dependence in all cases similar to before irradiation
-> “universal”
Summary and Conclusions

- Studied gain and time resolution of 50 µm thick LGAD from new CNM run 9088
  - For different implantation doses before and after irradiation up to 1e15 n_{eq}/cm^2

- Gain
  - Higher for higher implantation doses
  - Clear degradation after irradiation (acceptor removal)

- Time resolutions from AFP beam tests
  - <30 ps resolution achieved at 235 V (med) or 320 V (low dose) before irradiation
  - Similar resolution at 3e14 n_{eq}/cm^2 at ~440 V
  - At 1e15 n_{eq}/cm^2 achieved ~60 ps at 620 V
    - Gain reduction and high voltage stability currently not good enough to achieve more

- Implications on HEP applications
  - LGADs can survive peak fluence in AFP for >10 fb\(^{-1}\)
    (>1/3 year at full LHC luminosity or special runs)
  - But need to verify results also after charged hadron irr. (more gain loss)
  - And need to find ways to cope with non-uniform irradiation
    - Different parts of sensor need different V_{bias}, other parts might break already
    - Possible solutions:
      - Better V stability before irradiation
      - Multiple discrete small diodes instead of segmented big device
      - Pre-irradiation?
  - Further investigations needed to study if LGADs would survive fluence of full year in AFP/CT-PPS and HGTD

- Promising first results, but need to investigate further options to increase radiation hardness
Gain Measurement Setups

• **TCT**
  - TCT setup at IFAE Barcelona: scanning TCT from Particulars
  - IR laser from front-side
  - DRS4 readout
  - TCT PCB developed by DESY/Hamburg
  - Measurements performed on LGAD + reference without CM layer
    -> Gain as ratio
  - Measured LGADs before irradiation at room temperature

• **Sr90 charge collection**
  - Setup at Ljubljana
  - MIP-like $\beta$ particles
  - Charge-sensitive preamplifier (Ortec 142B) + shaper (25 ns shaping time)
  - Oscilloscope readout
  - Calibrated with Am241
  - Mounted inside Al box with hole
  - Scintillator trigger
    -> but samples were quite small, still many noise events
    -> but Landau-Gauss fit possible
  - Room temperature before irradiation, -10°C after (Peltier)
  - Measurements performed on LGAD + reference without CM
    - Reference: 2880 e⁻ (measured in big pad diode LGB)
    -> Gain as ratio
• TCT
  • TCT setup at IFAE Barcelona: scanning TCT from Particulars
  • IR laser from front-side, DRS4 readout, TCT PCB developed by DESY/Hamburg
  • Measurements performed on LGAD + reference without CM layer
    -> Gain as ratio

• Difference between TCT and Sr90 measurements
  • Gain higher at same voltage for TCT measurement
  • Difference seems to increase with V
  • Also spread between samples higher in TCT
  • Similar differences seen by other groups
  • Reason still under investigation

Unirradiated, IR TCT

TCT vs $^{90}$Sr Gain

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Pre-Studies and Remarks

- The system was carefully studied with unirradiated LGAD, med dose, typically at 200 V
- Reproducibility
  - Many measurements taken, typical reproducibility few ps
  - But noise and other environmental influences (T) fluctuating, test beam area known to be “noisy”
    - Cause and influence not yet well understood
    - Some results worse by 10 ps than best one, but typically 3-5 ps run-to-run variations
      -> default: best ones presented
- Studied impact of different triggers (different LGADs, SiPMs)
  - No systematic differences found -> default: LGAD trigger to increase purity/statistics
- Oscilloscope bandwidth variations studied (0.5 – 12 GHz)
  - Optimum found at 1-2 GHz -> default: 1 GHz
- Different oscilloscopes/sampling rates
  - No big difference (for 10-40 GS/s) at same band width -> default 40 GS/s
- Oscilloscope voltage scale
  - Influences precision and noise! Best to keep as low as possible without saturating signals
    -> default 50 mV/div
- Amplifiers
  - Best: CIVIDEC C2 (TCT) -> default
  - Particulars + AFP PAa+PAb ~5-10 ps worse
  - CIVIDEC CSA, 4 ns shaping, much worse (~100 ps)!
  - Uni Geneva CSA not optimized in Sep; much better after optimisations in Oct (similar to CIVIDEC C2)
- Raw/analog waveform vs. CFD data
  - No systematic difference found (within few ps) -> default raw data (full information + simpler)
  - But re-assuring for later use in real experiment with CFDs
Time Resolution Algorithm

- Time resolution from difference of arrival time between two channels, $\Delta t$

- Different analysis methods for time-of-arrival studied
  - A) Different threshold methods
    - Fixed threshold at different levels
    - Constant Fraction Discrimination (offline algo) at different fractional levels (10-90%)
  - B) For each threshold method one can interpolate bins in different ways to decide when threshold is passed
    - Linear interpolation of 2 surrounding bins
    - Linear fit of +/- N surrounding bins
    - Polynomial fits (3rd and 5th degree) of N surrounding bins
    - Fit from 20-80% or 10-90% of maximum
    - Spline Interpolation
  - C) Completely different methods
    - Time of max. amplitude

- Default: CFD algo with linear interpolation of 2 surrounding bins
  - Much better than fixed threshold (w/o time walk corr.)
  - Simple interpolation not much worse than others but simpler and more robust
  - Optimal CFD fraction depends on V (shape of waveform!)
    -> scan for each point and take optimum

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