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

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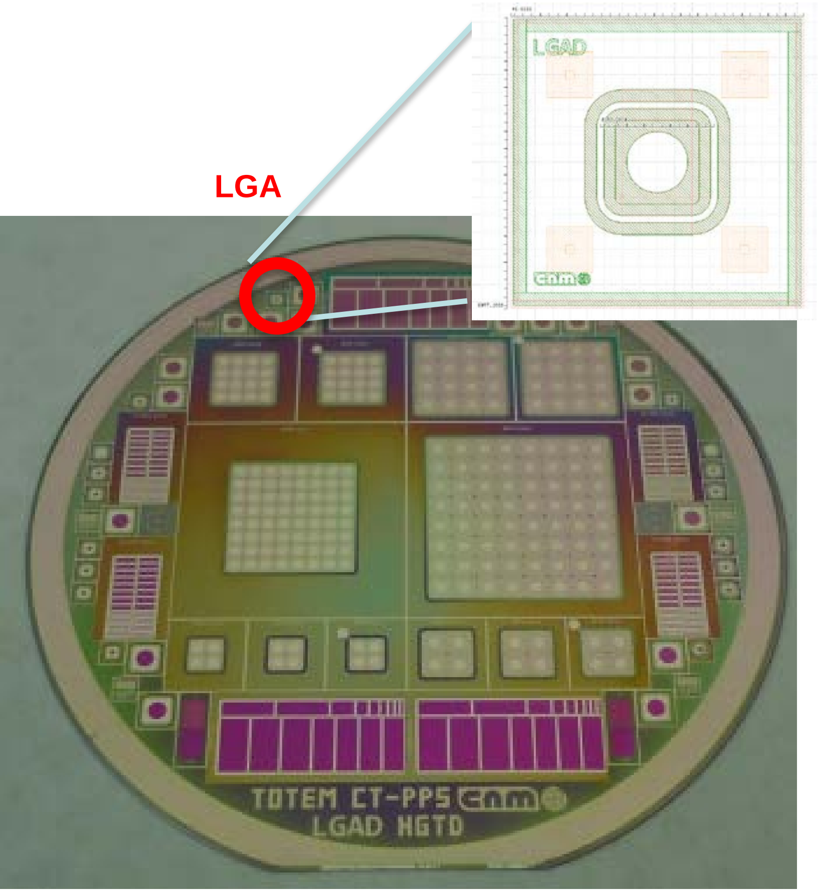
ATLAS

Samples from 50 µm LGAD Run

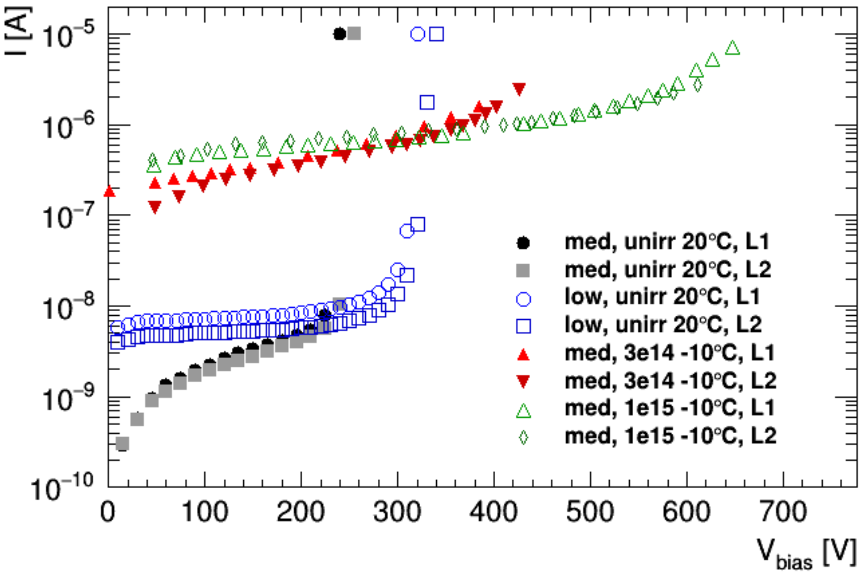
- Studied small LGAD pad diodes LGA from 50 µm SOI CNM run 9088
  - LGA: active area 1.3x1.3 mm², multiplication area 1.0x1.0 mm², active thickness ~45 µm
  - 3 different CM-layer implantation doses: 1.8 (low), 1.9 (med) and 2.0 (high) x 10^{13} cm^{-2}
  - Before and after irradiation with neutrons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



Sample	Dose [1e13 cm-²]	Fluence [n_{eq}/cm^2]	Measurements	Short Name
W3-LGA-61	1.8	0	IV,CV, Beam	low,unirr,L1
W3-LGA-71	1.8	0	IV,CV, Beam	low,unirr,L2
W3-LGA-33	1.8	0	Sr90	low,unirr,L3
W5-LGA-45	1.9	0	IV,CV,Sr90,Beam	med,unirr,L1
W5-LGA-81	1.9	0	IV,CV,Sr90,Beam	med,unirr,L2
W5-LGA-51	1.9	3e14	IV,Sr90,Beam	med,3e14,L1
W7-LGA-45	1.9	3e14	IV,Sr90,Beam	med,3e14,L2
W5-LGA-43	1.9	1e15	IV,Sr90,Beam	med,1e15,L1
W7-LGA-35	1.9	1e15	IV,Sr90,Beam	med,1e15,L2

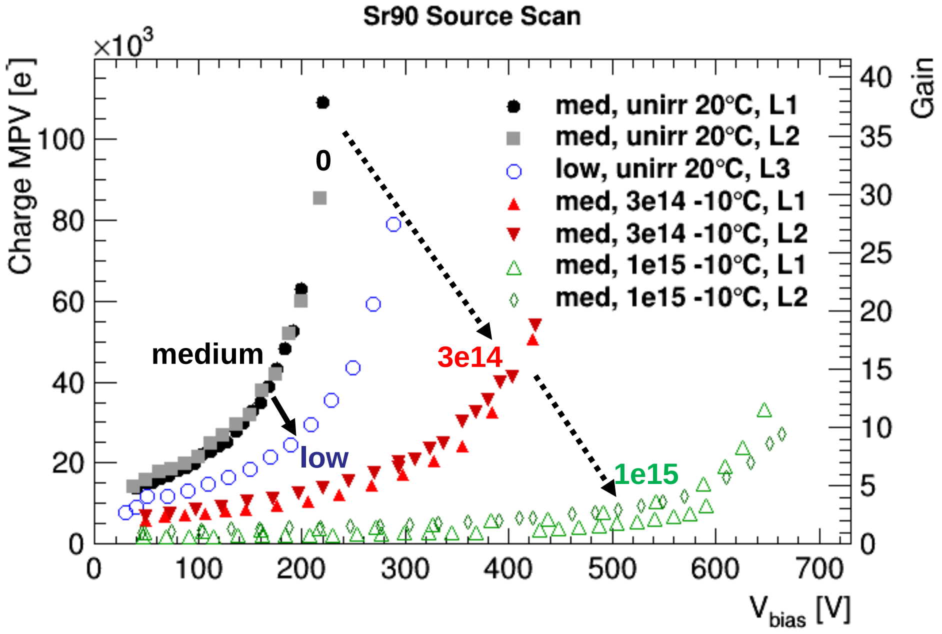
IV and Charge/Gain

- IV
  - Good behaviour before irradiation
    - V_{BD}(low)~320 V, V_{BD}(med)~240 V
    - Low current ~nA at 20°C
  - … and after irradiation
    - V_{BD} shifts higher with fluence: V_{BD}(3e14)~420 V, V_{BD}(1e15)~550 V
    - Radiation-induced current ~µA at -10°C



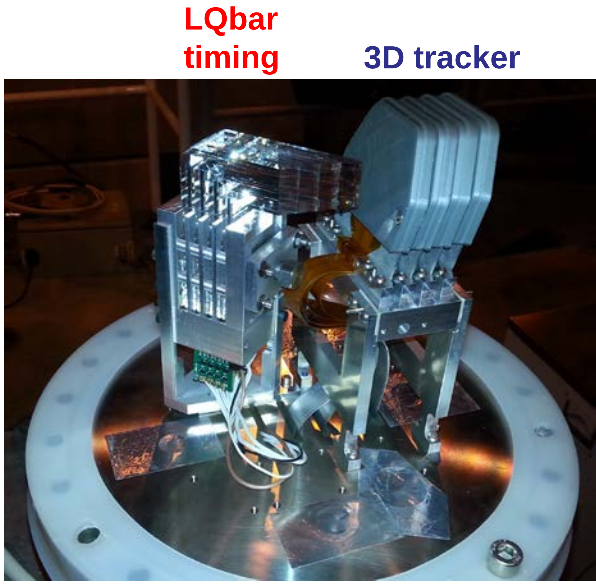
- Sr90 Beta
  - Setup at Ljubljana
  - Measurements performed on LGAD + reference without CM (Q_{ref}=2880 e^{-})
    - Gain as ratio
  - Gain at same V lower, but V_{BD} higher for lower dose and higher fluence
    - Probably same origin: less doping in CM layer (initially or due to acceptor removal)

      See G. Kramberger's talk
  - Measurements limited by noise and micro discharge increase after breakdown



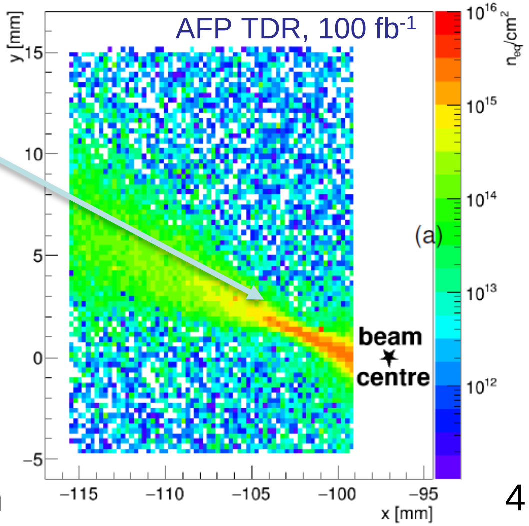
LGADs in AFP Beam Tests

- 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

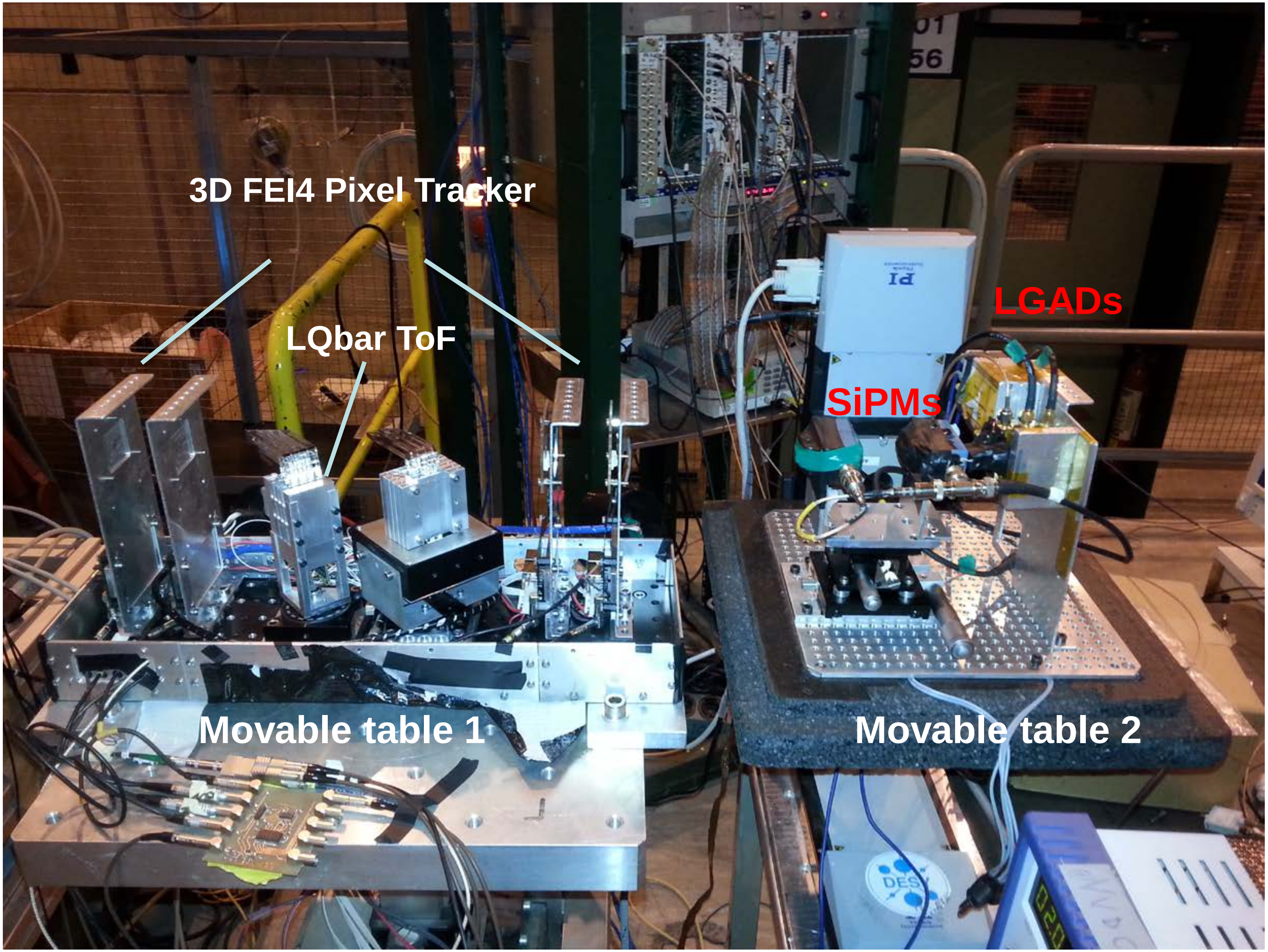


- AFP: ATLAS Forward Proton detector
  - Precision 3D tracking and timing
  - Trackers already (half) installed in 2016
  - Need 10-20 ps timing detectors for 2017
  - Baseline: L-shaped Cherenkov-radiating Quartz LQbars + MCP-PMT
    - 14 ps resolution achieved (w/o TDC)
    - Installation now in winter 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

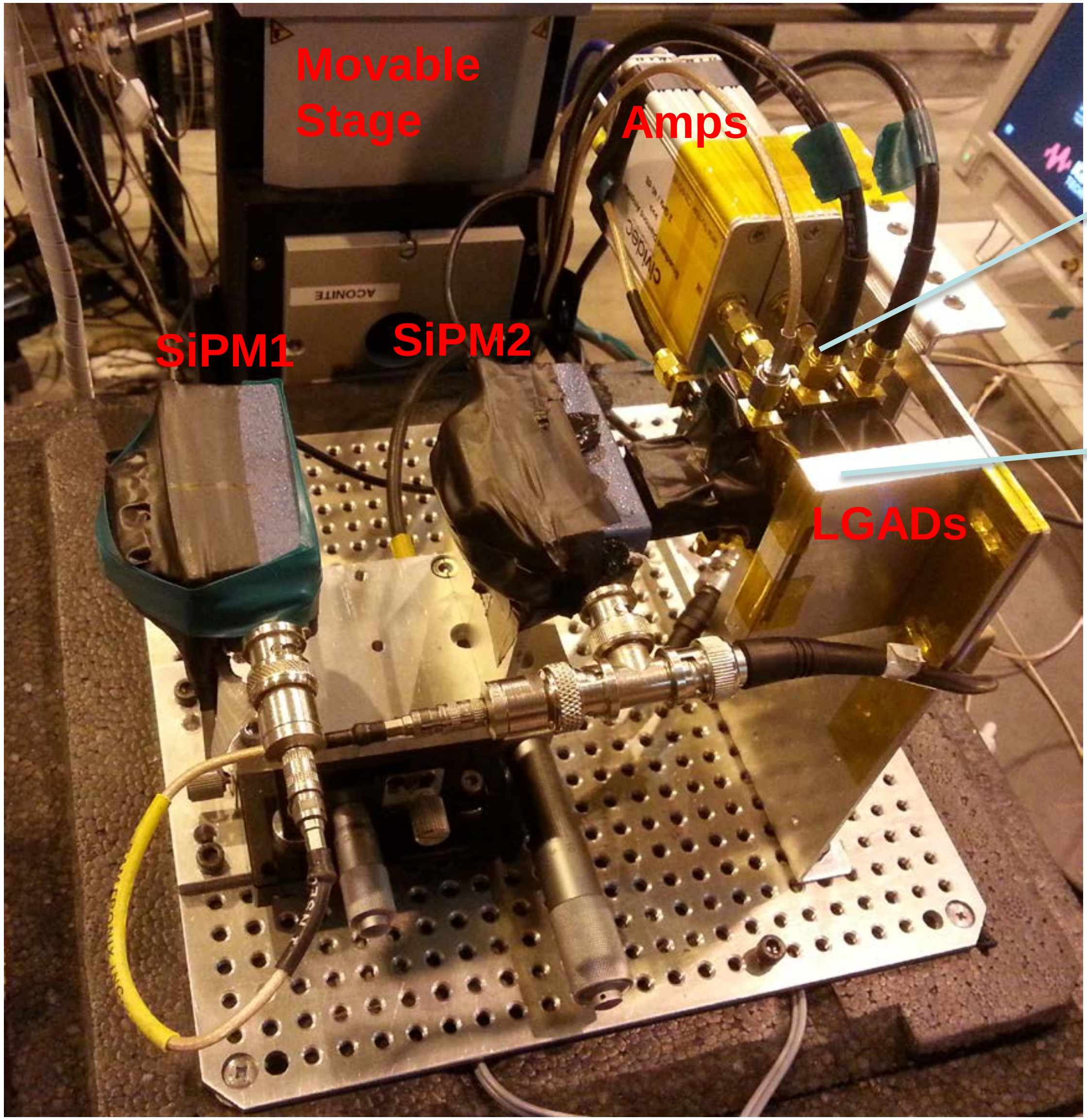
J. Lange et al., JINST 11 (2016) P09005

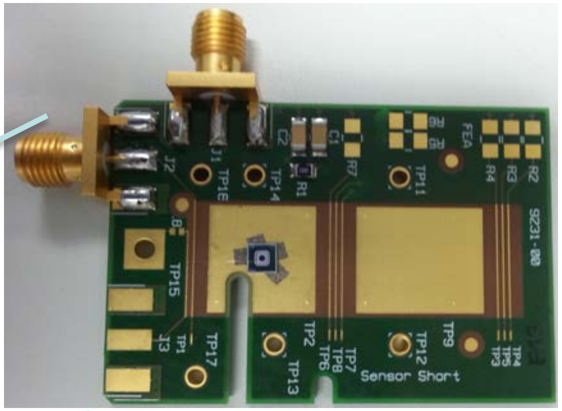


AFP Beam Test Setup



TB Setup – SiPMs and LGADs





- 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

Base plate in styro-foam box (dry ice cooling possible)

Readout

- 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

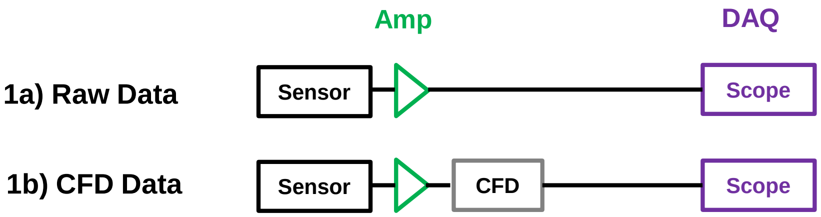
- Pre-amps:
  - CIVIDEC C2 TCT broadband 10 kHz-2 GHz, 40 dB
    -> default shown here
  - Particulars TCT (broadband)
  - AFP PAa+Pab (broadband)
  - CIVIDEC CSA C6 4 ns shaping
  - Uni Geneva CSA 1 ns shaping

    -> See talk by L. Paolozzi

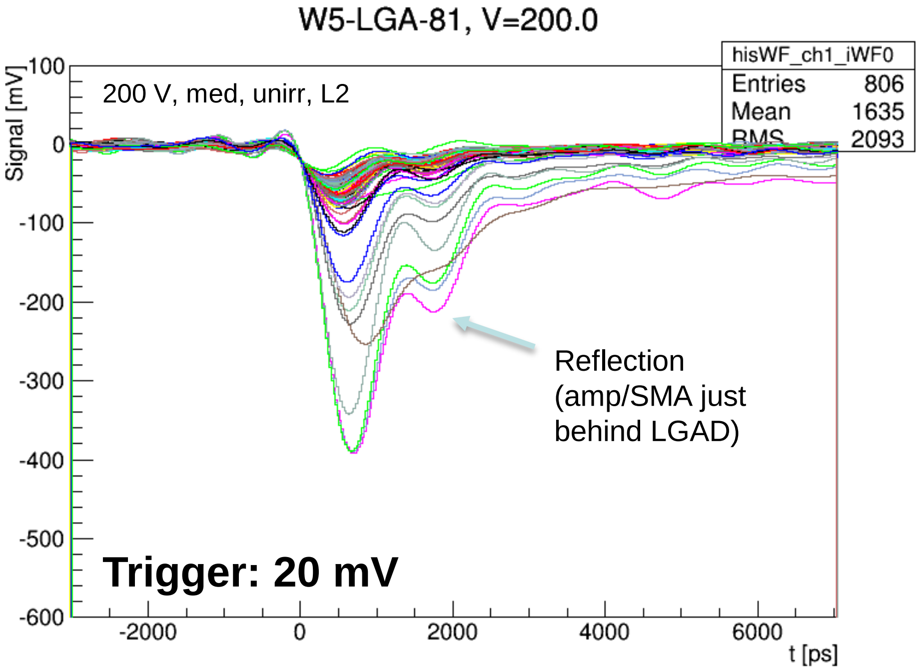
Thanks to M.Moll,
M.Fernandez,
E.Curras,
E.Griesmayer,
L.Paolozzi

- 10 ps timing reference: Quartz + SiPM + CFD, 3x3x30 mm^3

- 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)

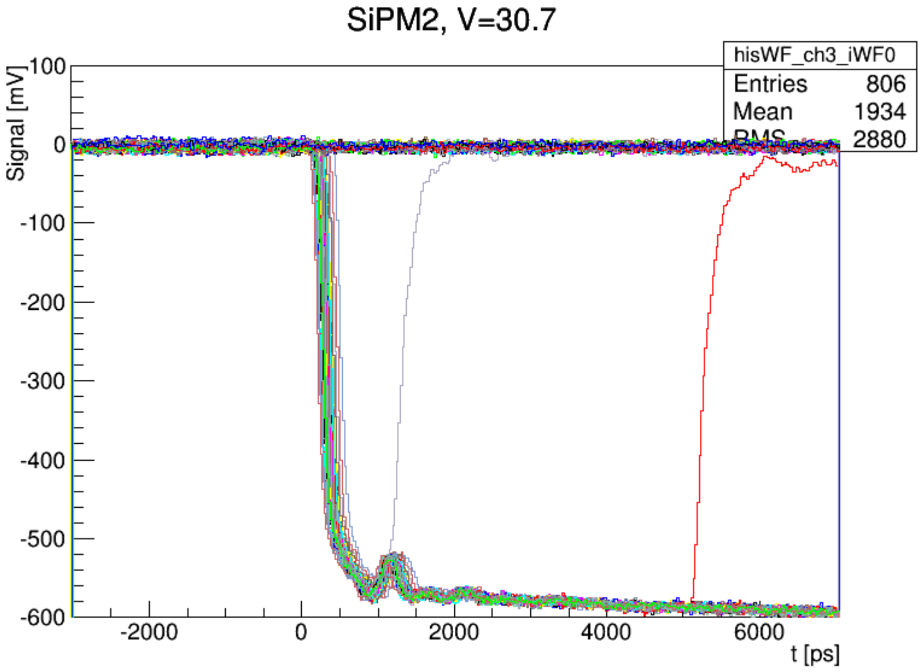


Waveforms



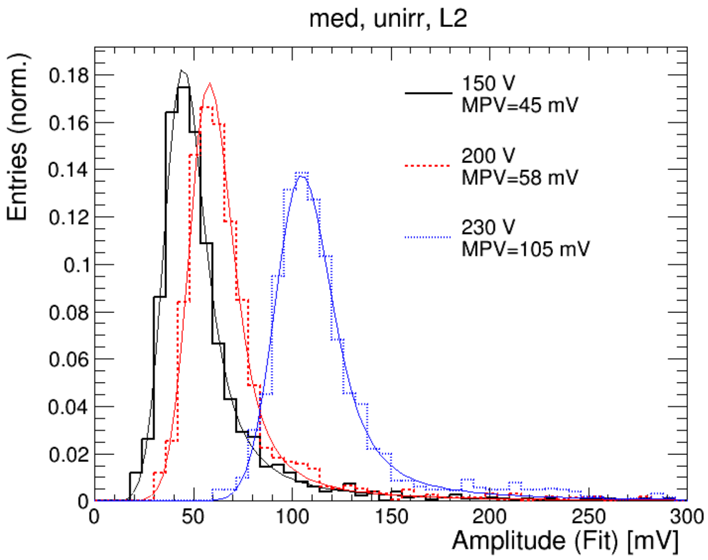
Reflection (amp/SMA just behind LGAD)

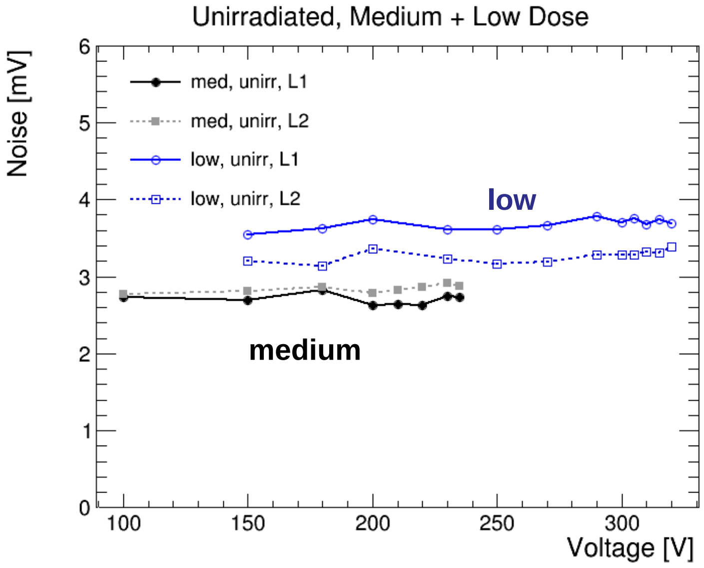
Trigger: 20 mV



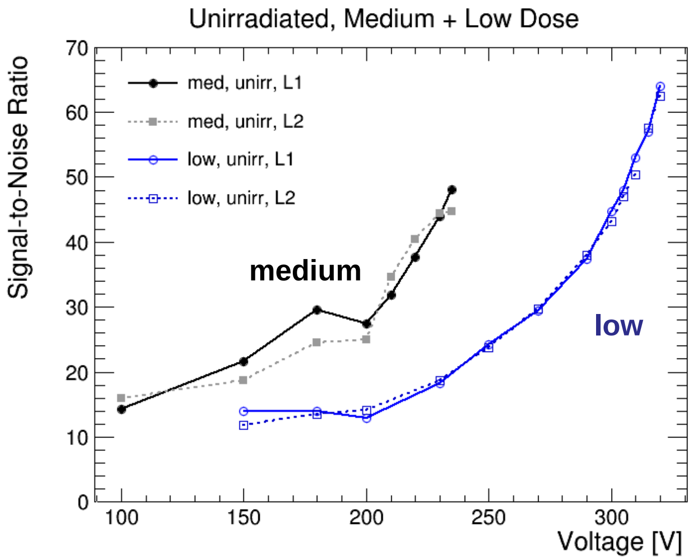
- LGADs: Raw analog waveform
  - Rise time ~500 ps (10-90%)
- SiPMs: CFD digital steep signal

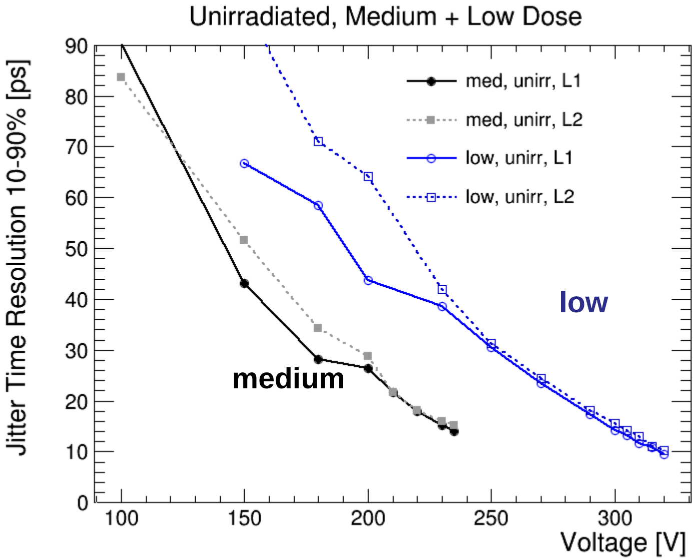
Waveform Properties (unirr)





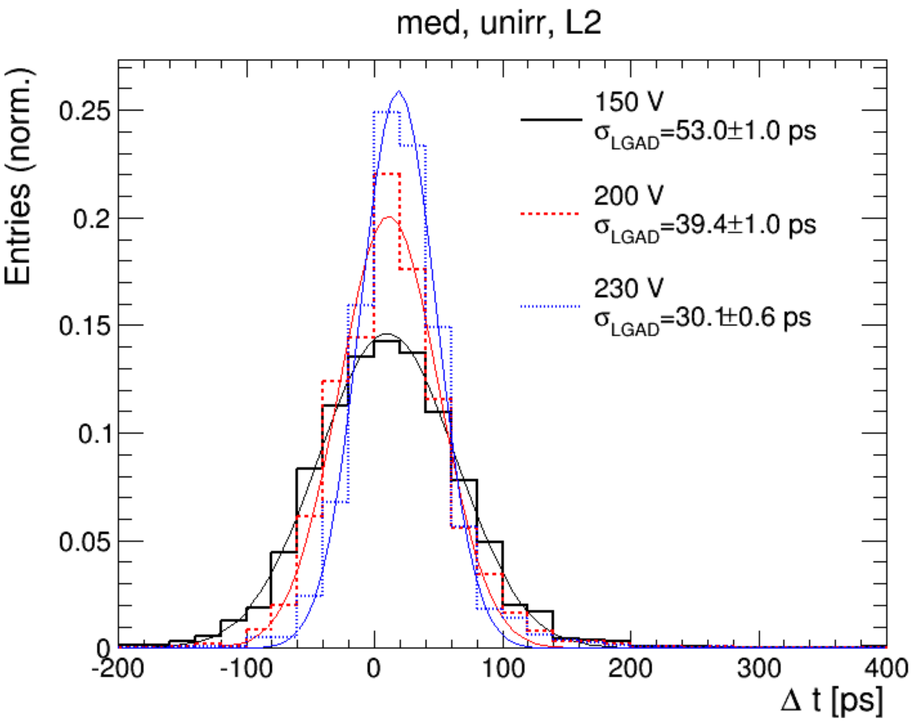
- Amplitudes increase with V as expected
- Noise 3-4 mV, consistent within run-to-run variations, no V dependence before irradiation seen



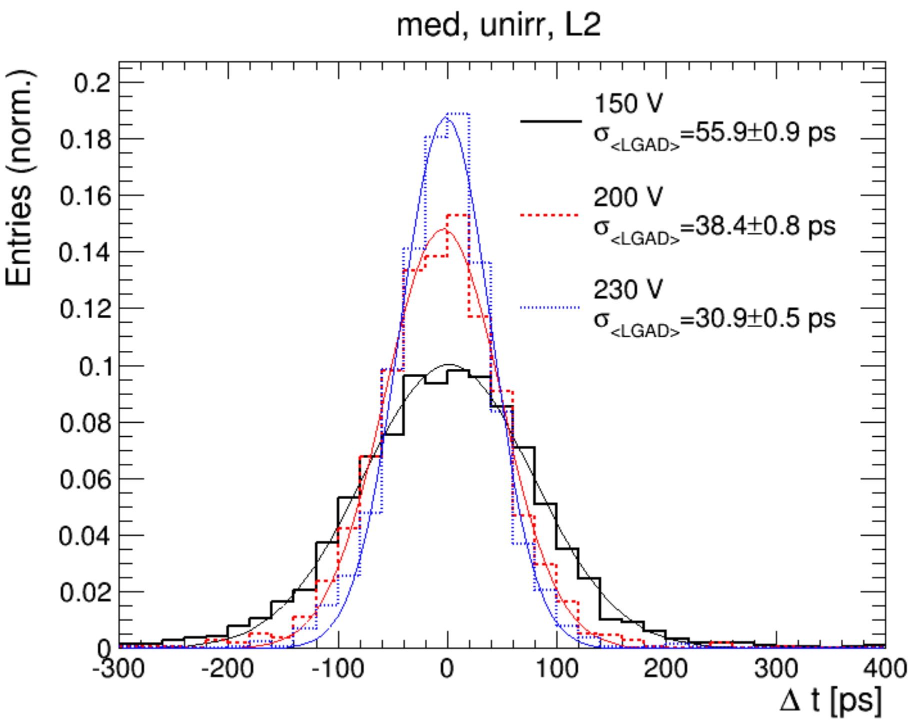


- Similar SNRs achievable (at different V)
- Strong decrease of jitter=noise/slew rate, 10-15 ps achievable at high V

Time Difference Distributions

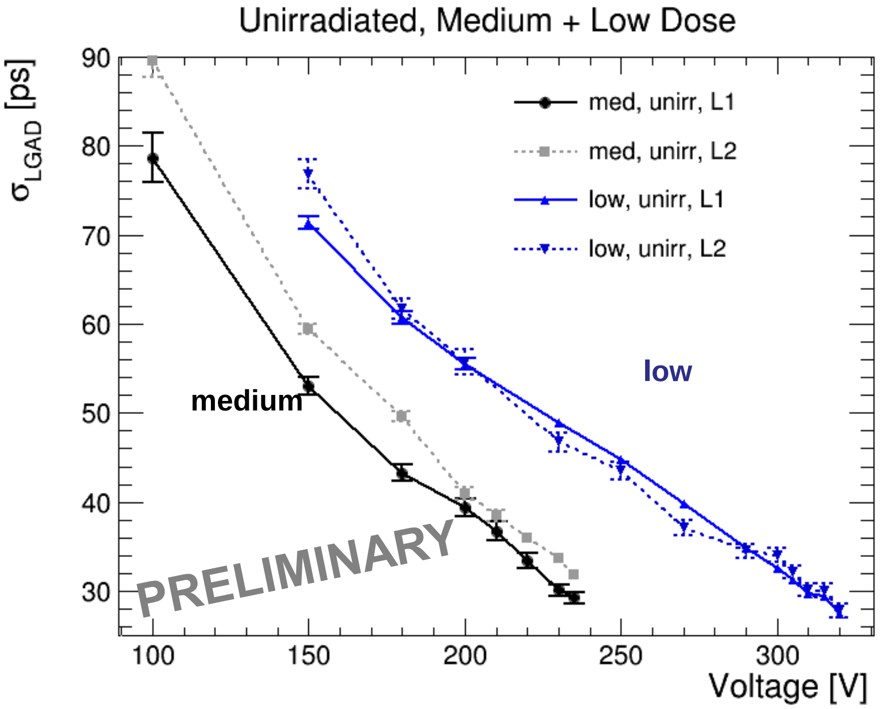


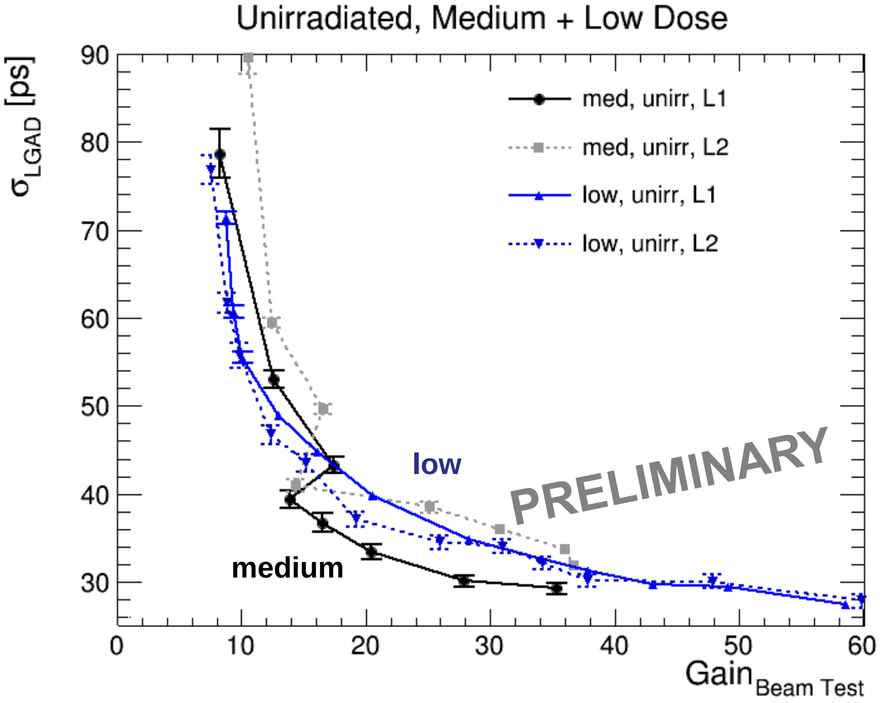
- Δt(LGAD – SiPM)
  - ToA from CFD algorithm: % of max. amplitude (optimised at each V)
  - Gaussian
  - Some runs with 2 LGADs + 2 SiPMs
    -> $\sigma_{SiPM,1/2}$ from combined analysis of all 4 ch.
    - 13 ps for SiPM1
    - 7 ps for SiPM2
  - In the following σ_{LGAD} from Δt(LGAD – SiPM2) after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



- Δt(LGAD1 – LGAD2)
  - ToA from CFD algorithm: % of max. amplitude (optimised at each V)
  - Gaussian
  - σ_{LGAD} (average) from √2 division
    - In the following only used as a cross check and in case no SiPM available
    - Good agreement with measurements using SiPM

Time Resolution (unirr)

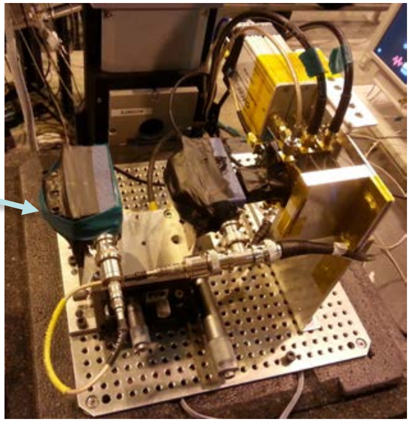




- As a function of V
  - Medium dose ~15 ps better at same V
  - Both reach similar end point at 235 V (medium) or 320 V (low)
  - **28 ps achieved!**
  - Similar results as HGTD and UCSC/Torino (N. Cartiglia et al., arXiv:1608.08681)
- As a function of Gain
  - Decreasing slope, need increasingly higher gain for resolution improvement
  - Similar **universal behaviour** for both doses

Beam Test of Irradiated LGADs

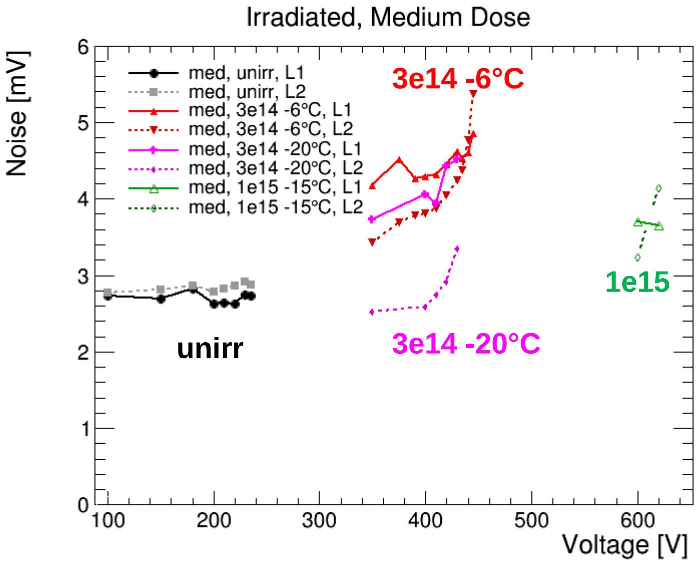
- Most measurements done in same setup as for unirradiated devices (“DO box”)
  - Cooled with dry ice, closed styrofoam box
  - Temperature on-sensor extracted from IV (comparing to lab measurements)
    - 3e14: ~ -6°C
    - 1e15: ~ -15°

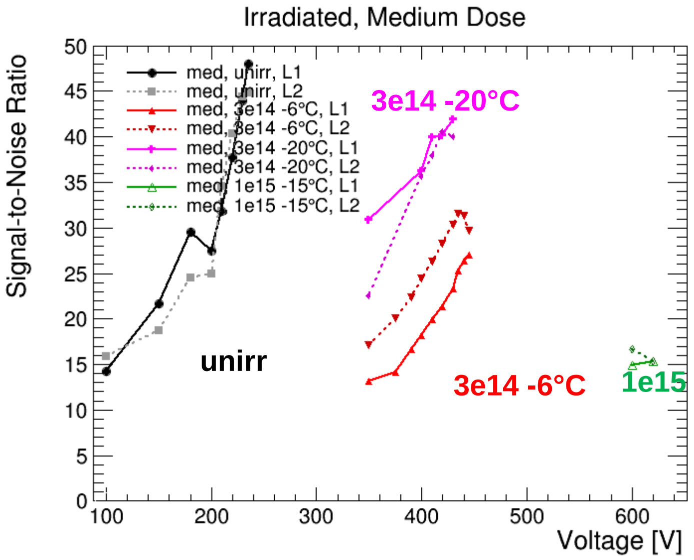


- One measurement for 3e14 also in climate chamber (“MPI cooling box”)
  - T set to -20°C
    - On-sensor T similar (cross-check with IVs)
  - Only the 2 LGADs measured (SiPM needed in other setup)

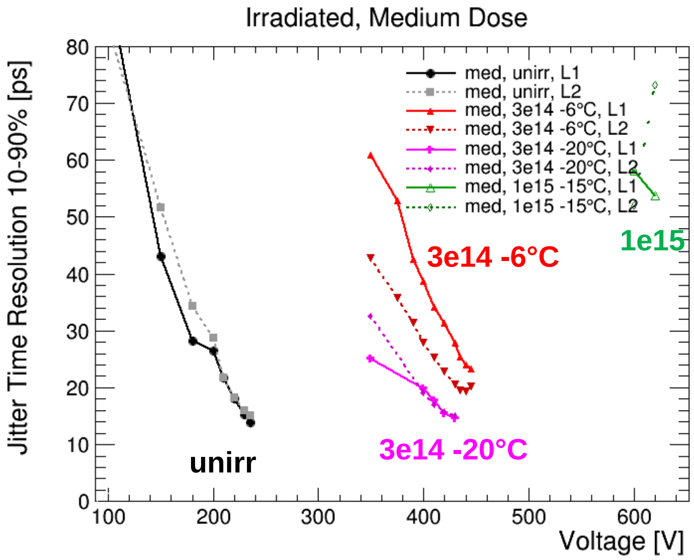
- Issues at 1e15
  - Sensors became instable at ~620 V
  - Both broke at that V after 1h of no beam (heating? Thermal runaway?)
    -> now breakdown V < 1V

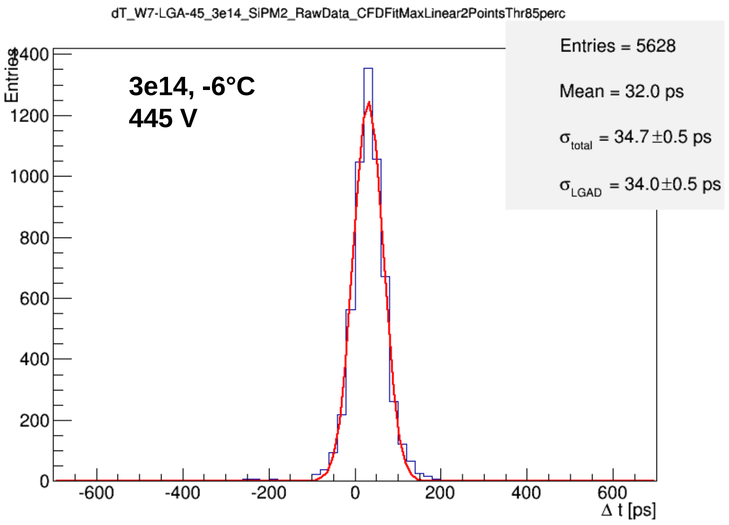
Waveform Properties (irr)





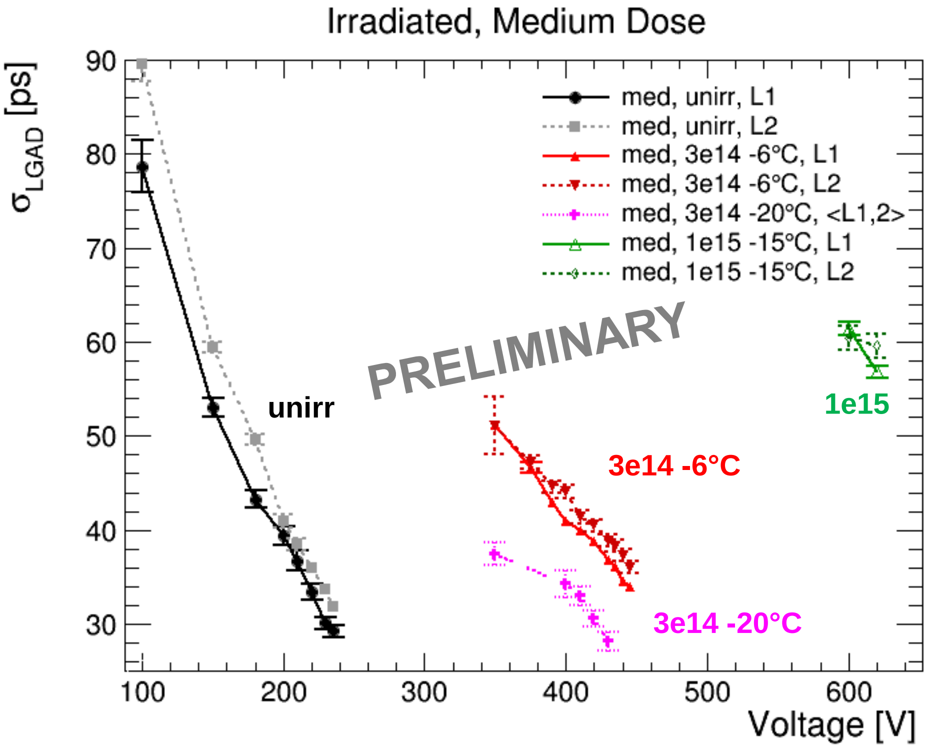
- Level of noise after irrad. covered by run-to-run variations; but increasing with V
- SNR higher at -20°C than -6°C for 3e14, similar values as before irr. achievable;
  but very low at 1e15

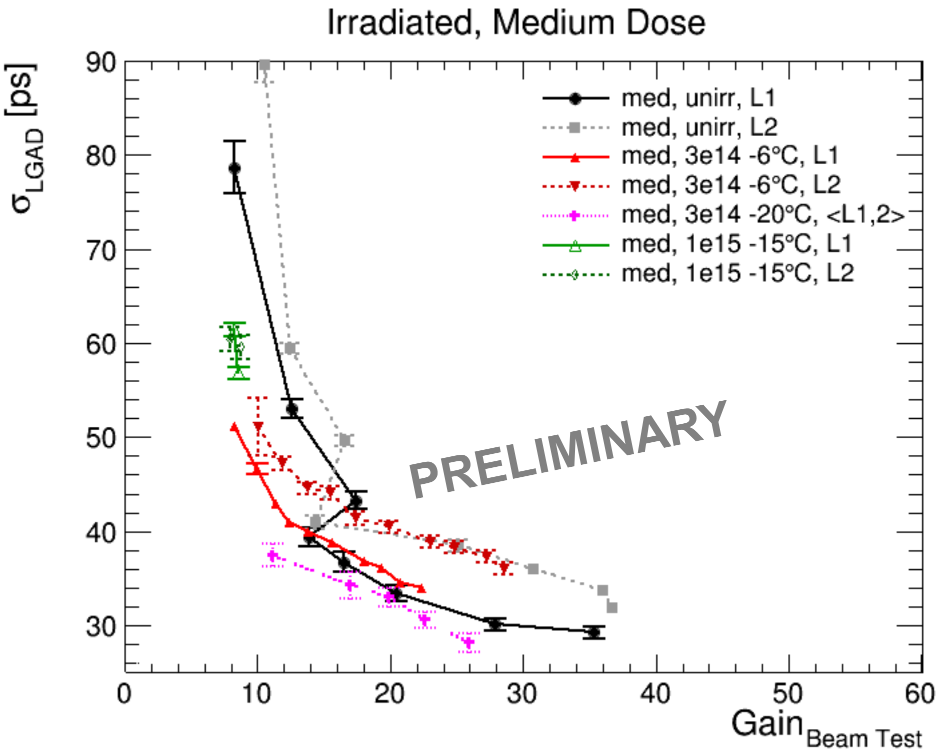




- Similar jitter values as before irradiation achievable at 3e14 (15-20 ps), but much worse at 1e15
- Δt: Good Gaussian behaviour also after irradiation

Time Resolution (irr)

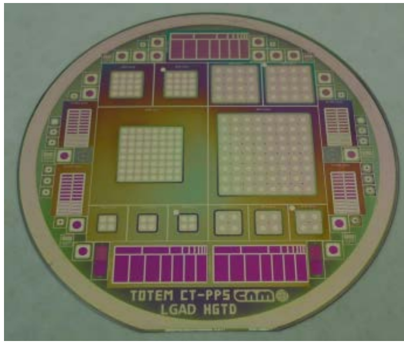




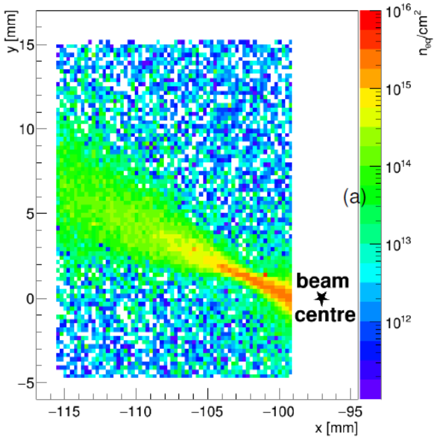
- At 3e14 similar time resolution achieved as before irradiation (at higher V)
    - -6°C: 34 ps at 445 V
    - -20°C: 28 ps at 430 V
- At 1e15 gain is highly reduced and voltage stability not high enough to compensate for it
    - ~60 ps at 620 V
- Gain dependence in all cases similar to before irradiation
  -> “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



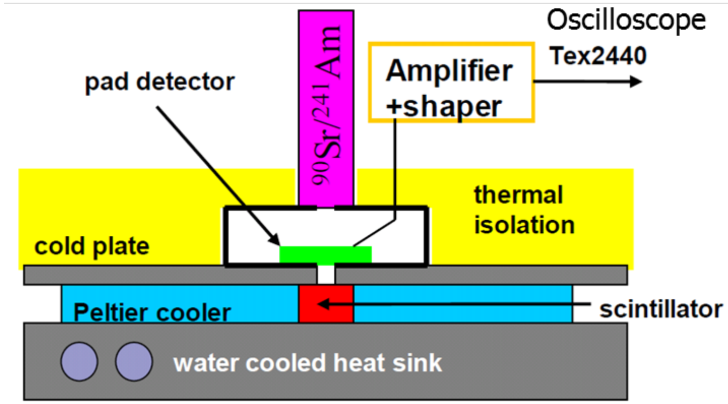
- **Promising first results**, but need to investigate further options to increase radiation hardness

Backup

Gain Measurement Setups

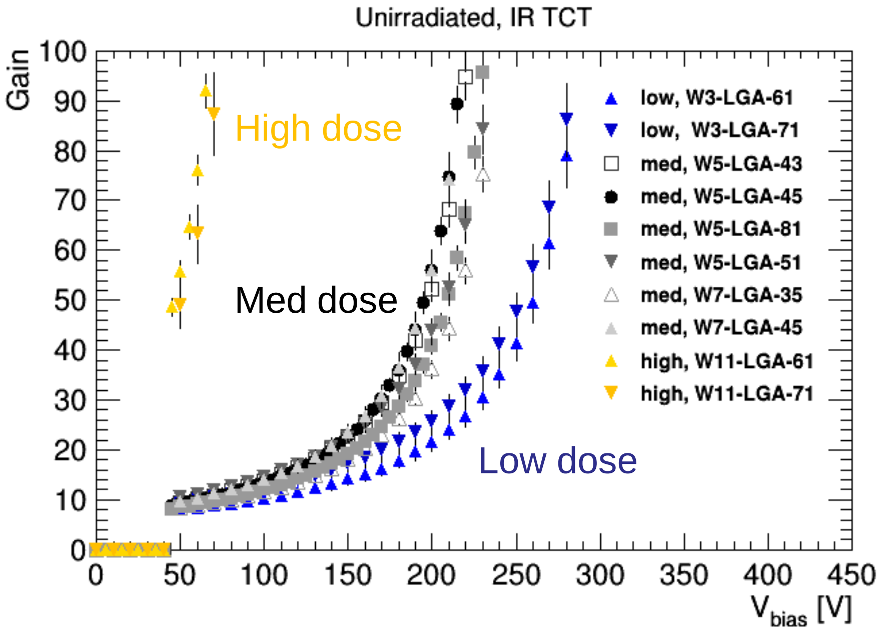
- TCT
  - TCT setup at IFAE Barcelona: scanning TCT from Particulars
  - IR laser from front-side
  - DRS4 readout
  - TCT PCB developed by DESY/Hamburg
  - Measurements performed on LGAD + reference without CM layer
    -> Gain as ratio
  - Measured LGADs before irradiation at room temperature

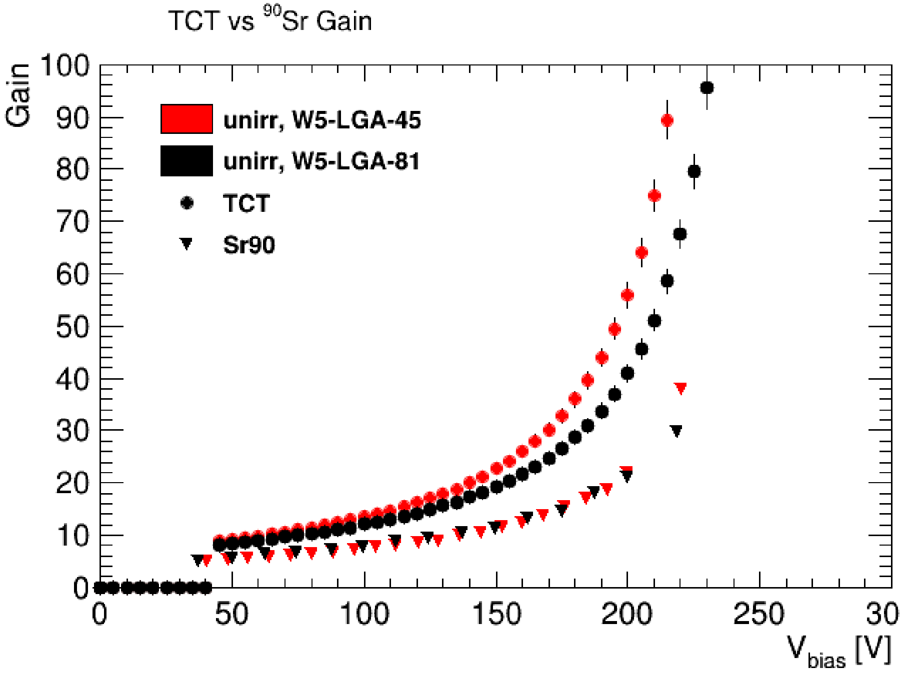
- Sr90 charge collection
  - Setup at Ljubljana
  - MIP-like β particles
  - Charge-sensitive preamplifier (Ortec 142B) + shaper (25 ns shaping time)
  - Oscilloscope readout
  - Calibrated with Am241
  - Mounted inside Al box with hole
  - Scintillator trigger
    -> but samples were quite small, still 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
  - 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



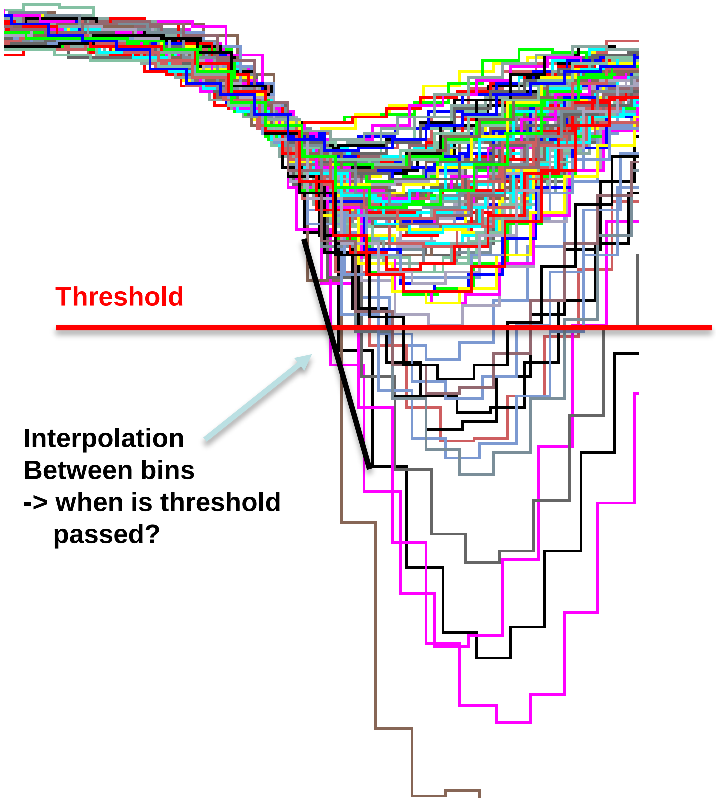


Pre-Studies and Remarks

- 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, Δt
- 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