Radiation Damage Effects on LGADs and Deep Diffused APDs

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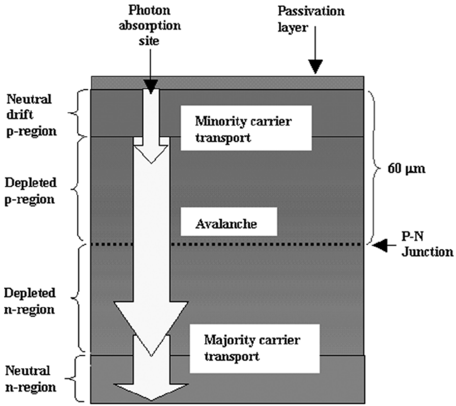
Deep Diffused Avalanche Photo Detectors

- Charge multiplication
- Gain: ≈ 500
- Bias: ≈ 1800 V
- Never fully depleted
- Die dimensions: $2.8 \times 2.8\,\mathrm{mm}^2$
- Nominal active area: $2 \times 2\,\mathrm{mm}^2$
- Thickness: $230 - 280\,\mu$m
- Custom fabrication process
- Produced by Radiation Monitoring Devices (RMD)

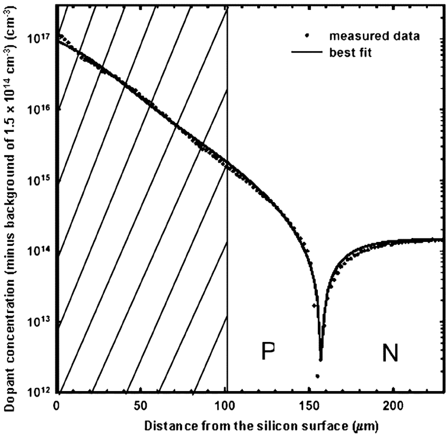


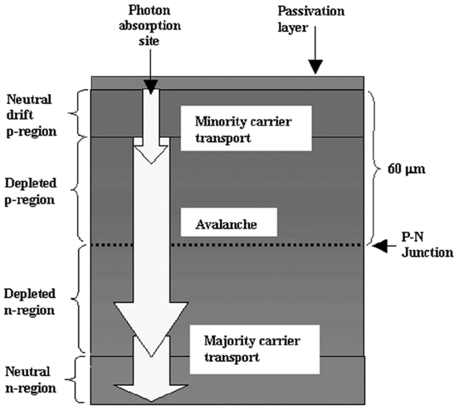
- Diffusion (non-depleted Si)
- Drift (depleted Si)
- Multiplication

M. McClish et. al. IEEE Trans. Nucl. Sci. Vol. 53, No. 5, 2006

Deep Diffused Avalanche Photo Detectors

Doping profile





- Diffusion (non-depleted Si)
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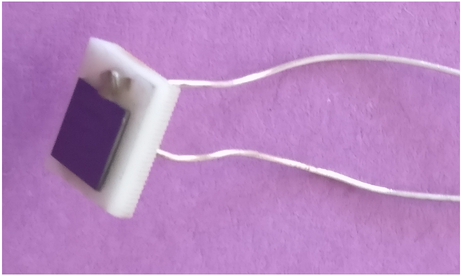
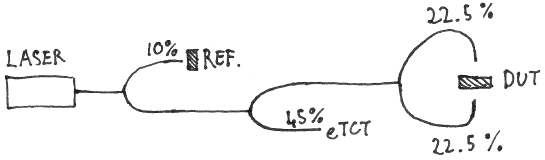
Sensors

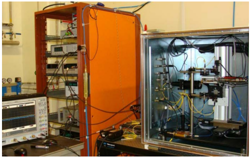
$2 \times 2\,\mathrm{mm}^2$ APDs



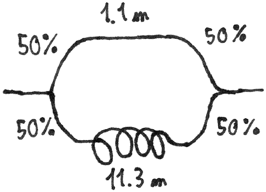
- Packaged
- Irradiated in Ljubljana (reactor neutrons)
- $\Phi_{eq} = 0, 3 \cdot 10^{13}, 6 \cdot 10^{13}, 3 \cdot 10^{14}, 10^{15}\ \mathrm{cm}^{-2}$
- Annealing of ≈ 70 min @ 21°C
- Sensor irradiated to $\Phi_{eq} = 3 \cdot 10^{14}\ \mathrm{cm}^{-2}$ is quite unstable
  $\Rightarrow$ no timing measurements

CERN SSD TCT Setup for Timing Measurements

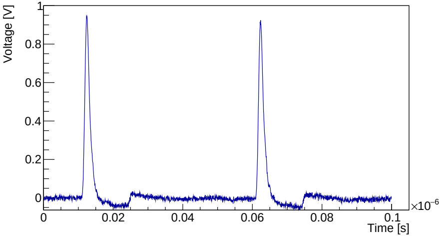




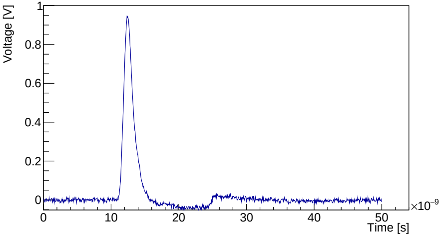
- Pulsed 1060 nm IR laser
  200 ps FWHM
- **0.8 MIPs** intensity
  1 MIP := 74 eh/μm
  (Without reflections)
- 50 ns delay line between laser and first splitter
- 2×2 mm^2 APD, non-irradiated
- 1745 V, 20°C
- 40 dB, 2 kV Cividec amplifier
- Amplitude difference of less than 5 %

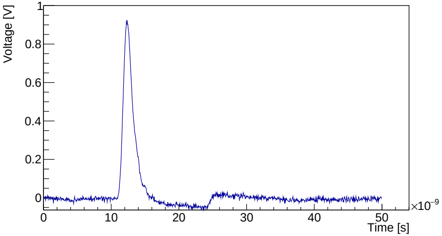


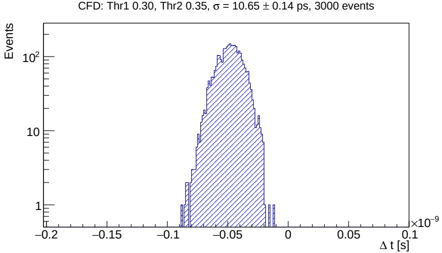
Single event



Analysis (2×2 mm^2 non-irradiated APD)







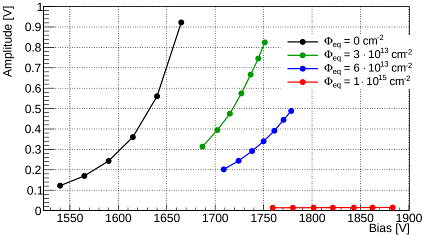
- Divide waveform in two parts
- Apply different thresholds to estimate time difference
- Select best threshold combination to minimize std. dev.

Divide std. dev. by $\sqrt{2}$ to get single pulse resolution: 7.5 ± 0.1 ps

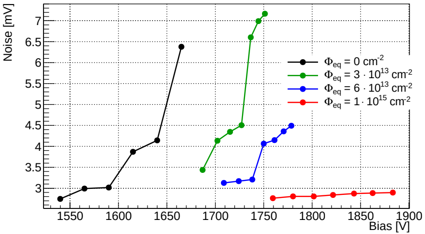
No timing reference needed

N-irradiated 2×2 mm^2 APDs, -20°C, 0.8 MIPs

Amplitude



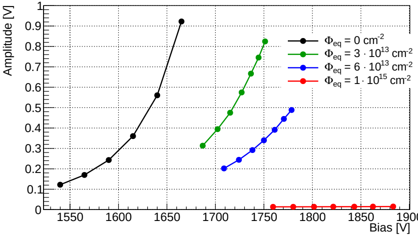
Noise



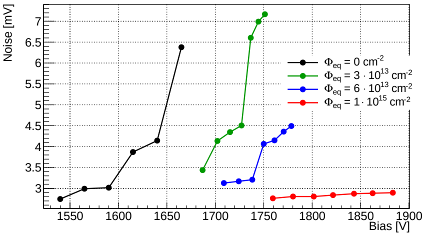
- Both dominated by multiplication
- $\Phi_{eq} \leq 6 \cdot 10^{13}$ cm^{-2}: amplitude is restored by applying bias
  Here current limit of 10 μA is hit
- $\Phi_{eq} = 10^{15}$ cm^{-2}: low or no multiplication

N-irradiated 2×2 mm^2 APDs, -20°C, 0.8 MIPs

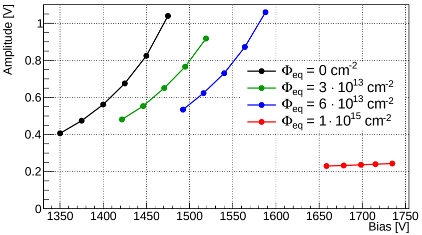
Amplitude



Noise

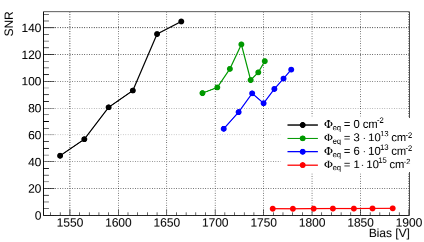


Amplitude, same detectors, **15 MIPs**

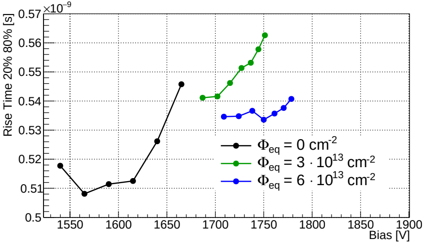


N-irradiated 2×2 mm^2 APDs, -20°C, 0.8 MIPs

SNR



Rise Time 20% 80%

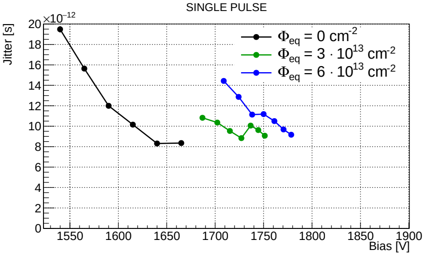


- Non-monotone function of bias voltage

- $\Phi_{eq} \leq 6 \cdot 10^{13}$ cm^{-2}: $\approx$ 550 ps, all points within 11%
- $\Phi_{eq} = 10^{15}$ cm^{-2}: around 5.1-5.3 ns, influenced by low SNR

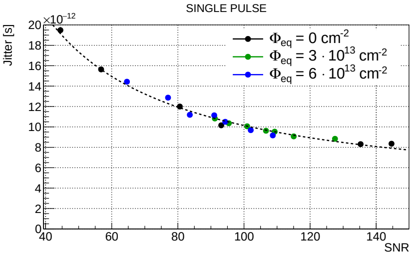
N-irradiated 2×2 mm^2 APDs, -20°C, 0.8 MIPs

Time Resolution for one pulse



- Obtained by dividing the 2 pulses std. dev. by $\sqrt{2}$
- $\Phi_{eq} \leq 6 \cdot 10^{13}$ cm^{-2}: $8 - 10$ ps
- $\Phi_{eq} = 10^{15}$ cm^{-2}: around 508-553 ps, low SNR

Time Resolution vs. SNR



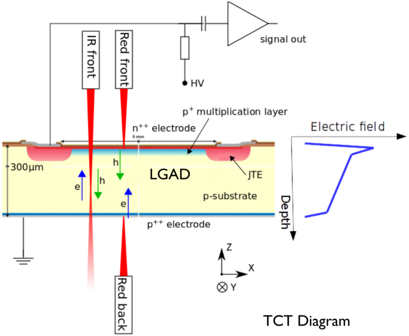
- Time resolution scales with 1/SNR

“Dark pulses”

“Dark pulses” with a frequency of ≈ 3 MHz are observed at -20°C, 1700 V for the sensor irradiated to $\Phi_{eq} = 10^{15}$ cm^{-2}.

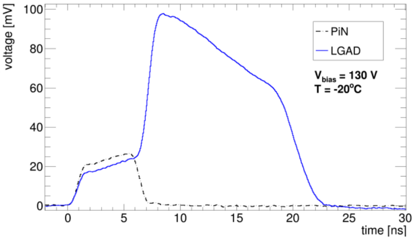
Radiation Effects in 285 μm Thick LGADs

- CNM run 7859
- Thickness: 285 μm
- Area: $3 \times 3\,\text{mm}^2$
- Multiplication layer dose: 1.8 and $2.0 \cdot 10^{13}\,\text{cm}^{-2}$
- $I < 0.3\,\mu$A @ 20°C, full depletion
- Irradiated with 24 GeV/c protons
- Initial annealing: 80 min at 60°C



TCT Diagram

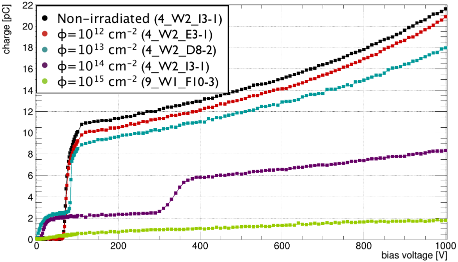
Red Back Illumination



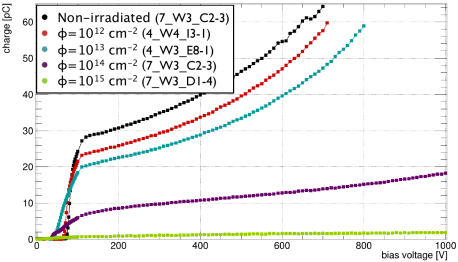
Charge Collection from “Red Back” Illumination

$\lambda = 660\,$nm, 25 ns integration time, -20°C   80 min @ 60°C

Mult. layer dose $1.8 \cdot 10^{13}\,\text{cm}^{-2}$



Mult. layer dose $2.0 \cdot 10^{13}\,\text{cm}^{-2}$

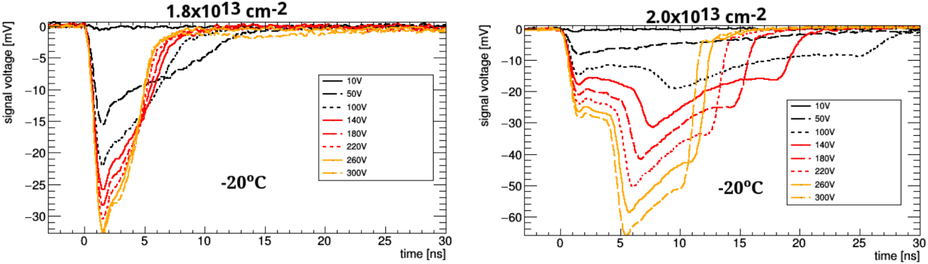


- Charge collection reduced by irradiation
- Two “steps” present in the $\Phi_{eq} = 10^{13}, 10^{14}\,\text{cm}^{-2}$ curves for mult. layer dose $1.8 \cdot 10^{13}\,\text{cm}^{-2}$
  $\Rightarrow$ the shape indicates that the depletion starts from the back of the detector

The sensors irradiated to $\Phi_{eq} = 10^{14}\,\text{cm}^{-2}$ were studied further.

S. Otero Ugobono, VERTEX 2017

Waveforms “Red Back” Illumination $\Phi_{eq} = 10^{14}\,\mathrm{cm}^{-2}$



The depletion region develops from the back of the device before the effects of multiplication can be seen in the collected charge.

This can influence the measurement of the effective doping of the multiplication layer after irradiation.

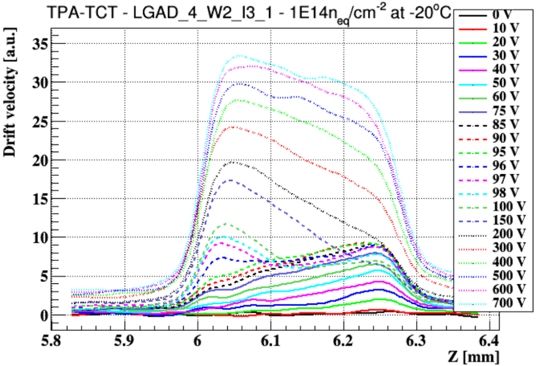
S. Otero Ugobono, VERTEX 2017

Two Photons Absorption TCT

For details about this technique, see talk from M. Fernandez Garcia.

- Point-like generation of charge carriers
- Generation point moved along detector thickness

Mult. layer dose $1.8 \cdot 10^{13}\,\mathrm{cm}^{-2}$, $\Phi_{eq} = 10^{14}\,\mathrm{cm}^{-2}$, $T = -20^{\circ}\mathrm{C}$



- Electric field develops from the back side until $\approx 95\,\mathrm{V}$
- Afterwards, the field starts to increase from the front of the detector

M. Fernandez Garcia, 31st RD50 workshop, 2017

Waveforms "Red Back" Illumination

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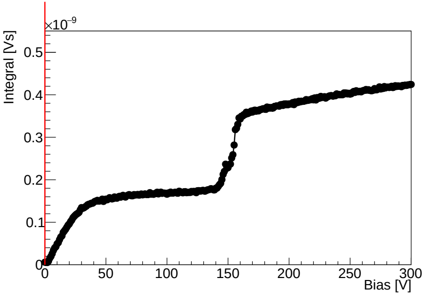

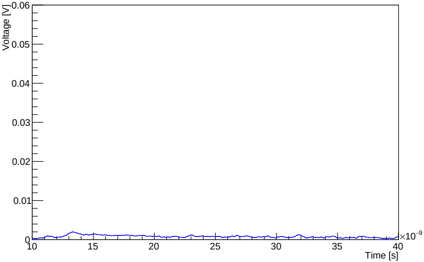

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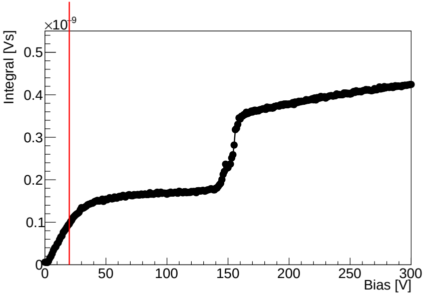

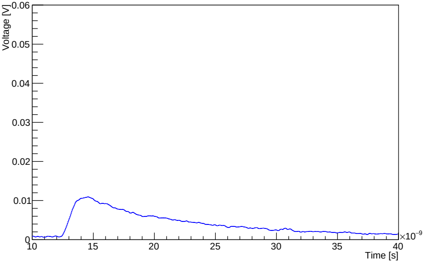

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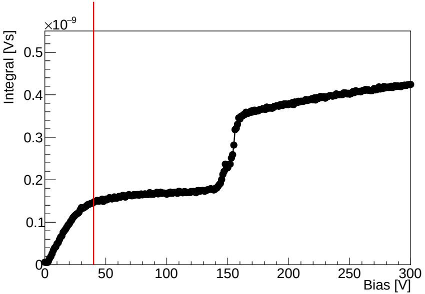

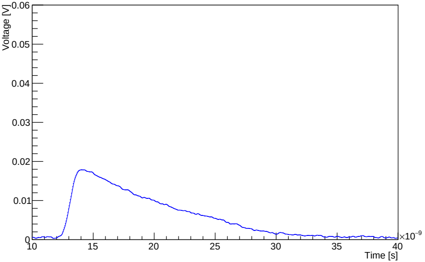

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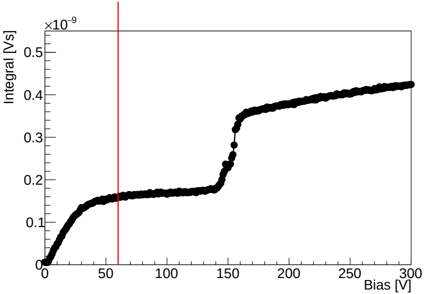

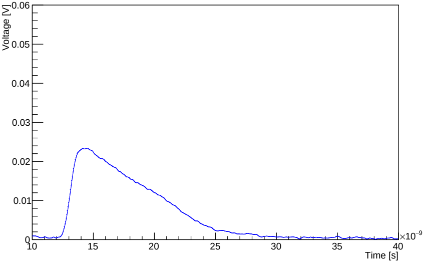

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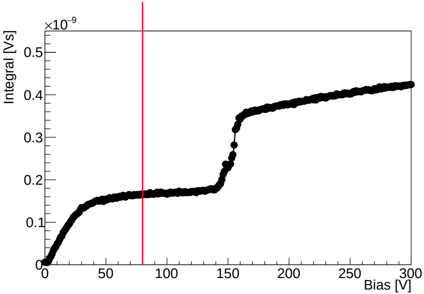

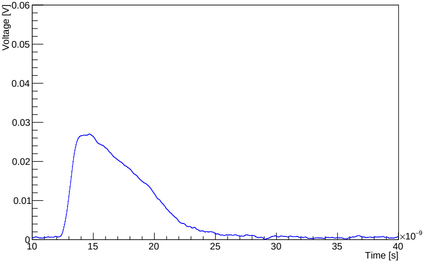

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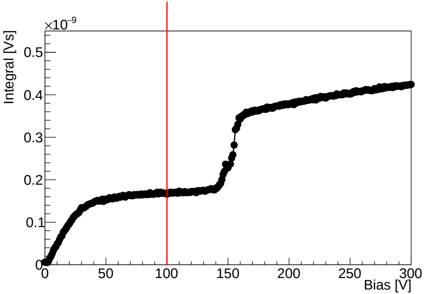

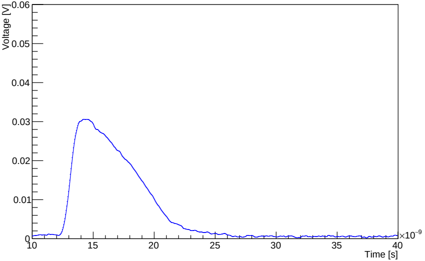

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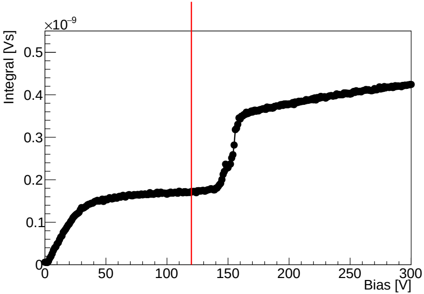

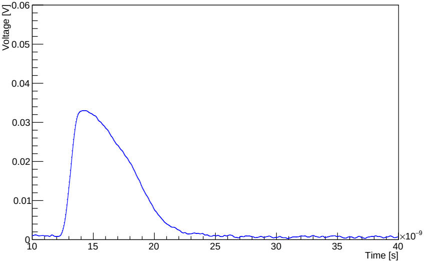

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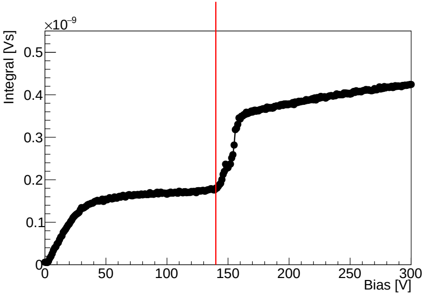

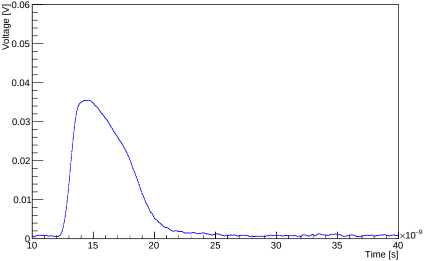

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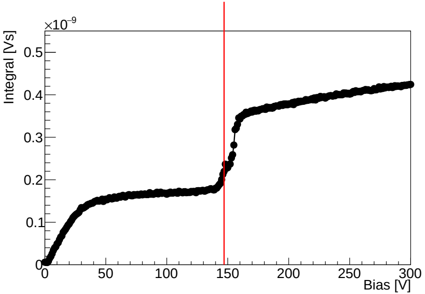

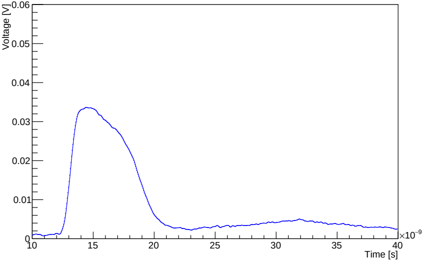

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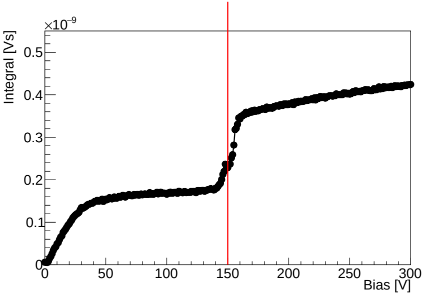

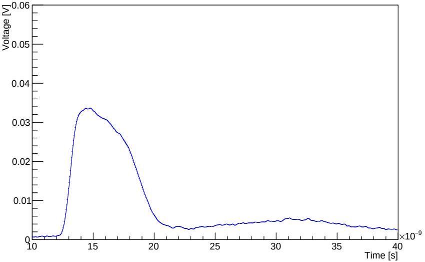

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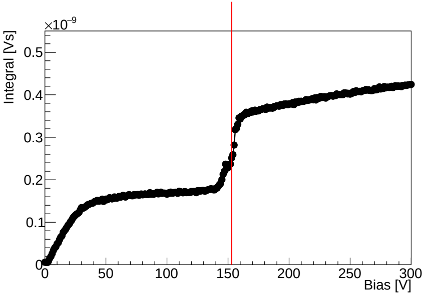

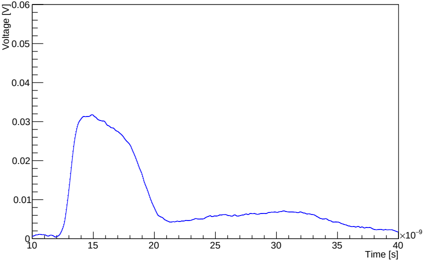

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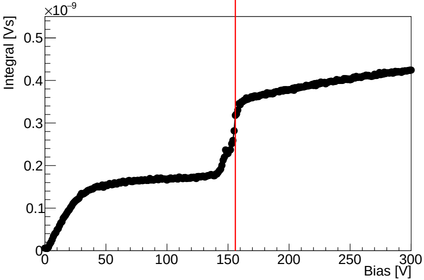

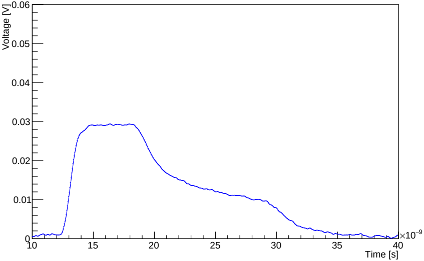

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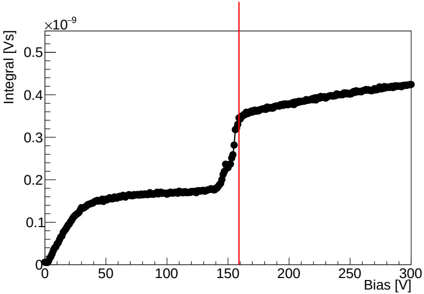
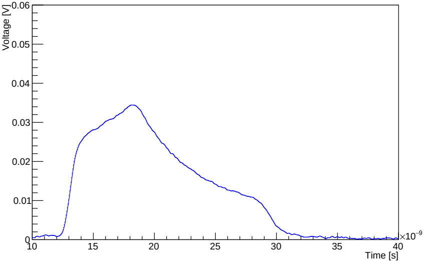
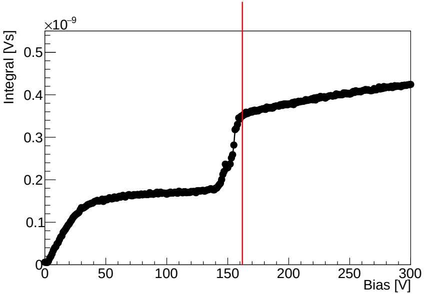
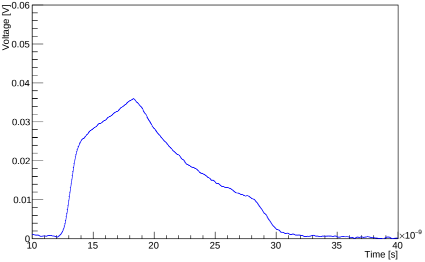




Waveforms “Red Back” Illumination

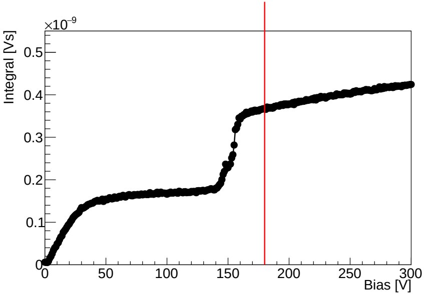
Mult. layer dose $1.8 \cdot 10^{13}\,\mathrm{cm}^{-2}$, $\Phi_{eq} = 10^{14}\,\mathrm{cm}^{-2}$, $T = -20^{\circ}\mathrm{C}$

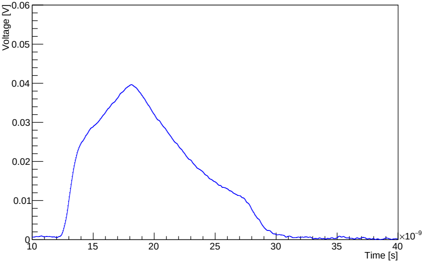




Waveforms “Red Back” Illumination

Mult. layer dose $1.8 \cdot 10^{13}\,\mathrm{cm}^{-2}$, $\Phi_{eq} = 10^{14}\,\mathrm{cm}^{-2}$, $T = -20^{\circ}\mathrm{C}$





Waveforms “Red Back” Illumination

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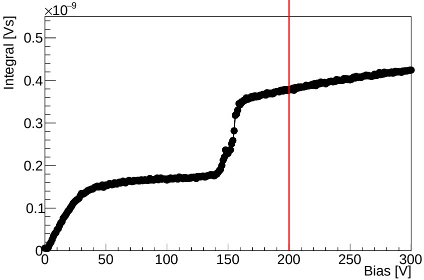
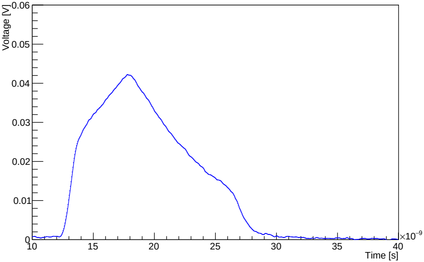
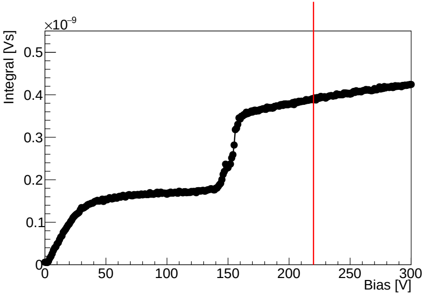
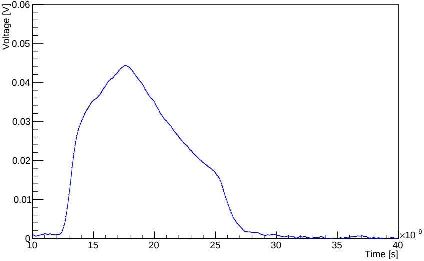




Waveforms “Red Back” Illumination

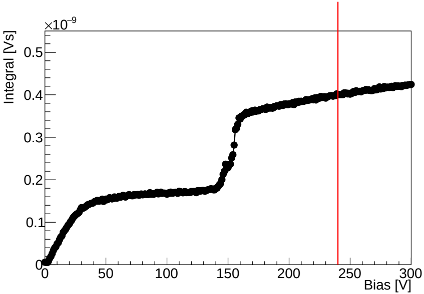
Mult. layer dose $1.8 \cdot 10^{13}\,\mathrm{cm}^{-2}$, $\Phi_{eq} = 10^{14}\,\mathrm{cm}^{-2}$, $T = -20^{\circ}\mathrm{C}$

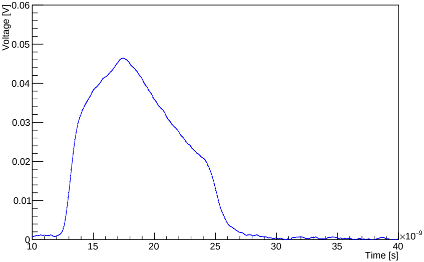




Waveforms "Red Back" Illumination

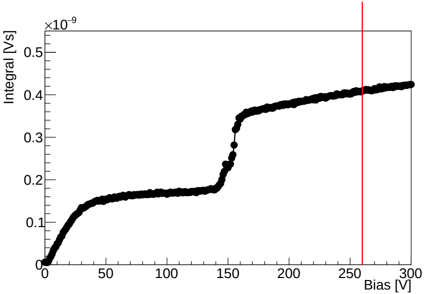
Mult. layer dose $1.8 \cdot 10^{13}\,\text{cm}^{-2}$, $\Phi_{eq} = 10^{14}\,\text{cm}^{-2}$, $T = -20^{\circ}\text{C}$

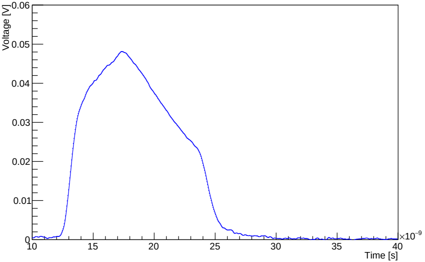




Waveforms “Red Back” Illumination

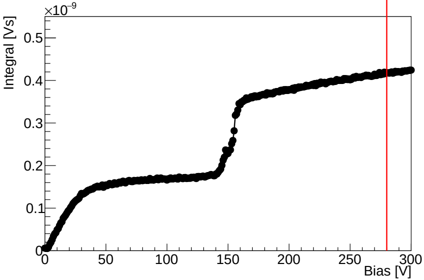
Mult. layer dose $1.8 \cdot 10^{13}\,\text{cm}^{-2}$, $\Phi_{eq} = 10^{14}\,\text{cm}^{-2}$, $T = -20^\circ\text{C}$

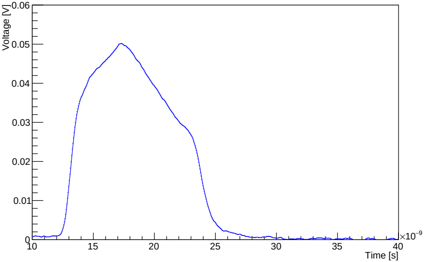




Waveforms “Red Back” Illumination

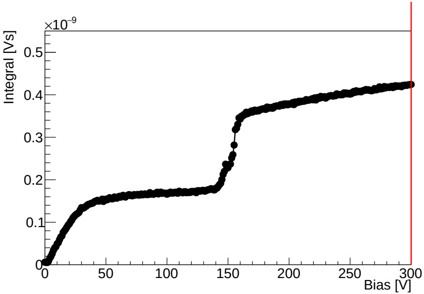
Mult. layer dose $1.8 \cdot 10^{13}\,\mathrm{cm}^{-2}$, $\Phi_{eq} = 10^{14}\,\mathrm{cm}^{-2}$, $T = -20^{\circ}\mathrm{C}$

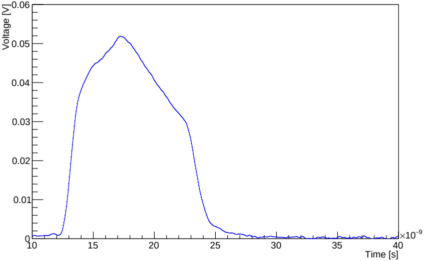




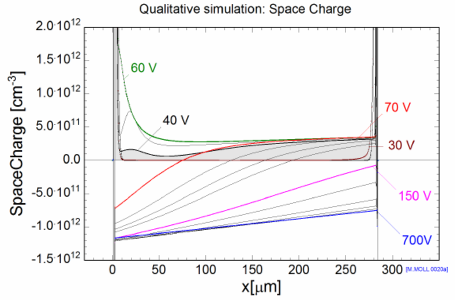
Waveforms "Red Back" Illumination

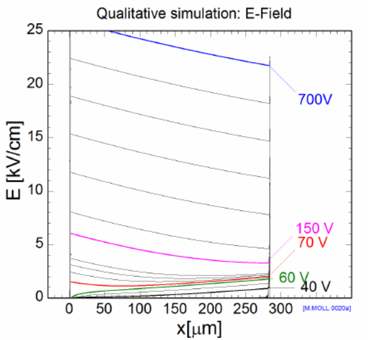
Mult. layer dose $1.8 \cdot 10^{13}\,\mathrm{cm}^{-2}$, $\Phi_{eq} = 10^{14}\,\mathrm{cm}^{-2}$, $T = -20^\circ\mathrm{C}$



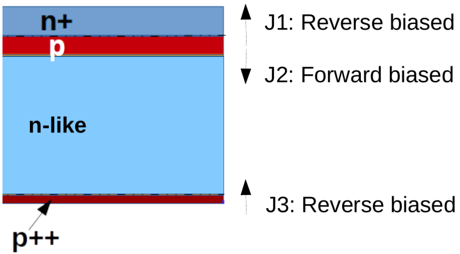


Qualitative Simulation





Triple junction



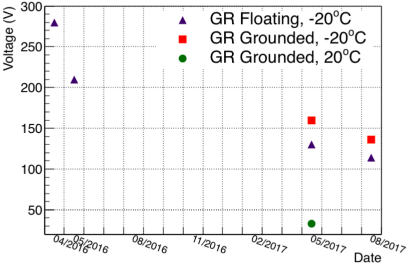
- Qualitative TCAD simulation can reproduce the features of the measurements
- The model and observations suggest the presence of three junctions

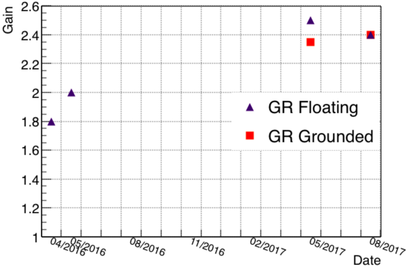
Further studies are needed.

Annealing Effects on $\Phi_{eq} = 10^{14}\,\text{cm}^{-2}$ Samples

Room temperature annealing due to measurements and samples handling

Mult. layer dose $1.8 \cdot 10^{13}\,\text{cm}^{-2}$, -20°C





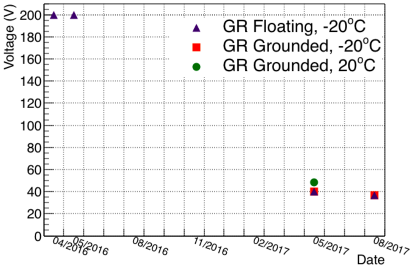
- Multiplication onset voltage (red front illumination) decreases with annealing
- Gain at 400 V (defined using PiN diodes) increases with annealing
- Both mult. layer doses show similar results
- Strong dependence on annealing, origin to be understood

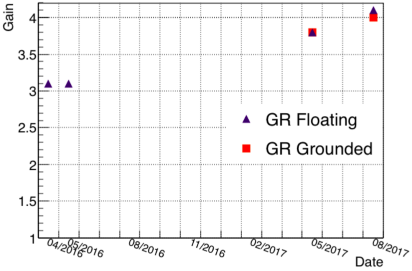
S. Otero Ugobono, VERTEX 2017

Annealing Effects on $\Phi_{eq} = 10^{14}\,\text{cm}^{-2}$ Samples

Room temperature annealing due to measurements and samples handling

Mult. layer dose $2.0 \cdot 10^{13}\,\text{cm}^{-2}$, -20°C





- Multiplication onset voltage (red front illumination) decreases with annealing
- Gain at 400 V (defined using PiN diodes) increases with annealing
- Both mult. layer doses show similar results
- Strong dependence on annealing, origin to be understood

S. Otero Ugobono, VERTEX 2017

Summary & Outlook

- Measured time resolution of neutron irradiated 2×2 mm^2 APDs
- Performance at det. center not degraded by neutron irradiation of at least $\Phi_{eq} = 6 \cdot 10^{13}$ cm^{-2} $\Rightarrow \sigma_t = 8 - 10$ ps @ 0.8 MIPs
- $\Phi_{eq} = 10^{15}$ cm^{-2}: very low or no gain, "dark pulses" are observed

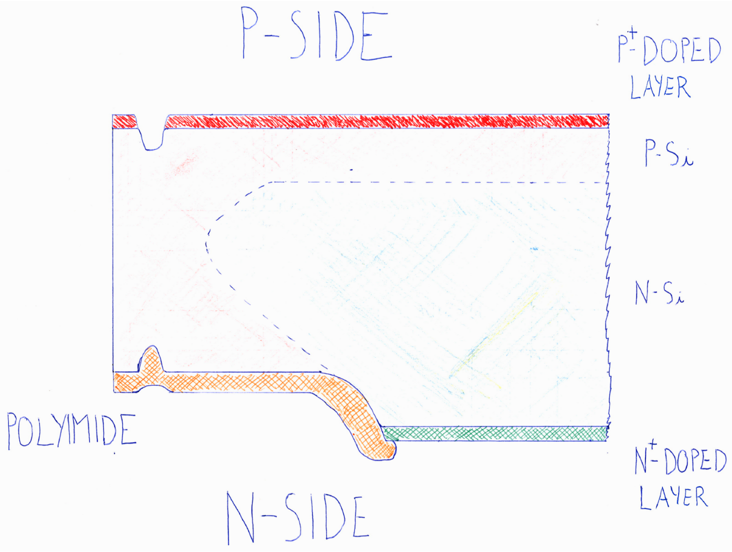
- Studied the properties of proton irradiated 285 μm thick LGADs
- In some cases the electric field develops from the back of the detector
- The measurements suggest the presence of three junctions in the detectors

Outlook:

- New APD irradiation to explore region $6 \cdot 10^{13} \leq \Phi_{eq} \leq 7 \cdot 10^{14}$ cm^{-2}
- Characterization of irradiated LGADs from CNM run 8622 and CNM run 10478 50 μm thick quad-diodes.
  Irradiation with 24 GeV/c protons is completed
- Extend study of annealing effects

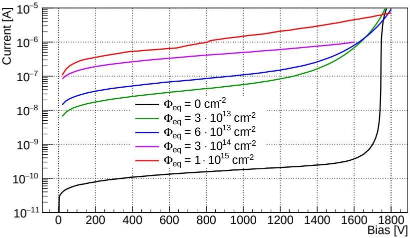
Backup Material

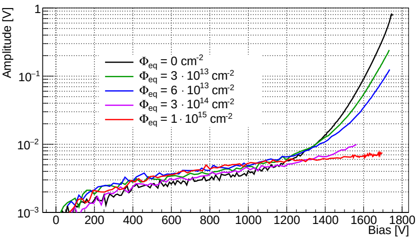
APD Section (not to scale)



IV and Signal Amplitude 2×2 mm^2 APDs

$T = -20°$C, $\lambda = 1060$ nm, **15 MIPs** equivalent intensity,
10 dB amplification, 256 averages in the scope

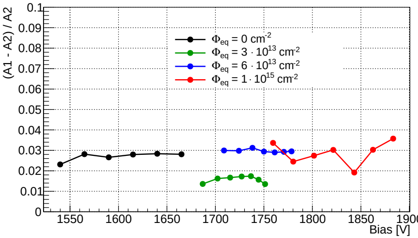




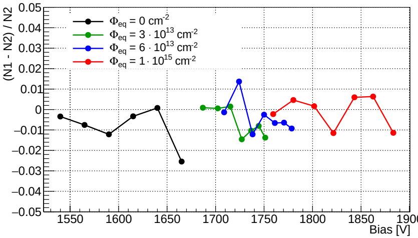
- Increase in bulk generation current
- Reduction of gain

Difference Pulses 2×2 mm^2 APDs

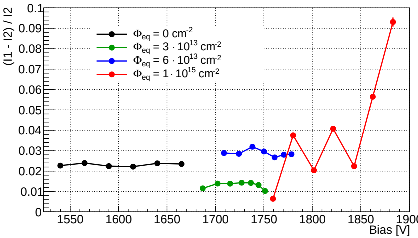
Amplitude



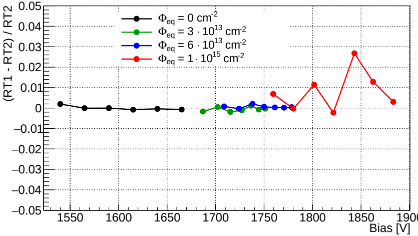
Noise



Integral



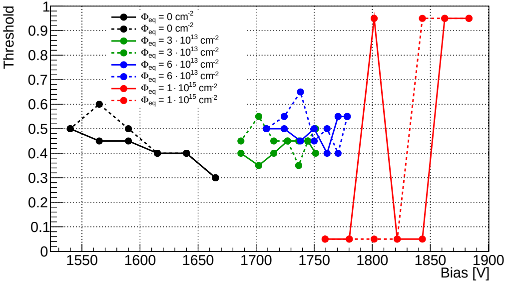
Rise Time 20% 80%



Data for $\Phi_{eq} = 10^{15}$ cm^{-2} influenced by low SNR

Properties of pulses equal within 5 %

Thresholds 2 × 2 mm^2 APDs



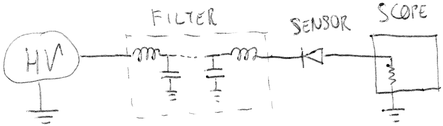
Continuos line: first pulse, Dashed: second pulse

Similar values, difference due to statistical fluctuations of the Δt std. dev.

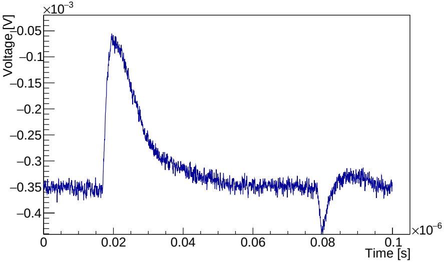
$\Phi_{eq} = 10^{15}$ cm^{-2}: jumps due to low SNR

Calibration IR back TCT+, without Amplifier

- 100 μm p-type FZ sensor, $V_{dep} \approx 2$ V
- 5 V bias from sensor back
- Long bias cable to avoid reflections
- 1024 averages in scope
- 20 repetitions
- Integrate (15 - 70) ns
- Intensity varied using shutter



20 mV amplitude on ref. photodiode

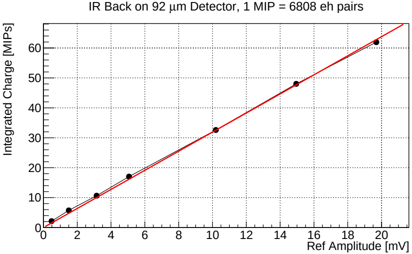


Calibration IR Back TCT+

Real det thickness 92 μm, 74 eh pairs / μm

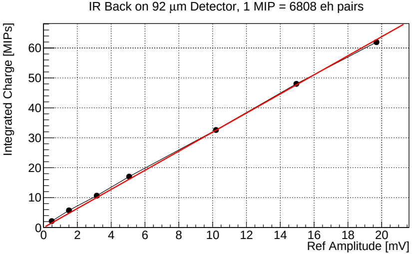
Fit: $y = ax$

Without amplifier



3.189 ± 0.007 MIPs/mV

With amplifier



3.1113 ± 0.0009 MIPs/mV

(No error due to ampli gain measurement considered)

Results in agreement within 3 %

3.2 MIPs/mV

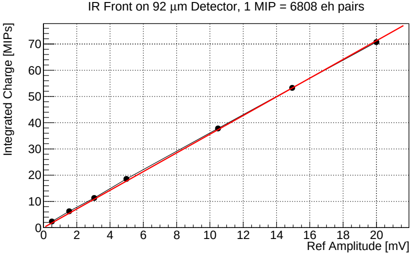
Also, the calibration of the ampli worked fine.

Calibration IR Front TCT+

Real det thickness 92 μm, 74 eh pairs / μm

Fit: $y = ax$

Without amplifier



3.562 ± 0.006 MIPs/mV

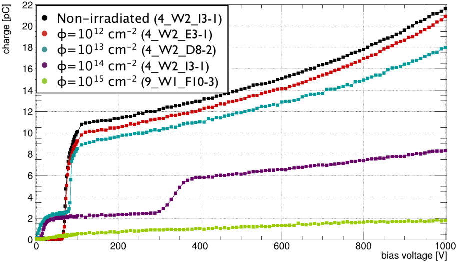
3.6 MIPs/mV

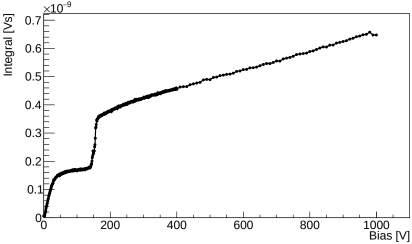
12 % difference with respect to IR back

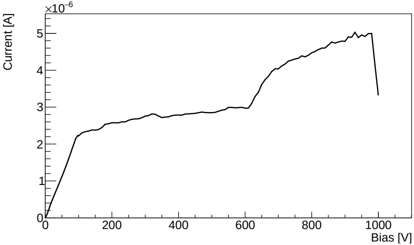
Annealing Effects

Red back Illumination

Mult. layer dose $1.8 \cdot 10^{13}\,\mathrm{cm}^{-2}$, $\Phi_{eq} = 10^{14}\,\mathrm{cm}^{-2}$, $-20^{\circ}\mathrm{C}$







(Right): IV from 28.04.2017, TCT from 12.05.2017