Characterization of Irradiated APDs for Timing Applications

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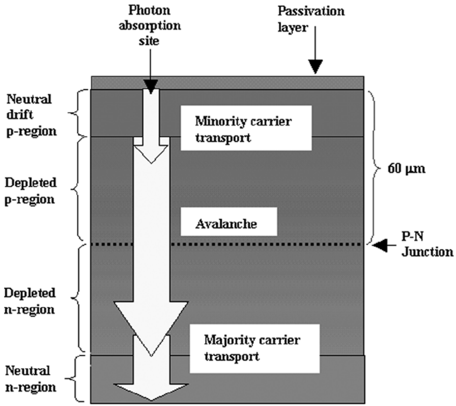
Deep Diffused Avalanche Photo Detectors

- Charge multiplication
- Gain: ≈ 500
- Bias: ≈ 1800 V
- Never fully depleted
- Die dimensions: $2.8 \times 2.8\,\text{mm}^2$ and $10 \times 10\,\text{mm}^2$
- Nominal active area: $2 \times 2\,\text{mm}^2$ and $8 \times 8\,\text{mm}^2$
- Thickness: $230 - 280\,\mu\text{m}$
- Custom fabrication process
- Produced by Radiation Monitoring Devices (RMD)

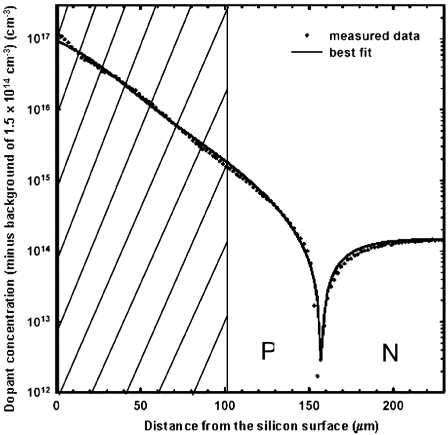


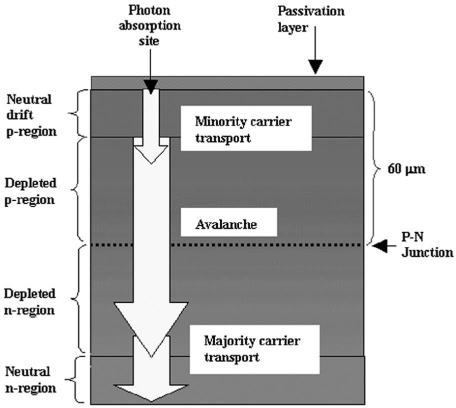
- Diffusion (non-depleted Si)
- Drift (depleted Si)
- Multiplication

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

Deep Diffused Avalanche Photo Detectors

Doping profile





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

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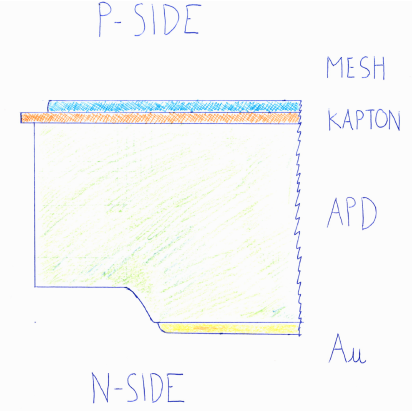
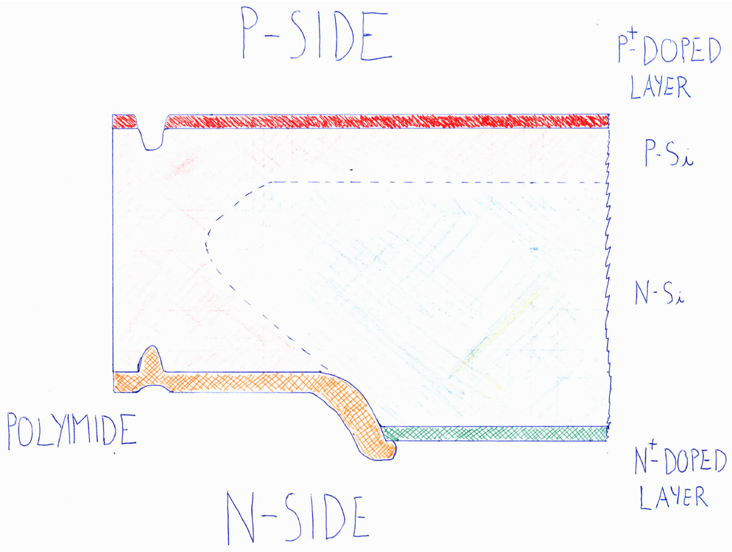
APDs with Mesh (AC coupled) Readout



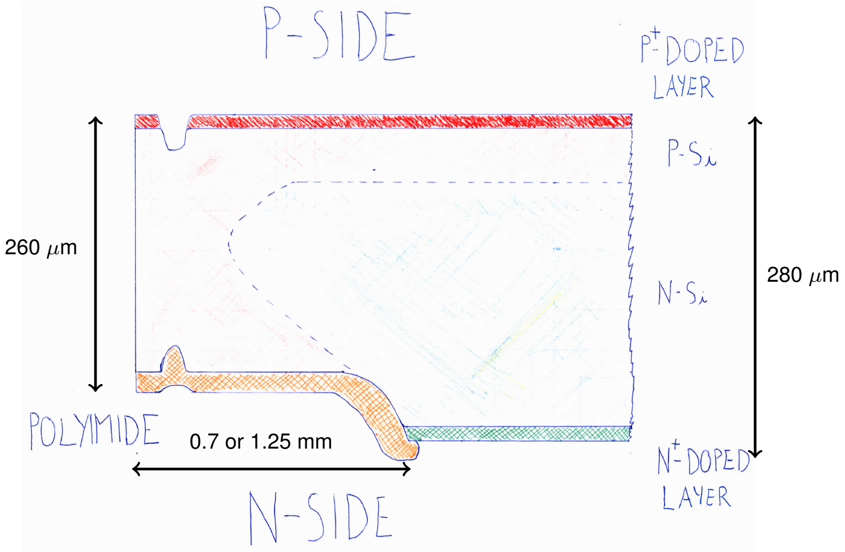
- Mesh to pick-up signal from p-side
- Au to improve conductivity of n-side
- Readout of mesh and n-side

These devices are not discussed in this talk

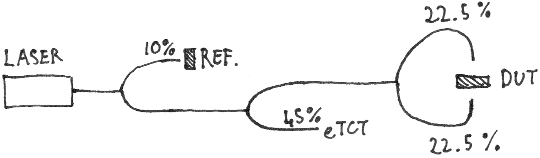
Section (not to scale)

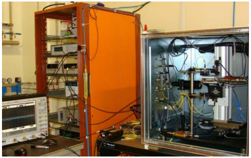


Section (not to scale)

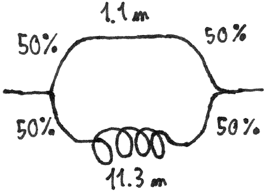


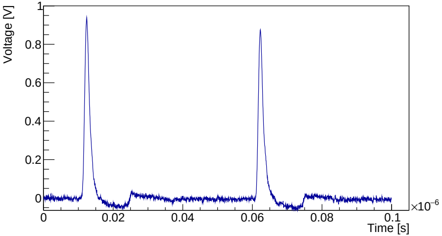
CERN SSD TCT Setup for Timing Measurements



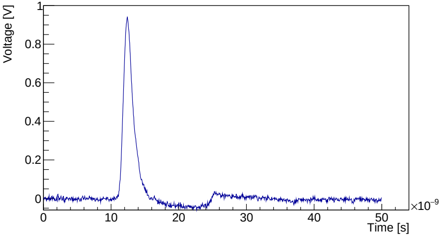


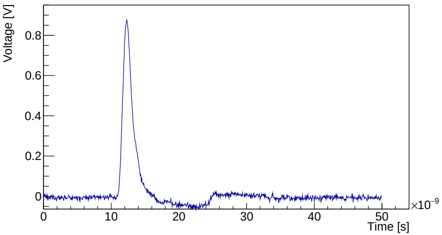
- Pulsed 1060 nm IR laser
  200 ps FWHM
- **0.8 MIPs** intensity
  1 MIP := 74 eh/μm
  (Without reflections)
- 50 ns delay line between laser and first splitter
- 2×2 mm^2 APD, non-irradiated
- 1745 V, 20°C
- 40 dB, 2 kV Cividec amplifier
- Amplitude difference of less than 5 %





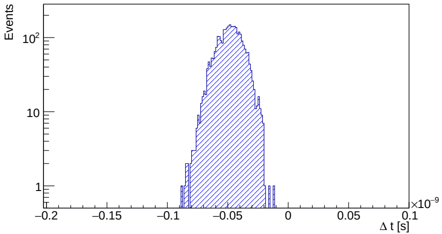
Analysis (2×2 mm^2 non-irradiated APD)





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

CFD: Thr1 0.30, Thr2 0.35, σ = 10.65 $\pm$ 0.14 ps, 3000 events

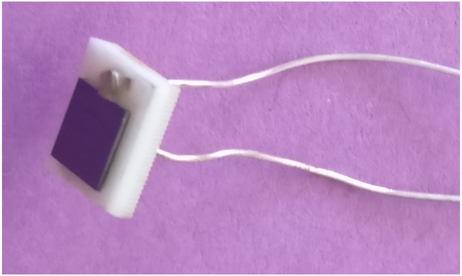


Divide std. dev. by $\sqrt{2}$ to get single pulse resolution: 7.5 ± 0.1 ps

No timing reference needed

Irradiated Sensors

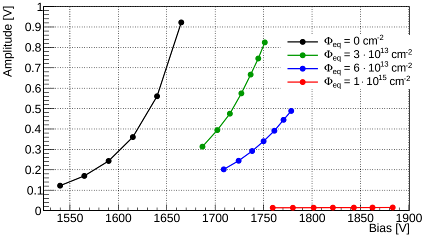
$2 \times 2\,\text{mm}^2$ APDs



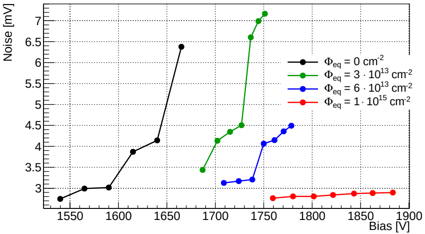
- Packaged
- Irradiated in Ljubljana (reactor neutrons)
- $\Phi_{eq} = 0, 3 \cdot 10^{13}, 6 \cdot 10^{13}, 3 \cdot 10^{14}, 10^{15}\ \text{cm}^{-2}$
- Annealing of ≈ 70 min @ 21°C
- Sensor irradiated to $\Phi_{eq} = 3 \cdot 10^{14}\ \text{cm}^{-2}$ is quite unstable (it eats amplifiers)

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

Amplitude



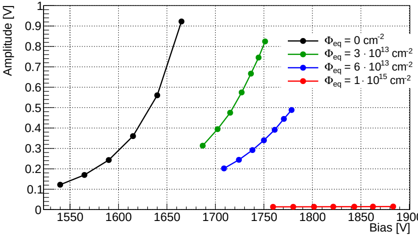
Noise



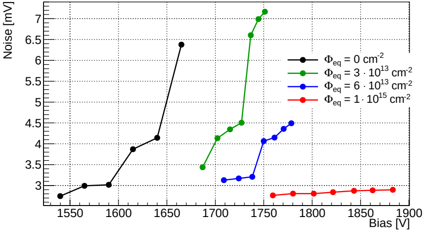
- Both dominated by multiplication
- $\Phi_{eq} \leq 6 \cdot 10^{13}$ cm^{-2}: amplitude is restored by applying bias
  Here current limit of 10 μA is hit
- $\Phi_{eq} = 10^{15}$ cm^{-2}: low or no multiplication

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

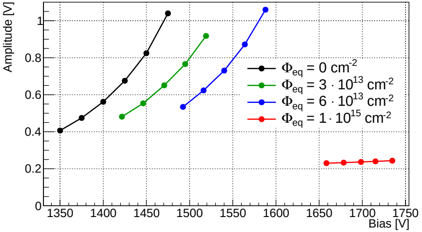
Amplitude



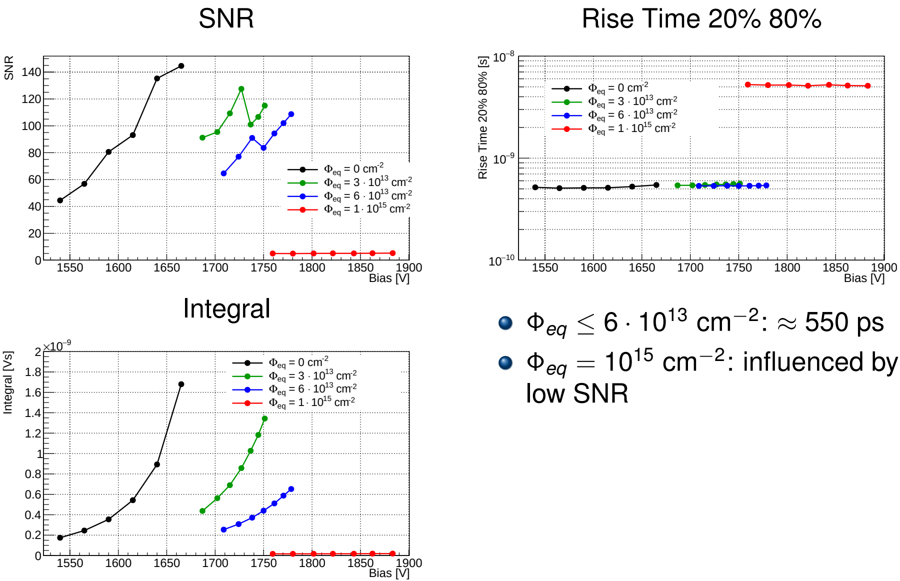
Noise



Amplitude, same detectors, **15 MIPs**

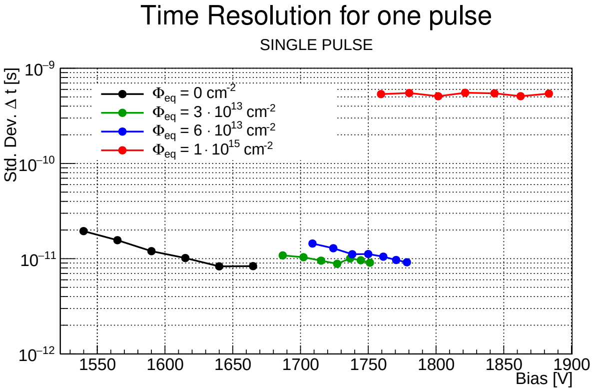


N-irradiated 2 × 2 mm² APDs, −20°C, 0.8 MIPs



- $\Phi_{eq} \leq 6 \cdot 10^{13}$ cm^{-2}: ≈ 550 ps
- $\Phi_{eq} = 10^{15}$ cm^{-2}: influenced by low SNR

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

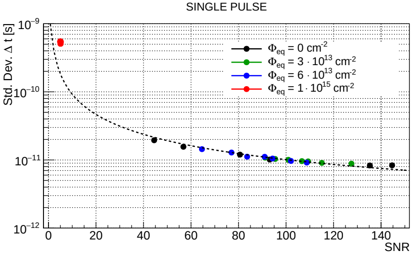


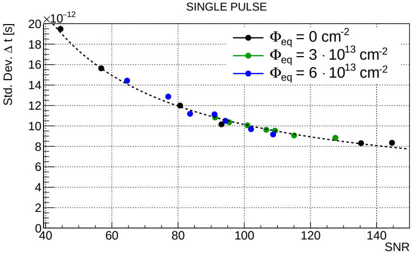
- Obtained by dividing the 2 pulses std. dev. by $\sqrt{2}$
- $\Phi_{eq} \leq 6 \cdot 10^{13}$ cm^{-2}: similar time resolution $8 - 10$ ps
- $\Phi_{eq} = 10^{15}$ cm^{-2}: low SNR

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

Time Resolution vs. SNR

Excluding $\Phi_{eq} = 10^{15}$ cm^{-2}





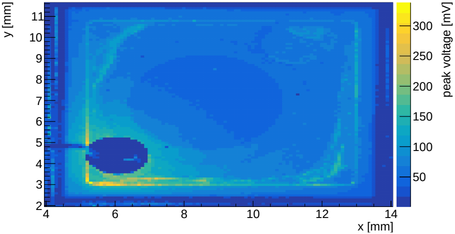
- Time resolution scales with 1/SNR
- SNR is not a monotone function of bias for $\Phi_{eq} \neq 0$ cm^{-2}

"Dark pulses"

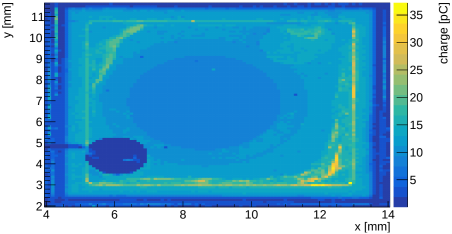
"Dark pulses" with a frequency of ≈ 3 MHz are observed for the sensor irradiated to $\Phi_{eq} = 10^{15}$ cm^{-2}.

$8 \times 8\,mm^2$ APD, Uniformity of Response

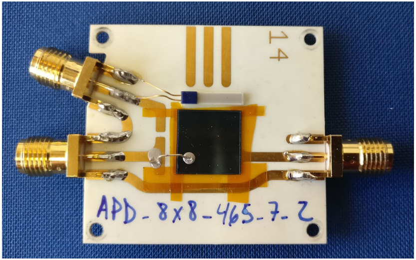
Amplitude



Charge in 25 ns



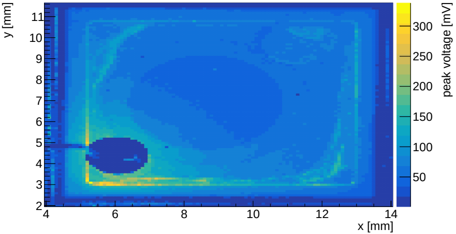
- IR laser, 1700 V, $-20°C$
- Features of background in both charge and amplitude
- Take ratio
  $\rightarrow$ remove charge influence on amplitude



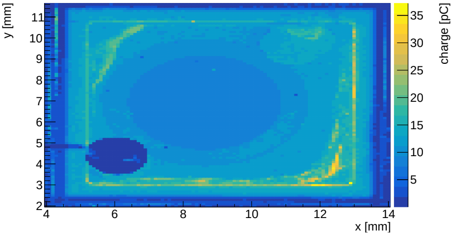
The amplitude is affected by the resistivity of the doped silicon

$8 \times 8\,\mathrm{mm}^2$ APD, Uniformity of Response

Amplitude

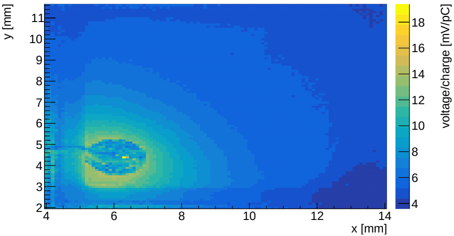


Charge in 25 ns



- IR laser, 1700 V, -20°C
- Features of background in both charge and amplitude
- Take ratio
  $\rightarrow$ remove charge influence on amplitude

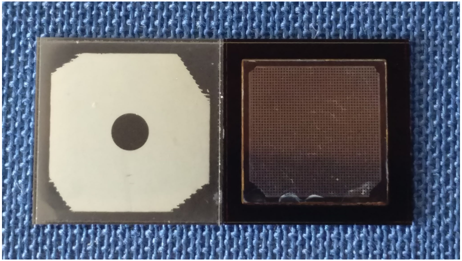
Amplitude / charge



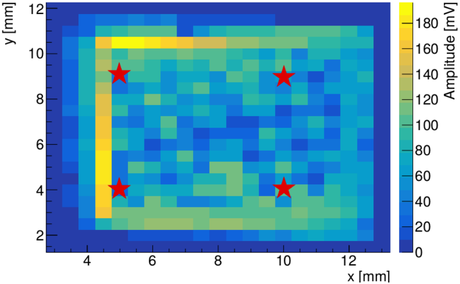
The amplitude is affected by the resistivity of the doped silicon

Metallized $8 \times 8\,mm^2$ APD, Uniformity of Response

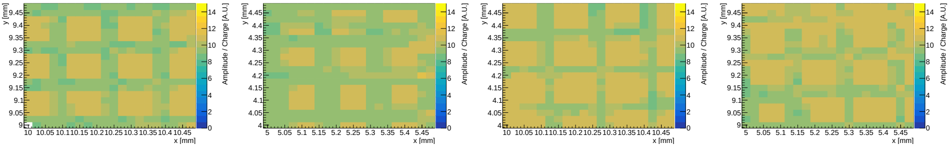
Metallization at EPFL-CMi, Lausanne



1800 V, 20 C



Ratio between charge and amplitude ($0.5 \times 0.5\,mm^2$ areas at stars position)

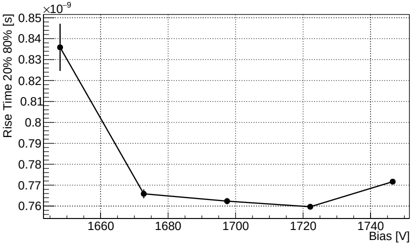


Good uniformity over the detector

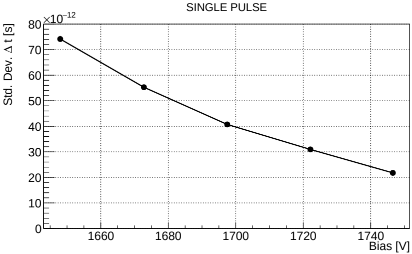
Thank you J. Bronuzzi for the help in the metallization procedure!

Metallized $8 \times 8\,\mathrm{mm}^2$ APD, 20°C, 0.8 MIPs

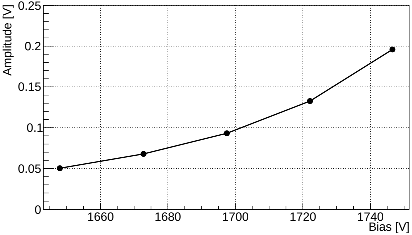
Rise Time 20% 80%



Time Resolution for one pulse



Amplitude



- Rise time $\approx$ 770 ps
- Lower amplitude than $2 \times 2\,\mathrm{mm}^2$ APDs
- Best single pulse resolution: 21.8 ± 0.3 ps

The metallized APDs are often unstable. To be investigated.

Summary & Outlook

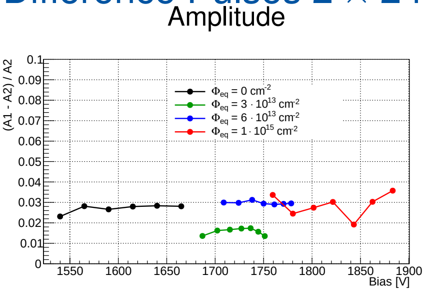
- Measured time resolution of neutron irradiated 2×2 mm^2 APDs
- Performance at det. center not degraded by neutron irradiation of at least $\Phi_{eq} = 6 \cdot 10^{13}$ cm^{-2} $\Rightarrow \sigma_t = 8 - 10$ ps @ 0.8 MIPs
- $\Phi_{eq} = 10^{15}$ cm^{-2}: very low or no gain, “dark pulses” are observed
- Modified the TCT setup for timing without external references
- Improved the uniformity of response of 8×8 mm^2 APDs by applying a metal layer, stability is under study
- Time res. of metallized 8×8 mm^2 APDs: $\sigma_t = 22$ ps @ 0.8 MIPs

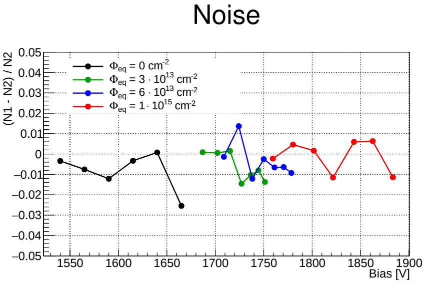
Outlook:

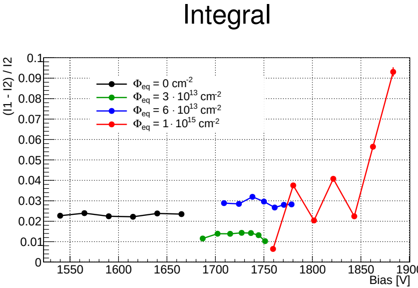
- Test different devices in the TCT setup
- New irradiation to explore region $6 \cdot 10^{13} \leq \Phi_{eq} \leq 7 \cdot 10^{14}$ cm^{-2}
- Use faster amplifiers to improve the time resolution
- Test the detectors in beam tests

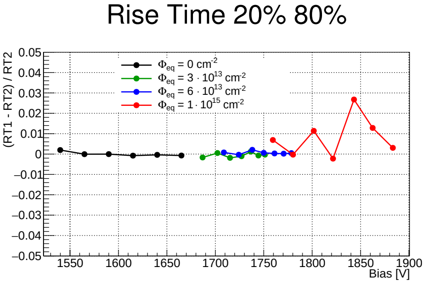
Backup Material

Difference Pulses 2×2 mm^2 APDs







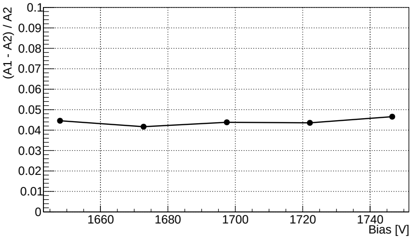


Data for $\Phi_{eq} = 10^{15}$ cm^{-2} influenced by low SNR

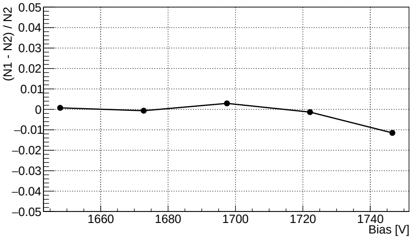
Properties of pulses equal within 5 %

Difference Pulses Metallized 8×8 mm^2 APD

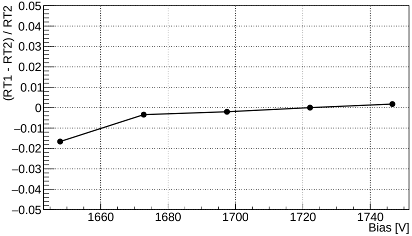
Amplitude



Noise

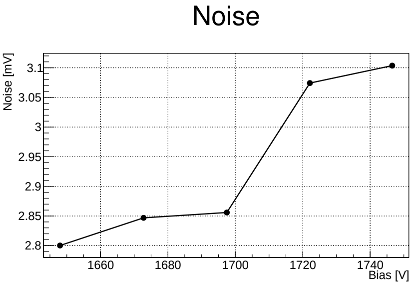


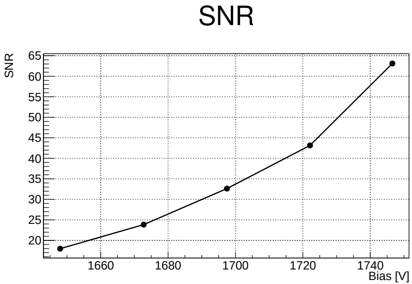
Rise Time 20% 80%

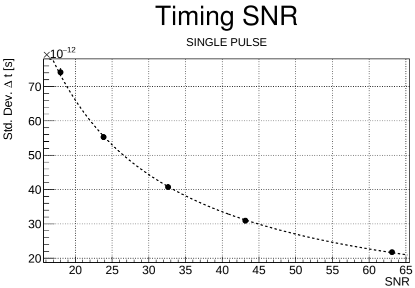


Properties of pulses equal within 5 %

Pulses Metallized 8×8 mm^2 APD

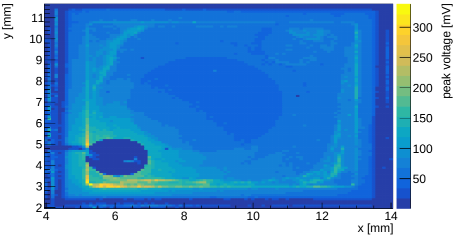




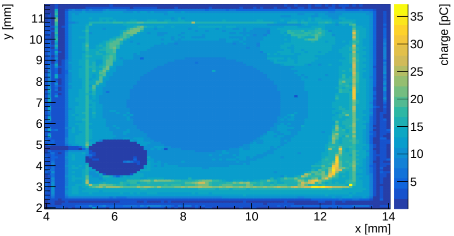


$8 \times 8\,\mathrm{mm}^2$ APD, p-side Electrode Resistivity

Amplitude

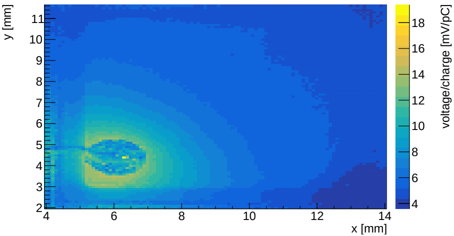


Charge in 25 ns



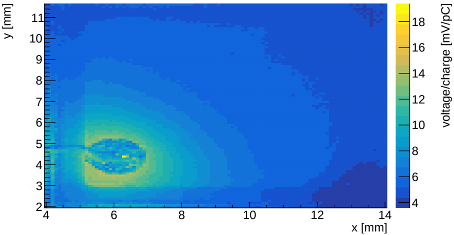
- IR front, 1700 V, -20°C
- Features of background in both charge and amplitude
- Take ratio
  $\rightarrow$ remove charge influence on amplitude

Amplitude / charge

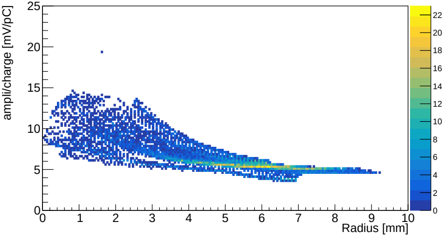


Ratio vs. Distance

Amplitude / charge



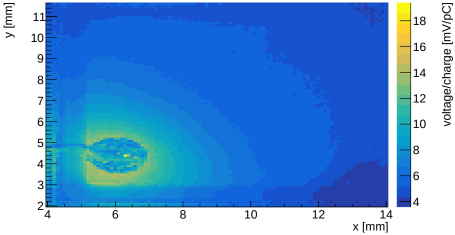
Scatter plot ratio vs distance



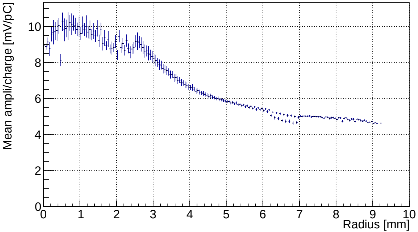
- Ratio depends on distance from contact
  $\rightarrow$ effect of surface resistivity
- Qualitative understanding of the effect
- Simple model does not provide fully satisfactory description of data (estimation of R_d vs distance to be improved)

Ratio vs. Distance

Amplitude / charge

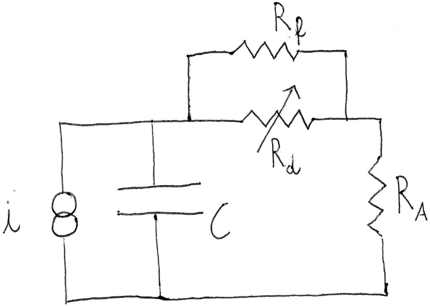


Average ratio vs distance



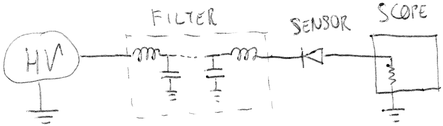
- Ratio depends on distance from contact
  → effect of surface resistivity
- Qualitative understanding of the effect
- Simple model does not provide fully satisfactory description of data (estimation of R_d vs distance to be improved)

Electrical model:

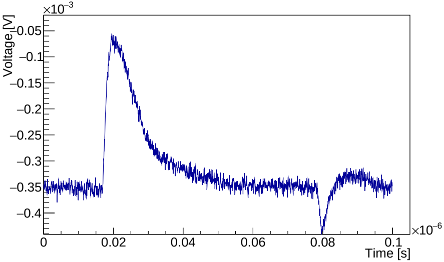


Calibration IR back TCT+, without Amplifier

- 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

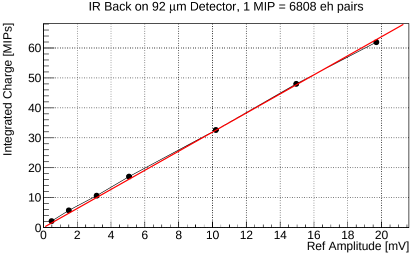


Calibration IR Back TCT+

Real det thickness 92 μm, 74 eh pairs / μm

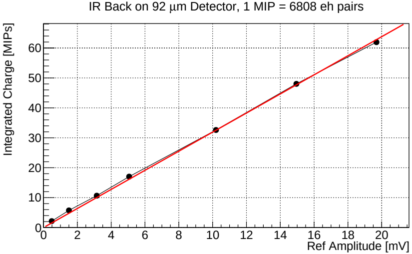
Fit: $y = ax$

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 %

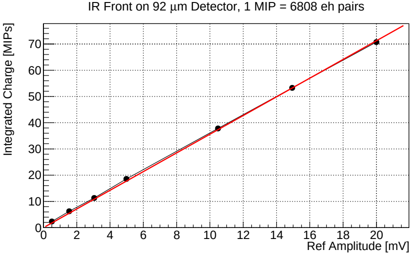
3.2 MIPs/mV

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