Investigation of afterpulse in irradiated SiPMs

DRD6 AHCAL "Marzipan" Meeting

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Outline

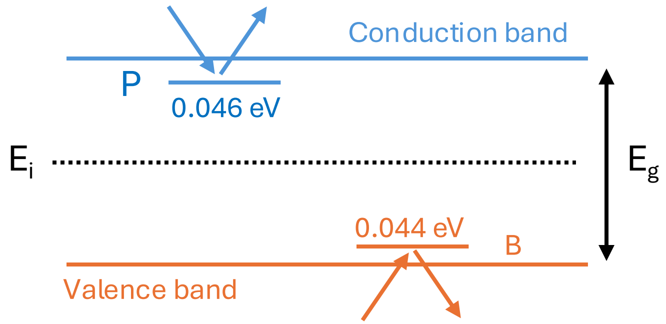
- Objectives
- Reminder on afterpulsing effect
- Experimental setup, SiPMs and data
- Methods of analysis
- Results
- Conclusions and next steps

Objectives

- **Quantitative and qualitative characterization of afterpulsing**
- **Develop methods** to accurately isolate and measure afterpulsing
- **Characterize afterpulsing behavior under different conditions**
  - Such as overvoltage and irradiation
- **Define the origin of the afterpulses**
  - To fight it back in the future

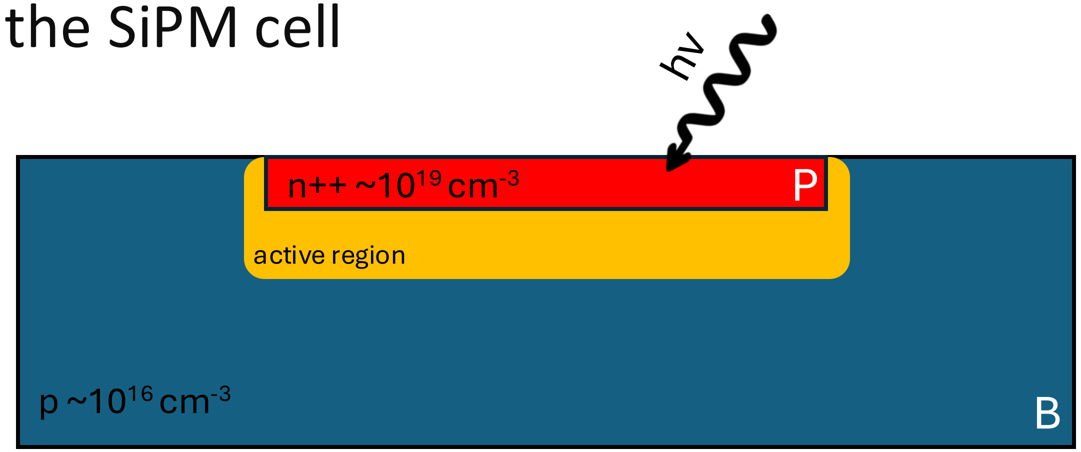
- All this would allow us to properly account for the afterpulsing effect in SiPM operations, improving performance in applications such as high-energy physics experiments and medical imaging.

What’s the afterpulsing (AP)?



Schematic representation trapping levels responsible for AP

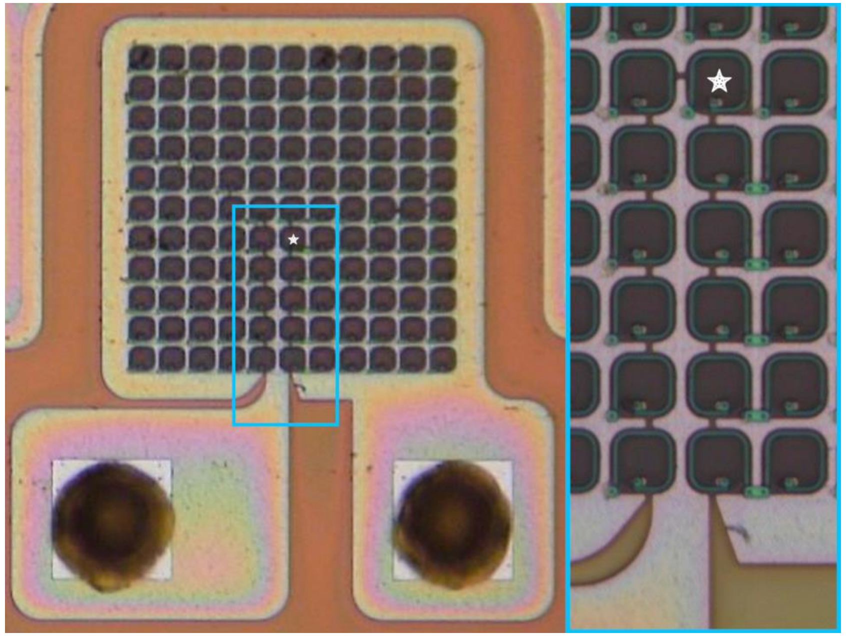
- During the primary Geiger discharge, charge carries might be trapped in defect states within the silicon lattice
- The trapped charge carries can be released after a delay
  - Triggering additional Geiger discharge of the SiPM cell
- Factors influencing AP
  - Defects density
    - Original Defects (manufacturing process)
    - Radiation-induced defects
  - Operation conditions
    - E.g. temperature and (over)voltage



Schematic representation of a SiPM cell

Experimental setup, SiPMs and data

- SiPMs:
  - HPK S14160 test structures
  - 11x11 cells, 15 μm pitch
  - Irradiated to Φ=2e12, 1e13, 5e13 cm^{-2}
    - Only Φ=0e00 and Φ=2e12 cm^{-2} are covered today
  - **Only 1 cell is read out!** (marked as ☆ on the pic)
    - Other 120 cells are biased below U_{bd}
- Configuration:
  - Climate chamber set to -30°C
  - Dual-Channel Bias and Readout Board
    - Each channel for either 1 or 120 cells
  - DAQ: amplifier and oscilloscope at 10 GS/s
  - Laser: 451 nm, 50 ps pulse length
  - Bias voltages: ≈1..5 V above breakdown
    - With step of 0.25 V



- Data:
  - Raw waveform
  - 1000 ns long
  - Laser fires at ≈313 ns
  - 30k w/f's for each BV point

Detailed description is available at [Single Cell SiPM](#) paper

Methods of analysis

Two independent methods developed in parallel:

Pulse finding/counting

- Based on multiple linear regression signal processing
  - SiPM Signal Processing via Multiple Linear Regression, 2023, W. Schmailzl et al
- Select laser events as primary ones
  - With no pre-history
  - And of full amplitude
- Count secondary pulses
- Subtract dark counts
- Calculate AP probability

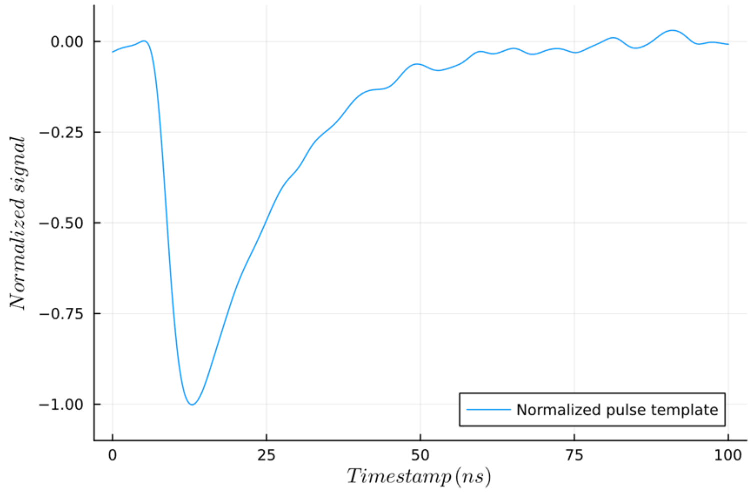
Charge integration

- 3 different windows for:
  - DCR estimation
  - Laser signal charge integration
  - Pre-selection of laser events
- Count laser events with excess charge
- Subtract dark counts
- Calculate AP probability

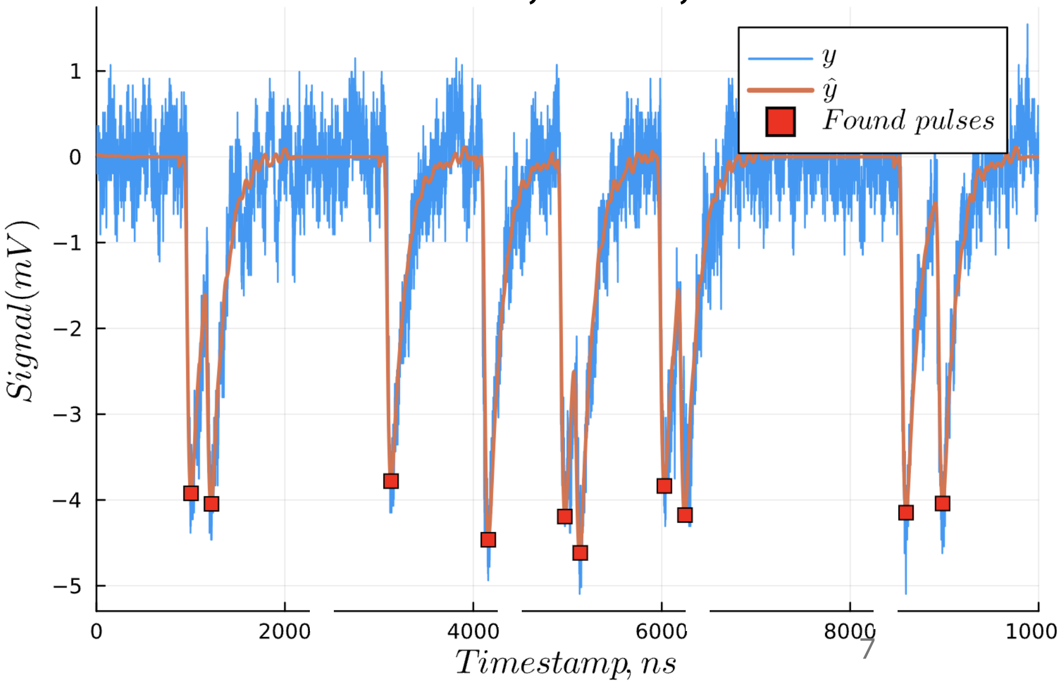
Pulse finding algorithm

- Detecting potential peaks with "dummy" template
  - Gauss+exponential function
- Update template with detected pulses shapes
- Iterative pulse position optimization:
  - Residual between the data and the model
  - Repeate to minizime residual
- Derived variables for detected pulses (■):
  - Timestamp
  - Amplitude
  - Pulse pedestal
  - Waveform number

Pulse template



Φ=1e13 cm^{-2}, ΔV=4 V, T=-30 °C



Afterpulsing probability calculation

- Estimate DCR from region before "laser" fires [1]
  - Recalculate to the number of DC events (N_{DC}) in signal region

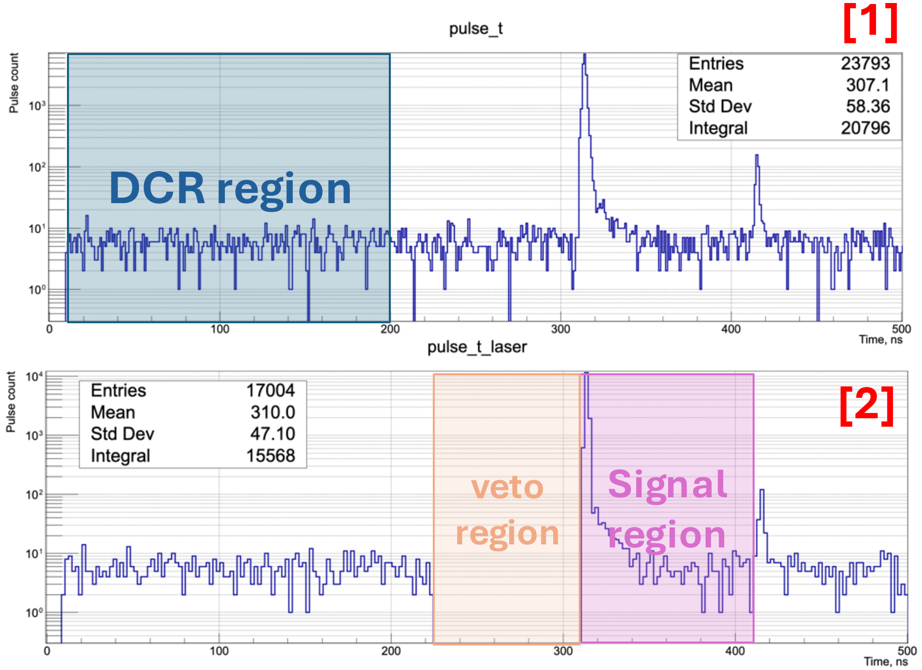
$$\mu_{DCR} = \frac{\int_{10}^{190} pulses(t)dt}{N_{waveforms} * 190} * 90 \qquad P(N_{DC}=1) = -\mu_{DCR} * e^{-\mu_{DCR}}$$

$$N_{DC} = P(N_{DC}=1) * N_{Primary}$$

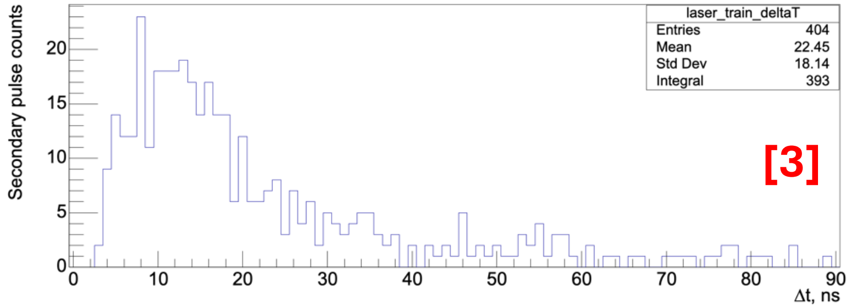
- Pre-select "clean" transients with "laser" response [2]
  - No pulses before the signal
  - Primary discharge is ≈ full amplitude
- Count only one secondary pulse in Δt=90ns* [3]
  - For each transient, starting from selected primary pulse
  - Subtract DC counts from step [2]
    - to get AP count and probability:

$$N_{AP} = N_{Secondary} - N_{DC} \qquad P_{AP} = \frac{N_{Secondary} - N_{DC}}{N_{Primary}}$$

*90ns window is chosen because of laser reflections spaced at 95-100ns after the main pulse



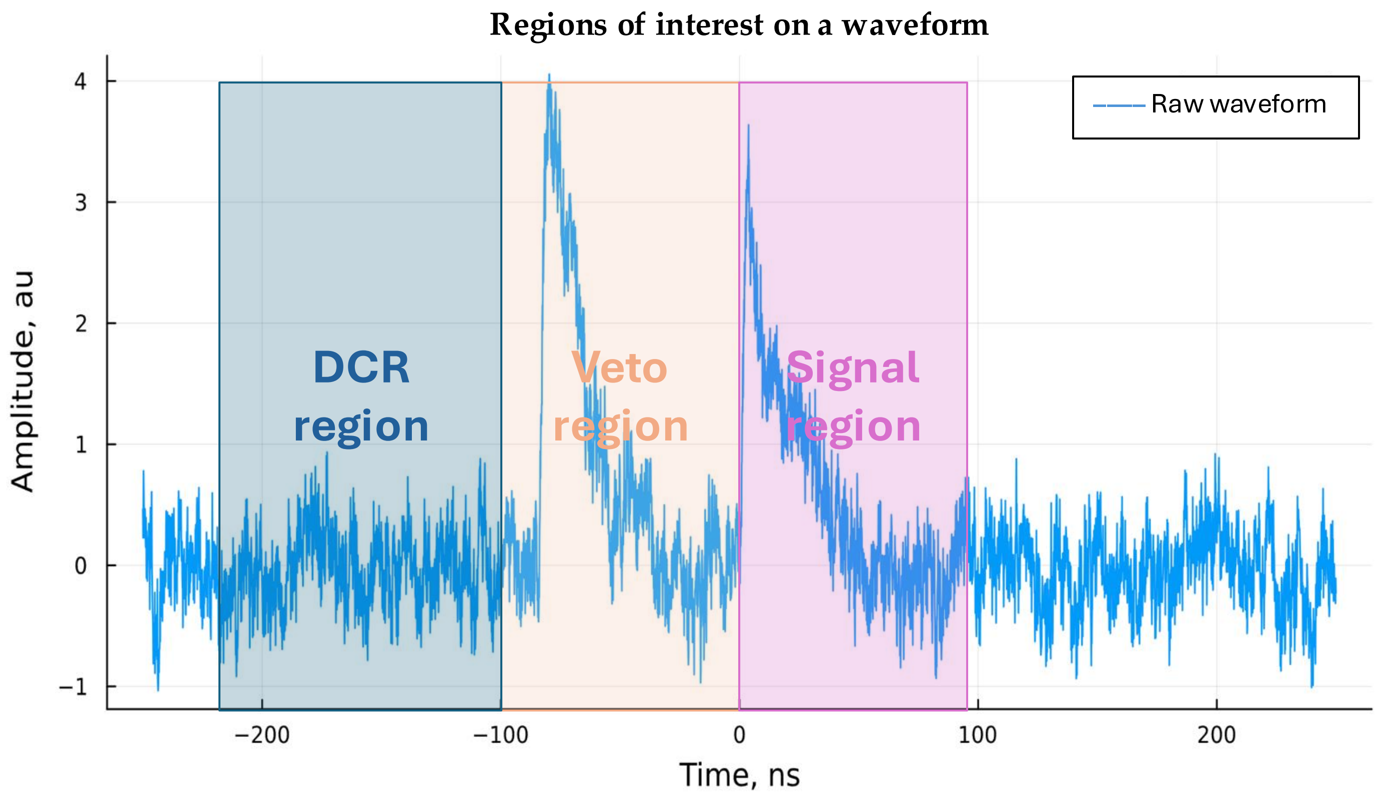
Number of detected pulses versus timestamp for all waveforms (top) and pre-selected waveforms (bottom)



Secondary pulse counts at Δt after primary discharge

Charge integration approach

- Integrate charge in DCR region
  - For all transients
  - To calculate DCR (see next slides)
- Pre-selecting laser events based on:
  - RMS and maximum amplitude in veto region
    - Low RMS and amplitude means no pulses
  - Amplitude maximum in signal region
    - To make sure there was “laser ” discharge
  - Wavelet transformation was employed to improve cutting (see backup)
- Integrate charge in signal region
  - Considering only pre-selected transients
  - Count events with excess charge
  - Subtract DC counts
  - And derive AP counts and probability



DC calculations

- Integrate charge in DCR and signal regions
  - Fit 0 and 1st peak to derive SiPM gain
- Calculate μ_{DCR} using P(N=0):

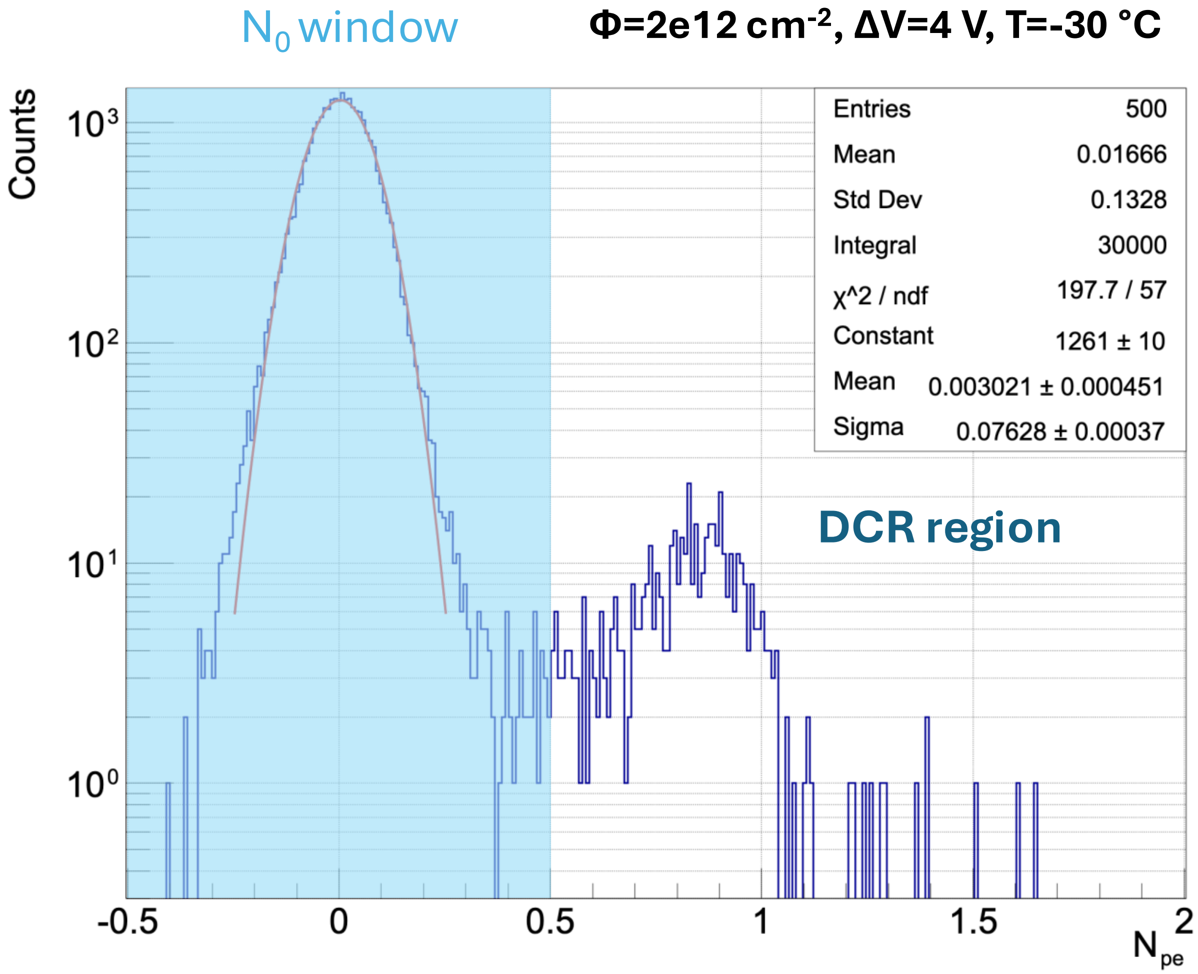
$$\mu_{DCR(100ns)} = -\ln\left(\frac{N_0}{N_{total}}\right)$$

$$where \quad N_0 = \sum_{Gauss_{Mean}-0.5*gain}^{Gauss_{Mean}+0.5*gain} N$$

- Then, DC number (N_{DC}) for a given gate is

$$N_{DC} = \mu_{DCR(gate)} * N_{Primary}$$

$$where \quad \mu_{DCR(gate)} = \frac{\mu_{DCR(100ns)}}{100} * gate$$



AP calculation

- Fit 1st PE peak with Crystall Ball function
  - To catch left tail due to under-shoot events
  - The peak represents "pure" laser response
- Calculating integral under the function

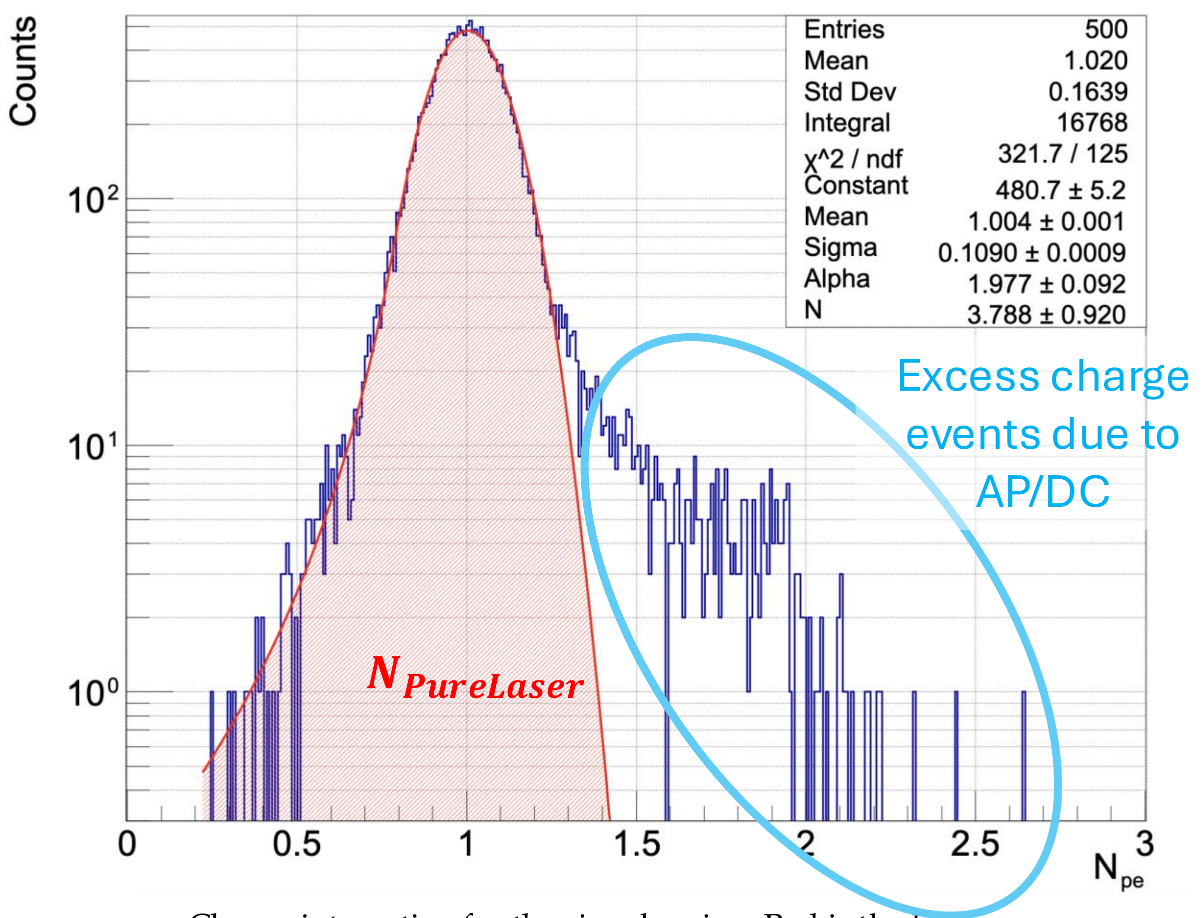
$$N_{PureLaser} = \int_{\mu-5\sigma}^{\mu+5\sigma} FitFunc(x)dx$$

- Excess charge occuring due to DC an AP events

$$N_{AP+DC} = N_{total} - N_{PureLaser}$$

  - Where N_{total} is the histogram entires
    - == number of pre-selected waveforms
    - == primary discharges ($N_{Primary}$)
- Then, AP counts: $N_{AP} = N_{AP+DC} - N_{DC}$
- And AP probability: $P_{AP} = \frac{N_{AP}}{N_{Primary}}$

Signal region



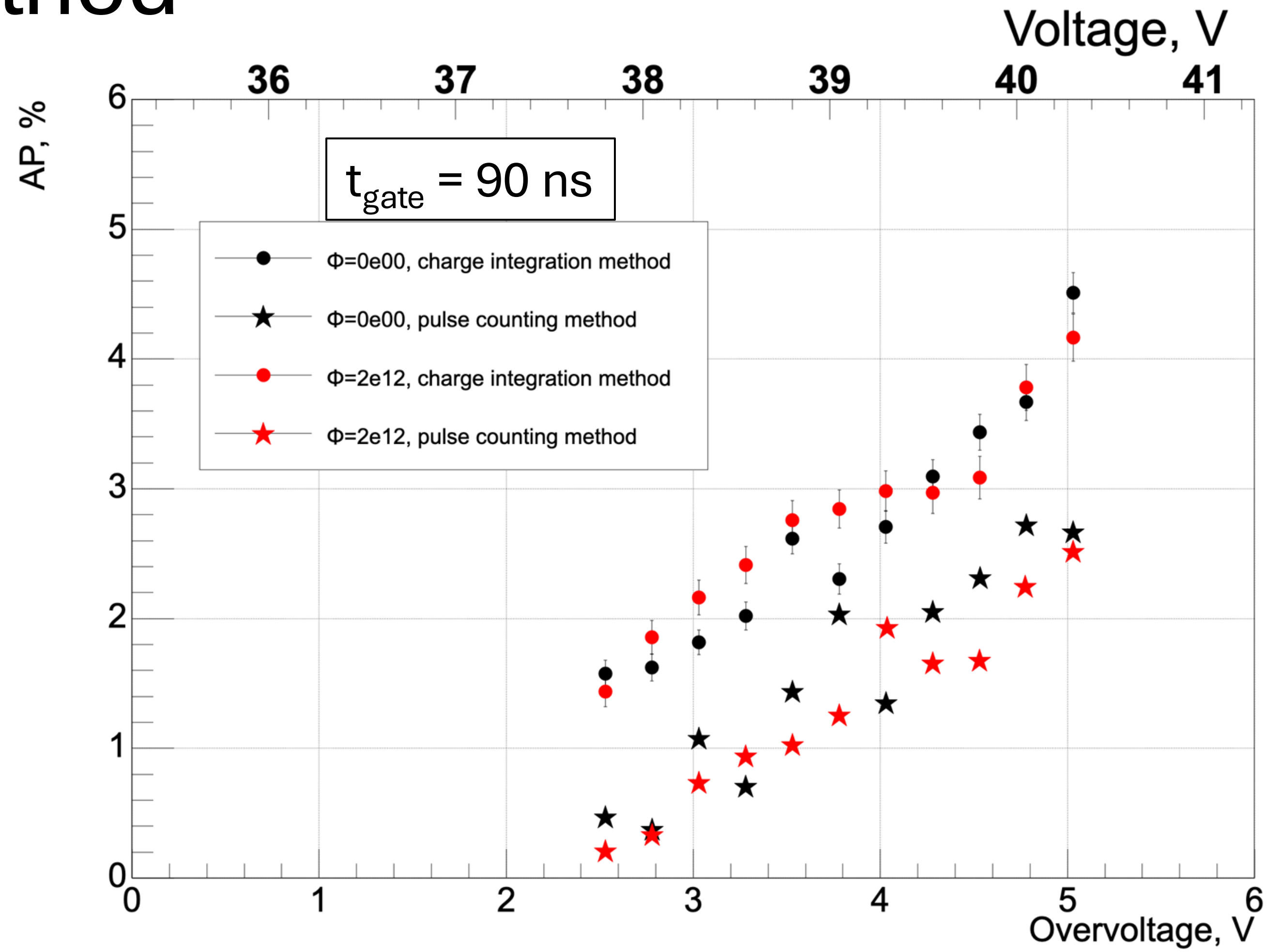
Charge integration for the signal region. Red is the laser response charge, while excess charge events are the tail to the right

Uncertainties

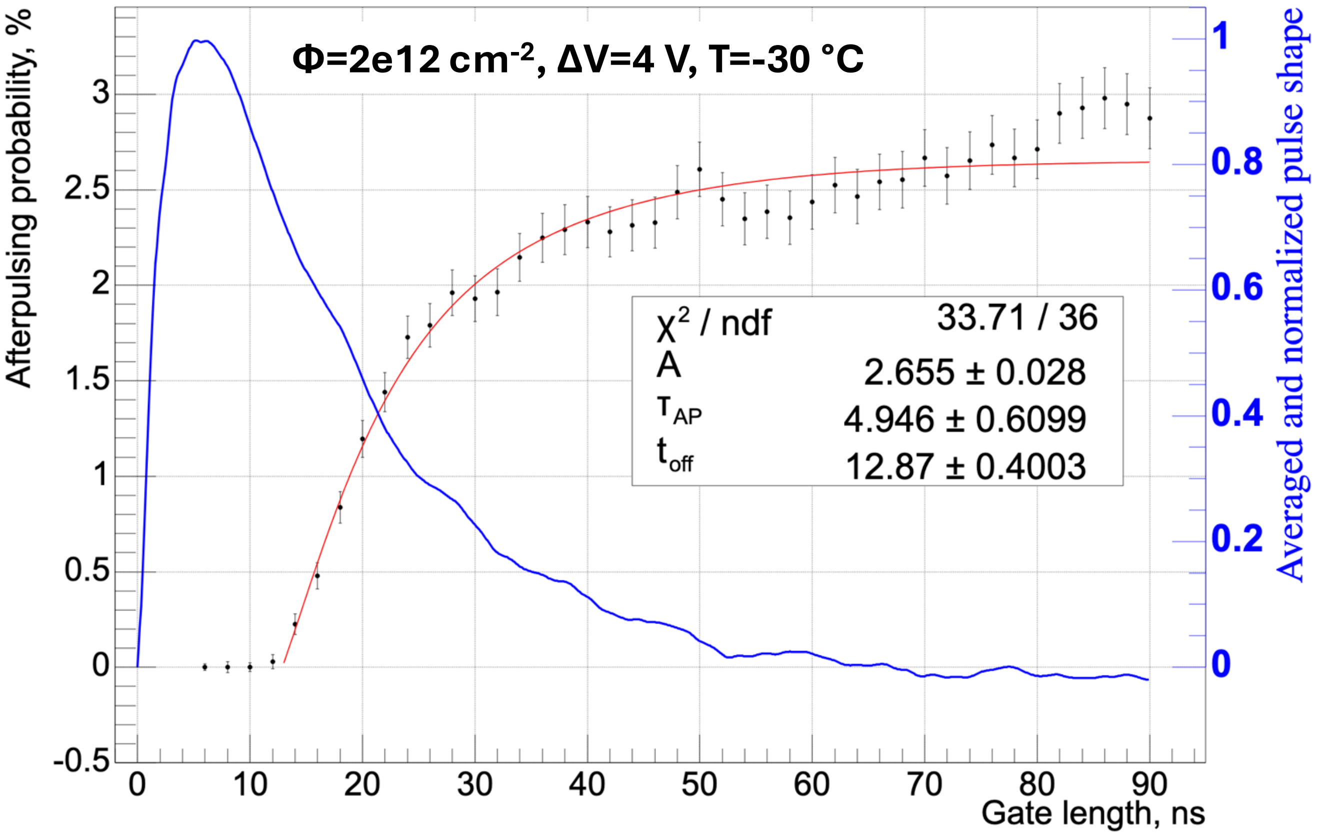
- For both methods the binomial errors model was considered
- The method is described in FERMILAB-TM-2286-CD by Marc Paterno
- Number of primary discharges is the sample size
- “Successful outcomes” is the number of AP+DC events
- Plus, individual error calculation for DC events (Poisson)
- Then, use error propagation to derive uncertainties for AP probability

Comparison of pulse counting and charge integration method

- Afterpulse probability P_{AP} increases as a function of overvoltage
- No increase observed for P_{AP} after irradiation to Φ=2e12 cm^{-2}
- Both methods show similar trends with voltage
- However, direct pulse counting gives slightly lower P_{AP}



Extraction of de-trapping time

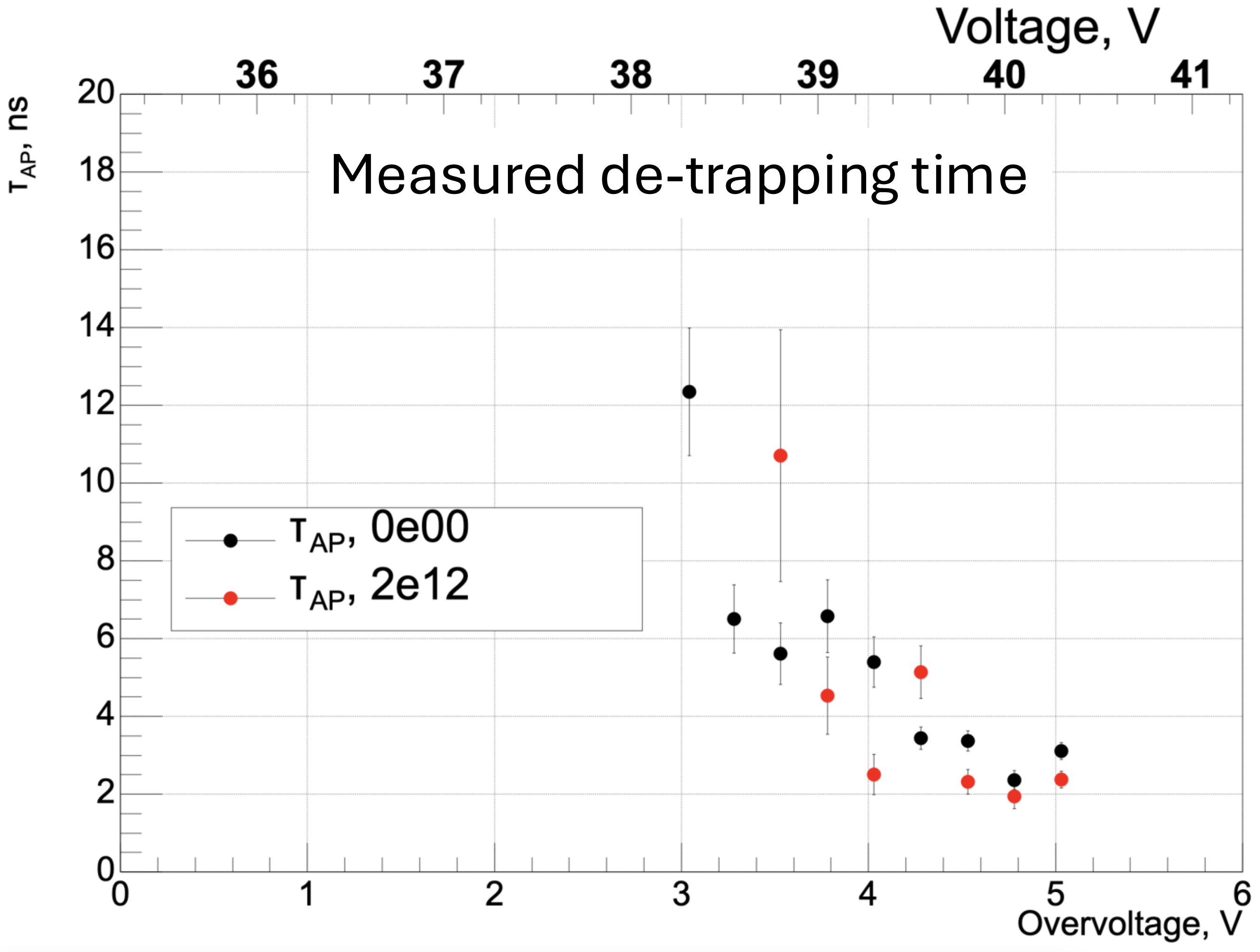


$$P_{AP}(\mathrm{t}) = \mathrm{A} \times \left(1 - \exp\left(-\frac{t - t_{off}}{\tau_{AP}}\right)\right) \times \left(1 - \exp\left(-\frac{t - t_0}{\tau_{rec}}\right)\right)$$

- Calculating AP probability for different gates provides an opportunity to derive the de-trapping time constant
- Considering two effects:
- De-trapping as $(1 - \exp\left(-\frac{t-t_{off}}{\tau_{AP}}\right))$
- Cell recovery as $(1 - \exp\left(-\frac{t-t_0}{\tau_{rec}}\right))$
  - t_0, τ_{rec} are taken from dedicated recovery curve fitting
- Extracted value of τ_{AP} offers insights into the de-trapping dynamics
  - Can later be used for the trapping levels characterization

De-trapping time versus overvoltage

- τ_{AP} can only be reliably derived for OV>3.5 V
- De-trapping time appears to be fast in this region
  - With τ_{AP} < 10ns
- Poole-Frenkel effect and/or shallow traps can be among responsibles
  - And this requires more careful checks and studies



Conclusions and next steps

- Two independent methods were developed to measure and characterize afterpulses in a single-cell SiPM
  - These allow us to measure the afterpulsing probability
  - And measure the time constant of a de-trapping time
- Both were successfully applied on non-irradiated and Φ=2e12 cm^{-2} samples
  - For those it was found that P_{AP} and τ_{AP} are not visibly changing at this fluence level

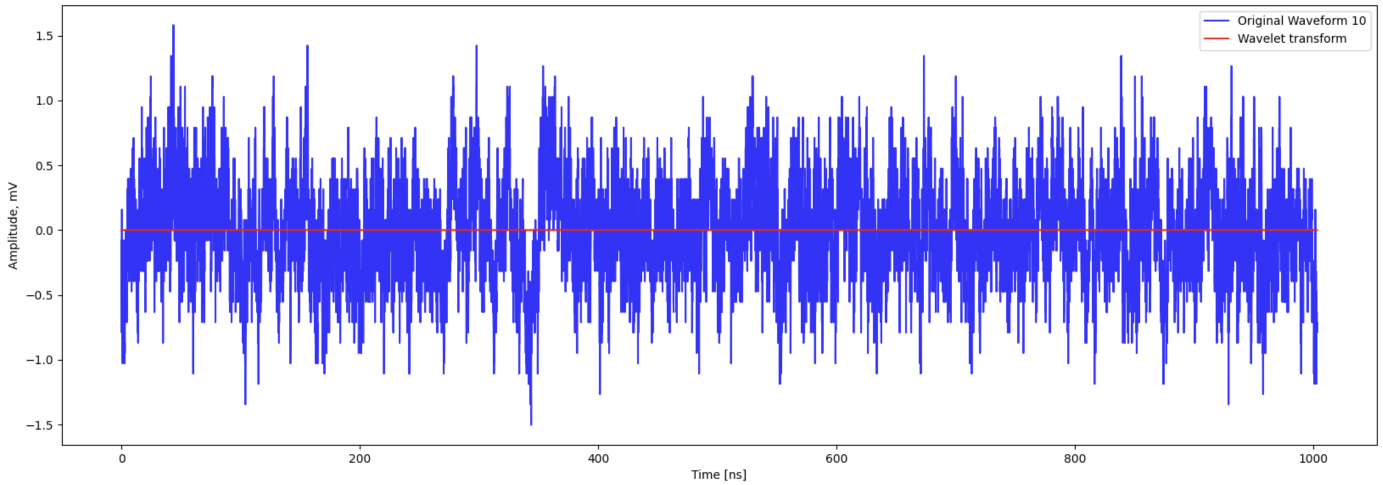
- Next: adopt the method to analyze sample irradiated to 1e13 sample
- Move to 120 cells, where direct 1 to 120 scaling is possible
  - Uniform radiation damage, DCR is proven to be scalabe -- Radiation damage uniformity in a SiPM
- Use all this knowledge to identify the source of the afterpulsing
  - What kind of defects is responsible for it

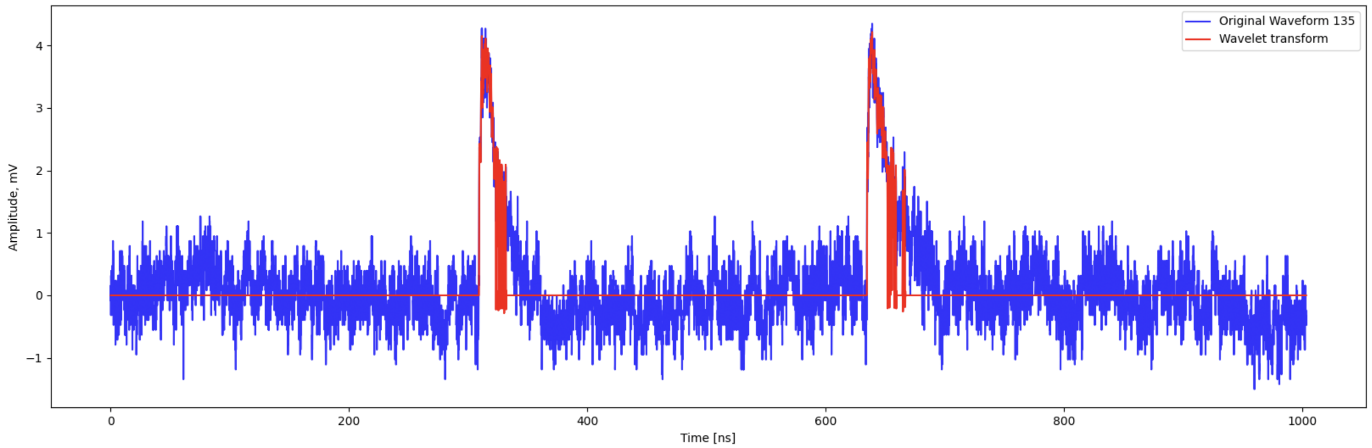
BACKUP

Charge integration – pre-selection

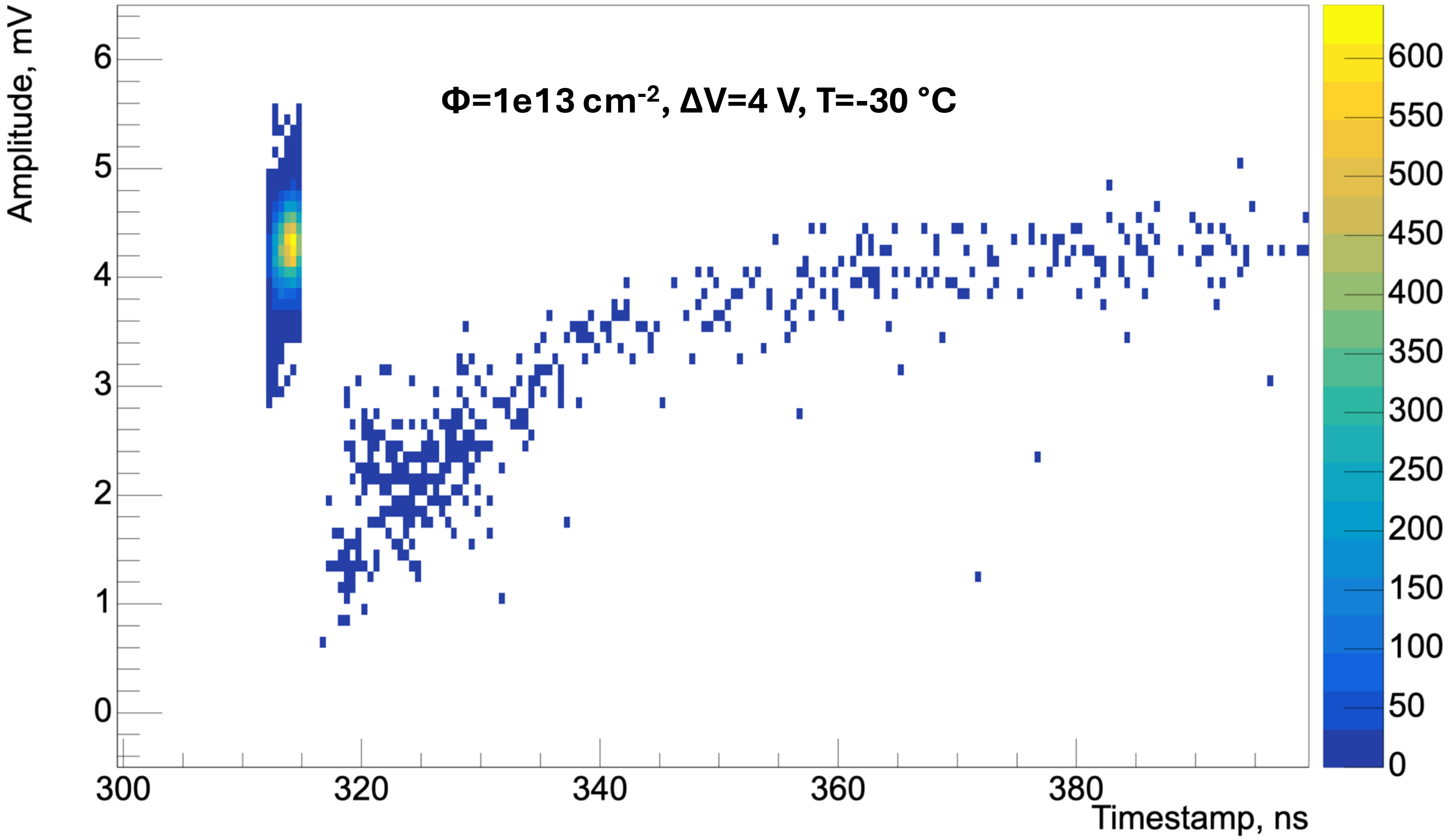
Φ=1e13 cm^{-2}, ΔV=4 V, T=-30 °C

- One of the complimentary waveform transformation is wavelet denoising
- At extreme levels it removes the electronics noise and somewhat corrupts the signal
- Yet, this allows to detect the presence of the signal in a given gate
- And use it for transients pre-selection



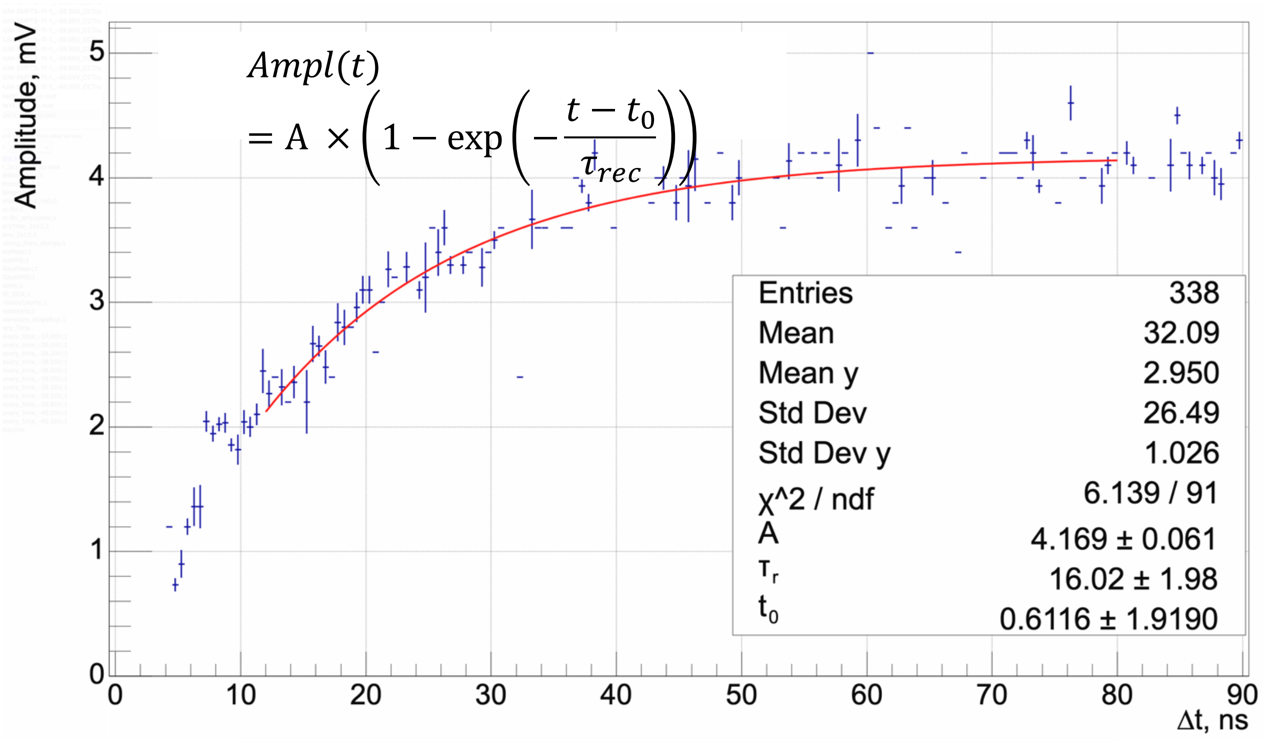


Laser primary pulse and afterpulses



- Non-irradiated sample
- Laser discharges and afterpulses are clearly visible when we plot detected pulses as a function of time
  - Cumulative for all transients

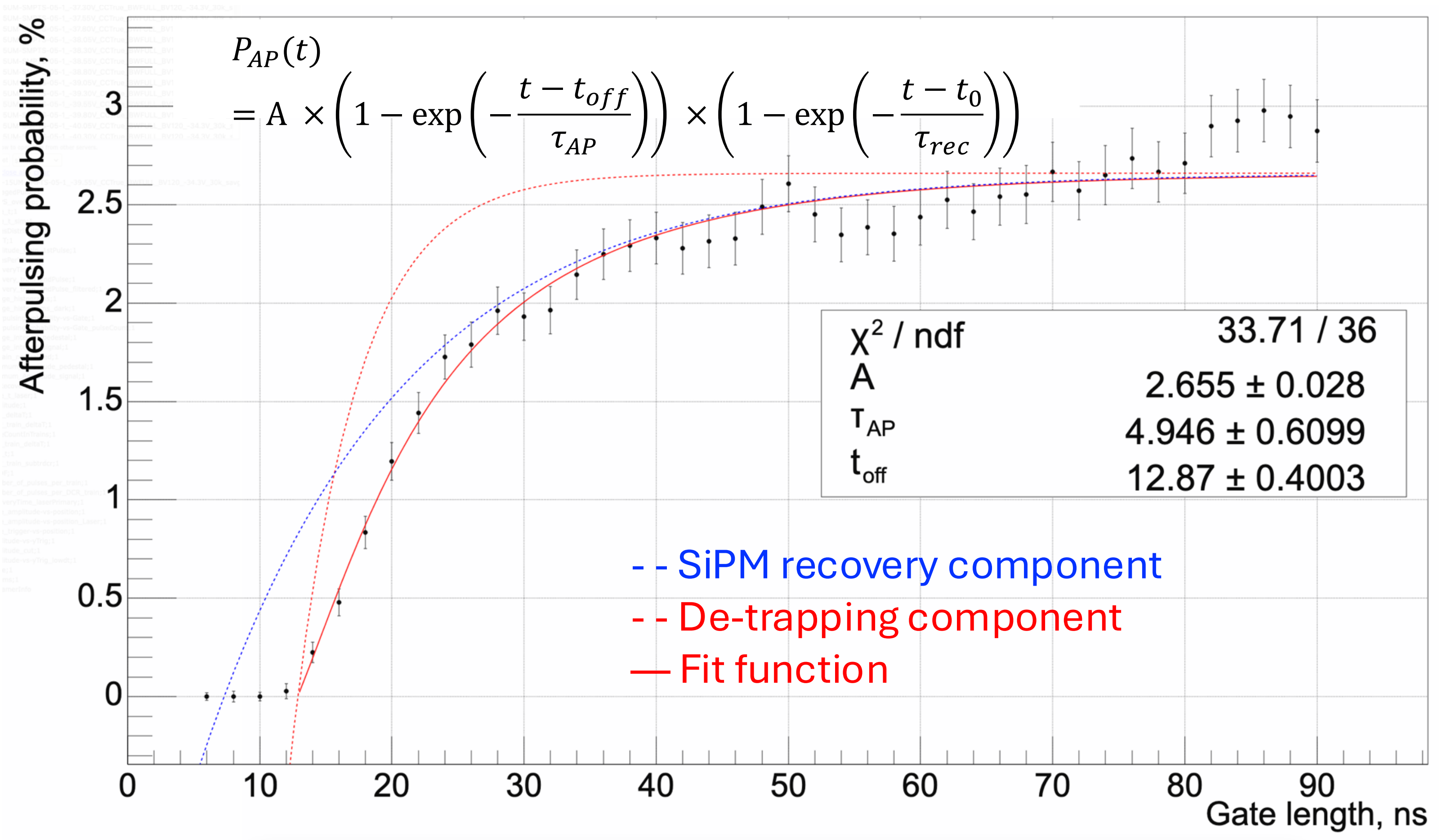
Recovery time



Φ=1e13 cm^{-2}, ΔV=4 V, T=-30 °C

- Example of a recovery time obtained using the amplitudes from the pulse finding algorithm
- t_0 and τ_{rec} are “deadtime” (time, during which bias voltage drops below U_{bd} until it comes back to operational value) and recovery time, respectively
- These are later used in function used to derive τ_{AP}

Fit function for τ_{AP} calculation



- Fit function for τ_{AP} calculation
- But with two components also plotted separately

Afterpulsing comparison

- Additionally, the charge integration method was included
- The same procedure as with the data
  - Histogram -> Fit -> Count
  - NB: no DCR in simulations!
- Couple of improvements:
  - Fit is now done in range based on gain
  - No baseline subtracted
    - The resolution of the afterpulse tail is better
- 90ns gate worked quite well
  - Falls closely to true AP