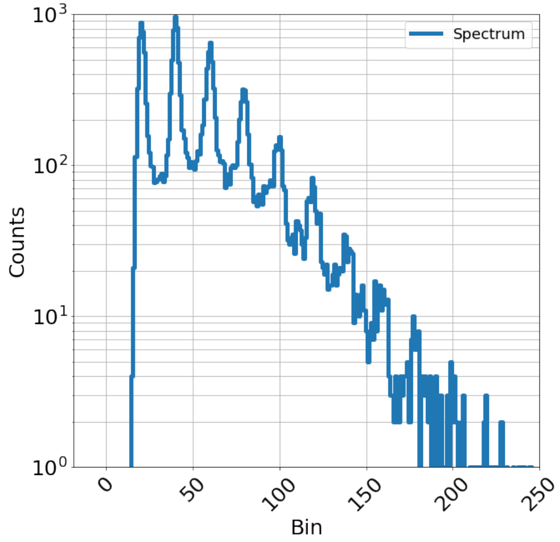
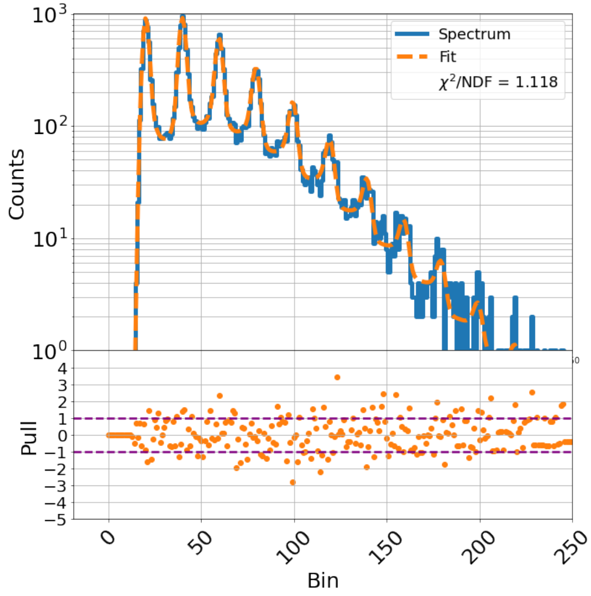
PeakOTron: A Tool For SiPM Characterisation





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University of Hamburg

PIER Workshop on ‘Joint DESY/UHH Perspectives In Detector Research’

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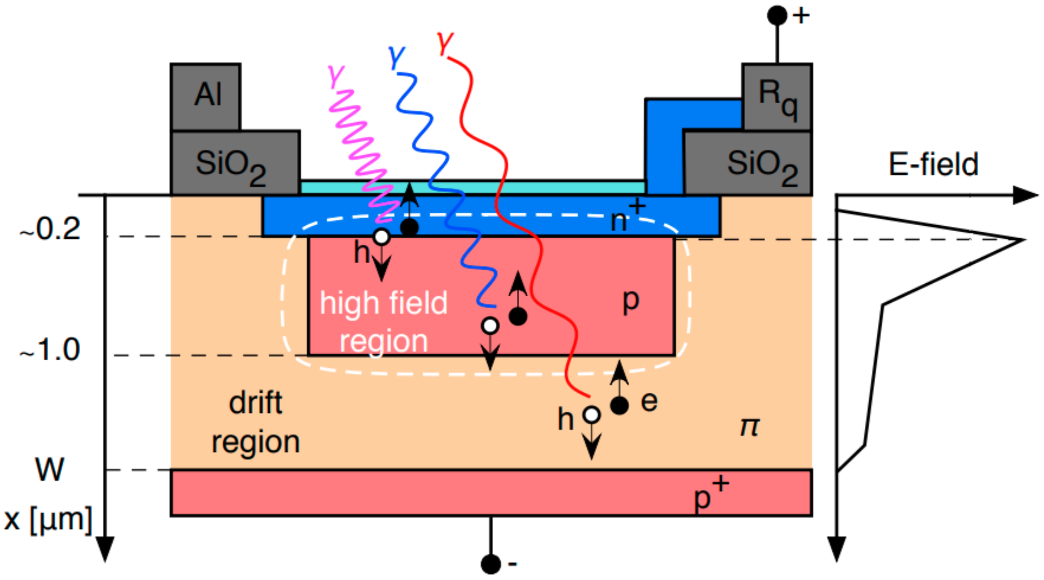
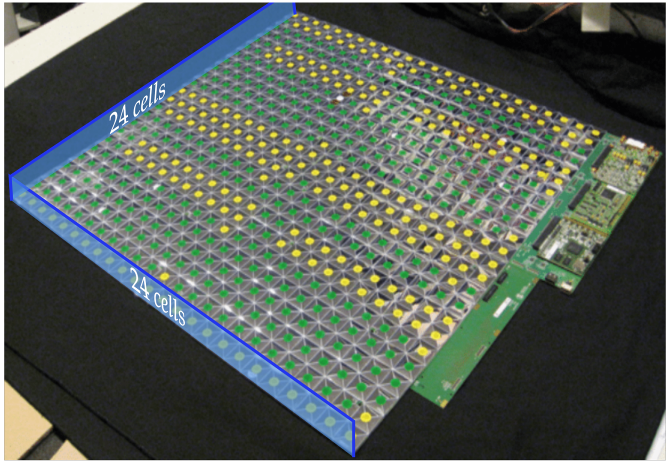
What is a SiPM?

- A Silicon Photomultiplier (SiPM) is a photo-detector operating in the red-to-near-ultraviolet frequency range.
- Useful properties:
  - high photon-detection efficiency (>50%);
  - good time resolution (< 100 ps);
  - low noise;
  - single-photon counting capability;
  - insensitivity to magnetic fields;

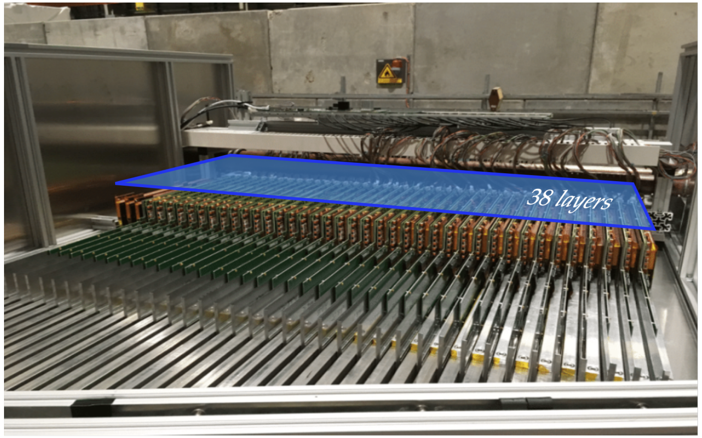


Characterising SiPMs

- It is often necessary to describe the properties of an SiPM;
- Example:
  - SiPMs can be used as detectors in highly granular calorimeters for Particle Flow;
  - CALICE Analogue Hadronic Calorimeter (AHCAL):
    → 22,000 individual channels
  - the response of each sensor must be calibrated individually;
  - accurate calibration improves calorimeter resolution.



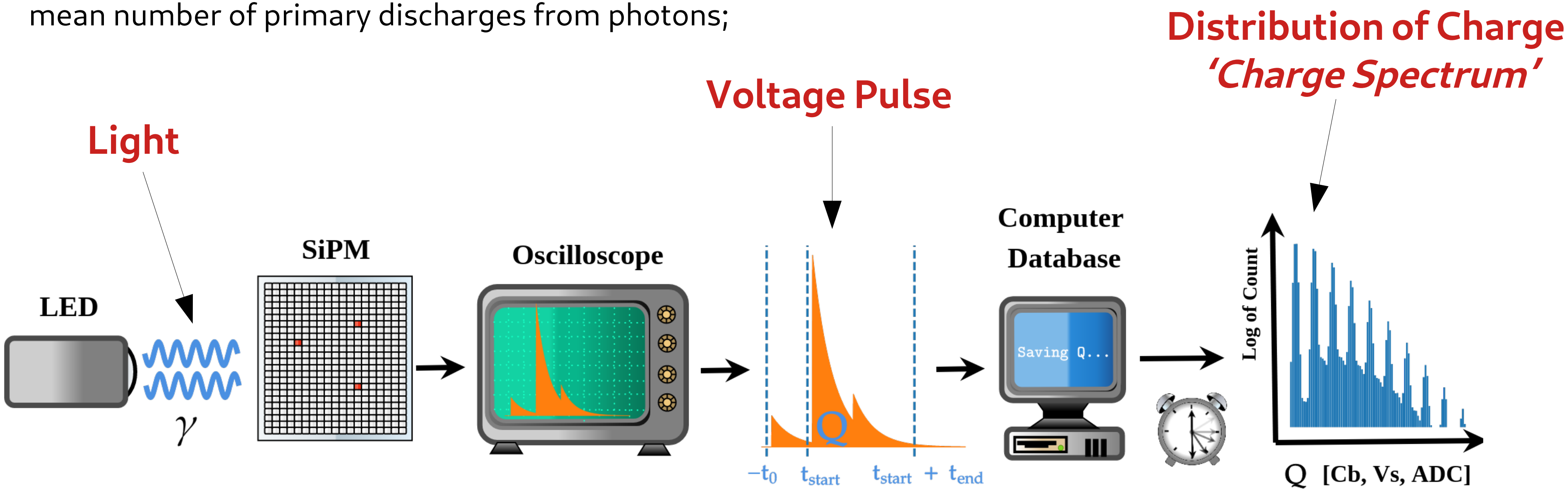
AHCAL Backface



AHCAL Layers

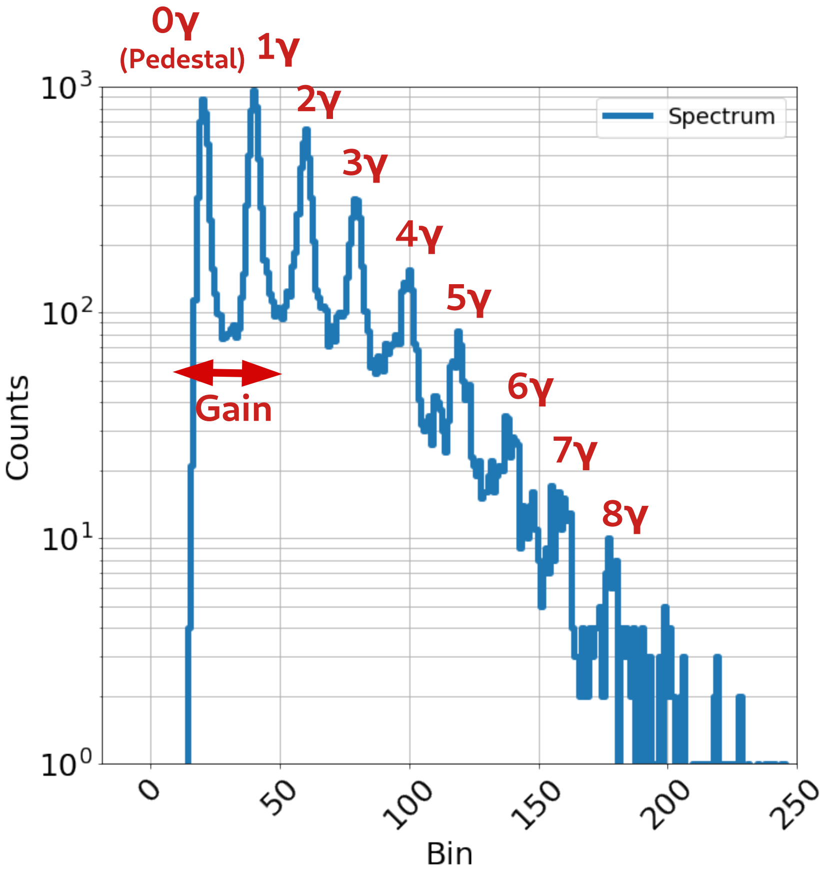
Modelling SiPM Charge Spectra

- Under illumination, an SiPM produces a voltage pulse → integrated over gate → charge.
- Charge distribution ('charge spectrum') of SiPM contains useful information about device. e.g:
  - single photon amplification factor (gain);
  - mean number of primary discharges from photons;



Modelling SiPM Charge Spectra

- Model can be fitted to extract parameters of interest;
- Perfect case:
  - Poisson-distributed light source often assumed (i.e. laser);
  - one discharge per incident photon.

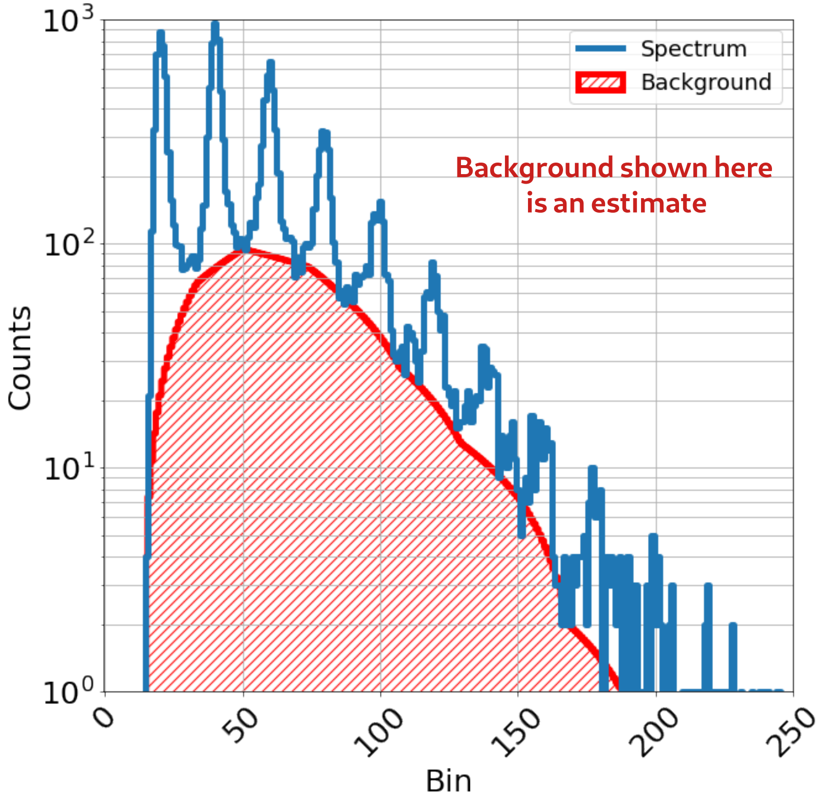


Modelling SiPMs

- Correlated noise effects also influence the distribution:
  - cross-talk between pixels;
  - dark counts;
  - after-pulses from de-trapping;
  - electronics noise;

- Shape of distribution can be *significantly* modified by noise
  → <u>must be accounted for in model, else inaccurate!</u>

- Detector response model of [1] describes a full detector response model, describing most of these effects.



[1] V. Chmill et. al. "On the characterisation of SiPMs from pulse-height spectra". In: NIMA arXiv:1609.01181

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PeakOTron: What It Does

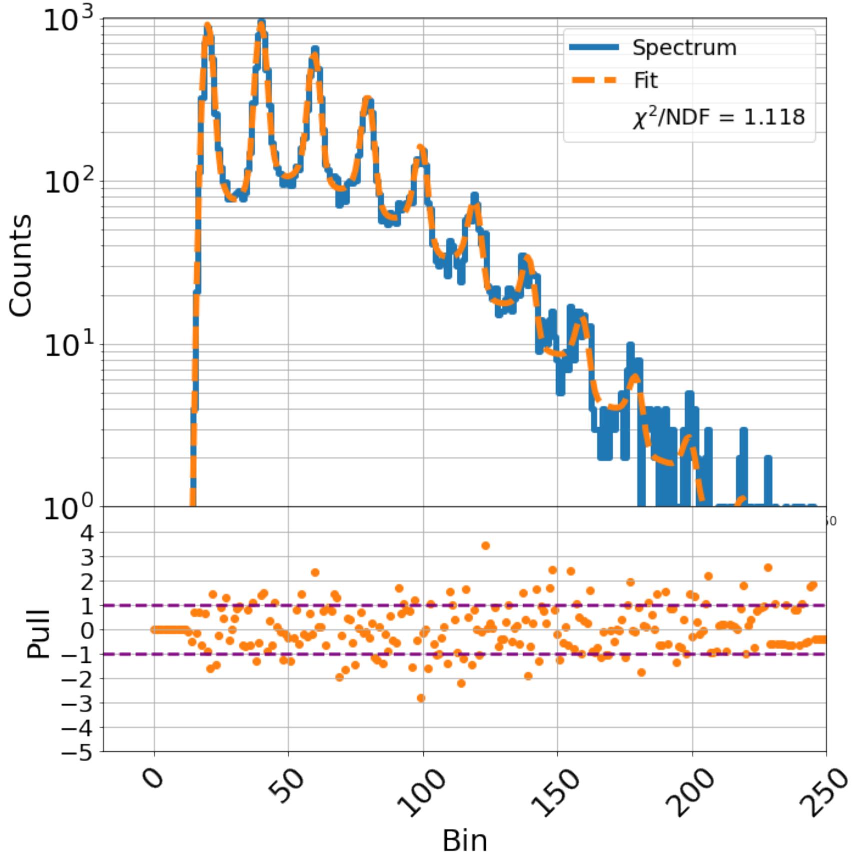
- The model of [1] has 9 free parameters;
  - charge spectra vary widely in shape/distribution;
  - hard model to fit;
  - fit of model must proceed automatically;
  - i.e. one cannot babysit individual fits to $O(10^4)$ SiPM charge spectra!
- accurate estimates for starting partameters required for fitting model;

Parameter	Definition	Range
μ	Mean Number of Primary Geiger Discharges from Photons	10^{-10} to ∞
λ	GP-Branching Parameter	10^{-10} to $1-10^{-10}$
G^*	Effective Gain	1 Bin to ∞
Q_0	Pedestal Position	$-\infty$ to $+\infty$
σ_0	Pedestal Width	0.1Bin to ∞
σ_1	Gain Spread	0.1Bin to ∞
DCR	Dark Count Rate	1 Hz to ∞
p_{Ap}	After-pulse Probability	10^{-10} to $1-10^{-10}$
τ_{Ap}	After-pulse Time Constant	3 ns to $t_{\mathrm{gate}}/2$
A_{sc}	Scale Factor	$N_{\mathrm{events}} \pm 3 \cdot \sqrt{N_{\mathrm{events}}}$

[1] V. Chmill et. al. "On the characterisation of SiPMs from pulse-height spectra". In: NIMA arXiv:1609.01181

PeakOTron: What It Does

- PeakOTron [2] is a Python tool for two tasks:
  - automatically finding good estimates for the starting parameters for the a fit of the model of [1];
  - performing a fit of the detector response model of [1];
- Program can be run in parallel to characterise many spectra at once;
- Of course, we have to ask:
  - how accurately can it measure parameters of interest?
  - how well does it describe experimental data?



[2] J. Rolph et al. 'PeakOTron: A Python Module for Fitting Charge Spectra of Silicon Photomultipliers'. In: arXiv:2301.11833 (under review)

Validation on Simulation

- Simulation of charge spectra based on [3] produced;
- Scans made over 'appropriate' ranges of parameters, relative to baseline:
  - 16 steps per scan;
  - 100 spectra per scan step;
  - 20,000 events per spectrum;
  - 1 bin width = 5% of gain;
  - accuracy of gain/pedestal measured as a fraction of a bin width;
- Statistical bias and systematic uncertainty measured for all of the 1600 spectra;
- Values compared to simulated value.

Parameter	Baseline	Scan Range	Scaling
Q_0	20.0 Bin	–	constant
G	20.0 Bin	–	constant
G^*	19.865 Bin	–	constant
μ	1	0.5 – 8	linear
λ	0.2	0.01 – 0.3	linear
σ_0	0.075 G	(0.02 – 0.15) G	linear
	(1.5 Bin)	(0.4 – 3) Bin	
σ_1	0.02 G	(0.02 – 0.15) G	linear
	(0.4 Bin)	(0.4–3) Bin	
DCR	100 kHz	100 kHz – 5 MHz	linear
p_{Ap}	0.0272	0.0027 – 0.0818	linear
τ_{Ap}	7.5 ns	(4.0 – 19.0) ns	linear
τ	20 ns	–	constant
τ_{rec}	20 ns	–	constant
t_0	100 ns	–	constant
t_{gate}	100 ns	–	constant
r_{fast}	0	-	constant
bin width	0.05 G	(0.01 – 0.25) G	linear
N_{events}	2×10^4 events	$(10^3 - 5 \times 10^5)$ events	linear

[3] E. Garutti et al., Simulation of the response of sipms; part i: Without saturation effects, NIMA (2021) 165853. doi:10.1016/j.nima.2021.165853

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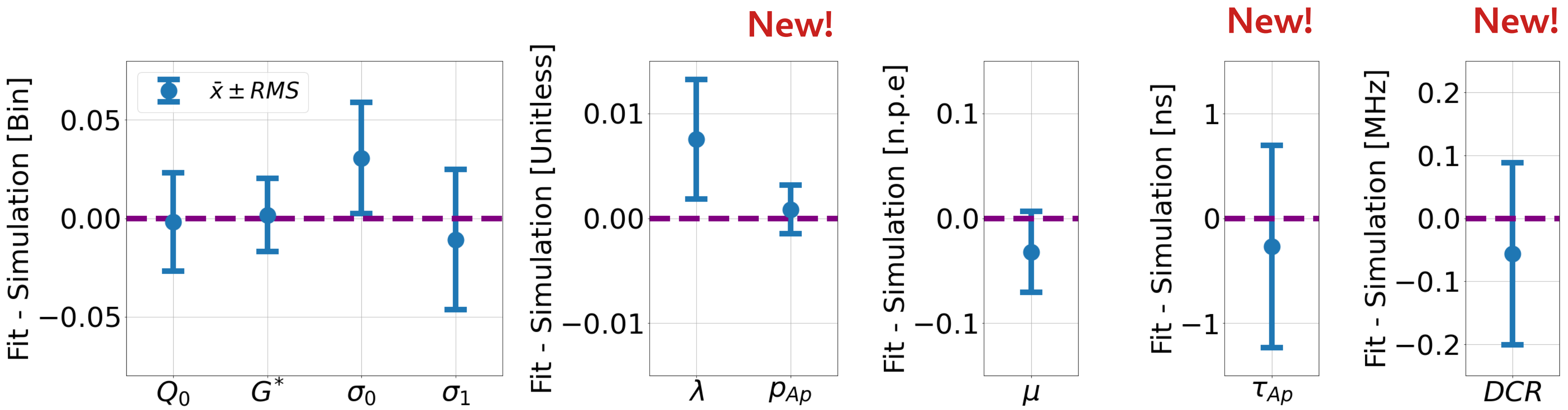
Validation on Simulation



What is shown:

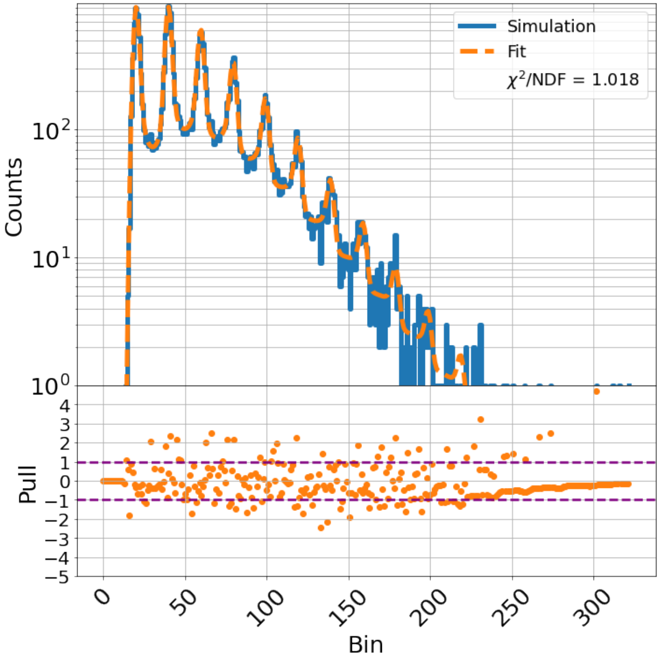
systematic biases (blue points) and statstical uncertanties (error bars) for each parameter over the entire scan range.

What we learn:

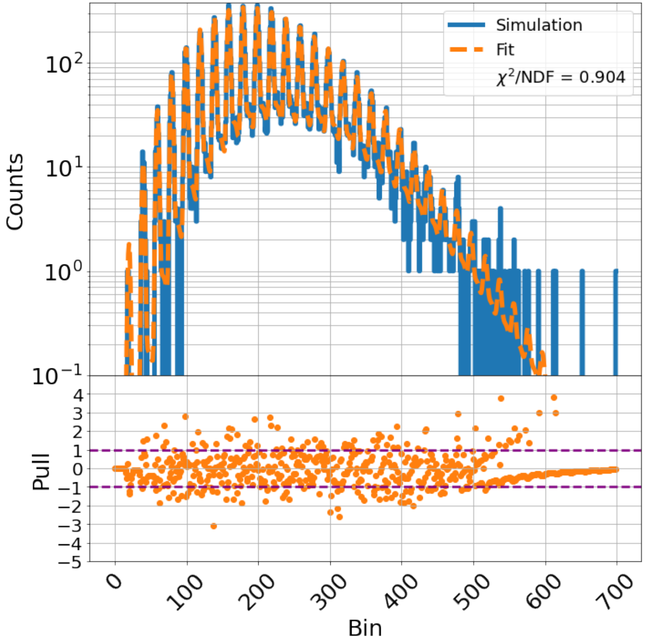
- gain and pedestal position accurate within 5% of a bin;
- afterpulse probability accurate within 1%;
- dark count rate accurate within 100 kHz → can estimate DCR from single spectrum!
- minor systematic biases → well within acceptable range

Validation on Simulation

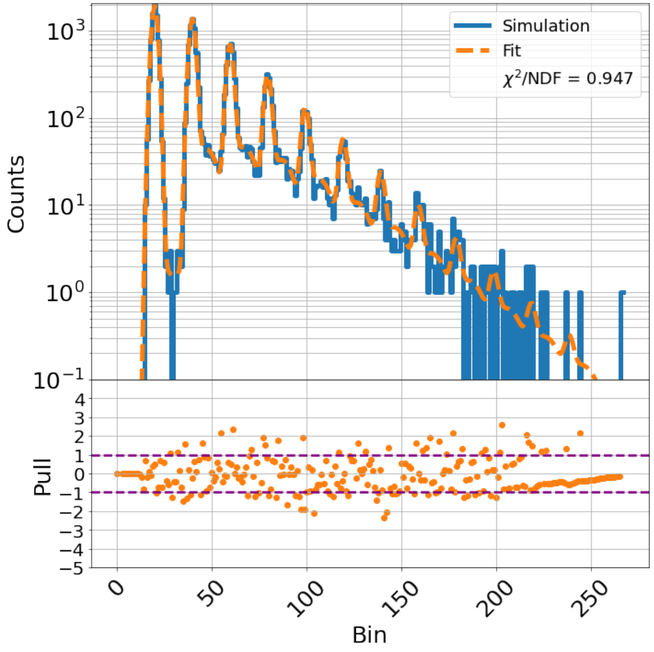
High Dark Count Rate
DCR = 5 MHz



High (ish) Illumination (below saturation) μ = 8



High Probability of Afterpulsing P_{Ap} = ~8%



PeakOTron + Model can describe a wide range of very different charge spectra

Measurement of Experimental Data

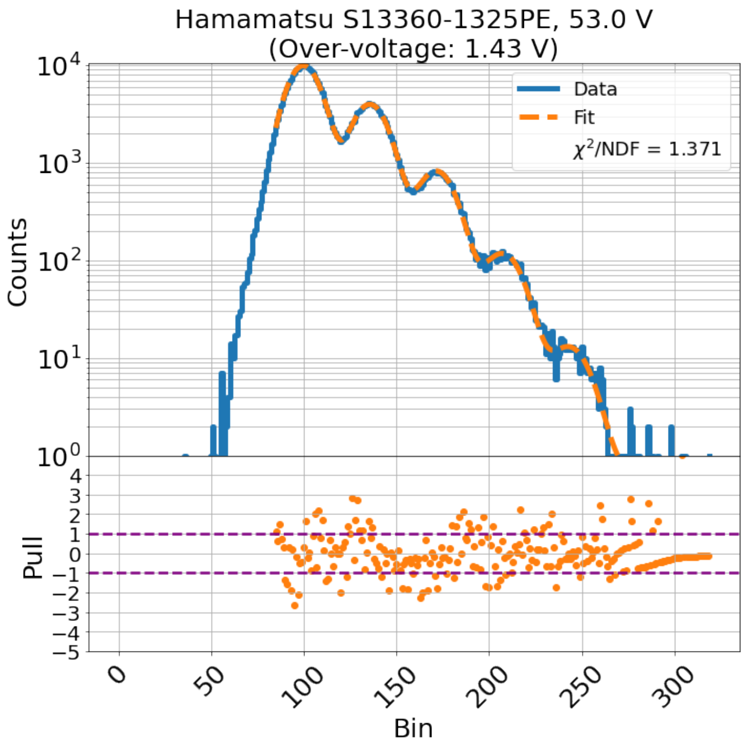
- PeakOTron was applied to charge spectra obtained from 2 SiPM sensors:
  - KETEK PM1125NS-SBO
  - Hamamatsu S13360-1325
- Charge measurements:
  - performed with CAEN Educational Kit in light-tight aluminium housing;
  - Illuminated by 400 nm LED;
  - light transported by optical fibre to SiPM;
  - scan of bias voltages performed for each sensor;

Table of Parameters For Each Sensor

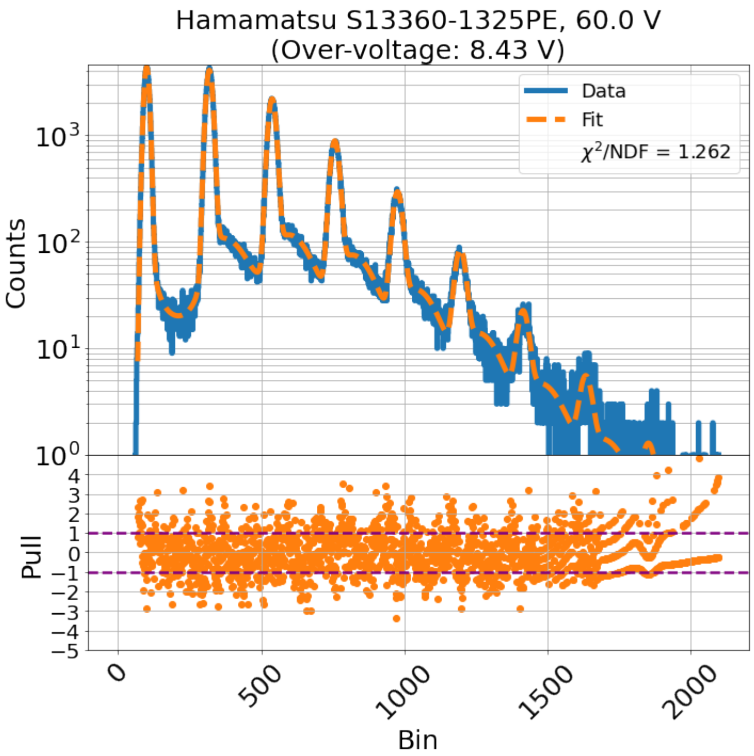
Sensor	Eff. area $[\mathrm{mm}^2]$	Pixel size $[\mu\mathrm{m}]$	Pixels	PDE [%]	Gain $[\times 10^6]$	Typ. DCR $[\mathrm{kHz/mm}^2]$	V_{bd} [V]
PM1125NS-SB0	1.2×1.2	25	2304	25	1.5	210	27.3
S13360-1325PE	1.3×1.3	25	2668	30	0.7	41	51.1

Hamamatsu Spectra Fitted With PeakOTron

Hamamatsu
Lowest Applied Voltage

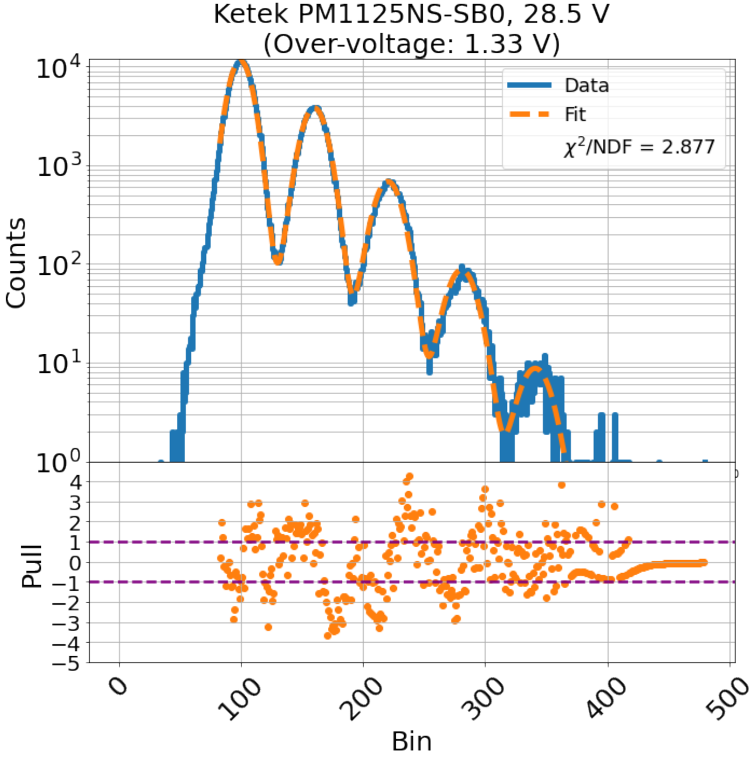


Hamamatsu
Highest Applied Voltage

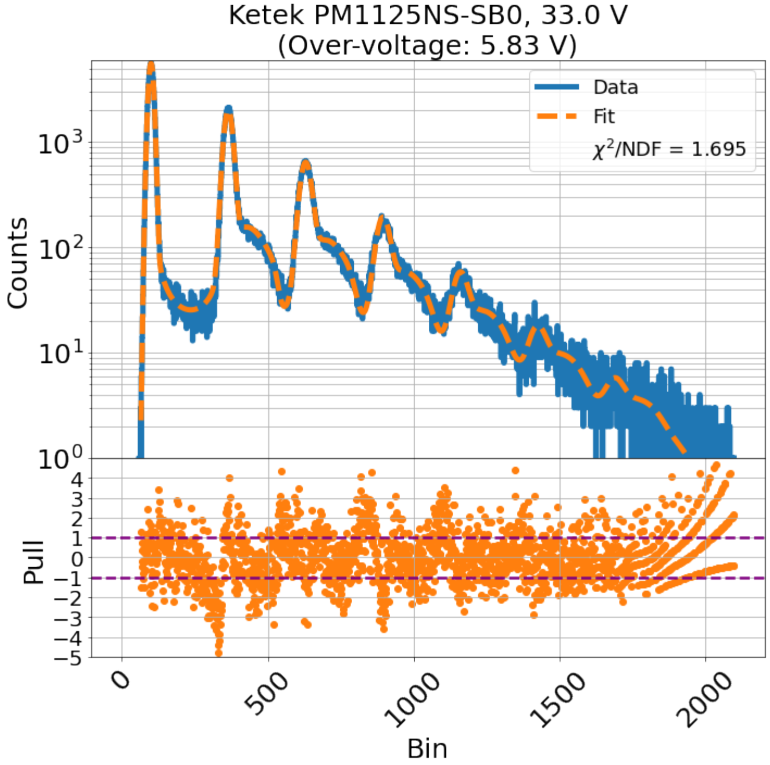


Ketek Spectra Fitted With PeakOTron

Ketek
Lowest Applied Voltage



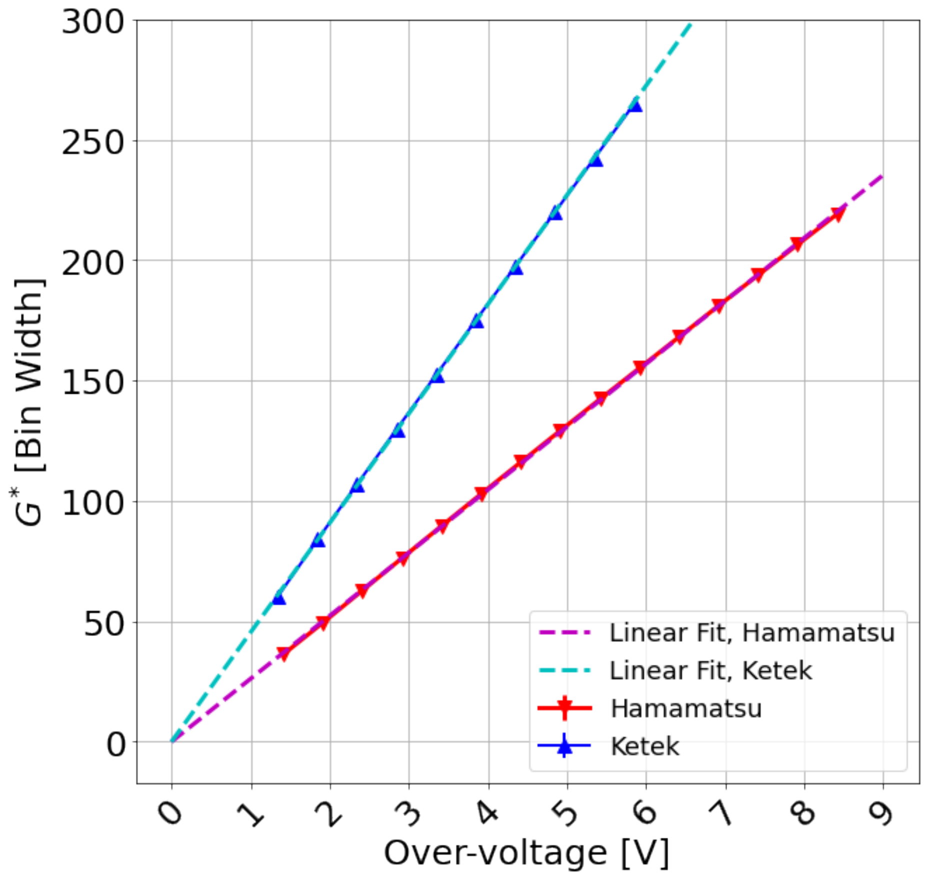
Ketek
Highest Applied Voltage



Selected Results: Gain

- SiPM gain increases linearly with over-voltage;
- Linear fit vs. over-voltage used to extract off-voltage;
- PeakOTron values for off-voltage agree with producer values;

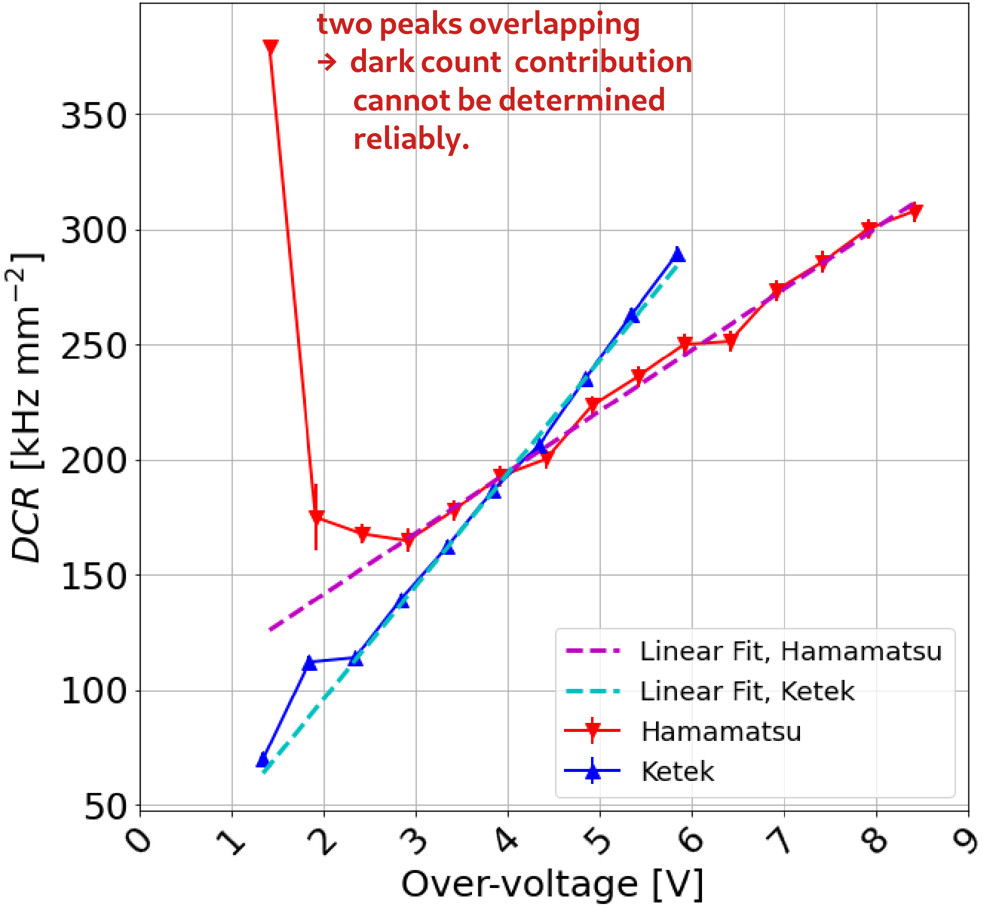
SiPM	V_{off} [V] Producer	PeakOTron
PM1125NS-SB0	27.3	27.17 ± 0.01
S13360-1325PE	51.1	51.57 ± 0.01



Selected Results: Dark Count Rate

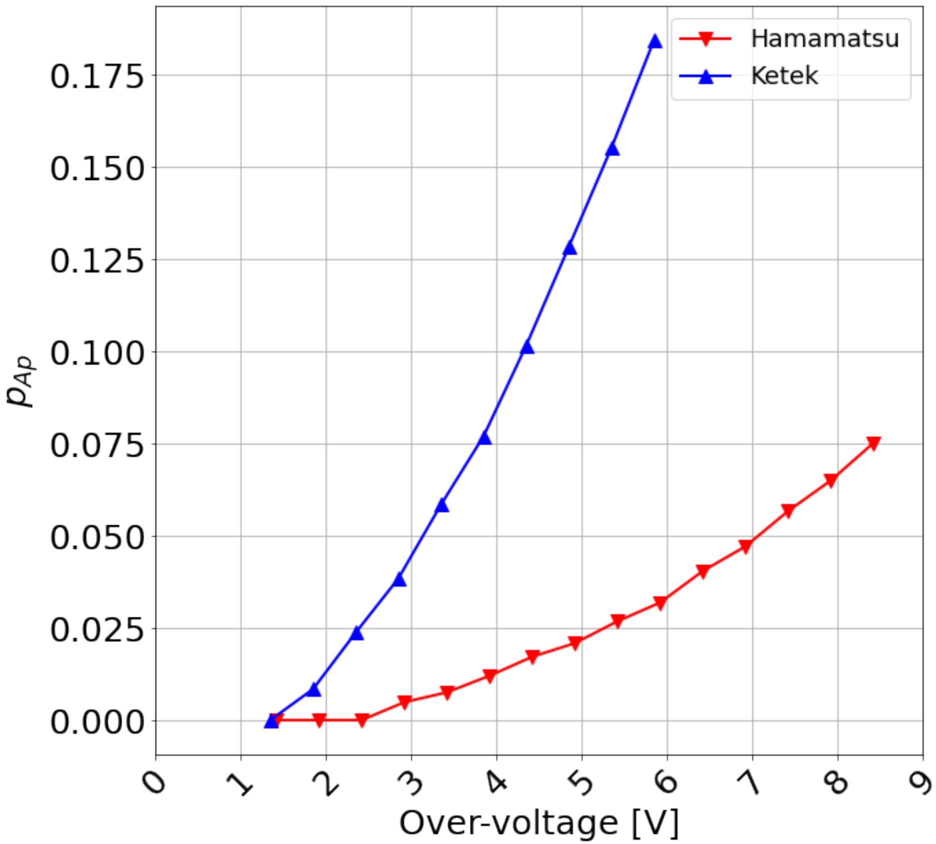
- DCR expected to increase with over-voltage;
- Approximately linear increase observed;
- Caveat:
  - DCR determined from region in-between peaks;
  - cannot be reliably extracted if they overlap
- PeakOTron values for DCR consistent with producer;

SiPM	DCR [kHz/mm^2] Producer	(V = 5 V , T=25°C) PeakOTron
PM1125NS-SB0	210	242 ± 3
S13360-1325PE	210	223 ± 4



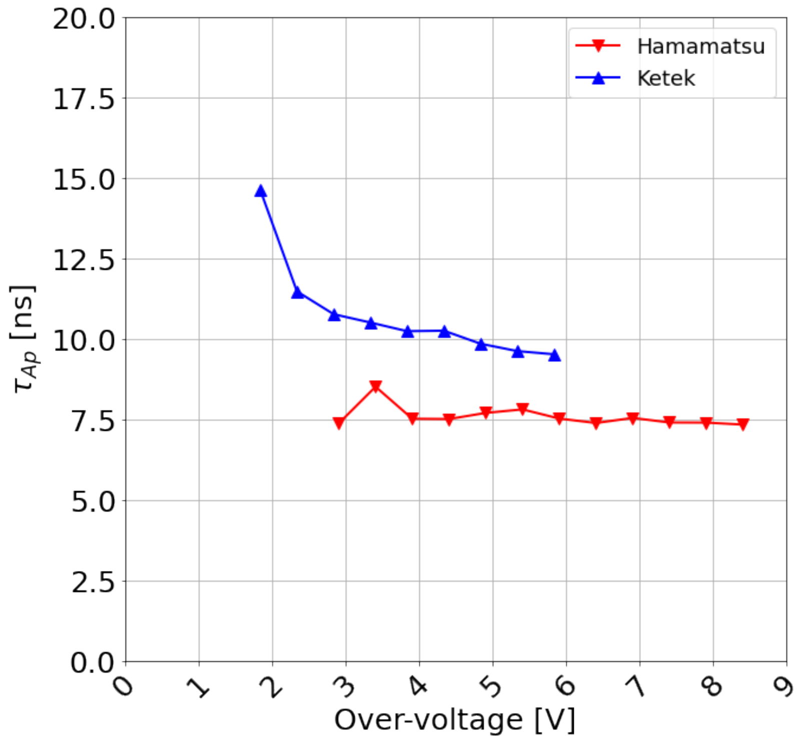
Selected Results: Afterpulse Probability

- Non-linear dependence expected for afterpulse probability →
- Reflects increased Geiger discharge probability in the high-field region of the SiPM;
- Non-linear increase observed;
- Ketek SiPM has signifcantly higher after-pulse probability than Hamamtasu SiPM.



Selected Results: Afterpulse Time Constant

- Minor/no voltage dependence expected for afterpulse time constants,
- PeakOTron values:
  - Ketek: τ_{Ap} ~ 10 ns
  - Hamamatsu: τ_{Ap} ~ 7.5 ns
- Not many studies of τ_{Ap} available in literature;
- Studies in [4] and [5] observe 'fast traps' with τ_{Ap} = 15 ns, ~10 ns
- Qualitative agreement with PeakOTron values.



[4] S. Du, F. Retière, After-pulsing and cross-talk in multi-pixel photon counters, Nucl. Instrum. Methods Phys. Res.A 596 (2008) 396–401. doi:10.1016/j.nima.2008.08.130.

[5] G. Kawata et al., Probability distribution of after pulsing in passive-quenched single-photon avalanche diodes, IEEE Trans. Nucl. Sci. 64 (8) (2017) 2386–2394. doi:10.1109/TNS.2017.2717463.

Conclusion

- An automated tool was developed to characterise SiPM charge spectra;
- Key SiPM performance parameters can be extracted from fits, including afterpulse information;
- PeakOTron:
  - accurately reconstructs these parameters;
  - provides excellent agreement with experimental data;

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https://gitlab.desy.de/jack.rolph/peakotron