SiPM non-linear response

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Why study SiPM non-linearity

Motivation

- SiPMs typically used in linear regime for single photon detection
- Pixel-like design leads to non-linear response to high photon numbers

$\longrightarrow$ Limits potential usage

Problems

- Time/spatial distribution of incoming photons
- Noise effects: cross-talk, delayed cross-talk and after-pulsing
- Partial pixel recovery
- Type of measurement: amplitude vs. charge
- No satisfying publications yet

Scope of Thesis

- Develop reliable method to asses non-linear response in SiPM
- Done by analysing statistical moments from integrated charge spectra
- Comparison with simulation
- Apply Generalised Poisson treatment to evaluate non-linearity
- SiPM response characterization based on the first three statistical moments (mean, variance, and skewness) as laid out in [S. Vinogradov (2022)]

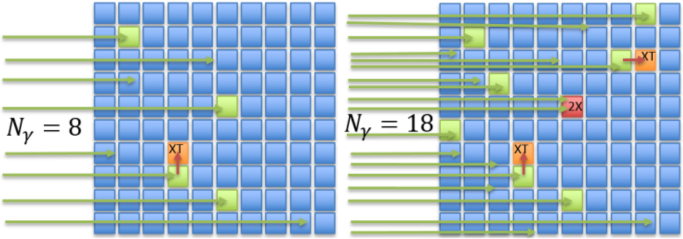
$\longrightarrow$ More possible application

SiPM non-linear response

- Charge generated by pixel avalanche q_{pixel}
- SiPM signal is charge generated by all fired pixels N_{fired}

$$Q = q_{\text{pixel}} \cdot N_{\text{fired}}$$

$\longrightarrow$ SiPM response is linear as long as all photons hit different pixels



Linear region　　Non-linear region

[Sascha Christian Krause (2020)]

Exemplary studies on SiPM response

Number of fired pixels as a function of incident photons: $N_{\text{fired}} = N_{\text{pix}} \cdot \left(1 - \exp\left(-\frac{\epsilon_{\text{PDE}} N_\gamma}{N_{\text{pix}}}\right)\right)$

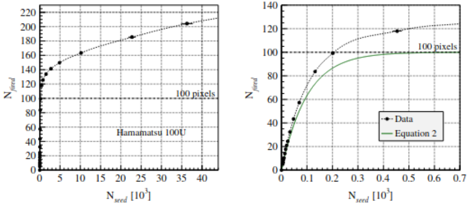
Photon detection efficiency: ϵ_{PDE}

100 pixel

100 μm

V_{over} =

0.5 V

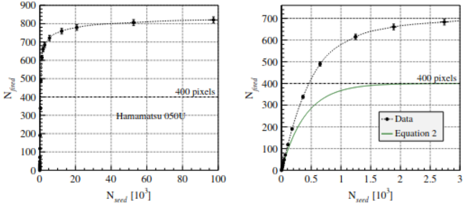


400 pixel

50 μm

V_{over} =

1.2 V

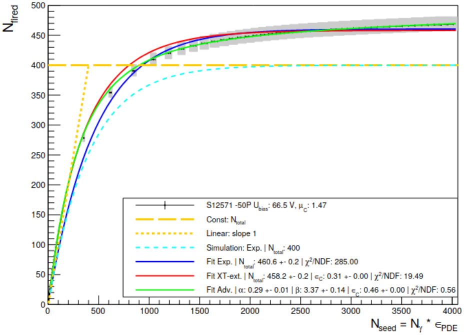


400 pixel

50 μm

V_{over} =

2.5 V

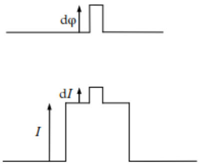


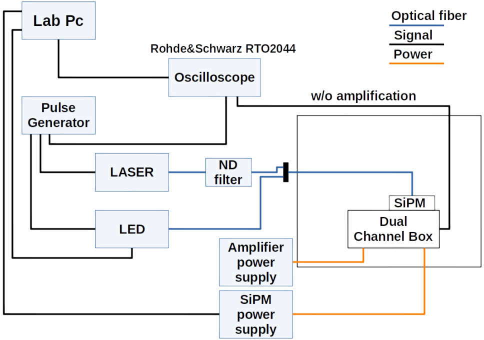
N_{fired} exceeds N_{pix} in both studies

[L. Gruber et al (2014)] [Sascha Christian Krause (2020)]

HIGH-D

- **Method:** Determine non-linearity by measuring the change in amplitude of fixed, small light pulse added onto variable intensity base pulse



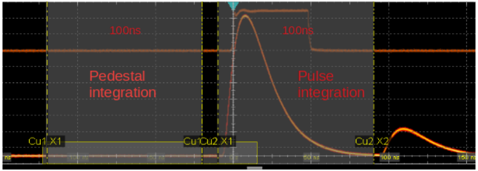


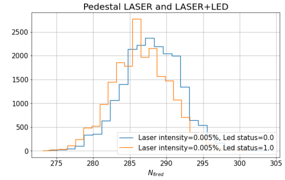
- $\mathrm{d}\varphi$: LED, I : LASER, $\mathrm{d}I$: LED*
- Add fixed, small amplitude $\mathrm{d}\varphi$ to existing amplitude I to give $I + \mathrm{d}I$
- Measure non-linearity with $(I + \mathrm{d}I) - I \leq \mathrm{d}\varphi$

[A. G. Wright. (2017)]

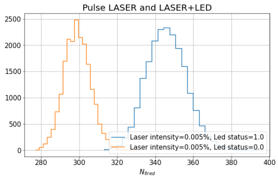
Measurement Procedure

1. Set LASER intensity with neutral density filters
2. Integrate pedestal and pulse region with scope
3. Turn on the LED light
4. Integrate pedestal and pulse region with scope
5. Go to step 1 and repeat

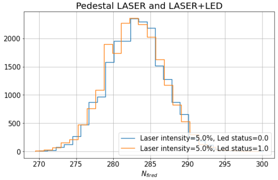




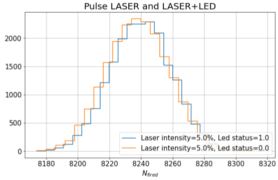
Pedestal low light



Pulse low light



Pedestal high light



Pulse high light

Present

Mean and variance are corrected by subtracting corresponding pedestal value

$$\mathrm{d}I = \mu_{\mathrm{LASER+LED}} - \mu_{\mathrm{LASER}}$$

Assess non-linearity by comparing $\mathrm{d}I$ with the mean of LED $\mathrm{d}\varphi$

$$\frac{\mathrm{d}I}{\mathrm{d}\varphi} = 1, \quad \text{only for linear response}$$

Future

Future Generalised Poisson treatment
Charge moments μ_i

$$\mu_i(Q_{photo}) = \mu_i(Q_{on}) - \mu_i(Q_{off}), \quad i = 1, 2, 3$$

$$\mu_1(Q_{photo}) = \mu = \eta\frac{1}{(1-\lambda)}g$$

$$\mu_2(Q_{photo}) = \sigma^2 = \eta\frac{1}{(1-\lambda)^3}g^2$$

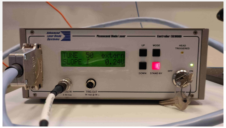
$$\mu_3(Q_{photo}) = \gamma \cdot \sigma^3 = \eta\frac{1+2\lambda}{(1-\lambda)^5}g^3$$

mean: η, cross-talk events: λ,
skewness: γ, gain: g

Pure Poisson $\mu_1 = \mu_2 = \mu_3 = \eta$, deviation towards GP as sign of non-linearity
[S. Vinogradov (2022)]

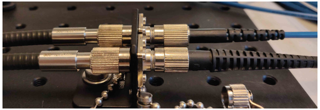
Measurement settings

- SiPM: Hamamatsu MPPC S14160-1315PS
  - Pixel pitch 15 µm
  - Sensitive area 1.3×1.3mm
  - Number of pixels 7296
  - $V_{over} = 3.8\,V$
- LASER: ASL EI61000D
  - $\lambda = 451\,nm$
  - $t = 50\,ps$
- LED: PicoQuant PLS 450
  - $\lambda = 458\,nm$
  - $t = 890\,ps$
- Integration window 20 ns
  - due to reflection at various fiber connections
- Bandwidth 20 MHz
  - resolve pulse heights from mV to V in one scale

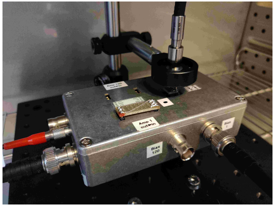


LASER

LED

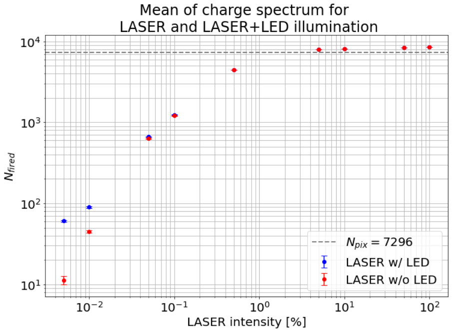


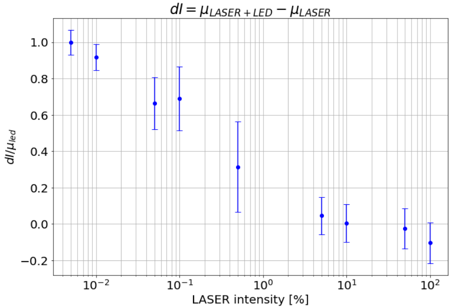
Bifurcated Fiber



Box with SiPM

Proof of concept: Mean and measure of non-linearity





- Saturation already visible for $t_{gate} = 20\,\mathrm{ns}$
- Exact saturation level requires more precise characterisation
- Add more data points

Outlook

- Iron out kinks in setup
  - Reflections
  - Optimal Oscilloscope settings
  - Minor technical issues
- Start take first data sets
- Implement the GP treatment of non-linearity

Thank You

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HIGH-D

References

[1] L. Gruber et al. "Over saturation behavior of SiPMs at high photon exposure". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 737 (Feb. 2014), pp. 11–18. DOI: 10.1016/j.nima.2013.11.013. URL: https://doi.org/10.1016%2Fj.nima.2013.11.013.

[2] Stephen Kokoska and Daniel Zwillinger. "CRC Standard Probability and Statistics Tables and Formulae, Student Edition". In: 1999.

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[4] Sascha Christian Krause. "Studies of the Response of Silicon Photomultipliers and Testbeam Data Analysis of a Highly Granular Analog Hadron Calorimeter Prototype". eng. PhD thesis. Mainz, 2020. DOI: http://doi.org/10.25358/openscience-1642.

[5] S. Vinogradov. "Skewness-based characterization of silicon photomultipliers". In: *The European Physical Journal C* 82.5 (May 27, 2022), p. 490. ISSN: 1434-6052. DOI: 10.1140/epjc/s10052-022-10444-4. URL: https://doi.org/10.1140/epjc/s10052-022-10444-4.

[6] A. G. Wright. *The Photomultiplier Handbook*. Oxford University Press, June 2017. ISBN: 9780199565092. DOI: 10.1093/oso/9780199565092.001.0001. URL: https://doi.org/10.1093/oso/9780199565092.001.0001.

Data analysis - Moments of statistics

- Each measurement steps results in 4 charge spectra
  - LASER, pedestal for LASER, LASER+LED, pedestal for LASER+LED
- Compute the mean, variance, and skewness of the histograms

Histogram moment r

$$m'_r = \sum_{i=1}^{N} f_i x_i^r$$

$$m_r = \sum_{i=1}^{N} f_i (x_i - \bar{x})^r$$

Mean, Variance and Skewness

$$\mu = \frac{m'_1}{N}$$

$$\sigma^2 = \sqrt{\frac{m_2}{N-1}}$$

$$\gamma = \frac{N\sqrt{N-1}}{N-2} \frac{m_3}{m_2^{3/2}}$$

f_i: counts, x_i: bins
[Stephen Kokoska and Daniel Zwillinger (1999)]

Backup – variance and skewness