Non-linear Response of Silicon Photomultipliers

Lukas Brinkmann

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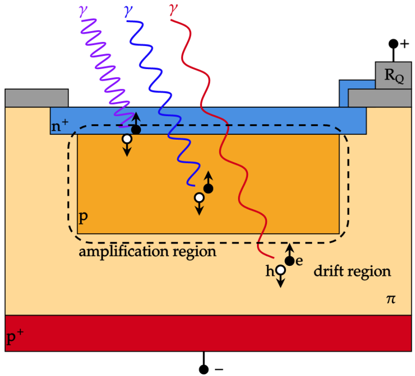
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

What is a SiPM?

- A Silicon Photomultiplier (SiPM) is a photo-detector operating in the red-to-near UV range
- Some useful properties;
  - high photon-detection efficiency ($> 50\%$)
  - good time resolution ($< 100\,\text{ps}$)
  - low noise
  - single-photon counting capability
  - insensitivity to magnetic fields
- Used for Particle Physics Experiments, Medical Imaging, LiDAR (Light Detection and Ranging), ...



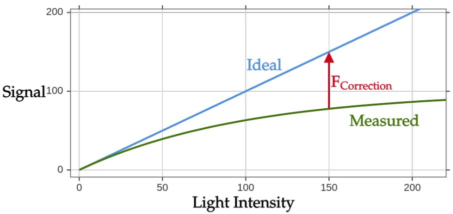
Motivation and Scope of Work

Motivation

- SiPMs used for single photon detection in linear regime
- Array of single-photon avalanche diodes (binary devices)
- Pixel-like design introduces non-linearity at high photon numbers

Scope of the Work

- Develop measurement for non-linearity
- Analyze statistical moments for SiPM response characterization
- Implement corrections; Expand applications



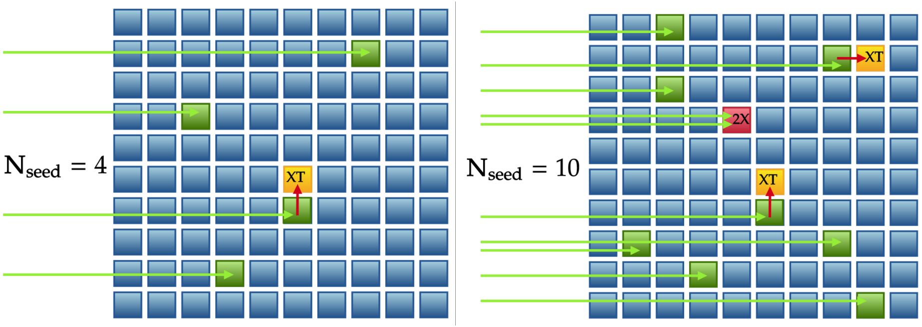
Understanding SiPM Non-Linear Response

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

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

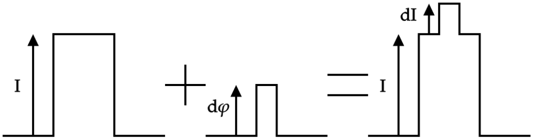
$\longrightarrow$ SiPM response is linear when each incoming photon triggers a different pixel

$\longrightarrow$ Challenge: Photon time distribution (late arriving photons on partially recovered pixels)



Measurement Setup: Single Step Method

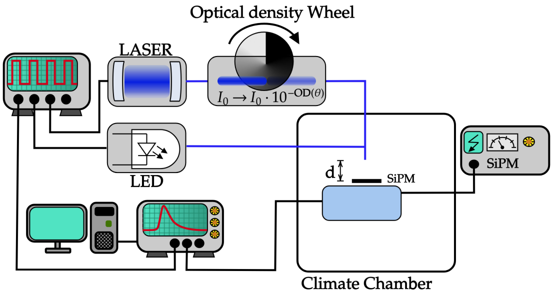
- **Method:** Determine non-linearity by measuring the change in amplitude when a fixed, small light pulse is added to a variable intensity base pulse.



I : LASER, $\mathrm{d}\varphi$: LED, $\mathrm{d}I$: LED*(effective LED light)

- Add fixed, small amplitude $\mathrm{d}\varphi$ to the existing amplitude I, resulting in $I + \mathrm{d}I$
- Measure non-linearity with $(I + \mathrm{d}I) - I \leq \mathrm{d}\varphi$

Setup and Measurement

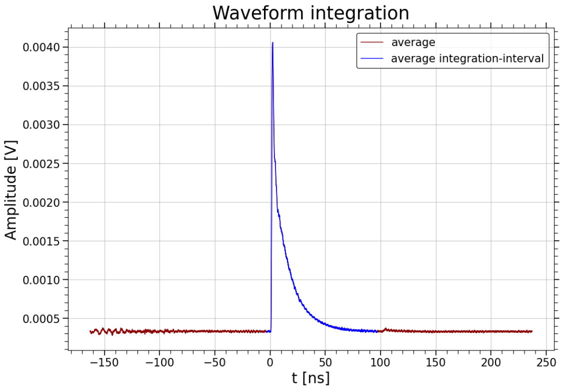


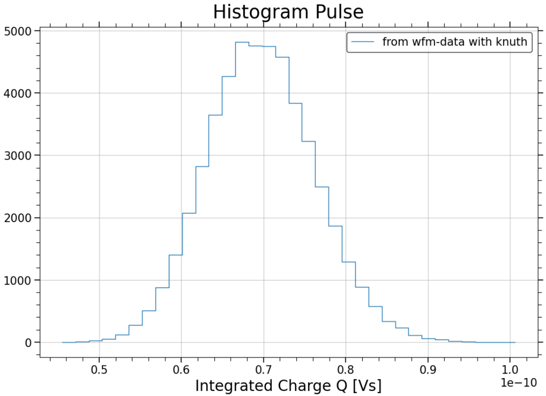
Parameter	Symbol	Value
Wavelength LASER	λ_{LASER}	451 nm
Wavelength LED	λ_{LED}	458 nm
Effective photosensitive area	-	1.3×1.3 mm
Pixel pitch	-	15 µm
Photon detection efficiency at λ_{LED}	PDE	32 %
Number of pixels	N_{pixel}	7296
Breakdown voltage	V_{br}	(37.270 ± 0.023) V

1. Regulate the LASER intensity by setting the angle of the neutral density filter wheel
   - $\mathrm{OD} = f(\theta)$, OD = optical density
   - $\mathrm{Intensity}(\theta) = 100 \cdot 10^{-\mathrm{OD}} = 100 \cdot 10^{-f(\theta)}$
2. Acquire 50k waveforms with 1 kHz frequency
3. Turn ON the LED and acquire 50k waveforms with 1 kHz frequency
4. Turn OFF the LED and go back to point 1
5. Waveforms are integrated over a gate with a tunable length

Integration of the waveforms

Average waveform for LASER intensity 0.0021% without LED





Integrate 50k waveforms over $t_{\text{gate}} = 100$ ns $\rightarrow$
$Q_{\text{Pulse}} = [Q_{\text{Pulse1}}, Q_{\text{Pulse2}}, \ldots, Q_{\text{Pulse50000}}]$

Calculate the Mean, RMS and Skewness of the integrated charge histogram

Parameter Scans

Time Delay Measurement

Scan	V_{over}	T	f_{pulse}	t_{gate}	P_{Led}	Δt_{Led}
Time delay	3.94 V	20 °C	1 kHz	100 ns	52%	0 ns – 40 ns

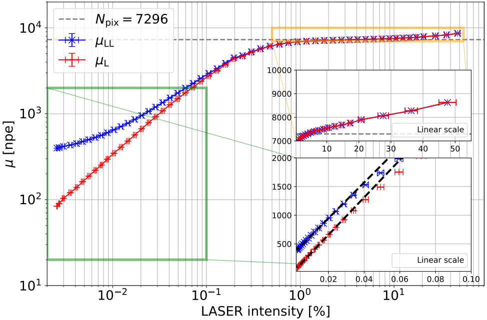
- Effect of late arriving photons from the LED with respect to primary LASER pulse
- Not like real case scenario: All photons are continuously distributed in time

Overvoltage Measurement

Scan	V_{over}	T	f_{pulse}	t_{gate}	P_{Led}	Δt_{Led}
Overvoltage	1.94 V – 4.94 V	20 °C	1 kHz	100 ns	52%	0 ns

- Effect of varying overvoltages on the response function

Mean of the integrated charge

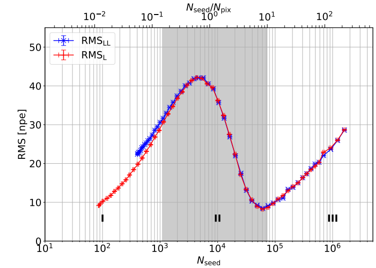


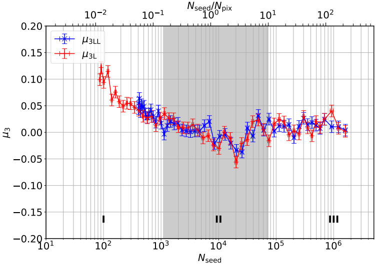
- Mean values of μ_L and μ_{LL} versus linear LASER intensity
- Y-axis converted to unitless number of photo electrons (npe):

$$\mu[npe] = \frac{\mu}{R_{\text{L}} \cdot e \cdot G}$$

- LASER+LED and Laser illumination charges differ at low-intensity
- Difference decreases with increasing LASER intensity
- SiPM response exceeds 7296 physical pixels
- Full saturation does not occur for this SiPM

RMS and skewness of the integrated charge





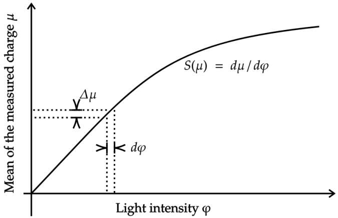
- RMS increases with light intensity, peaking before seed photons match total pixels
- RMS decreases to a minimum, akin to low light intensity
- Second RMS growth after minimum not understood
- RMS broader for LASER+LED at low intensity than LASER alone for same seed photons
- Increase in RMS possibly due to difference in pulse widths (LASER 50 ps, LED 980 ps)
- Skewness consistent with zero for $N_{\text{seed}} > 1000$, approaching Gaussian

Correcting Non-Linearity: Method

Goal

Correct response function only using measured quantities, x-axis independent.

- Single-Step $d\varphi$ (LED only)
- Mean LASER μ_L
- Mean LASER+LED μ_{LL}



$$\mu = (\mu_{\mathrm{LL}} + \mu_{\mathrm{L}})/2$$

$$S(\mu) = \frac{d\mu}{d\varphi}$$

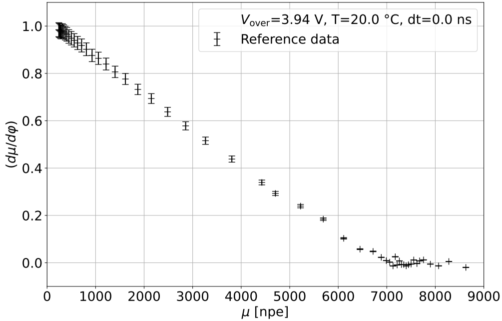
$$d\varphi = \frac{d\mu}{S(\mu)}$$

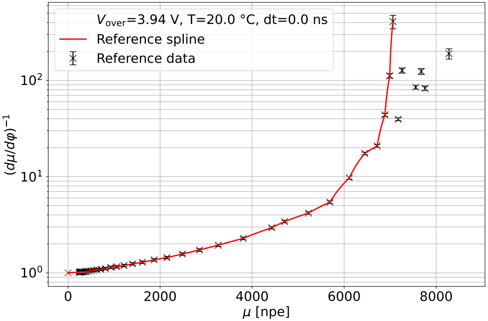
$$\varphi = \int_0^{\mu} \frac{1}{S(\mu)} d\mu$$

$$\varphi = \int_0^{\mu} \frac{1}{\frac{\Delta\mu}{d\varphi}} d\mu$$

$$\varphi = \int_0^{\mu} \left(\frac{(\mu_{\mathrm{LL}} - \mu_{\mathrm{L}})}{d\varphi} \right)^{-1} d\mu$$

Correcting Non-Linearity: Function



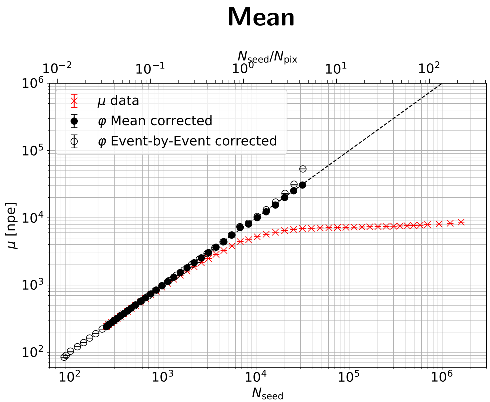


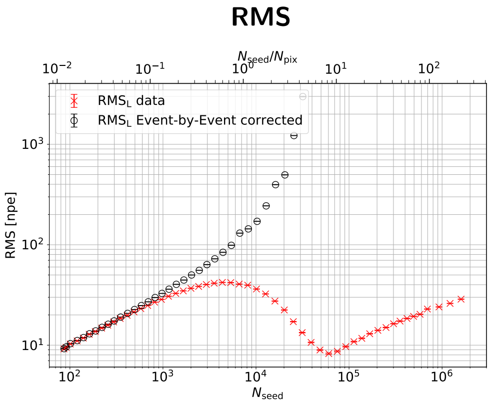
- Normalized difference $\frac{(\mu_{\mathrm{LL}} - \mu_{\mathrm{L}})}{d\varphi}$ starts at 1 (full LED detection)
- Falls off to 0 (no LED detection) at $\mu \approx N_{\mathrm{pix}} \approx 7300$

- Inverse of the normalized difference is the integrand of:

$$\varphi = \int_0^\mu \left(\frac{(\mu_{LL} - \mu_L)}{d\varphi} \right)^{-1} d\mu.$$

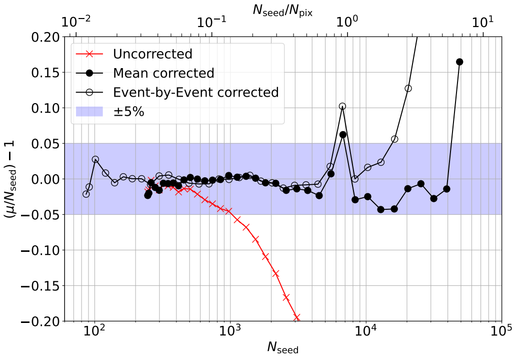
Event-by-Event application of correction





- Two correction methods presented: correction of mean at equal light intensity and event-by-event correction
- In both cases, mean value of corrected data is linear
- Event-by-event correction linearizes the RMS up to a point of slight overcorrection

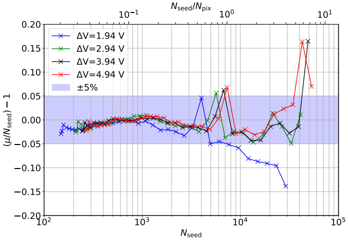
Event-by-Event application of correction



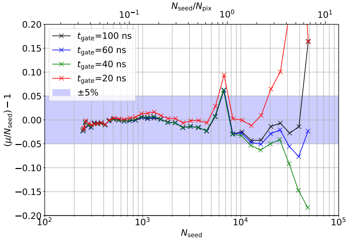
- Response linearity is plotted by subtracting a slope of one from the data
- Uncorrected data diverges from linearity by more than $\pm5\%$ for $N_{\text{seed}} \geq 1000 \sim 0.15 \cdot N_{\text{pix}}$
- Mean corrected data stays within $\pm5\%$ of linearity up to $N_{\text{seed}} \geq 45000 \sim 6 \cdot N_{\text{pix}}$, excluding the single outlier at $N_{\text{seed}} \sim N_{\text{pix}} = 7296$
- Event-by-Event corrected data diverges at $N_{\text{seed}} \geq 15000 \sim 2 \cdot N_{\text{pix}}$

Correcting non reference data

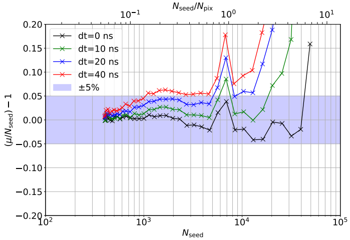
Overvoltage



Integration gate length



LED time delay



- Response linearized to $\pm$ 5% up to a signal equal to N_{pix} even if integration gate of the data is significantly shorter than that used to determine the calibration curve
- Reference calibration function can linearize data taken with different overvoltage or with different delay between the two light sources

Conclusion and Outlook

Conclusion

- Developed method/setup to measure SiPM response
- Response function of Hamamatsu SiPM (S14160-1315PS) was measured
- Response function shows **negligible dependence on the operating voltage** within the $2\,\mathrm{V} - 5\,\mathrm{V}$ overvoltage range
- Possibility to measure response function of SiPM once and still correct it if operating voltage changes
- Minor dependence on integration gate within $20\,\mathrm{ns} - 100\,\mathrm{ns}$ for specific signal shape of this SiPM
- Event-by-event correction of each measured charge demonstrated to work

Outlook

- Temperature, noise and radiation dependence of response curve
- SiPM type dependencies

Thank You! Questions?

Thank you for listening

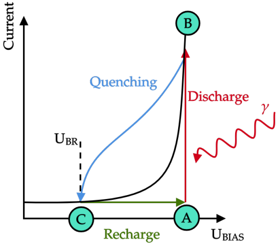
Any questions or suggestions?

How does a SiPM work?

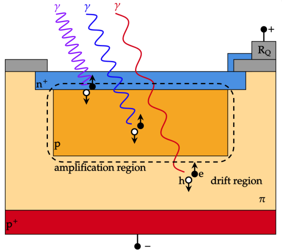
A Switch open and SiPM at V_{BIAS}

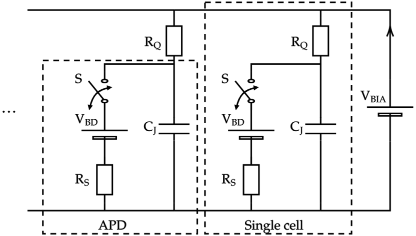
B Switch closed, avalanche breakdown and voltage drop to V_{BD}

C Switch open, avalanche quenched and recharge to initial state



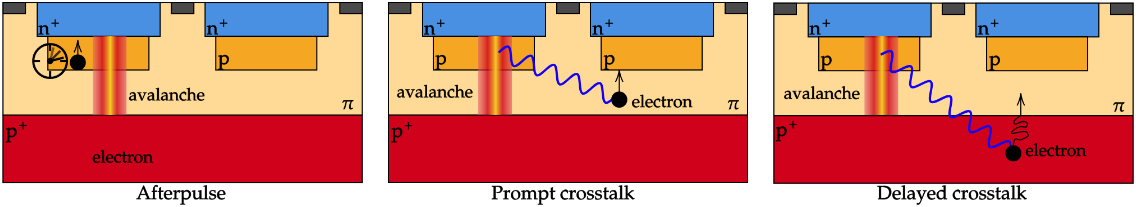
SiPM cycle





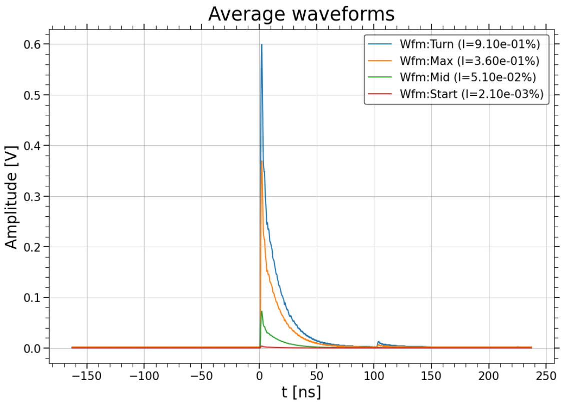
SiPM equivalent circuit

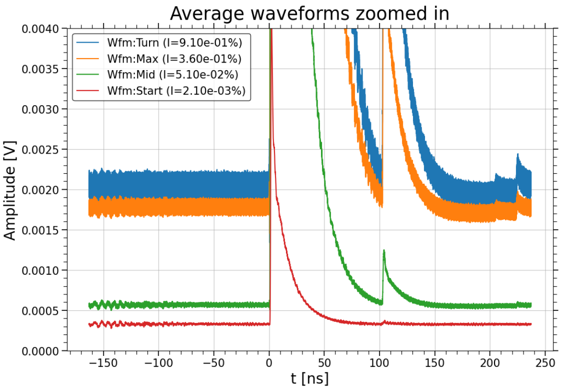
Afterpulse and Crosstalk



Waveforms

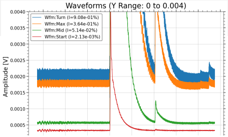
Average waveforms for different LASER intensities: 0.0021%, 0.051%, 0.36%, 0.91%



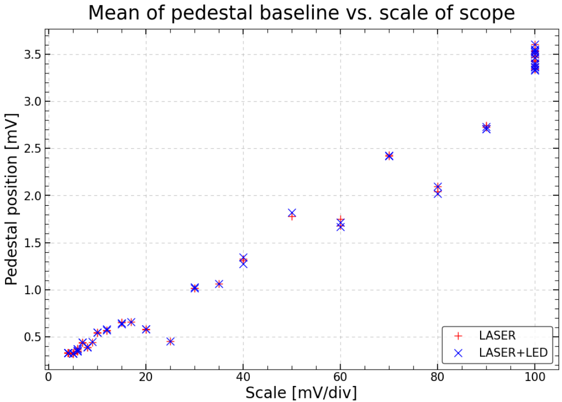


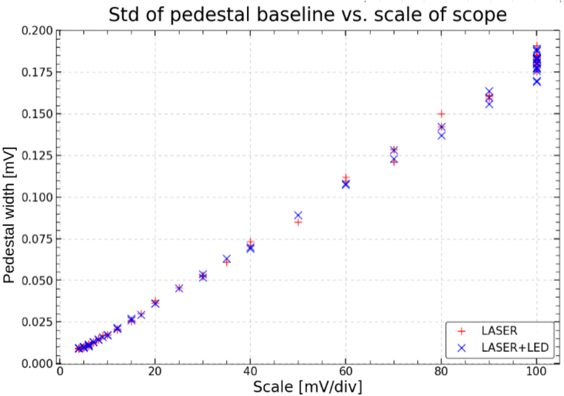
$\rightarrow$ Shift of pedestal caused by change in vertical scale of oscilloscope?

Pedestal Shift



Position and width of pedestal (before the pulse) for different vertical scales

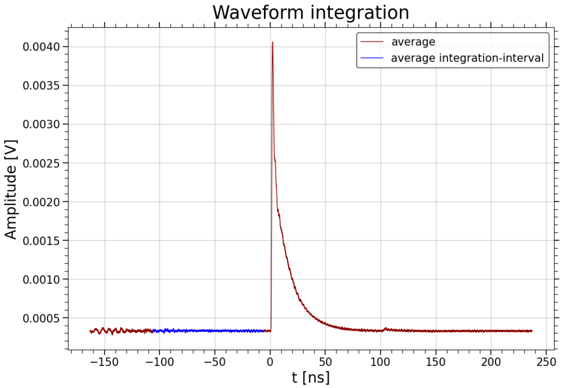


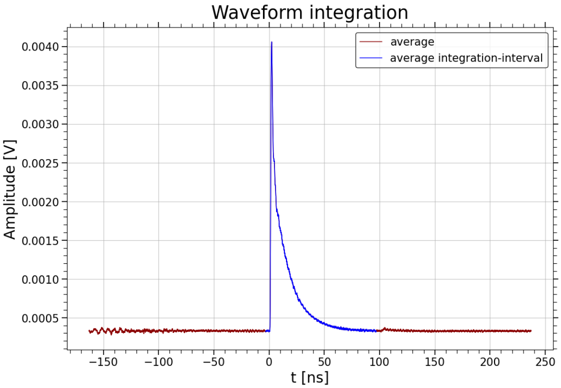


→ Clear correlation between pedestal position/width and vertical scale

From Waveform to Histogram

Average waveform for LASER intensity 0.0021% without LED



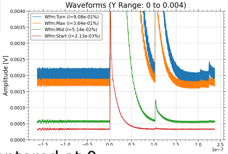


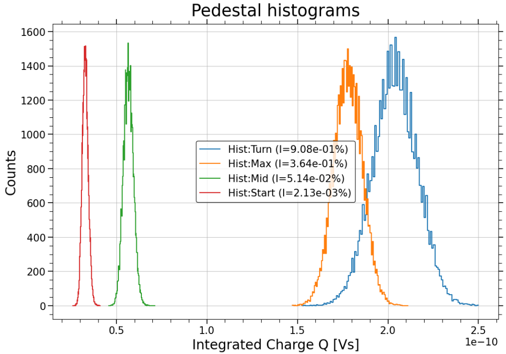
Integrate 50k waveforms over $t_{\text{gate}} = 100\,\text{ns} \rightarrow$
$Q_{\text{Ped}} = [Q_{\text{Ped1}}, Q_{\text{Ped2}}, \ldots, Q_{\text{Ped50000}}]$

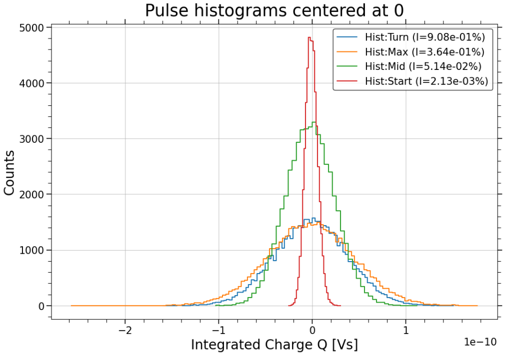
Integrate 50k waveforms over $t_{\text{gate}} = 100\,\text{ns} \rightarrow$
$Q_{\text{Pulse}} = [Q_{\text{Pulse1}}, Q_{\text{Pulse2}}, \ldots, Q_{\text{Pulse50000}}]$

Histograms

Integrated charge histograms for pedestal and pulse: 0.0021%, 0.051%, 0.36%, 0.91%.





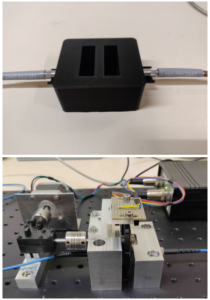


Position and width change for integrated charge similar to baseline.

The largest width does not correspond to the highest intensity (see upcoming slides).

- Light source used with 450+10nm color filter
- Neutral density filters and wheel placed in 3D printed mount
- Spectrometer fiber and light source fiber also coupled in 3D housing

OceanOptics Miniature Flame Spectrometer



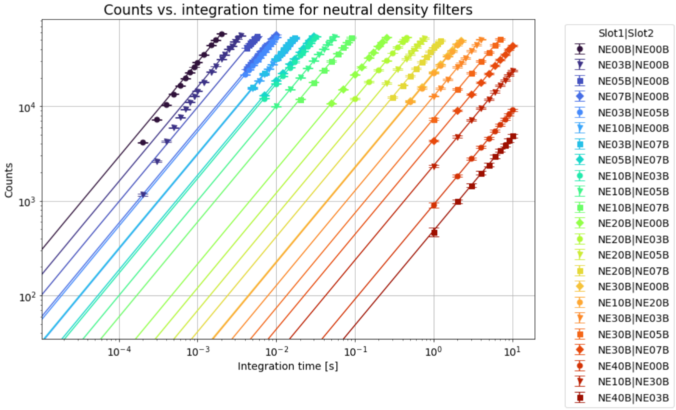
(Top) 3D printed housing for the filters; (Bottom) Wheel and motor control

Light source with color filter

Analysis neutral density filters

- Right shows the mean count for different integration times for half of the filter combinations
- Fit in the linear range
  - The last 7 points since low optical density (left side of plot) shows non-linearity
  - For high optical densities full range can be fitted
- Calculate optical density with:

$$\mathrm{OD} = -\log\left(\frac{a_{\text{filter}}}{a_{\text{ref}}}\right)$$



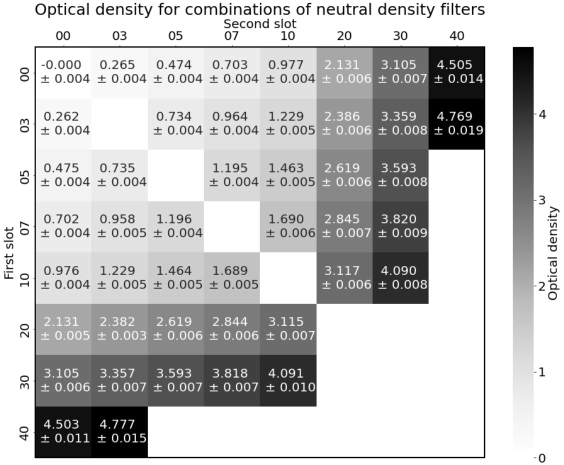
Counts vs. integration time

Results for neutral density filters

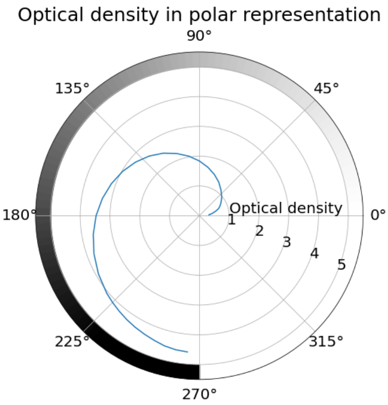
- Optical density for every possible filter combination. The column and row labels are shorthand, e.g. 07=NE07B.
- Order does not matter (symmetric)
- Optical densities add as expected $\mathrm{OD}_{\mathrm{filter1}} + \mathrm{OD}_{\mathrm{filter2}} = \mathrm{OD}_{\mathrm{combined}}$

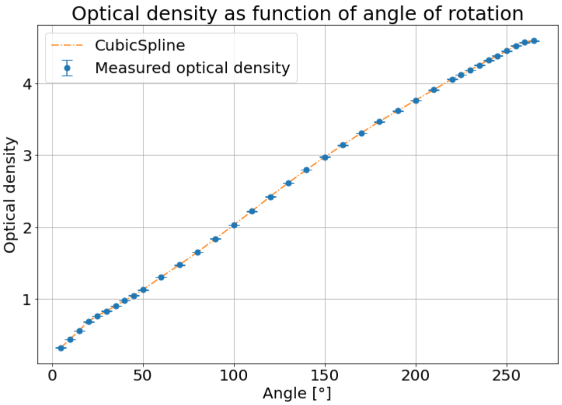
! 50% deviation for NE40B

Id	OD theo. (datasheet)	OD meas.	T_{meas} [%]	T_{theo} [%]
NE03B	0.3 (0.283)	0.264	54.5	52.20
NE05B	0.5 (0.498)	0.475	33.54	31.80
NE07B	0.7 (0.667)	0.702	19.84	21.46
NE10B	1.0 (0.993)	0.976	10.56	10.02
NE20B	2.0 (2.048)	2.131	0.74	0.89
NE30B	3.0 (3.156)	3.10	0.080	0.070
NE40B	4.0 (4.196)	4.504	0.0031	0.0063



Results neutral density wheel

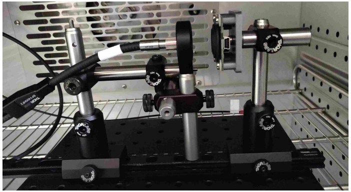


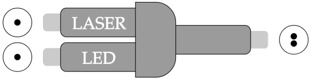


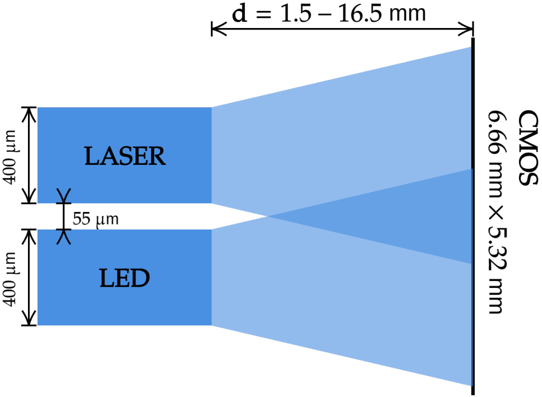
- Optical density is not linearly dependent on turn angle
- Use CubicSpline fit for intermediate optical densities

Illumination study

- Motivation: Check spatial uniformity of LASER/LED light
- Method: Measure spatial distribution with CMOS camera at various distances
- Goal: Find minimal distance at which overlap of one standard deviation occurs

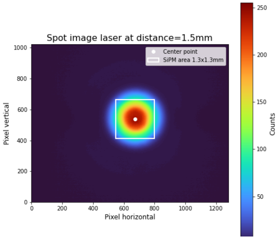


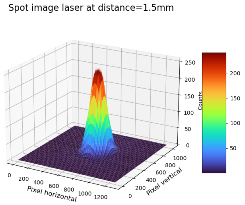


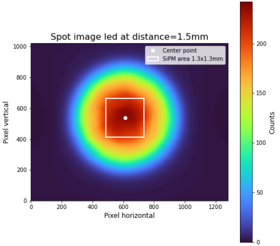


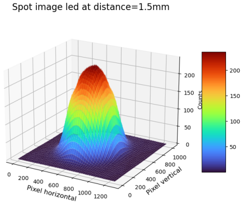
Images of LASER and LED spots

- Both light sources exhibit Gaussian intensity profiles
- LED produces a spatial larger profile
- SiPM represented as a white box
- Calculate mean position and standard deviation for d ranging from 1.5 mm to 16.5 mm

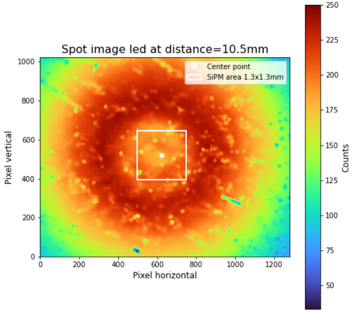


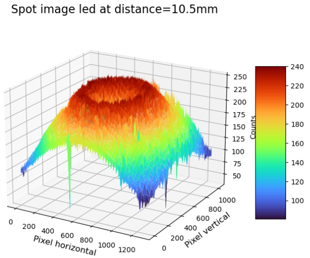






50/50 Splitter wrong end





Non-Gaussian intensity profile from tap port

Illumination Study Results

- SiPM centered around the LASER spot, using the larger LED spot
- Distance d of 7.5 mm is sufficient for achieving coverage within one standard deviation
- However, this distance results in a reduced overall light intensity