Report – Characterization of a Silicon-Photomultiplier Using Ultra-Fast Pulsed LED

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Contents

1 Getting to Know the Silicon-Photomultiplier Signals

Using the oscilloscope function of the PSAU, the signals can be investigated. The resolution is limited, which is why an external oscilloscope had to be used.

1.1 Amplitude:

As described in the manual, the amplitude of the 1 pe peak was determined using the cursor functions on the scope. Figure 1 shows the results for 9 different voltage values between

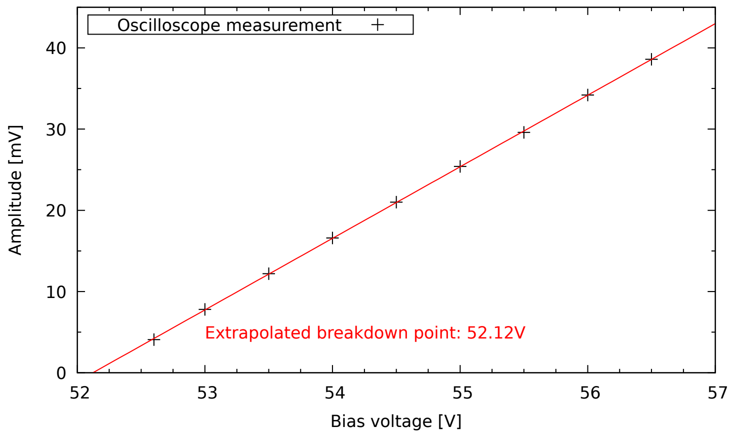

Figure 1: Amplitude of the 1 photon peaks versus voltage measured with an oscilloscope. A linear extrapolation was used to determine the breakdown point of the SiPM.

52.6 V and 56.5 V. A linear extrapolation towards 0 mV was performed to estimate the breakdown-point. A value of V_{BD}=52.12 V was found. This will be repeated in similar fashion using charge values (section 2.2).

1.2 Peak Width:

The time over threshold (TOT) value depends strongly on the trigger level. The higher the trigger the lower the measured ToT values and vice versa. Compare chapter 11 in [Bay20]. TOT values in this experiment were measured at a trigger level of 5 mV and 5 mV voltage division. They were found to lie in a range between 20.4 ns at 53 V bias voltage and 78.0 ns at 56 V bias voltage.

2 Silicon-Photomultiplier Characteristics in the Absence of Light

2.1 General Measurement Techniques

At first, the behavior of the measurement outcome under the change of some parameters was investigated. These parameters are the trigger level of the internal trigger, which works like the trigger of an oscilloscope. To demonstrate the influence of the trigger, charge histograms were recorded for different threshold values. The data taking time per histogram was 10 s. The histograms are shown in figure 2.

When the trigger threshold is set too low, noise begins to be recorded as well. Noise signals are random fluctuations of the baseline in the absence of light or a dark signal and are smaller than the 1 pe peak. If such a fluctuation is triggered, the integrated charge is zero on average. In the charge spectrum a peak occurs around QDC channel 0 or close to it, which is calles *pedestal* (see top left graph in figure 2). When the trigger is increased, the height of the pedestal decreases and the 1 pe peak becomes dominant (top right).

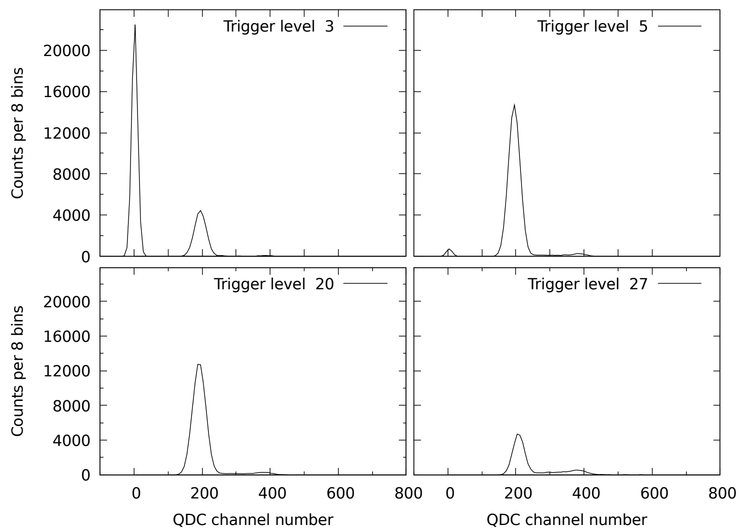

Figure 2: Influence of the trigger threshold level on the measured charge spectrum. At extremely low values the pedestal can be seen at around QDC channel 0 (top left), while for too high levels, the one photon peak might be cut off (bottom right).

In this measurement, the full 1 pe peak without any pedestal contribution could be observed for trigger values of about 20 (See bottom left graph in figure 2). If the trigger threshold is set too high, the 1 pe peak might be missed during the measurement and the 2 pe peak becomes more prominent. This is shown in the bottom right graph.

The choice of the internal trigger threshold also depends on the applied bias voltage, which influences the SiPM gain and therefore the distance between the individual peaks. Thus, after changing the bias, re-adjustment of the trigger threshold might be necessary.

The second parameter to be investigated was the length of the gate which was used to integrate over the wave form. Again, charge spectra were recorded for about 15 s and are depicted in figure 3. When the gate is increased, the width of the peaks in the charge spectrum grows as well. This can be explained by the growing amount of noise that is integrated as well, when the gate is too large. This is visualized using an extreme example of a gate width of 392 ns in the bottom right graph of figure 3. On the other hand, when the gate is too narrow, the wave form is not captured by the gate in its full width any more and therefore also some charge is lost. The measured charge is then an underestimation of the actual deposited charge by that signal. The peaks in the spectrum shift towards the left and eventually the width of the peaks decreases (top left graph in that same figure).

2.2 The break-down voltage

Approach using Charge Spectra in Darkness

The measured charge of the 1 pe (photon equivalent) peak was determined in darkness. For this measurement procedure the internal trigger was used and set to a level of 30. The applied voltage was varied in a range from 53.5 V to 57 V and a charge spectrum was recorded. The

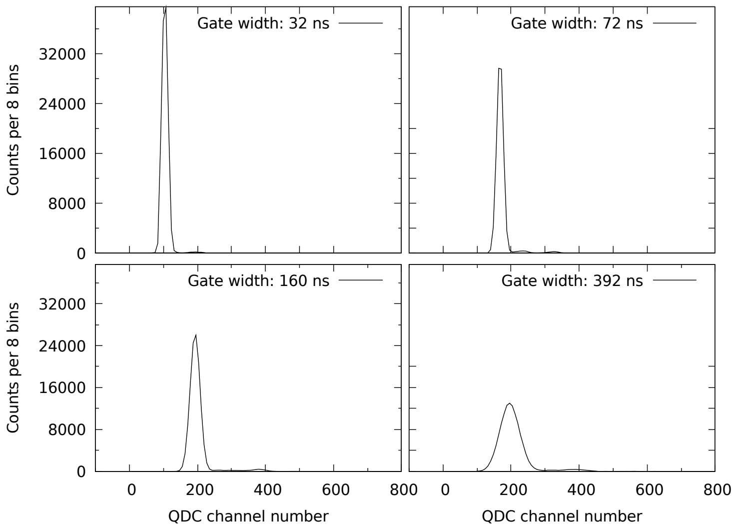

Figure 3: Influence of the gate width on the charge histogram in darkness. If the gate is too narrow, the signals are only partly integrated and the 1 pe peak appears at smaller QDC channel numbers (top left). If on the other hand, the gate is too wide, too much noise will be integrated and the peak width increases significantly (bottom right). An intermediate gate value needs to be chosen based on the expected signal width.

following measurement parameters were chosen: The pre-gate was set to 16 ns, the gate length was 208 ns and the hold-off for the trigger between events was set to 504 ns.

The spectrum for every bias voltage is shown in figure 4 in the top half of the graph. The peaks correspond to the 1 pe peak and the trigger level was adjusted for every voltage such that the pedestal (noise level) was not triggered on. The different peak heights for different voltages originate from varying run times of the individual measurements. Furthermore, the dark rate also fluctuates when the bias voltage is changed. The lower the voltage the smaller the QDC channel number at which the 1 pe peak occurs. QDC stands for *charge to digital converter*. An extrapolation to QCD channel zero gives an estimate for the break down point.

Analysis and Results

The maximum peak position of the 1 pe peak was read out from the data for every voltage. Afterwards, the applied bias voltage was plotted against the determined peak positions and a linear fit was applied. This is shown in the bottom half of the graph in figure 4. The intersection of the linear function with the y-axis was the desired break-down voltage as at this point the charge value is zero. For the fit the following function was used:

$$V(Q_{\mathrm{QDC}}) = a \cdot Q + b$$

where Q_{QDC} denotes the measured charge given as QDC channel number and a and b are the fit parameters. The values for the fit parameters were

$$a = (0.00989 \pm 0.00009)\,\mathrm{V/C}$$
$$b = (52.35 \pm 0.03)\,\mathrm{V} = V_{\mathrm{BD}}$$

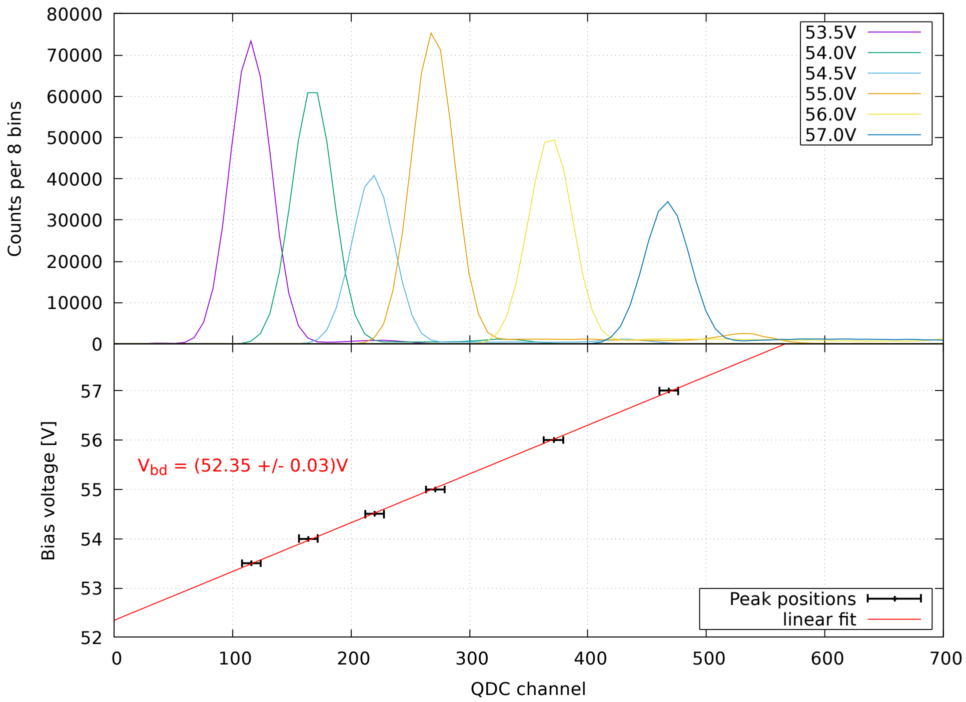

Figure 4: Charge spectrum (top) for various bias voltages in the absence of light. The peaks of the 1 pe peak shift towards higher charge values when the voltage is increased. The bottom of the graph shows the applied voltage versus peak position and the corresponding linear fit function to determine the break-down voltage.

a is the slope of the curve and b is the offset, which in this case is the desired quantity – the break-down voltage V_{BD} of the Silicon-Photomultiplier at room temperature. The data sheet stated a value of 53 V, which is significantly higher, judging by the given uncertainties of the fit result.

2.3 Dark Count Rate

Measurement Procedure

For the measurement of the dark count rate, two options are available: the straight-forward one is to use the counter integrated in the GUI, called *PSAU counting*. The acronym PSAU stands for p*ower supply and amplification unit*. The second option is to use the PSAU staircase window, which scans the threshold in a certain range and displays the obtained dark rate. The latter option was used in this case.

The threshold was scanned in a range from -10 mV to -100 mV [1] The trigger step size was 1 mV. Two further parameters are of importance for this measurement: firstly, there is the *gate width*, which determines the time window within which the PSAU counts the events. secondly, there is the number of *points for mean*, which is basically the total amount of the aforementioned time windows that are used to determine the mean value. The exact values

[1] The signals are somehow processed after being inverted. This explains negative threshold values.

for this measurement were as follows: 20 points for mean and a gate width of 10 ms. These staircase graphs were created for 5 different bias voltages between 54 V and 58 V.

Analysis and Results

Figure 5 shows the resulting stair case functions for different bias voltages. One can see the characteristic staircases, where the first plateau corresponds to a trigger level on 1 pe level and the second plateau to a trigger on 2 pe level etc. The steps occur whenever the trigger exceeds the amplitude of a photon level causing a jump in the graph. For the calculation of the dark count rate the mean value of the data points of the first plateau was calculated, which corresponds to a trigger on the 1 pe level.

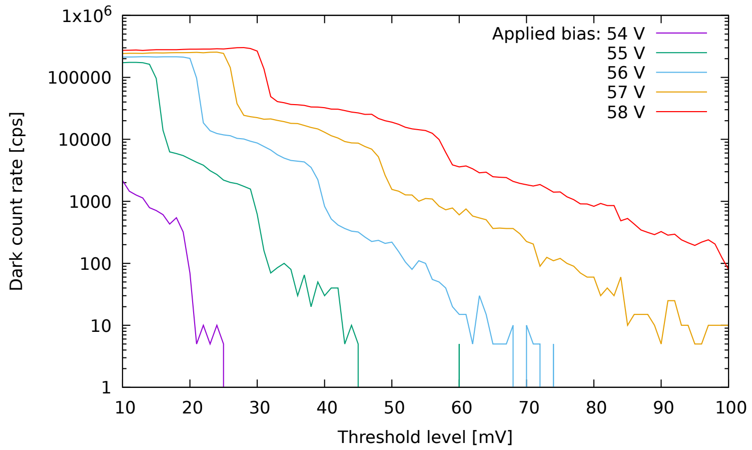

Figure 5: Staircase function for various bias voltages. The threshold is scanned in steps of 1 mV and the dark rate is recorded. The plateaus denote the individual photon levels – the highest one being the 1 pe level, the second one the 2 pe level etc.

The dark count rate at a certain photon level is calculated by taking the mean dark count rate of all data points from the plateau. To obtain the length of the plateau, the numeric derivative of the data points is taken, which is shows a clear minimum at the step between the 1 pe and the 2 ps level. Figure 6 shows such a derivative for the example of 57 V. There is a clear minimum at a threshold value of 26 mV. A comparison to the graph in figure 5 proves that at this point the step between 1 pe and 2 pe plateau occurs (dark yellow curve).

The dark count rate mean value on 1 pe level was then calculated using all the data points from the first plateau until threshold level $t_S - 3\,\text{mV}$, where t_S is the trigger level where the step occurred. The additional 3 mV offset were introduced to not include data points from the step itself but only from the plateau. The uncertainty on this mean value was calculated using the standard deviation divided by the square root of the number of points contributing to the mean value. The described procedure could only be carried out for bias voltages between 55 V and 58 V, since the 1 pe plateau of the 54 V data set was not displayed properly.

Figure 7 shows the mean value for the dark count rate for bias voltages between 55 V and 58 V. An increasing dark count rate with increasing voltage is obtained.

Discussion

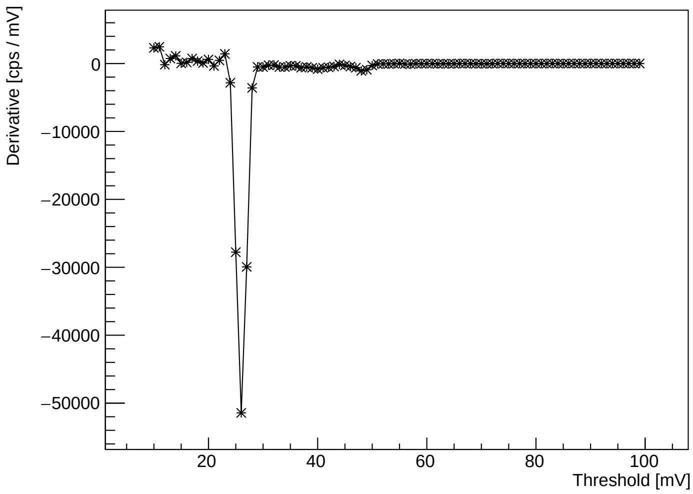

Figure 6: Example of a derivative of the staircase plot for the example of 57 V. The minimum occurs at the position of the step in the staircase plot (see figure 5).

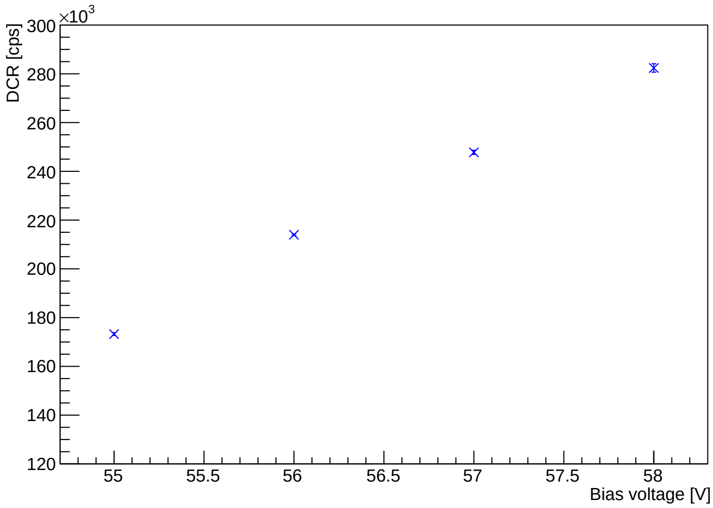

Figure 7: Dark count rate versus bias voltage. The rate increases with increasing bias.

The data set taken with 54 V could not be used, since the plateau appeared to be cut off. Thus, an increase of the threshold range towards smaller values might be beneficial. Also, the step size of 1 V in between the individual data sets might be too coarse and more measurements should be performed to get a better curve.

The resulting dark count rate for all voltages is higher than the value given in the data sheet (see table in the manual), which was 90 kcps. One reason might be that the value from the data sheet was given for room temperature, which is usually on the order of 20°C. The temperature measured with the SP5600 read-out device, however, was over 30°C. Since the dark count rate increases exponentially with temperature, this could explain the deviation.

2.4 Cross Talk Probability

Procedure

The probability for the occurrence of cross talk can be calculated in two different ways: in a first approach, one can further analyze the staircase plot and also determine the level of the 2 photon signals. The probability for cross talk can then be calculated using the following expression:

$$p_{\mathrm{CT}} = \frac{\mathrm{DCR}_{2\,pe}}{\mathrm{DCR}_{1\,pe}},$$

which is basically the fraction of all events that triggered *at least one* additional signal in one of the neighboring micro cells. The value $\mathrm{DCR}_{1\,pe}$ is the dark rate on 1 pe level which automatically incorporates *all* signals that are larger than a 1 pe signal, as they can also be triggered with a 1 pe trigger level. $\mathrm{DCR}_{2\,pe}$ is the dark rate on 2 photon level, accordingly.

One can get to a similar result by taking the peak integral spectrum and count its entries. Then, one obtains the number of entries with more than 1 photon by subtracting the number of entries in the 1 pe peak. Dividing this result by all entries yields the probability for cross talk as defined above. However, in the following, the first method – using the staircase plot – will be explored.

The mean value of the dark count rate on 2 pe level was calculated by using the DCR entries after the first step and before the second step in the graph. From these points the mean value was calculated. However, the algorithm was not capable of identifying the 2 pe step reliably in every data set. Therefore, simply the first 7 DCR values after the first step plus 3 mV were used. Again the additional 3 mV were introduced as a safety margin to not include values from the step itself. Then, the cross talk probability could be calculated using the above stated formula.

Results

Figure 8 shows the results of the calculation of the cross talk probability. An over-proportional increase of the cross-talk probability with increasing voltage is observed. This behavior is in good agreement with results from Eckert et al, 2010 [Eck+10].

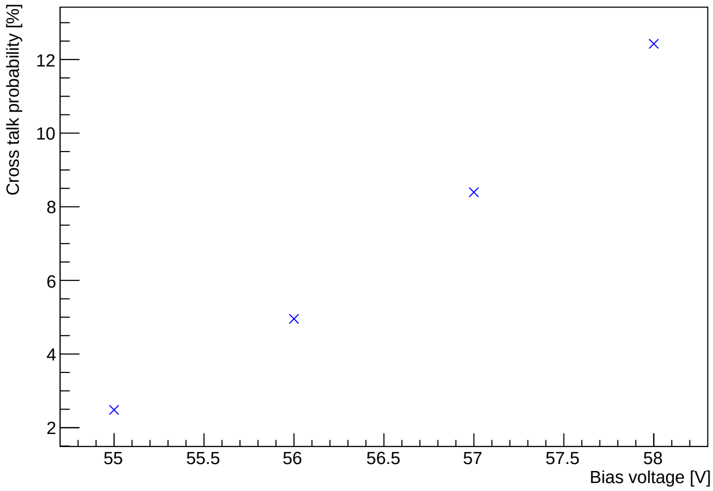

Figure 8: Crosstalk probability versus bias voltage.

3 Characterization of the Silicon-Photomultiplier with an Ultra-Fast Pulsed LED

High frequency LED pulses were used to create light signals in the SiPM. The LED light pulses were sent from the frequency generator to the SiPM using a fibre.

3.1 General Measurement Techniques

3.1.1 Internal and External Trigger

The difference between internal trigger of the PSAU and the external trigger coming from the frequency generator was investigated. The most significant difference is that with an internal trigger the pedestal (also called 0 pe peak) can be excluded entirely, while using the external trigger, a pedestal occurs. This is due to the fact that the amount of emitted photons as well as the number of detected photons follows Poisson distributions. Therefore, it is possible that even though the LED was triggered, no photon was detected by the SiPM and, thus, the charge integral is zero. When the LED intensity is increased, the pedestal peak can be reduced to almost zero, since the probability to not detect any photons from a pulse decreases with increasing light intensity.

3.1.2 Variable Gate Width

The next parameter to be examined was the width of the gate for the integration. The integrated charge is basis of the charge spectrum given in QDC values. For the test measurements, a voltage of 54 V was applied and an external trigger was used. The LED intensity was set to 350, which is given in arbitrary units.

Figure 9 shows the charge spectrum for two different gate widths. If the gate is too narrow (72 ns), some of the charge is not recorded and the distance between the peaks is

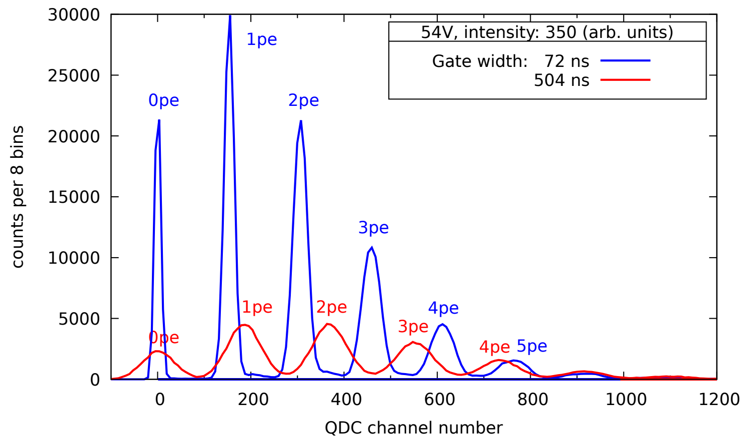

Figure 9: Charge spectrum for two different gate widths. If the gate is too narrow (72 ns), some of the charge is not recorded and the distance between the peaks is shorter. However, if the gate is too large, the peaks appear broadened, as more noise is integrated as well. The different peak heights in this case originate from different run times of the measurement.

shorter. However, if the gate is too large (504 ns), the peaks appear broadened, as more noise is integrated as well. Differences in the total amount of counts in both spectra originate from different run times of the measurement.

3.2 Gain Versus Bias Voltage

Method Description

In order to determine the gain for various over voltages, charge spectra were recorded in a bias range from 53.5 up to 56.5 V. The LED intensity was set to a fixed level of 3.50.

Figure 10 shows an example of two charge spectra using two different bias voltages of 53.5 V and 54.5 V. Although the difference in voltage is only 1 V, there is a significant difference in the peak spectrum: the 1 pe peak has a smaller distance from the pedestal (0 pe) in case of the smaller voltage. Also, the distance between the peaks is smaller as well. This indicates that the gain – which determines the deposited charge per detected photon – increases with growing bias voltage.

Analysis and Results

To perform a quantitative analysis the positions of the 1 pe and 0 pe peaks were determined using a peak finding algorithm and a gauss fit. The mean value of the gauss fit was used as peak position and was naturally given in units of the QDC channel number. Then the difference between 1 pe and 0 pe peak was calculated:

$$\Delta\mathrm{QDC}_{pp} = \mathrm{QDC}_{1\,\mathrm{pe}} - \mathrm{QDC}_{0\,\mathrm{pe}},$$

where the index *pp* means *from peak to peak*.

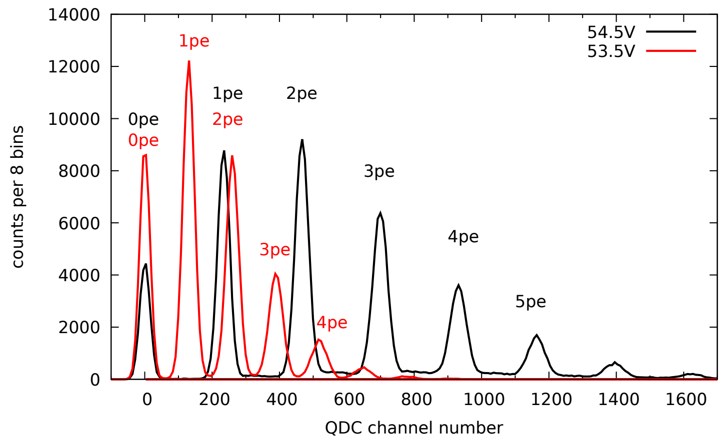

Figure 10: Charge spectrum for two different bias voltages. The distance between the peaks is smaller for lower voltages.

The QDC channel conversion factor (here denoted with F_{QDC}) can be calculated according the Application Note AN2502 by CAEN:

$$F_{\mathrm{QDC}} = \frac{\text{QDC channel}}{\text{Coulomb}} = 1.235\,\mathrm{fC/QDC}$$

This factor depends on G_{PSAU}, which was 30 in this case. Now, the gain G can be calculated, which is in the following shown using the example of 54.5 V:

$$G = \frac{\Delta\mathrm{QDC}_{pp} \cdot F_{\mathrm{QDC}}}{\text{electron charge}} = \frac{233.93\,[\mathrm{QDC}] \cdot 1.235\,\mathrm{fC/QDC}}{1.6 \cdot 10^{-19}\,\mathrm{C}} = 1.81 \cdot 10^{6}$$

Comment be RB: the uncertainty estimation is still missing. FIXME.

Figure 11 shows the result for all voltages in the range. A linear dependency of the gain on the bias voltage is observed. Comparing the above stated gain for 54.5 V (which corresponds to an over voltage of about 2 V) to the data sheet of the Silicon-Photomultiplier one obtains a slight difference. the gain at 2 V over voltage as statet by the manufacturer is about $1.2 \cdot 10^{6}$ and, thus, lower than the measurement.

Discussion

One could improve the analysis method by using not only the difference between 0 pe and 1 pe peak, but take the difference between all consecutive peaks and calculate the mean value. The uncertainty would be reduced and the result would become more reliable.

Furthermore, the step size of the QDC could be reduced. Here, it is 8 QDC bins per step, which makes the peaks look sharp and the precision of the gauss fit is diminished.

3.3 Photon Number Resolution

The goal of this section is to determine how the width of the peaks changes with increasing peak number (i.e. photon number). To that end, Gauss fits were performed to every individual peak in the charge spectrum and the sigma-parameter was used to quantify the width of the peaks. The bias voltage was set to 54 V and The results are plotted in figure 12.

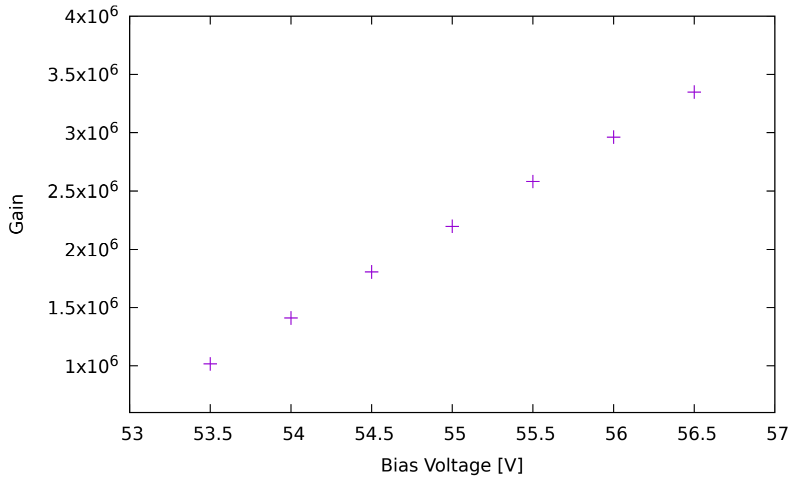

Figure 11: Gain versus bias voltage (the break down point is at about 52.35 V). A linear increase with voltage is observed. Measurement values are higher than the manufacturer's statement in the data sheet.

The widths of the peaks increase with larger number of photons that created that signal. A linear fit was performed:

$$\begin{aligned} f(x) &= a \cdot x + b \\ \text{where} \quad a &= 2.20 \pm 0.05 \\ b &= 15.18 \pm 0.11 \end{aligned}$$

Assuming that the mean distance between two peaks is on the order of 233.93 QDC channels (according to the gain calculation), one can determine the photon number above which the peaks must inevitably overlap. The overlapping is defined as two neighboring peaks having widths that are larger than half the distance in between them. Using above fit function, this value can be calculated:

$$\begin{aligned} 2.20\,x + 15.18 &= 233.93/2 \\ \Leftrightarrow = x &= 49.72 \end{aligned}$$

Thus, above a photon number of 50, no clear peaks will be identified due to overlapping. However, practically this threshold will be reached at smaller photon numbers already, due to further influences like noise and especially after pulsing, which contributed to the gaps in between the peaks. Furthermore, depending on the size of the integration gate, higher peaks (which have larger peak widths) might be cut off, which would distort the peak spectrum.

3.4 Mean Number of Detected Photons

Measurement Description

The following settings in the PSAU were used to read-out the LED light signals: the gate was set to 208 ns and the pre-gate to 64 ns. A fixed bias voltage of 54 V was used. The signals were triggered externally using the frequency generator's output. The intensity of the LED could be adjusted using a knob at the generator, which changes both amplitude and

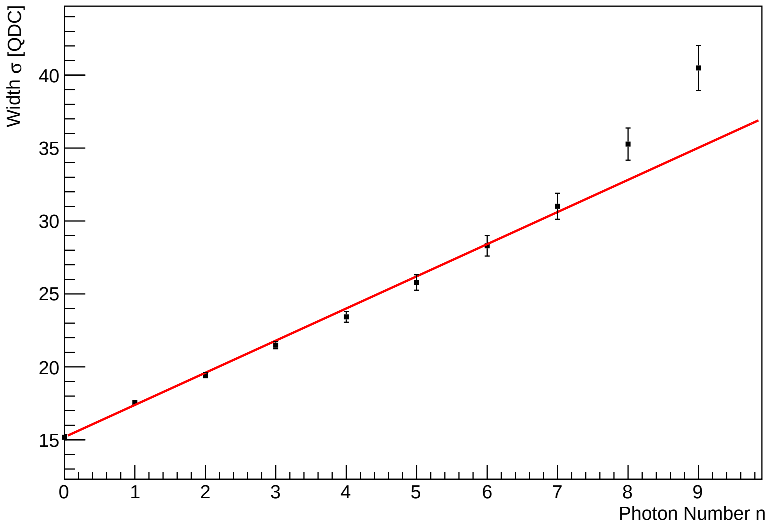

Figure 12: Width of the peaks in the charge spectrum versus photon number. Gauss fits to the individual peaks in the spectrum were performed and the σ parameter was taken as width.

frequency of the pulses. Different intensities were used and a charge spectrum was recorded for each of them.

Analysis and Results

Figure 13 shows a charge spectrum for an intensity of 4.00 with the corresponding peaks indicated including error bars. The peaks were subsequently used to perform a Poisson fit and obtain the mean number of detected photons per LED pulse. In this example the obtained mean number was $\lambda = 4.00$ detected photons per event. This is also an estimator for the expectation value for the number of detected photons per pulse.

This analysis procedure was repeated for every LED intensity between 150 and 450 (in arbitrary units). However, for small intensities below 250, no successful Poisson fit was possible. The results are shown in figure 14. Apparently, there is an over-proportional increase of the mean value of the number of detected photons with LED intensity. Assuming constant pde of the SiPM, one can deduce that the actual intensity of the LED increased over-proportionally with respect to the value set at the SP6500. This might be due to a change of both amplitude *and* frequency of the LED when the knob is tuned and the intensity value is increased.

A potential improvement might arise from using more intensities between 300 and 400. Maybe for the actual measurement give certain values, like 280, 320, 360, 400, 440 and the students have to record a spectrum for each of them.

Discussion

The Poisson distribution can only be used under the assumption that the influence of dark count contribution to the charge spectrum is negligible. Otherwise the distribution might be skewed. The probability to have $k \in \mathbb{N}_0^+$ dark events within the integration gate is itself

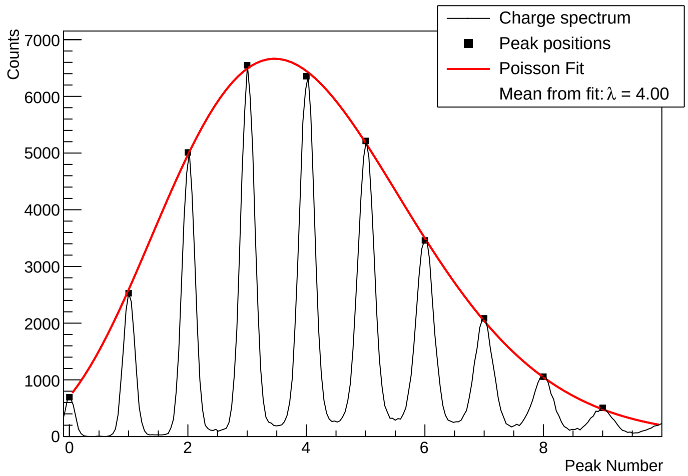

Figure 13: Charge spectrum taken with pulsed LED and an intensity value of 4.00 (arbitrary units). A Poisson fit was applied to the peaks of the spectrum and the mean value was obtained from it.

Poisson distributed with an expectation value $\lambda \ll 1$. Here, it is assumed that this contribution is small for any $k > 0$, especially since an external trigger is being used. Assuming a dark rate of 150 kcps and an integration window (gate) of 208 ns, the probability for a dark event within that window is on the order of 3 %.

3.5 Influence of the Bias on the Photon Detection Efficiency

The photon counting experiment was performed for different bias voltages but same LED intensity. The intensity of the LED was set to 350. A change in the mean value for various bias voltages was observed. The mean value should increase for higher voltages, representing the increased detection efficiency. This could be verified successfully. Results are shown in figure 15.

Recommending a bias voltage:
Considering an increased dark count rate and cross talk probability, the applied bias voltage should not be too high. On the other hand, the detection efficiency and the gain increase significantly for higher bias. Thus, for detecting pulsed LED light, an intermediate voltage level would be best. For the device in this experiment, a value between 54 V and 55.5 V might be optimal. If a coincidence measurement with two or more SiPMs is performed, dark events could be rejected and a higher bias voltage might be applicable.

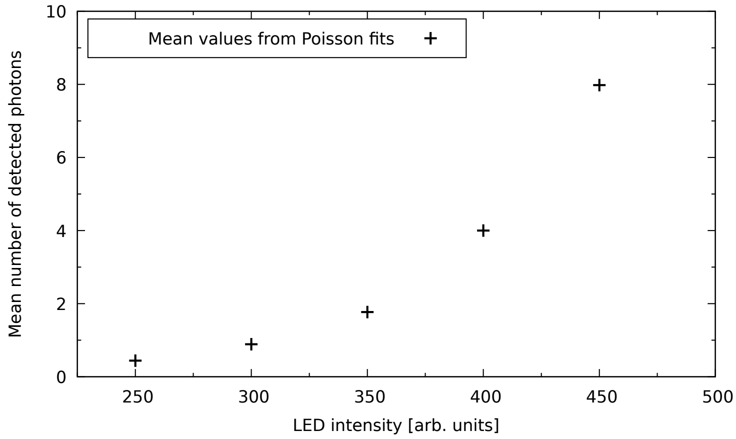

Figure 14: Mean number of detected photons obtained from Poisson fits to the peak hight distribution as shown in figure 13. The LED intensity is shown on the right axis using arbitrary units.

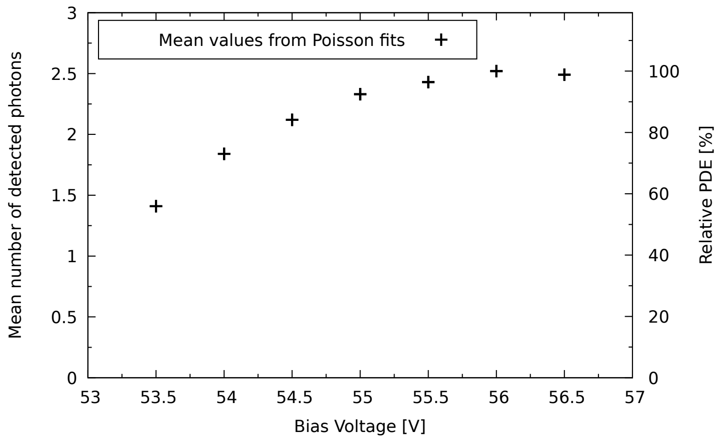

Figure 15: Detected photon number versus bias voltage for fixed LED intensity. The change in photon number originated from the change in detection efficiency with bias voltage.

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