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

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Contents

1 Introduction – the Silicon-Photomultiplier (SiPM)

A thorough introduction to the physical principle, the design and the properties of Silicon-Photomultipliers can be found in [Bay20].

1.1 Semiconductor Detectors

Semiconductor detectors are essentially ionization chambers: incoming radiation ionizes individual atoms to form electron-hole (*e*-*h*) pairs [Spi05]. An applied field enables the separation of the charge carriers and drifts them towards electrodes where they induce a signal. The required minimum ionization energy is equal to the band gap energy between valence and conduction band.

Mostly used semiconductor elements are Silicon (Si) and Germanium (Ge), which are group 4 elements having 4 valence electrons. When combined in a lattice, the discrete energy states of the individual atomic shells broaden and form bands. The electrons from the outermost shells overlap to form the valence band, which is separated from the conduction band by a forbidden band gap. Without additional energy, no higher state can be occupied by a valence electron. If, however, energy is imparted to electrons via incident radiation, an electron can be excited to the conduction band leaving a vacancy (typically called *hole*) behind. This is shown schematically in figure 1.

The electron can move freely in the conduction band. Holes move as well, as the vacancy is filled up by an electron from a neighboring atom. They can be seen as positive charge carriers, but their speed is much lower than that of electrons in the conduction band. This movement of the *e*-*h* pair can be guided by an external electric field. Thus, semiconductors act as an ionization chamber and the minimum detectable quantum of energy is determined by the band gap energy between valence and conduction band. [Spi05]

The pn-junction

For successful radiation detection, the created *e*-*h* pairs need to be drifted towards electrodes with a sufficiently high field. To form a high field region with low thermally induced leakage current, a reverse-biased *pn*-junction can be used. To that end, impurities are brought into the material to control the conductivity. This procedure is called *doping*.

- **n-doping:** atoms that have one valence electron more than the semiconductor elements are implanted into the crystal lattice during the manufacturing process. Typically used elements with 5 valence electrons are phosphor (P), arsenic (As) or antimony (Sb) and are also referred to as *donator*. The bound level of the unpaired additional electron from these impurity atoms is just below the conduction band so that at room temperature electrons are introduced into the conduction band.

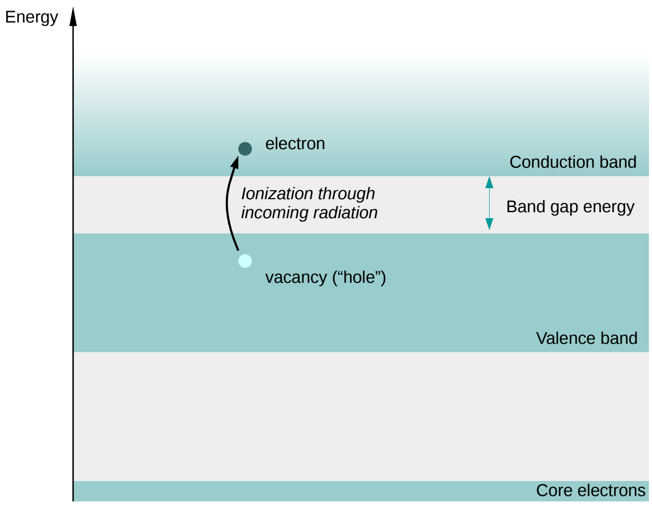

Figure 1: Band structure of a semiconductor and electron-hole creation. Valence and conduction band are separated by a forbidden band gap. Due to incident radiation an electron from the valence band can receive enough energy to reach the conduction band leaving a vacancy (hole) behind. Adapted from [Spi05].

- **p-doping:** in this case atoms with one less valence electron are used for doping, which are amongst others boron (B), aluminum (Al), gallium (Ga) or indium (In). These impurities borrow an electron from the semiconductor and are therefore also called *acceptor*. The electron is bound by the acceptor in an energy level just above the valence band in the forbidden band.

When p- and n-doped semiconductor materials are brought together to form a pn-junction, charge separation occurs. Figure 2 demonstrates the processes happening at a pn-junction.

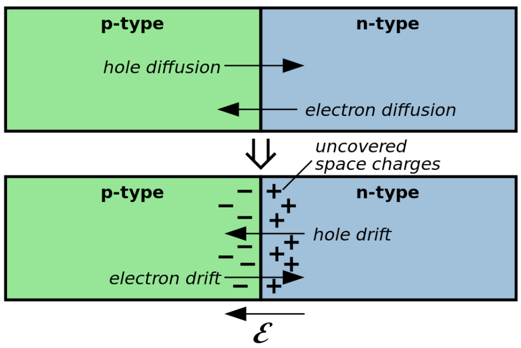

Figure 2: Visualization of the processes occurring at a pn-junction. When the two doped regions are joined together, electrons move towards the p-doped regions via thermal diffusion leaving positive space charges behind, while holes move to the n-type region. A potential is formed at the junction. Electrons lifted into the conduction band can now be drifted towards the n-region. [Ind07]

Both materials are actually neutral when separated, but when joined together, electrons and holes will cross the junction via thermal diffusion. Electrons leaving the n-doped area are accepted in the p-doped region and will leave the donors behind as uncovered positive space charges. A positive space charge acts on the electrons that moved to the p-region and, thus, a potential is formed. The movement stops when the energy required for thermal diffusion becomes smaller than the space charge potential that has evolved between the two regions. Right at the junction between the two doped areas, a region free of mobile charge carriers is formed. It is called *depletion region*.

The reverse-biased diode
The pn-junction can be seen as capacitor, since the depletion region is a charge-free volume and the p- and n-regions serve as electrodes. With an applied reverse voltage, the electric field is capable of moving charge carriers to the electrodes quickly. That way, an ionization chamber is formed with depletion regions on the μm-scale.

1.2 Photodiodes

In contrast to charged particle and X-ray detectors, photodiodes have only a small absorption length. The devices investigated in this experiment are solely silicon-based photon detectors. The absorption length of photons in silicon depends strongly on the wavelength. At a photon wavelength of $\lambda = 400\,\text{nm}$ the absorption length is of order 100 nm, whereas at $\lambda = 700\,\text{nm}$ it is about $5\,\mu$m [HB19]. In silicon photodiodes, quantum efficiencies[1] for the creation of an *e-h* pair are on the order of 80 % and sensitivity down to photon wavelength of $\lambda = 200\,\text{nm}$ is possible [Spi05].

PIN Diode
The PIN diode is in principle the realization of the reverse-biased pn-junction that has been explained in the previous section. It has an additional intrinsic, high-ohmic piece of semiconductor between highly doped (n^+ and p^+) regions. The basic design is schematically shown in figure 3. A field is produced across the intrinsic layer (i-layer) to separate charge carriers and drift them towards the electrodes for detection [GH20]. An incoming photon creates an *e-h* pair with the electron reaching the conduction band to be drifted towards the cathode at the end of the n-doped layer. The signal is, therefore, proportional to the intensity of the incoming light. Most incoming photons are absorbed in the i-layer and can contribute to the photo current at the electrodes. Speed and spectral response are determined by the doping-concentration of the pn-junction. [Din13]

The undepleted p-layer on top must be transparent to incoming light. Its thickness is on the order of $1\,\mu$m [Din13]. The active area of the diode is often covered with an anti-reflective coating to reduce reflection of light of a specific wavelength. Passive areas are usually coated with silicon oxide. Sometimes protective layers are used, which cut off detection of incoming light at 290 nm - 320 nm.

[1] The quantum efficiency describes the probability for an incoming particle to create an electron hole pair in the depletion region.

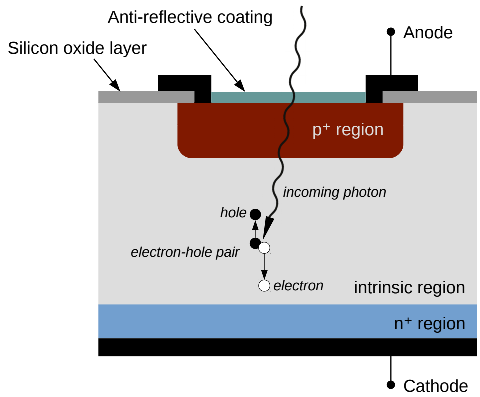

Figure 3: PIN diode structure. An intrinsic layer is sandwiched between two highly doped regions. Ionizing radiation creates charge carriers that are drifted towards the electrodes. Adapted from [RL09].

The PIN diode shows efficiency for the absorption of photons in the optical wavelength range up to 1100 nm, which corresponds to the band gap energy in silicon (1.1 eV).

The PIN diode has no internal gain. Therefore, PIN diodes are only sensitive to a minimum photon number of 200-300. Complex read-out electronics including charge-sensitive amplifiers and low band filters are needed. Due to filter time constants on the order of 1 μs, signals tend to become slow and high signal rates cannot be processed.

Avalanche Photodiodes (APD)

APDs attempt to overcome the aforementioned downsides of PIN diodes are another step towards the development of a single photon detector. APD exploit avalanche charge multiplication as internal gain mechanism. When the field at the pn-junction is increased by applying a higher bias voltage, electrons gain enough energy to create secondary *e-h* pairs and the total amount of charge carriers per incident photon is increased. This process is called *impact ionization*. Only electrons create secondary charge carriers, while holes do not have enough energy. With an APD the minimum detectable number of photons is on the order of 10-20, while a bandwidth in the MHz range is possible [RL09].

If the voltage is increased even more above the so called *breakdown point*, holes also create secondary *e-h* pairs. The field is high enough so that a single charge carrier in the intrinsic layer can trigger a self-sustained avalanche. This is the regime of a Single Photon avalanche Diode or also called Geiger-mode APD. The avalanche in the diode is stopped with help of a quenching resistor causing the bias voltage to drop below the breakdown point. The diode recharges afterwards for further detection. A Geiger-mode APD is capable of single photon detection, but works in binary mode and the signal does not contain information on the intensity of the incoming light. Figure 4 shows the three regimes of operation in a photodiode: The PN/PIN diode without any gain, the APD with linear gain and the Geiger-mode APD with exponential multiplication in a self-sustained avalanche process.

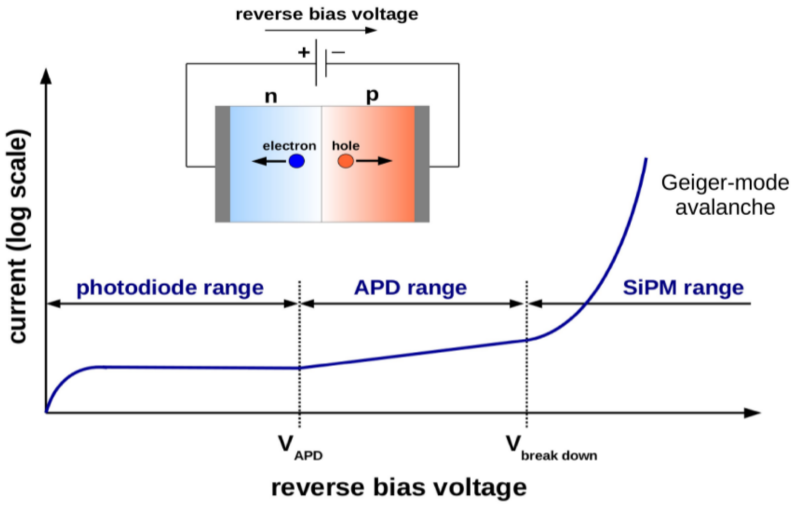

Figure 4: The three operational regimes of a photodiode depending on the applied reverse-bias. PIN diodes work without gain (left regime), while APDs have linear gain (center regime). Above a certain voltage, breakdown occurs and the gain response is exponential forming a Geiger-mode avalanche (right regime). [GH20].

1.3 Silicon Photomultiplier (SiPM)

1.3.1 Working Principle

Geiger-mode APDs are binary devices and their signal does not contain information on the number of impinging photons. To overcome this drawback, APDs can be arranged in a matrix structure consisting of a large number of micro-cells, which are connected in parallel. Every individual cell is a Geiger-mode APD in series with a quenching resistor. This constitutes the basic design of an SiPMA [Din13] and is shown in figure 5. The size of the micro-cells is on the order of 15-100 μm. An anti-reflecting coating on top of the matrix increases the transmission for impinging photons. This design is shown in figure 6.

1.3.2 Characteristics and Properties

The SiPM signal is a sum of all signals from the individual micro-cells. The measured output signal is proportional to the number of incident photons on different cells. This is shown in figure 7 on an oscilloscope graph. The measured voltage signal has discrete heights corresponding to the different detected photon numbers. This allows for counting the number of photons detected by the Silicon-Photomultiplier either by determining the peak height or by measuring the deposited charge. This is shown in the charge spectrum in figure 8. Each peak corresponds to a certain number of photoelectrons or **pe** signals. The presence of a peak at zero photons originates in the specific measurement method and corresponds to events where no photon was detected [Eck+10].

The dynamic range is limited by the probability of 2 photons hitting the same cell and by the number of cells in total. Single photon sensitivity is possible and the maximum number of photons equals the number of micro-cells in the device.

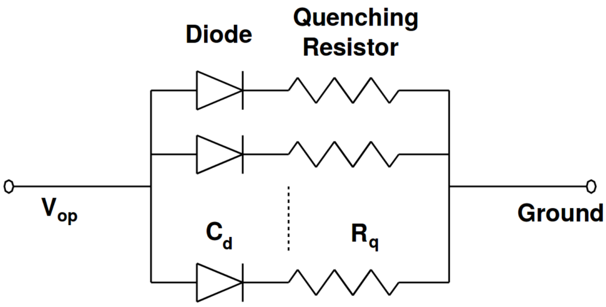

Figure 5: Equivalent circuit of Geiger-mode APD connected in parallel, which constitutes the basic design of an SiPM. [Oto+08]

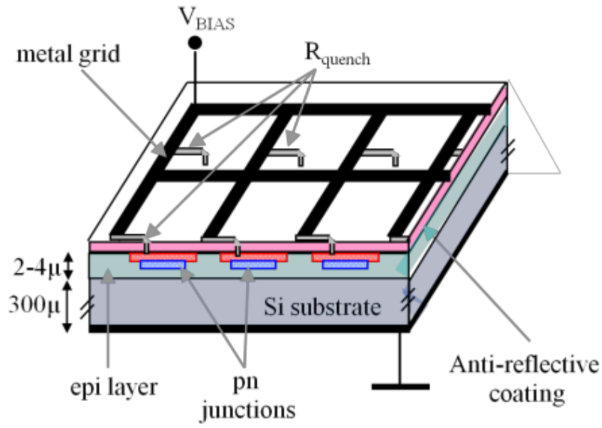

Figure 6: Schematic drawing of an SiPM. The pn-junctions and quenching resistors are interconnected via a silicon substrate and a metal grid. Anti-reflective coating increases the transmission. [Din13]

Breakdown voltage

The voltage above, which Geiger-mode avalanche multiplication occurs, is called the *breakdown point* or *breakdown voltage* V_{bd}. Since the required bias voltage V_{bias} for SiPM operation needs to be above this value, it has direct impact on the properties of the SiPM. It defines the applied overvoltage as $V_{over} = V_{bias} - V_{bd}$, which, in turn, influences other quantities like dark count rate, probability for optical cross talk (OCT) and the detection efficiency, all of which are explained in the scope of this chapter. [GH20]

Photon detection efficiency (PDE)

The SiPM's efficiency for the detection of photons is defined by the number of detected photons divided by the number of impinging photons on the detector area. It can be calculated as follows:

$$\mathrm{PDE}(V_{over}, \lambda) = \mathrm{QE}(\lambda) \cdot p_A(V_{over}) \cdot \epsilon_{geo} \tag{1}$$

where QE(λ) describes the wavelength dependent quantum efficiency. It is the probability for a photon to be transmitted into the sensitive volume through the entrance window or anti-reflective coating and then to be absorbed in the valence band of the silicon with the subsequent creation of an *e-h* pair. $p_A(V_{over})$ denotes the avalanche trigger probability, which depends on the overvoltage. This value quantifies the chance of an *e-h* pair to trigger an avalanche and, thus, a measurable signal. Finally, the geometric efficiency or fill factor ϵ_{geo} determines the fraction of the detector's front face that is sensitive to incoming light. The metal frame and quenching resistors as well as trenches in between micro-cells limit the area where photons can be detected. Depending on the cell size, this value can reach up to 80 %. Smaller cells limit the geometric efficiency due to larger dead space, but a larger number of cells is possible, which increases the dynamic range of the SiPM. The PDE increases for higher overvoltage.

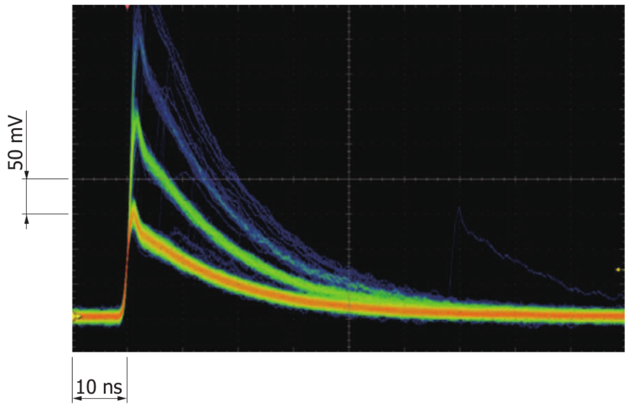

Figure 7: Oscilloscope graph showing waveforms of an SiPM of type S13360-3050 by Hamamatsu. The discrete signal height represents the number of detected photons [Ham16].

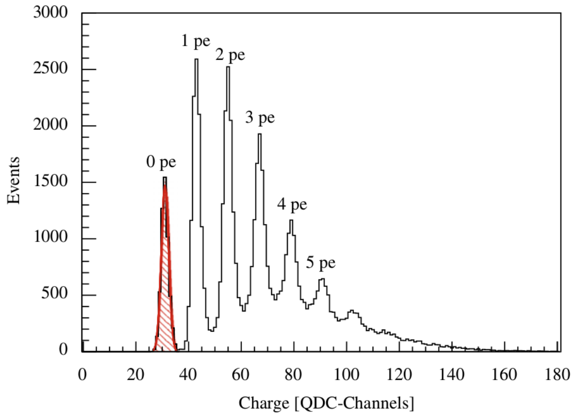

Figure 8: Single photo electron spectrum recorded using charge integration with a Hamamatsu SiPM. Each peak corresponds to a certain number of photons. [Eck+10]

Gain

The number of charge carriers that are created during an avalanche discharge process of a micro-cell and that contribute to the signal, defines the gain of the detector [Din13]. Using the capacity of a micro-cell C_D, the electron charge e and the applied overvoltage, the gain can be calculated [Oto+08]:

$$G = \frac{C_D \cdot V_{over}}{e} \tag{2}$$

The gain increases with the applied overvoltage V_{over}. Just like the PDE it is independent of the temperature as long as V_{over} is constant [GH20]. The gain strongly depends on the capacitance C_D and therefore varies especially for different cell sizes [Ham16]. Typical values are on the order of 10^6 [Eck+10].

Dark count rate (DCR)

The number of produced output pulses per second in total darkness is called *dark count rate* (DCR). Its origin can be summarized best with the term *thermally generated charge carriers*. The DCR increases strongly with temperature and shows linear increase with applied overvoltage [Ram08; Sot+13].

The following two characteristics are commonly referred to as *correlated noise sources*. The term indicates that this type of noise is a follow-up product of a primary event – may it be a detected photon or a dark event. Figure 9 gives an impression of these different types of signals as they will be discussed in the following.

Optical cross talk (OCT)

A secondary photon can be created in an avalanche and can subsequently enter one of the neighboring cells and induce a second avalanche. This process is called optical cross-talk

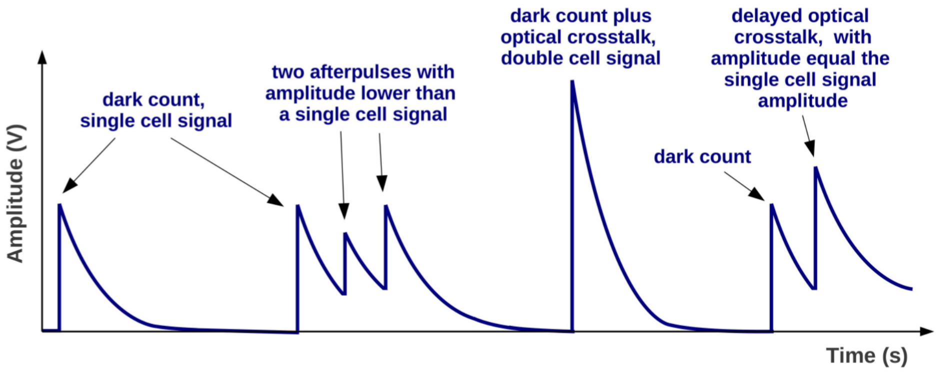

Figure 9: Waveform sketches of Silicon-Photomultiplier signals together with explanations on the different types of correlated noise signals. [GH20].

(OCT) and it can occur both for dark signals and actual photon induced signals. The likelihood for an avalanche to create another signal via emission of a secondary photon into a neighboring cell is called cross talk probability and is on the order of a few percent. Exact values mostly depend on the applied overvoltage. A quadratic dependency on the overvoltage has been reported by Soto et al. [Sot+13] and Eckert et al. [Eck+10]. For *constant* overvoltage, cross talk is independent of temperature [Din13].

Possible explanations for the light emission in an avalanche are bremsstrahlung or a multi-mechanism scenario including indirect and direct inter-band and intra-band transitions [RL09]. Since this process takes place on time scales of not more than a few hundred picoseconds [GH20], the two signals appear as one larger signal twice the size.

OCT can be via direct emission of a photon into a neighboring micro cell or as external cross talk, where the photon leaves the cell through the active side of the SiPM and can then be reflected by the glass window or epoxy resin covering the surface. Therefore, OCT depends on the architecture of the Silicon-Photomultiplier as its intensity increases for smaller distance between the cells. Introducing trenches in between the individual micro-cells can help block the photon's way to the next neighboring cell. That way cross talk can be reduced but not entirely prevented.

After pulse

An electron that is released in an avalanche can get trapped in material defects or impurities and released again after some time. This electron can then create a second signal in that same cell. The time delay between primary signal and after pulse is on the order of nanoseconds up to microseconds. The charge Q_{AP} of the pulses depends on the recovery state of the cell and can be expressed in terms of a single photon equivalent charge signal:

$$Q_{AP} = Q_{1\,pe} \cdot \left(1 - \exp\left(-\frac{t}{\tau}\right)\right) \tag{3}$$

Here, τ denotes the recovery time constant of the Silicon-Photomultiplier . For small times t, the height of the after pulse is smaller than that of a 1 pe signal. After pulses are illustrated in figure 9 as signals that are smaller than the 1 pe peak. For large time delays between the primary signal and the after pulse, the standard avalanche signal is triggered. Then, no distinction from delayed cross talk or a dark or single photon event is possible.

1.3.3 SiPM Hamamatsu S13360-1350CS

The SiPM that is being used in this experiment is the model S13360-1350CS by Hamamatsu. All important quantities regarding this device are shown in table 1.

Property	**Value**	**Unit**
Area	1.3×1.3	mm^2
Fill factor	74	%
Micro cell size	50	μm
Number of micro cells	667	-
photon detection efficiency (pde)	40^*	%
dark count rate (DCR)	90^*	kcps
break-down voltage (V_{BD})	53	V
cross-talk probability (CT)	3^*	%
Gain (G)	$1.7 \cdot 10^{6\,*}$	-

* Measured at 3 V over voltage and at room temperature.

Table 1: Properties of the Hamamatsu Silicon-Photomultiplier type S13360-1350CS.

2 Experimental Set-Up

This part contains info on the experiment and its components. A description is provided on how to operate the system and read out data with the graphical user interface (GUI).

Figure 10 shows the set-up of the experiment. The detector sits in its sensor holder, which in turn is mounted to the device named SP5600. It provides the bias voltage and sends the analog detector output to the digitizer. The digitizer (DT5720A) serves as communication unit between detector and read-out software and converts the analog signals into digitized values to be further analyzed with the GUI. On the left in figure 10, the LED driver is shown (device number SP5601), which enables to send ultra-fast pulsed LED light towards the SiPM via an optical fibre.

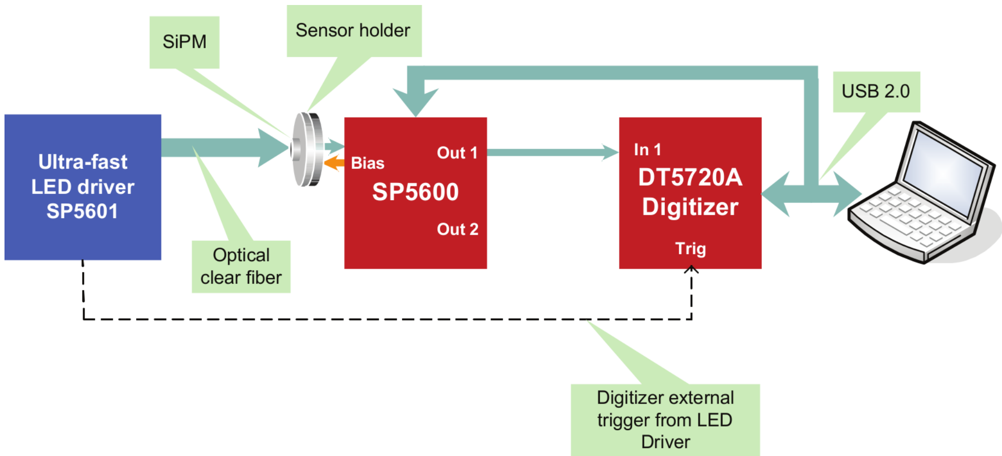

Figure 10: Schematics of the experimental set-up: the SiPM sits on the SP5600 and the DT5720A serves as communication and data taking unit. For the second part of the measurements, a fast pulsed LED can be coupled to the SiPM holder via an optical fibre.

Figure 11 shows the GUI. The GUI main panel is structured as a "virtual instrument": its appearance and operations imitate a real central system. Three sub-panels may be identified:

- The Power Supply and Amplification Unit (PSAU) sets the bias voltage. It becomes active after the communication with the PSAU is started, through the "START PSAU" button. This button opens the communication with the PSAU by the selected COMM Port.

- The digitizer contains the parameters to tune the trigger threshold and the size of the integration window for the charge measurement. The digitizer has a special firmware dedicated to SiPM. In the external triggering mode, the only parameters the user has to set are the "Gate parameters" in order to allow the firmware to integrate all the digitized signals. This tab includes also information about connection and errors.

- The right hand side shows the visualization tabs – different panels that host the display of various measurements. These are most importantly the charge measurements in the tab named `Histogram`, the dark count measurements in `PSAU staircase` and a waveform display under the tab named `wave`.

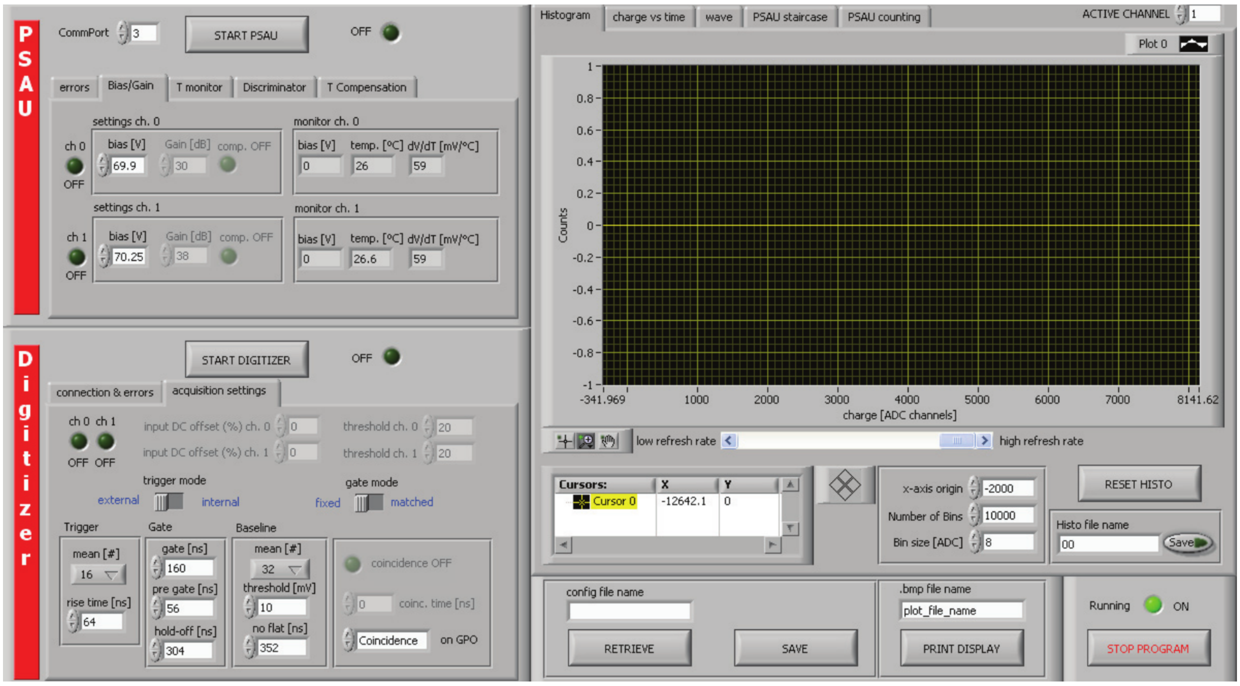

Figure 11: The graphical user interface (GUI): power supply unit at the top left, digitizer below and on the right hand side the measurement results can be displayed graphically.

Further explanations can be found in the educational kit's user guide [SpA16]. Instructions on how to set the measurement parameters are explained together with the measurement tasks in the next section.

3 Tasks

3.1 Getting to Know the Silicon-Photomultiplier Signals

WARNING

The bias voltage must NOT exceed 58 V to prevent damage at the Silicon-Photomultiplier !

In the very first part of the experiment, the signals of the Silicon-Photomultiplier will be investigated. To that end, the output of the SP5600 of channel 0 has to be connected to one input of the oscilloscope, instead of the digitizer. The signals will at first not be examined using the GUI in the software but "by hand" on the oscilloscope.

The SP5600 and the digitizer must be switched on before a connection to the GUI can be established. After checking the communication port of the PSAU, the PSAU itself must be started by clicking on "START PSAU" (the green light 'ON' switches on). In the PSAU the SiPM nominal operation voltage can be set as well as the gain of the amplifier of the PSAU. Only *after* connecting, the bias voltage can be switched on at the PSAU. At the beginning a value well below the break-down point must be chosen (like 50 V), and then ramped up in small steps (1 V for instance) until signals can be seen on the oscilloscope screen. This should happen at around 53 V. In order to trigger signals at the oscilloscope one must set the trigger threshold relatively low (below 10 mV) and chose a small voltage division (like 5 mV).

With the oscilloscope several SiPM characteristics can easily be investigated quantitatively: for example the peak height (given in millivolts) and an estimation of the width of the signal (in nanoseconds). Especially the latter of these quantities plays an important role for charge integration in the later experiment.

Signal Amplitude

The amplitude can be measured using the *cursor* function of the oscilloscope in the *voltage type*. To be able to estimate the mean peak height of the signal, the averaging function of the oscilloscope may be used. Averaging over 16 waveforms should be sufficient in this case. Then the cursor can be moved to the tip of the wave form and the position of the cursor is shown at the right side of the screen.

Width of the Signal

Knowing the width of the Silicon-Photomultiplier signal is crucial for setting the integration gate right for the later measurements. There are vertical time-based cursors that can be used to measure a time difference on the oscilloscope screen. It is also advisable to use waveform averaging for this measurement. The width of a signal can – amongst others – be described as the time-over-threshold (TOT). This is the time the signal is above the trigger threshold and for typical Silicon-Photomultiplier signals lies in a range of 10 ns up to several μs. Figure 12 shows an example of such a measurement. Finding an estimate of the width

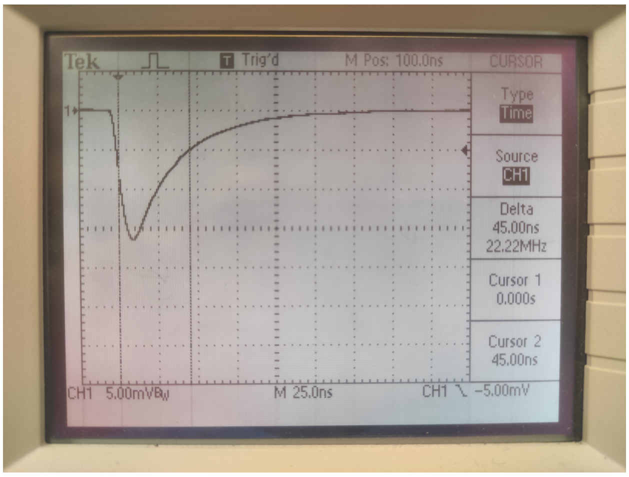

Figure 12: Screen shot of an oscilloscope measurement of the signals width (time-over-threshold TOT) using vertical time-based cursors and averaging over 16 waveforms.

will help setting the parameters right for performing a measurement of the deposited charge in an SiPM signal.

MEASUREMENT TASK

1. **Amplitude measurement:**
   (a) Set the voltage between 53 V and 57 V. Play with the trigger until you have identified the single photon peak.
   (b) Using the waveform averaging function of the oscilloscope as well as the voltage cursor as described above, measure the peak amplitude of the signal. Repeat this measurement for at least 5 different bias voltages in the range between 53 V and 57 V.
   Hint: do not modify the voltage division at the oscilloscope in between different measurements as it might change the input impedance of the channel and distort your result!
2. **Width or TOT measurement:**
   Again, set the voltage between 53 V and 57 V and trigger on the single photon peak. Now, use the the time type cursors of the oscilloscope and measure the width of the signal defined as the time the signal is above the trigger threshold. Figure 12 shows an example of such a measurement. Repeat this measurement for at least 5 different bias voltages between 53 V and 57 V.

ANALYSIS

1. (a) Describe your measurement. How did you identify the 1 photon peak? What happened when you moved the trigger above the level of the single photon amplitude?
   (b) Plot the measured peak amplitude versus bias voltage.
2. Plot the measured widths versus bias voltage. How does the trigger level influence your result? What would have happened if you had chosen a higher or lower trigger level?

3.2 Silicon-Photomultiplier Characteristics in the Absence of Light

WARNING

Switch the bias voltage off before making changes at the set-up like unplugging cables!

For the rest of the experiment, the output from the SiPM at SP5600 must be connected to the digitizer. The digitizer must be switched on at the back of its housing. It is then started at the GUI by clicking on "START DIGITIZER" (the related green light 'ON' switches on). Switch on channel 0 at the digitizer afterwards. The trigger should be set to *internal* for the first part of the measurements. Now the system is up and ready to run.

For all measurements of this section, it is important to note the temperature! Only then reliable comparison of the results to the data sheet or reference measurements is possible. The temperature can be found in the PSAU window in the tab `T monitor`.

3.2.1 General Measurement Techniques

For the first test measurements, the bias voltage of the Silicon-Photomultiplier should be set to an intermediate value for example 54-55 V.

Figure 13 shows the digitizer unit of the read-out software, which converts the analog signals from the detector into digitized data. To do so, some parameters have to be set, so that the signals can be processed correctly. In this section, the influence of two of these data-taking parameters are investigated: the first one is the trigger threshold level and the second one is the gate length for the charge integration.

The trigger threshold basically determines how large a signal has to be to be captured by the digitizer and to be further processed. An *internal* trigger must be used in this section, which means that the digitizer itself sets the trigger and a signal is only processed when exceeding this threshold. One can also switch to an *external* trigger, where the trigger command comes from an external device which is fed into the digitizer. This will be used in the last part of this experiment. There is a switch at the digitizer window that allows to change from internal to external trigger and vice versa.

The other parameter is the gate width, which determines the interval within which the charge of the signal is being evaluated. To check for correct gate, the `wave` tab in the

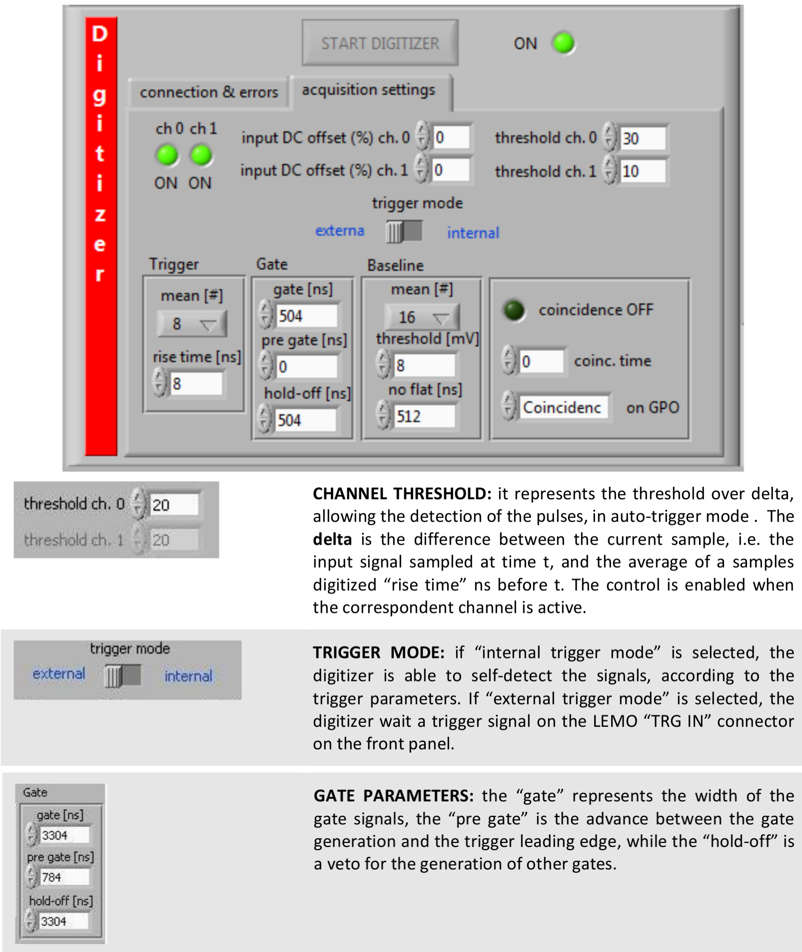

Figure 13: Digitizer unit of the read-out software. The two parameters to be investigated in this section are the trigger treshold and the gate width.

visualization window must be selected, where signal and gate are displayed. The charge is in principle the integral between waveform and baseline (corresponding to the noise level with zero amplitude). The gate must be set such that it easily captures the entire waveform. A pre-gate must be defined, which shifts the gate to the left to start the integration a little earlier and to prevent cutting off the rising edge of the signal. A reasonable value for the pre-gate for internally triggered signals is 16 ns.

In the histogram tab, the charge of the captured signals is displayed.[2] Whenever one of the digitizer parameters is changed, the histogram resets and is filled from scratch automatically. Thus, one can directly observe the influence of the trigger threshold and gate width.

All data are saved to the following folder location by default:
`Downloads/SiPMkit_ControlSoftware_00.29/data/`.

[2] In darkness, the 1 photon peak should appear prominently and any higher photon peaks should be significantly smaller.

MEASUREMENT TASK

1. Investigate the influence of the trigger threshold. Choose a bias voltage of 54-55V. Set the gate width to 208 ns. Record charge histograms with different trigger thresholds and observe the changes. Save meaningful histograms by giving them a unique name in the `Histo file name` section at the bottom right of the visualization tab. When you are done, set the trigger threshold to a level where the 1 photon peak can be seen.

2. Investigate the influence of the gate width. Now, leave the trigger threshold fixed but change the gate width in a range between about 60 ns and 500 ns and observe the change. Also, save some histograms for different gate widths for later analysis. When you are done, set the gate to a reasonable value such that the entire Silicon-Photomultiplier signal can be captured.

ANALYSIS

1. Describe the influence of the trigger on the histogram. What happens for extreme trigger values? Explain your findings with 2 or 3 meaningful histograms.

2. Describe the influence of the gate width on the charge histograms. How does the peak form and position change? What happens for very narrow and wide gate widths? Explain your findings with 2 or 3 meaningful histograms.

3.2.2 Break-Down Voltage

An important quantity of the Silicon-Photomultiplier is the break-down voltage V_{BD} above which avalanche multiplication in the detector occurs. It defines the lower end of the voltage range within which the Silicon-Photomultiplier can be operated.

One possibility to determine V_{BD} is to measure the charge of the 1 photon equivalent peak (1 pe peak) for various bias voltages and to extrapolate to a charge value of 0 C. The bias voltage determines the gain of the Silicon-Photomultiplier such that lower bias implies lower gain. The break-down point is defined as that voltage, where the gain reaches zero.

For the measurements in this section, those gate and trigger values should be used that proved to be optimal for detecting the 1 pe peak in the previous task 3.2.1.

MEASUREMENT TASK

Take a charge histogram for at least 4 different bias voltages between 53.5 V and 57 V. Leave all other parameters constant.
Hint: set the bin width of the histogram to a value of 4 QDC channels or less to get smooth curves! This is called `bin size [ADC]` in the software.

ANALYSIS

Determine the peak position of the 1 photon peak in all the recorded histograms. You can use the mean value of a gauss fit for example. For this analysis, you do not need to convert the QDC value into a value charge, yet.
Create a plot with the applied voltage versus the peak positions and use a linear extrapolation to determine the break-down point at which the charge is zero.
Compare your result with the data sheet (see table 1).

3.2.3 Dark Count Rate (DCR)

The detector is based on a semi-conductor material with a certain band gap. Although the thermal energy of the electrons is significantly smaller than the band gap, electron energy levels still follow the Fermi distribution and, thus, some of the electrons can reach the conduction band [Spi05]. There, they get accelerated and multiplied. Consequently, even in the absence of impinging photons on the detector, a signal is created, which has the same amplitude and deposited charge as a photon-induced signal. Since this indistinguishability makes a rejection of dark events impossible (at least when using only a single SiPM), the rate of these dark events is of great importance for measurements.

The easiest way to determine the rate of signals in darkness (i.e. the dark count rate) is to simply count how many signals were triggered in darkness. In this experiment, a different approach will be used that provides more information than simple counting.

The tab *PSAU staircase* provides the option to scan through the trigger threshold range. In each step of this routine, the DCR is measured. To obtain best results, the step size should be chosen as low as possible (1 mV). The *"gate width"* in this tab describes the length of the window that is used to count the dark events. The value *"points for mean"* is the number of gates that are used to create the mean dark rate for a certain step. Figure 14 shows an example of such a DCR scan for one voltage.

MEASUREMENT TASK

Take a stair case plot for 5 different voltages between 54 V and 58 V. You can start a measurement by clicking the `REFRESH` button in the `PSAU staircase` tab. You can save the data by entering a file name in `PSAU name file user` prior to starting the run and switching the `save staircase` button on.

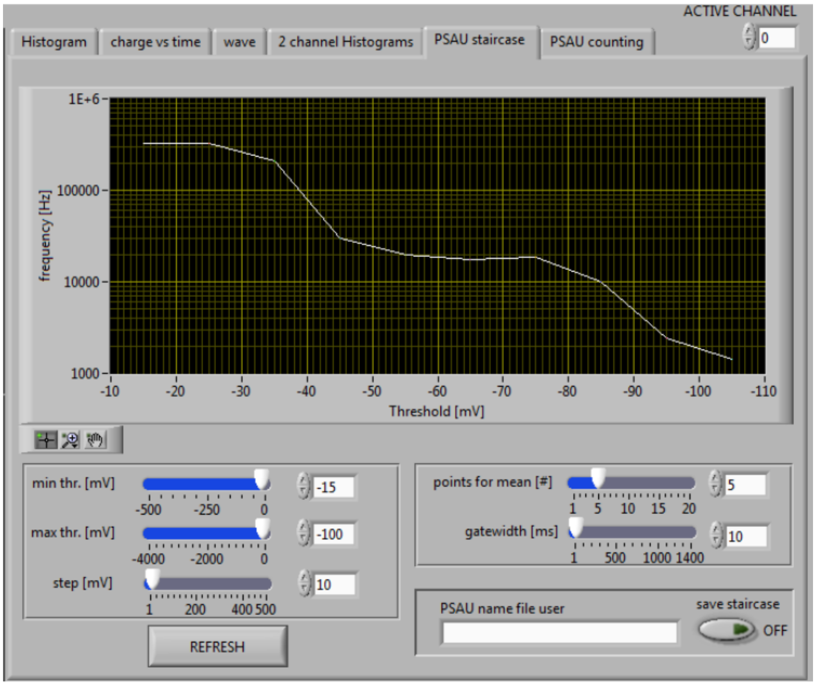

Figure 14: Staircase plot showing the dark count rate versus trigger threshold.

ANALYSIS

1. Explain the origin of the steps in the graph.
   Hint: consider that the Silicon-Photomultiplier signals have discrete amplitude due to the discreteness of the number of detected photons.
2. For every voltage calculate the dark count rate. To that end, take the mean value of the data points of the first plateau in the graph. This is the dark count rate on single photon level. Find a reliable and reproducible method to define the end of the plateau (e.g. the position of greatest slope etc.).
3. Create a plot with the dark count rate versus bias voltage.
4. Compare your results with the values from the data sheet (see table 1). Try to find an explanation for potential deviations.

3.2.4 Cross Talk Probability

With a certain probability, an avalanche in a micro cell can trigger one or more additional avalanches in neighboring cells. This happens on time scales much shorter than the rise time of the Silicon-Photomultiplier signal. Thus, the two avalanches cannot be separated and appear as one larger signal – with an amplitude which is an integer multiple of the 1 pe signal.

The probability for the occurrence of cross talk can be calculated by using the dark rate measured on the second plateau of the staircase plot (see figure 14 as example) and dividing it by the dark rate measured on the first plateau:

$$p_{\mathrm{CT}} = \frac{\mathrm{DCR}_{2\,pe}}{\mathrm{DCR}_{1\,pe}}, \tag{4}$$

ANALYSIS

1. (a) Take the data from task 3.2.3 and determine the mean value of the data points on the second plateau.
   (b) Calculate the cross talk probability according to formula 4.
   (c) Create a plot with the cross talk probability versus bias voltage.

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

For the second part of the experiment, the fast pulsed LED will be used. Again, special care must be taken to switch the bias voltage OFF *before* making changes to the set-up! The LED driver, which houses the LED and a frequency generator, needs to be connected with the SP5600 via a glass fiber. The trigger output of the driver has to be connected to the DT5720A Digitizer to be able to use the external trigger signal from the driver. In the digitizer window of the software, *external trigger* can be selected.

WARNING

Do not bend the glass fiber at any times, as it can easily break and become unusable!
Rather place LED driver and SP5600 in front of each other with the correct distance and carefully install the fiber in both devices.
AND: switch the bias voltage off before making alterations to the set-up!

3.3.1 General Measurement Techniques

Internal and external trigger
At first, the difference between internal and external trigger will be examined. Using the external trigger means that the software digitizer starts with the charge integration when it receives the signal from the LED driver. To get good alignment between LED pulse and integration window, the pre-gate and gate might require adjustment. The LED intensity (in arbitrary units) can be modified using the black knob at the front side of the LED driver housing. For this task it should be set to a value, such that several peaks can be seen in the charge spectrum. An intermediate voltage of about 54 V should be chosen.

MEASUREMENT TASK

Set the pre-gate and gate so that the whole waveform of the signal can be recorded and used for integration.
Record a charge histogram once with *internal* trigger on 1 photon level and once with *external* trigger.

ANALYSIS

Explain the difference between the two measurements. Why is there an additional peak around QDC=0 (called *pedestal*), when using the external trigger? What has been recorded in this case?

Variable Gate Width
The choice of the gate width has an impact on the histogram as well, as could already be demonstrated in task 3.2.1. When using the pulsed LED, this influence becomes even more prominent.

MEASUREMENT TASK

Record three charge histograms: one for an extremely narrow gate, then for a very wide gate and finally for an intermediate gate width.
The same voltage as before should be used and signals should be triggered *externally*.

ANALYSIS

Explain the influence of the gate width on the shape of the peaks and their position and distance from one another.

3.3.2 Gain versus Bias Voltage

The gain determines how much electric charge is created in the micro cell per photo electron. This quantity depends on the bias voltage. The gain influences the peak positions in the charge spectrum and especially the distance in between peaks. This influence can be quantified by recording and analyzing charge spectra for various bias voltages.

In general, the gain of the SiPM is given by

$$G = \frac{\Delta q_{pp}}{q_e}, \tag{5}$$

where q_e is the charge of an electron $1.6 \cdot 10^{-19}$ C. The index pp means *from peak to peak*. Therefore, q_{pp} denotes the charge difference between two consecutive peaks in the charge histogram. The distance between two peaks is simply calculated as the difference between the QDC values of neighboring peaks:

$$\Delta \mathrm{QDC}_{pp} = \mathrm{QDC}_{1\,\mathrm{pe}} - \mathrm{QDC}_{0\,\mathrm{pe}} \tag{6}$$

Since the charge is given in terms of QDC channels, this value must be converted to Coulomb charge. The required QDC channel conversion factor (here denoted with F_{QDC}) can be calculated according the Application Note AN2502 by CAEN [SpA11]:

$$F_{\mathrm{QDC}} = \frac{\text{QDC channel}}{\text{Coulomb}} = \frac{V_{pp} \cdot \Delta t}{R_{IN} \cdot 2^{Nbit} \cdot G_{PSAU}} \tag{7}$$

G_{PSAU} is the amplification gain of the PSAU. The other quantities are as follows:

V_{pp} = 2V, Digitizer dynamic range

R_{IN} = 50Ω Digitizer Input impedance

Nbit = 12 bit Digitizer resolution

Δt = 4 ns, Digitizer sampling period

For example, for an amplification gain of $G_{PSAU} = 30$, the conversion factor would be $F_{\mathrm{QDC}} = 1.235\,\mathrm{fC/QDC}$. Now, the gain G can be calculated::

$$G = \frac{\Delta \mathrm{QDC}_{pp} \cdot F_{\mathrm{QDC}}}{q_e} \tag{8}$$

MEASUREMENT TASK

Chose an intermediate LED intensity so that the pedestal and *at least 3* more peaks can be seen in the charge spectrum.
Now, vary the bias voltage between 53 V and 57 V in at least 5 steps and record a charge spectrum for each voltage.

ANALYSIS

(a) Determine the position of the pedestal and the 1 pe peak in every spectrum and calculate the distance.

(b) Calculate the gain based on equation 8.

(c) Show your results: plot a graph with gain versus bias voltage. What is your suspected relation between gain and voltage?

3.3.3 Photon Number Resolution

In photon counting experiments, the resolution of the photon number is important. This quantity describes how well a measured charge value can be attributed to a specific photon number. The resolution of the system can be evaluated by plotting the width of each peak σ versus the photon number n that created the peak. σ is the width that can be obtained using a gauss fit to a peak.

ANALYSIS

(a) Use the data set from the 54 V measurement from the previous task 3.3.2 and perform a gauss fit to every peak in the histogram that can be clearly identified.

(b) Plot the width versus photon number and discuss your findings: how does the width behave for growing photon number? What does this tell you about the resolution for higher photon numbers?

(c) Above which photon number has the resolution decreased such that no peaks can be identified any more? To determine that, perform a linear fit to your data and extrapolate to the point where the width exceeds half the distance between two peaks.

3.3.4 Number of Detected Photons

In this section, the number of detected photons will be calculated using the charge histograms. The LED intensity can be varied with the black knob at the LED driver. Higher intensity means that there are on average more photons emitted per pulse and vice versa. The number of photons per pulse follows a Poisson distribution. Since every photon is detected with a certain probability – which is determined by the p.d.e. of the SiPM – the number of detected photons is also Poisson distributed.

MEASUREMENT TASK

1. Set the bias voltage to 54 V and use the external trigger. Observe the changes in the charge spectrum, while tuning the LED intensity in a range between 150 and 500.
2. Record charge spectra for at least 5 different LED settings between 250 and 450. Make sure that at least 4 peaks can be seen even for low LED intensity! In case of high intensity the pedestal must still be visible!

ANALYSIS

1. Explain why higher photon peaks occur, when the intensity is ramped up. Why do peak width and distance not change with LED intensity?

2. (a) Extract the peak heights from the spectrum with the corresponding photon number. Create a graph with these peak heights.

   (b) Perform a Poisson fit to the data points as shown in the example in figure 15. Obtain the mean number of detected photons from that fit.[a]

   (c) Plot all mean values versus LED intensity. Describe your observations.

[a] On the Desktop of this PC you can find a C++ script that performs such a Poisson fit. It utilizes the ROOT data analysis toolkit. The script can be executed using the terminal command `root -l Poisson.cpp++`.

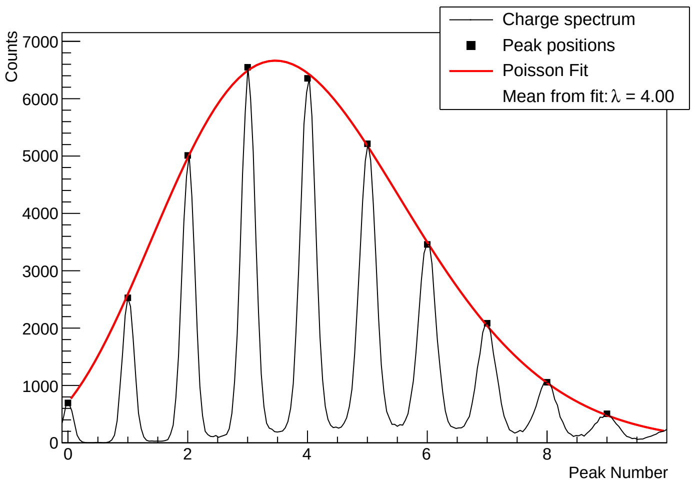

Figure 15: Example of a Poisson fit to the peak heights of the charge spectrum. From the fit, the mean number of detected photons per LED pulse can be extracted.

3.3.5 Influence of the Bias on the Photon Detection Efficiency

The bias voltage has in important influence on the number of detected photons, as it determines gain and photon detection efficiency (p.d.e.) of the SiPM. The measurement of the absolute value of the p.d.e. is very challenging, required additional equipment and cannot be performed in the scope of this experiment. However, the behavior of the p.d.e. with changing bias can be visualized using the mean number of detected photons for *fixed* LED intensity but *variable* bias voltage.

ANALYSIS

(a) Use the data sets from task 3.3.2, where the voltage was scanned through a certain range with fixed LED intensity.

(b) Again, perform Poisson fits to obtain the mean value of the number of detected photons.

(c) Plot all mean values versus bias voltage and interpret your result.

(d) Considering the results from the other tasks, make a recommendation for an operating voltage to obtain best results. Explain which quantities you took into account for your decision.

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