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MEASUREMENT AND CALIBARATION OF KEY PARAMETERS OF A SILICON PHOTOMULTIPLIER

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INTRODUCTION

Silicon Photomultipliers (SiPMs) are highly sensitive, solid-state photodetectors designed for the detection of low-intensity light, often at the level of single photons. They are used extensively in fields like medical imaging, high-energy physics, astrophysics, and optical communication, industrial applications, etc. SiPMs are a modern alternative to traditional photomultiplier tubes (PMTs). They offer several advantages over PMTs, including high sensitivity, immunity to magnetic fields, compact design, and cost-effectiveness. However, it also has several disadvantages: its performance is dependent on temperature (by a few percent per degree Celsius), and it exhibits higher noise levels (ranging from hundreds of kHz to several MHz per square millimeter of the sensitive area).

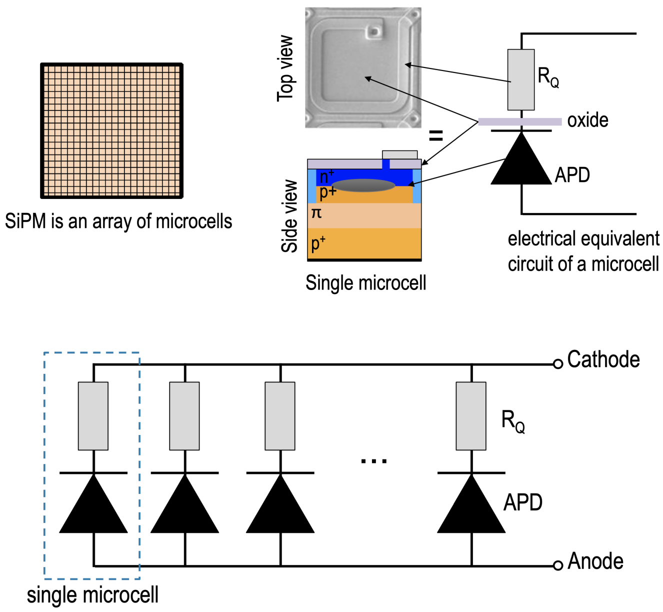

Figure 1: SiPM structure [1].

Silicon Phtomultiplier

SiPMs are comprised of an array of microcells or pixels (photons microcounters), operating in the so-called "Geiger" mode with a gain of $10^4 - 10^6$. Each pixel functions as a binary device in "yes/no" mode (unable to measure light intensity). In a SiPM, each pixel is connected in parallel with all other pixels (Fig. 1). If the illumination of the SiPM is uniform and the number of incident photons is significantly smaller than the total number of pixels, the probability of two or more photons being detected by the same pixel is low. Under these conditions, the SiPM acts as an analog detector, recording the intensity of the incident light. Overall, the SiPM is an analog device whose dynamic range is limited by the number of pixels. This pixel density significantly limits the use of SiPMs in detector applications that require a wide dynamic range, such as calorimeters, or high amplitude resolution.

Key characteristics of SiPM:

- **PDE** - The Photon Detection Efficiency (PDE) of a Silicon Photomultiplier (SiPM) is a measure of how efficiently the device detects incoming photons. It represents the probability that a photon incident on the active area of the SiPM will produce a detectable signal (avalanche breakdown) in one of the microcells. PDE is a critical performance metric that determines the SiPM's sensitivity to light. PDE depends on three primary components:

  . Quantum Efficiency (QE) -represents the probability that a photon incident on the silicon surface will generate an electron-hole pair. It depends on the silicon material, the wavelength of the photon, and the design of the SiPM.

  . Geometrical Fill Factor is the fraction of the total SiPM surface area that is photosensitive. The remaining area includes regions for circuitry, insulation, and gaps between microcells, which are not sensitive to photons. Typical fill factors range from 30% to 70%, depending on the pixel size and layout.

  . Probability of Avalanche Breakdown - even if a photon generates an electron-hole pair, it will only trigger an avalanche if the electric field in the microcell is strong enough. This probability depends on the applied overvoltage (the difference between the operating voltage and the breakdown voltage). Higher overvoltage increases the avalanche probability, but also increases noise.

  Thus, PDE can be expressed as:

$$\text{PDE} = \text{QE} \times \text{Fill Factor} \times \text{Avalanche Probability} \tag{1}$$

  The PDE of an SiPM varies with the wavelength of the incident light and the operating overvoltage. Typical PDE values range from 20% to 50% for visible light wavelengths (400–700 nm) under optimal operating conditions. SiPMs are often optimized for specific wavelengths depending on the application: often in the range of 400–500 nm (blue to green light), where silicon is highly sensitive.

- **Gain** - refers to the amount of charge generated by the avalanche process in response to a single photon. It is a measure of how much the signal is amplified when a photon triggers an avalanche breakdown in a single microcell (pixel). Gain is defined as the number of charge carriers (electrons or holes) collected at the output of a single pixel due to a photon-induced avalanche. Mathematically:

$$\text{Gain} = \frac{Q_{\text{pixel}}}{e} \tag{2}$$

  where Q_{pixel} is the total charge generated in the pixel, e is the elementary charge ($1.6 \times 10^{-19} C$).

  The gain is proportional to the overvoltage, as a higher overvoltage increases the amount of charge collected during an avalanche. And can be approximated as:

$$\text{Gain} = C_{\text{pixel}} \cdot \Delta V / e \tag{3}$$

  where C_{pixel} is the capacitance of a single pixel, ΔV is the overvoltage. Each avalanche in a pixel generates a charge that is collected and summed across all triggered pixels. Since the gain is constant for a given overvoltage, SiPM signals are linear for low photon flux (when multiple photons do not hit the same pixel).

- **DCR** - The dark count rate (DCR) of a SiPM refers to the rate at which the device produces spontaneous electrical pulses in the absence of incident light. These pulses are caused by thermally or electrically generated carriers in the SiPM microcells, which trigger avalanches similar to those caused by photon detection. The dark count is one of the main sources of noise in SiPMs and affects their performance in low-light applications. Dark count rate is measured in counts per second (cps) per unit area, e.g., kHz/mm^2 or MHz/mm^2. For a typical SiPM, the DCR ranges from hundreds of kHz to several MHz per mm^2 at room temperature. The dark count rate is highly temperature-dependent. It increases exponentially with temperature due to the thermally activated generation of carriers. The DCR approximately doubles for every 8-10 ^{o}C increase in temperature. Higher overvoltage increases the DCR because it enhances the avalanche triggering probability for thermally generated carriers. Optimizing the operating voltage is essential to balance sensitivity and noise.

- **Crosstalk** - refers to the phenomenon where a single photon detection event in one microcell (pixel) causes avalanches in neighboring microcells. This unintended triggering can create false signals and affects the accuracy of photon counting. Crosstalk is a form of noise that limits the performance of SiPMs, especially in applications requiring precise light intensity measurements. When an avalanche occurs in one microcell, it generates photons as part of the avalanche process. These photons can travel to neighboring microcells and trigger secondary avalanches. Higher overvoltage increases the sensitivity of microcells to incoming photons, making them more prone to crosstalk. Closely packed microcells with high fill factors are more susceptible. Crosstalk increases the apparent number of detected photons, leading to an overestimation of the light intensity. Crosstalk is typically expressed as a percentage of secondary avalanches relative to the primary avalanches. For example, if an SiPM has 5% crosstalk, this means that, on average, 5 out of 100 primary avalanches cause secondary avalanches in neighboring microcells.

Experimental Setup

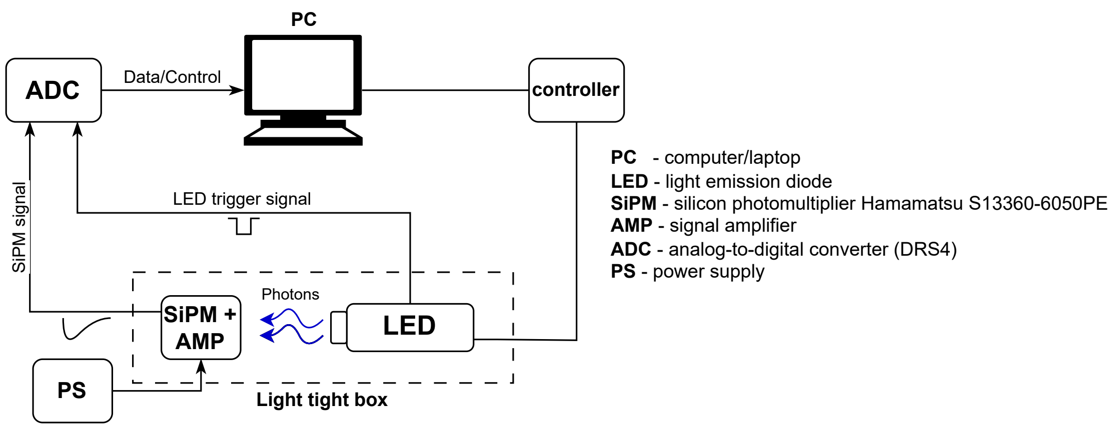

Figure 2: Experimental setup.

The calibration of photodetectors involves the determination of their main characteristics, including photon detection efficiency (PDE) and gain. For the calibration of SiPMs, the low-intensity light flash method is used [2]. To perform this calibration, a dedicated setup has been prepared (Fig. 2). The setup includes a 6×6 mm^2 SiPM (Hamamatsu S13360-6035PE [3]), which is mounted on a printed circuit board (PCB) together with a signal amplifier. A special, self-stabilized pulsed light flash source is used as the light source, based on an LED with a wavelength of 425 nm from HVSys [4] (JINR development). This LED is controlled by dedicated software (Fig. 3), and also provides a trigger signal for the analog-to-digital converter (ADC) to start data acquisition. The SiPM and LED light source are housed in a light-tight box. The light from the LED is detected by the SiPM, and the signal from the SiPM is then transmitted to the ADC for further processing. The DRS4 [5] ADC board developed by PSI is used for this purpose. Special software is employed to record the output data from the ADC on a computer, allowing for modification of various ADC settings and recording parameters (Fig. 4). Additionally, an online signal visualizer similar to an oscilloscope is provided. Data analysis is carried out using a specialized software (Fig. 5) that allows for the processing of data through charge histogram analysis. The SiPM and amplifier are powered by an external power supply.

Software

To launch the LED control window (Fig. 3), run the command [**./ledgen_s.tcl /det/ttyUSB**N X Y] in the terminal of the Linux operating system,where N represents the number of the USB port to which the LED controller is connected and X and Y represent the range of the search for the device.

The control window has a number of settings that must be set when the LED is started for the first time.

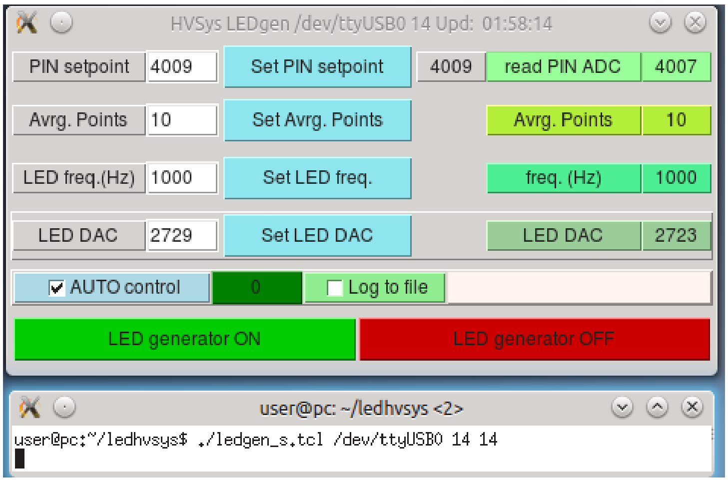

Figure 3: LED control window.

- **PIN setpoint** - The amount of light detected by the PIN diode can be adjusted between a minimum value of 10 and a maximum value of 4096 in arbitrary units. Due to the fact that the PIN diode operates in feedback with the LED, this settings also controls the light of the LED

- **Avrg. Points** - The number of averaging points for the signal from the PIN diode in the feedback circuit - typically between 10 and 100
- **LED freq.(Hz)** - The frequency of light pulses emitted by the LED in hertz (Hz)
- **LED DAC** - The pulse value of the LED is in the range of 10 to 4096, in arbitrary units
- **AUTO control** - Feedback mode control is a self-regulating mode of light output from an LED. If it is enabled, the light output is set according to a specified PIN value (PIN setpoint), otherwise it is determined by the LED's digital-to-analog converter (LED DAC)
- **LED generator ON** and **LED generator OFF** - ON and OFF buttons of LED

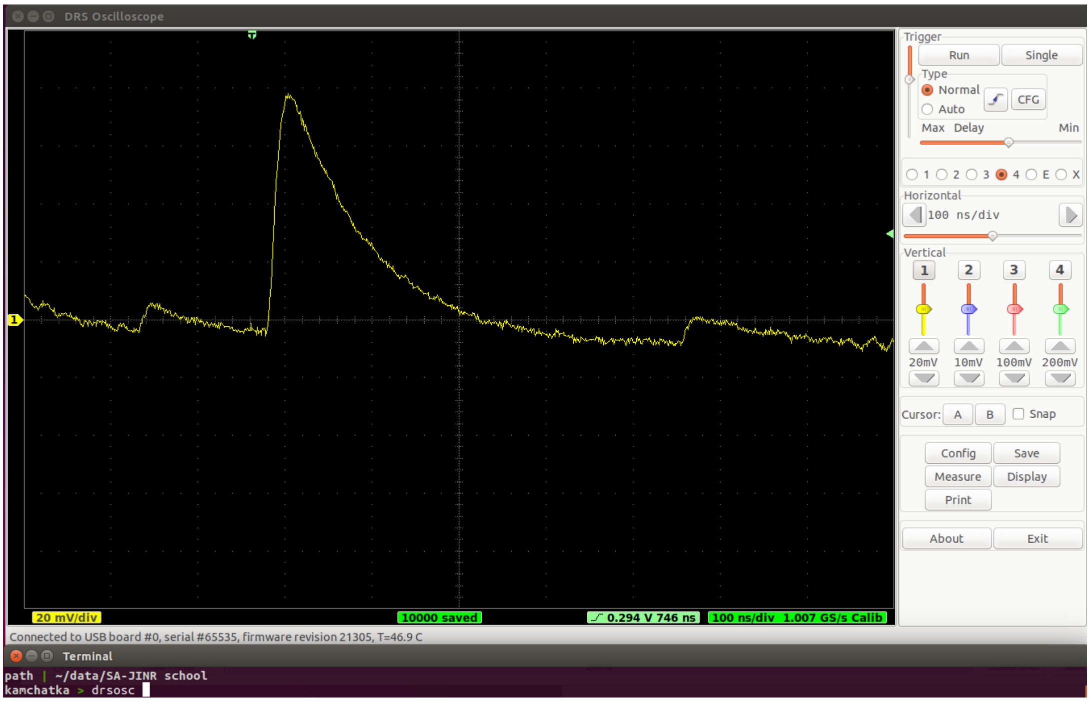

Figure 4: ADC control window.

To operate the DRS4 analog-to-digital converter (ADC), software must be installed from the manufacturer's official website [5] (Fig. 4). This software is then launched on the Linux operating system (OS) using a specific command in the terminal: [**drsosc**].

The DRS4 has four channels for signal acquisition and additional channels for triggering logic. The main control window (Fig. 4) provides the following control buttons and settings:

- **Stop/Start** - stop/start signal acquisition
- **1,2,3 or 4** - The on and off buttons for the 1st, 2nd, 3rd, and 4th channel, respectively.
- **Normal and Auto** - Selecting the run mode
- **Trigger(vertical slider) or CFG** - trigger threshold settings
- **Delay(horizontal slider)** - Settings of delay between trigger and signal
- **Horizontal (arrow buttons)** - selection of the sampling frequency and, accordingly, the width of the acquisition window
- **Config** - ADC calibration. Need to be done before the first run
- **Save** - Data recording to a computer

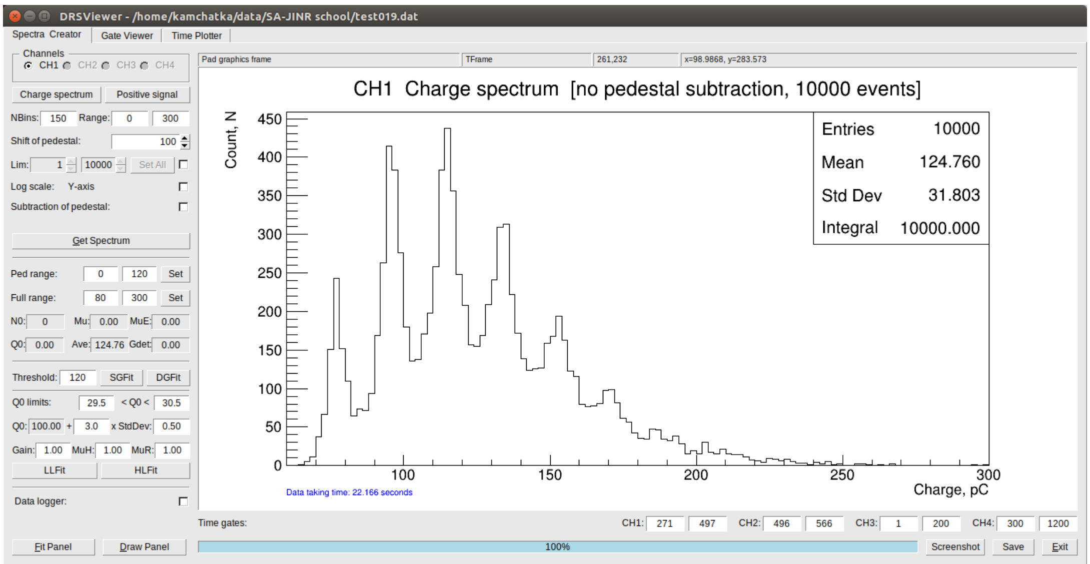

Figure 5: DRSViewer control window.

The DRSViewer software, which is a specialized tool developed by the Joint Institute for Nuclear Research (JINR), is used to analyze the data collected from DRS4. This software runs on Linux in a terminal using the command [**DRSViewer**], and after launching, a control window appears (Fig. 5). This window has two main tabs that are used for various operations.

- **Gate Viewer tab** - The drawing of single, average signals and the selection of an integration window to plot a charge spectrum.
- **Spectra Creater tab** - Building a charge spectrum with and variety of additional settings.
- **Save button in Spectra Creater tab** - Opens a dialog box for saving a spectrum file.

Data Recording and Analysis

To begin the practical work, the equipment should be assembled in accordance with the schematic shown in Fig. 2. After that, configure the setup elements (light intensity, ADC settings), and turn on the power supply. The desired light intensity (~ 1 photoelectron or dark signals) need to be selected, and then data should be recorded. The recorded data must be converted using DRSViewer to a charge spectrum histogram (Fig. 6). By analyzing the obtained spectra, SIPM parameters such as gain, detection efficiency, and cross-talk can be determined.

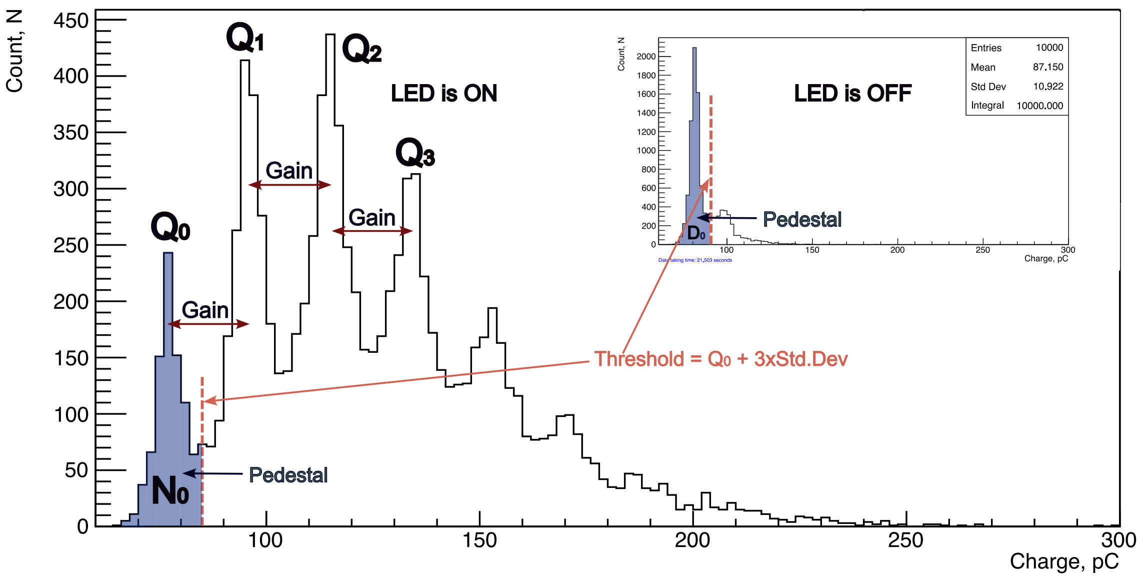

Figure 6: SiPM spectrum and the values used in the data analysis.

Both light and dark spectra (Fig.6) can be approximated by the Poisson distrubution:

$$P(n, \mu) = \frac{e^{-\mu}}{n!} \mu^n \tag{4}$$

From this, an average number of the distributions can be calculated using the pedestal probability (case of no signal), as follows:

$$P(\mu, n=0) = e^{-\mu} \implies \mu = -\ln(P(\mu, n=0)) \tag{5}$$

According to the method depicted in [2], the average number of photoelectrons detected by SiPM can be evaluated by using the pedestal probability of both spectra as follows:

$$\mu = -\ln(\frac{N_0}{N} / \frac{D_0}{D}) = -\ln(\frac{N_0}{N} \cdot \frac{D}{D_0}) = \mu_{\text{light}} - \mu_{\text{dark}} \tag{6}$$

This μ value represents the detection efficiency of the SiPM. In order to evaluate the absolute PDE of the SiPM, the μ must be compared with a similar value obtained for a calibrated photodetector (e.g. PMT, SiPM, etc.).

The position of each peak represents the charge obtained from the pixels triggered by photons simultaneously. Thus, the distance between the peaks in the light histogram spectrum (Fig. 6) corresponds to the gain of the SiPM. The SiPM pixel's gain is calculated as follows:

$$\text{Gain}_{\text{pixel}} = \frac{Q_1 - Q_0}{K_{amp} \cdot q} \tag{7}$$

where $K_{amp} = 50$ is the amplification factor of the signal amplifier in our case, and $q = 1.6 \times 10^{-19} C$ is the elementary charge, Q_1 and Q_0 represent the positions of the first peak and the pedestal in the spectrum, respectively.

Crosstalk is resulting in an excess signal in the charge histogram and can be assessed based on [6]. Excess signal can be evaluated as:

$$n = \frac{S}{\mu_{\text{light}} \cdot \text{Gain}_{\text{pixel}}} \tag{8}$$

where $S = \text{Mean}_{\text{spectrum}} - Q_0$, Mean is average value of the charge histogram.

According to the [6], the probability of crosstalk can be expressed as:

$$\lambda = 1 - \frac{1}{n} \implies P_{\text{crosstalk}} = 1 - e^{-\lambda} \tag{9}$$

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