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Dzhelepov Laboratory of Nuclear Problems

FINAL REPORT ON THE START PROGRAMME

Study of Silicon Photomultiplier external cross-talk

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Abstract

The Taishan Antineutrino Observatory (TAO) experiment utilizes silicon photomultipliers (SiPMs) as the primary photon detectors in its search for reactor antineutrinos within a liquid scintillator. However, SiPMs face the issue of optical cross-talks, a form of correlated noise that can compromise the precision of photon detection. Optical cross-talks occur when secondary photons, generated during the avalanche process in one microcell, trigger neighboring microcells, producing false signals. This is particularly problematic for experiments like TAO, where precise measurements of the antineutrino spectrum are crucial.

This report investigates the nature of cross-talks in SiPMs and explores methods to minimize their impact. By analyzing the cross-talk probability in different materials (Mylar, air, and glass) under varying voltages, we found that Mylar exhibited the steepest decline in cross-talk probability with decreasing voltage, indicating high sensitivity. Furthermore, external optical cross-talk (OCT), which originates from photons escaping the SiPMs, was studied to assess its contribution to overall noise. The cross-talk probabilities for Hamamatsu SiPM models were measured to be on the order of tens of percent. Additionally, the impact of the light reflection coefficient from the SiPM optical window material and overvoltage on cross-talk behavior was examined. Understanding and mitigating these effects are critical for enhancing the performance of low-noise detectors like those in the TAO experiment.

Contents

1. Introduction

Silicon Photomultipliers (SiPMs) have emerged as a revolutionary advancement in photon detection, replacing traditional photomultiplier tubes (PMTs) in a variety of experimental applications. Originally developed as an alternative to PMTs, SiPMs offer numerous advantages, including compactness, high sensitivity, and immunity to magnetic fields. Their ability to detect single photons with good timing resolution has made them indispensable in fields like high-energy physics, medical imaging, and astroparticle physics.

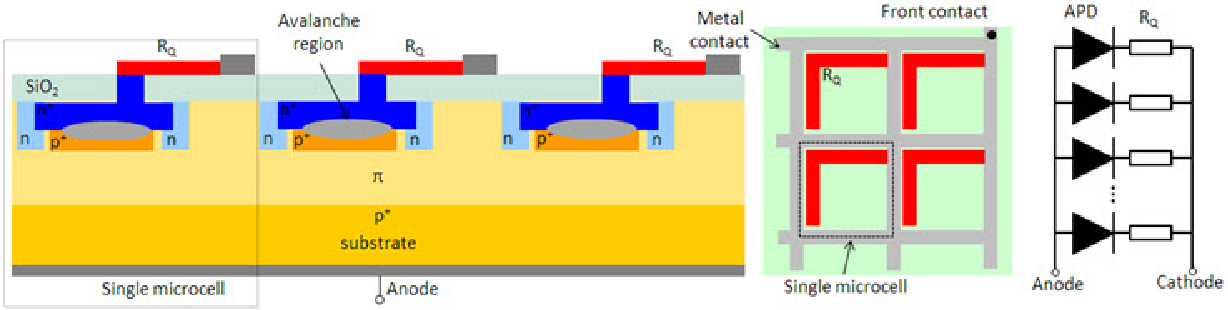


Figure 1. This figure depicts a typical structure of a SiPM.

SiPMs consist of arrays of avalanche photodiode (APD) cells operating in Geiger mode. When a photon strikes a pixel (or microcell) within the SiPM, it generates an electron-hole pair via the photoelectric effect. This occurs within the depletion region of the silicon. The generated charge carrier is rapidly accelerated by the electric field within the microcell. If the applied voltage exceeds the breakdown voltage of the silicon, the charge carriers initiate an avalanche breakdown, multiplying exponentially as more electron-hole pairs are generated. This creates a large current pulse in response to a single photon. After the avalanche is triggered, a resistor in series with each pixel limits the current and quenches the avalanche, allowing the cell to recover and be ready for subsequent photon detections. The quenching resistor ensures that each cell operates independently, preventing continuous breakdown. Each pixel in the array operates as a binary detector (i.e., it either detects a photon or does not). The output signal is the sum of all avalanches triggered by photon hits across the entire array. This gives the SiPM a proportional output to the number of detected photons, which is critical for applications requiring precise photon counting or energy measurement.

The ability of SiPMs to resolve individual photons is what distinguishes them from other detectors, making them exceptionally sensitive in low-light conditions.

1.1 Key Characteristics of SiPMs

- SiPMs have high internal **gain**, similar to that of PMTs, typically in the range of 10^5 to 10^7. The gain in SiPMs is controlled by the breakdown voltage and the design of the microcells.
- **Photon Detection Efficiency (PDE)** is a crucial metric for SiPM performance and is influenced by several factors, including the quantum efficiency of the silicon, the fill factor (i.e., the fraction of the total area occupied by active photodetectors), and the photon wavelength. SiPMs typically offer PDE values between 40% and 50% in the visible spectrum, with optimizations available for ultraviolet (UV) and near-infrared (NIR) detection.
- SiPMs offer good **timing resolution**, often in the picosecond range, which is crucial for time-of-flight applications in particle physics and medical imaging.
- A significant limitation of SiPMs is the **dark count rate**, where thermally generated carriers can trigger an avalanche without photon detection. Manufacturers have worked to minimize these counts, but they remain higher than those found in PMTs, especially at room temperature.

SiPMs are more sensitive to temperature changes, which can shift the breakdown voltage and increase the dark count rate. This can complicate their operation in environments with fluctuating temperatures, whereas PMTs are less affected by temperature.

Applications of SiPMs in Experiments

SiPMs have found application across a wide range of experiments due to their versatility, high sensitivity, and compact size.

1. High-Energy Physics;
2. Astroparticle Physics;
3. Medical Imaging.

1.2 The cross-talks problem in SiPMs in the TAO experiment

The Taishan Antineutrino Observatory (TAO) experiment employs SiPMs as the primary detectors for capturing photons generated by reactor antineutrinos in the liquid scintillator. One of the challenges with SiPMs is **optical cross-talks**, a form of correlated noise that can significantly affect the precision of photon detection, especially in low-noise environments such as neutrino detectors.

1.3 Nature of cross-talks in SiPMs

Optical cross-talks occurs when a photon detected by one microcell within an SiPM triggers an avalanche in a neighboring microcell. This happens because secondary photons, often in the near-infrared range, are generated during the Geiger-mode avalanche process and can travel to adjacent cells, where they initiate additional avalanches. This leads to false signals that mimic true photon events, affecting the accuracy of measurements in experiments like TAO.[1]

In the TAO experiment, where precise measurement of the reactor antineutrino spectrum is critical, minimizing cross-talks is essential to ensure the integrity of the data. cross-talks can lead to erroneous high-energy signals that obscure the detection of rare antineutrino events.

Studying and minimizing cross-talks in SiPMs remains highly relevant today, especially in the field of low-background detectors like those used in dark matter and neutrino experiments. cross-talks can significantly affect the signal-to-noise ratio, making it crucial to address this issue in experiments requiring ultra-sensitive photon detection.

2. Calculating cross-talk from single-electron spectra

Calculating cross currents from single-electron spectra involves analyzing the noise or signal produced by individual electrons or dark counts in a detector, often in the context of photomultiplier tubes (PMTs), avalanche photodiodes (APDs), or other photon-sensitive devices. Cross currents typically refer to small leakage currents or unwanted signals that can be induced by noise or dark counts, and their estimation is important for understanding the performance of such devices.

2.1 Single-Electron Spectra Analysis

Single-electron spectra (SES) refer to the signal distribution generated by a detector when it detects individual photoelectrons, typically from a single photon event. This is commonly studied in devices like photomultiplier tubes (PMTs), avalanche photodiodes (APDs), and other photon-sensitive detectors that convert photon interactions into electron signals. Analyzing the single-electron spectrum is crucial for characterizing the performance of such detectors, including their gain, noise characteristics, and overall efficiency.

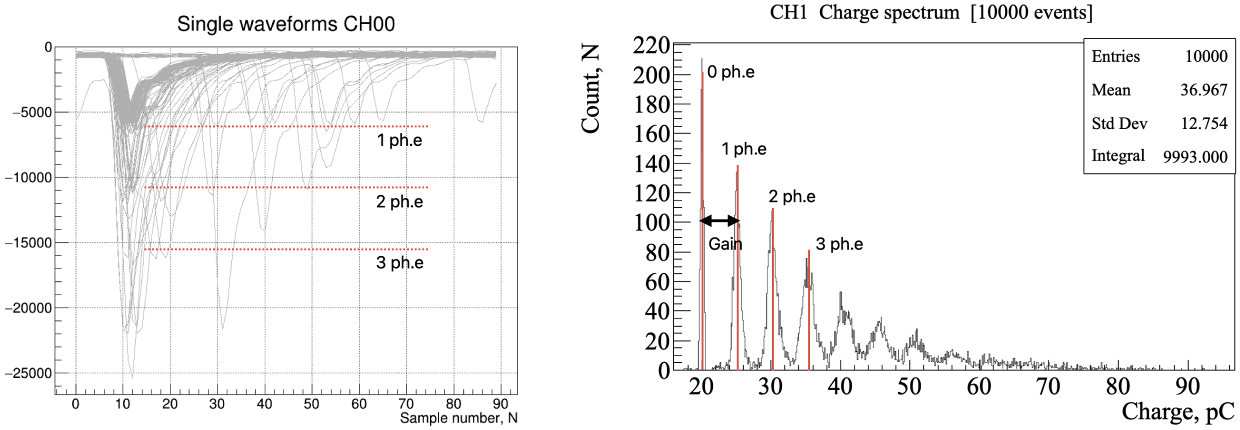


Figure 2. The typical waveforms and single-electron spectrum.

The experimental setup is presented below. The ADC on the RS4 chip allows digitizing signals from the detector with a time resolution of the order of picoseconds and makes it possible to use an external trigger to start the LED. This chip is capable of digitizing data at a sampling rate of up to 5 Gbit/s, and the board is powered via a USB port and contains built-in startup logic. The ready-made ADC software allows you to save data in a binary file for further processing.

When a single photon strikes a microcell in a SiPM, it initiates an avalanche breakdown that produces a current pulse. This pulse is collected and measured to generate a signal corresponding to the detected photon. The amplitude of these pulses is analyzed to create the single-electron spectrum. In an ideal scenario, this spectrum displays distinct peaks corresponding to single-photon events, with each peak representing a unique detection event. The spectrum typically shows a peak corresponding to the charge generated by a single photon. This peak's position reflects the magnitude of the signal produced by a single photon in the SiPM.

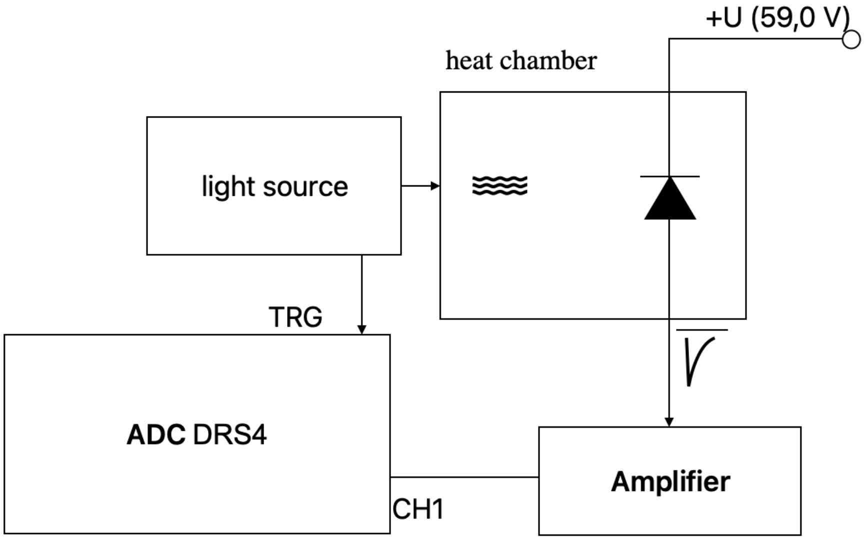


Figure 3. Block diagram of the experimental setup used in experiments.

As a result of the measurement, single-electron spectra were obtained for various values of the MAPD supply voltage, the characteristic shape of the spectrum is shown in Fig. 3, where each peak reflects the operation of a certain number of diode cells.

Due to the intrinsic noise of the detector, the reading electronics and other factors, an effective displacement of the photoelectronic peaks occurs.

Each detected photon has a probability of generating secondary photons, which may in turn cause further avalanches in adjacent microcells. This branching continues, leading to multiple microcell firings from a single photon event. Optical cross-talks is an example of a correlated noise: it can be present only if a primary discharge is present. The primary discharge can be due to 1) absorption of a photon, 2) thermal generation of a charge carrier in the multiplication region, 3) injection of a charge carrier, thermally generated outside of the avalanche region, into the avalanche region, or 4) cross-talks-induced secondary discharge becoming the primary discharge for subsequent cross-talks events. If not corrected for, cross-talks makes the output signal higher than that implied by the amount of the incident light. Poisson statistics allows you to calculate the probability of events at the peak, taking into account the average value (mathematical expectation).

$$P_n = \mu^n \cdot e^{\frac{-\mu}{n!}}$$

A zero peak is used to determine it, since sneakers do not contribute to its statistics. Knowing the ratio of events in the zero peak to all events in the single-electron spectrum, it is possible to calculate P_n, where n = 0

$$\mu = - \ln P_0.$$

The gain of one pixel can be calculated as the ratio of the output signal (S_{Out}) to the input signal (Sin). To calculate the Sout output signal for the case of a single photoelectron

$$S_{out} = Mean_1 - Mean_0,$$

and the input signal (S_{in}) is calculated from statistics, that is, this is the expected value of the signal. The gain of one pixel is the ratio of the output signal to the input signal:

$$Gain = \frac{S_{out}}{S_{in}}.$$

The crossstock indicator is n, which is equal to the ratio of the detector gain to the gain of a single pixel:

$$n = \frac{Gain_{det}}{Gain_{pix}} = \frac{1}{1 - \lambda}$$

from where it is equal $\lambda = \frac{n-1}{n}$.

Finally, the magnitude of the cross current is defined as a function of the Poisson probability

$$P = 1 - e^{-\lambda}.$$

To evaluate if there are random and uncorrelated noises. The number of noise pulses m in the time window τ in this case can be approximated by a Poisson distribution $m \sim P\,(m|\lambda)$, where $\lambda = \tau R$ and R is the count rate of noise pulses per unit of time.Since convolution of two

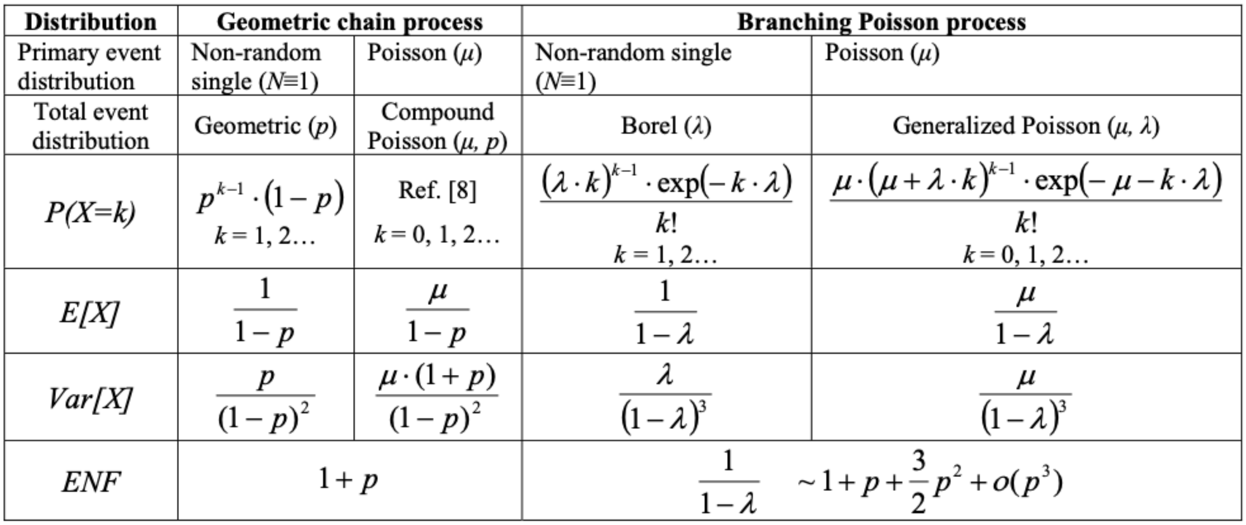
Poisson processes is a Poisson distribution, the number of pulses n in the resulting spectrum (signal+noise) also obeys the Poisson distribution $n \sim P\,(n|\xi)$, where $\xi = \mu + \lambda$. Of course, in order to evaluate μ, it is necessary to evaluate λ. In practice, this can be done by measuring the noise spectrum in the same way as light, but with the light off.and the lights are off:

$$\mu \;=\; -\;ln\,(\frac{N_0}{N}\cdot\frac{D}{D_0}),$$

$$\mu \;=\; -\;ln\,\frac{N_0}{D_0}.$$

2.2 The Generalized Poisson distribution

Vinogradov's work [2] offers a deep theoretical analysis of how cross-talks affects SiPM performance. By modeling cross-talks as a branching Poisson process, it provides a statistical framework for predicting cross-talks events and their contribution to noise. The introduction of the Borel distribution for modeling the ENF represents an advancement over previous methods, allowing for a more accurate understanding of how cross-talks and afterpulsing deteriorate photon detection efficiency.



Distribution	**Geometric chain process**		**Branching Poisson process**	
Primary event distribution	Non-random single (N≡1)	Poisson (μ)	Non-random single (N≡1)	Poisson (μ)
Total event distribution	Geometric (p)	Compound Poisson (μ, p)	Borel (λ)	Generalized Poisson (μ, λ)
P(X=k)	$p^{k-1}\cdot(1-p)$ $k = 1, 2\ldots$	Ref. [8] $k = 0, 1, 2\ldots$	$\frac{(\lambda\cdot k)^{k-1}\cdot\exp(-k\cdot\lambda)}{k!}$ $k = 1, 2\ldots$	$\frac{\mu\cdot(\mu+\lambda\cdot k)^{k-1}\cdot\exp(-\mu-k\cdot\lambda)}{k!}$ $k = 0, 1, 2\ldots$
E[X]	$\frac{1}{1-p}$	$\frac{\mu}{1-p}$	$\frac{1}{1-\lambda}$	$\frac{\mu}{1-\lambda}$
Var[X]	$\frac{p}{(1-p)^2}$	$\frac{\mu\cdot(1+p)}{(1-p)^2}$	$\frac{\lambda}{(1-\lambda)^3}$	$\frac{\mu}{(1-\lambda)^3}$
ENF	$1+p$		$\frac{1}{1-\lambda}\quad \sim 1+p+\frac{3}{2}p^2+o(p^3)$	

The Excess Noise Factor (ENF) quantifies the increase in noise within a detector, relative to the expected noise level from purely random photon detection events. In SiPMs, cross-talks and afterpulsing introduce additional false signals, which degrade the signal-to-noise ratio and the accuracy of photon detection. They improve upon existing models by introducing a new analytical approach using the Generalized Poisson distribution. This distribution is often used to model processes where each event can generate a random number of new events-making it ideal for SiPMs where each photon detection can lead to multiple secondary detections due to cross-talks. [3]

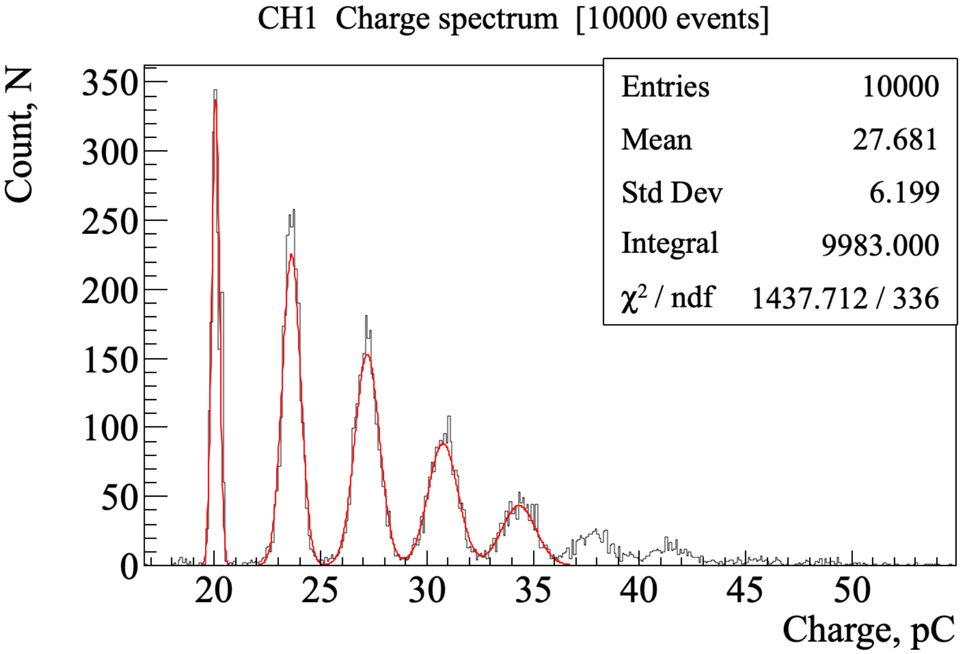


Figure 3. An example of fitting a single-electron spectrum.

2.2 Results and analysis

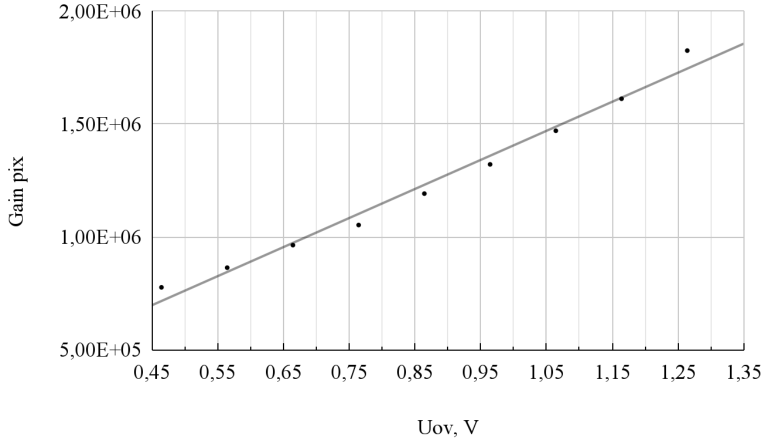


Figure 4. Dependence of pixel gain on MAPD overvoltage.

The pixel gain (Gain pix, fig.4) specifically refers to the gain of an individual microcell or pixel in the SiPM. Pixel gain is essentially a component of the SiPM gain. SiPM gain is the cumulative effect of the gain from all pixels that are triggered in response to incident photons. If multiple pixels fire, their gains contribute to the total SiPM gain. Like SiPM gain, pixel gain also depends on the overvoltage applied. However, the gain of each pixel is ideally uniform across the SiPM, as all microcells should have the same response to overvoltage.

Below is a graph (fig.5) for comparing the two estimates , which were calculated using the ratios

$$\mu = -\ln\frac{N_0}{N},$$

$$\hat{\mu} = -\ln\frac{N_0}{D_0}$$

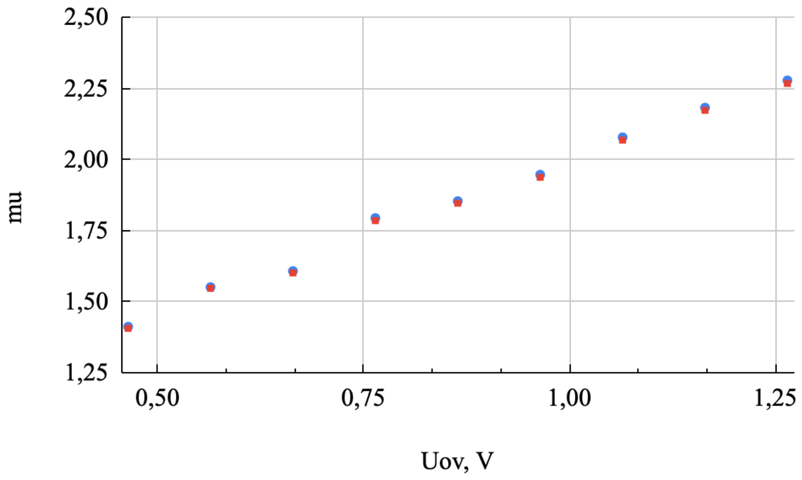


Figure 5. The relation to the overvoltage of MAPD, where the values are shown in blue μ, red – $\hat{\mu}$.

The dependence of the probability of a cross-talks of the overvoltage for two measurements on different days is shown below

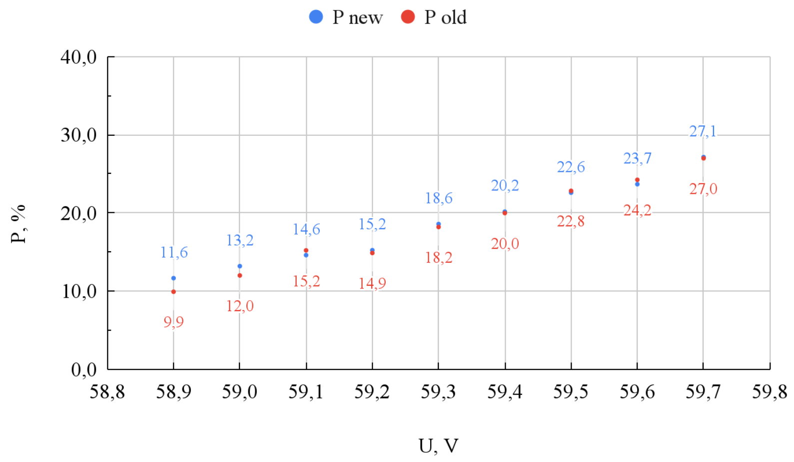


Figure 6. Dependence of the probability of MAPD cross-talks on voltage.

Increasing the overvoltage in a SiPM enhances the electric field in the microcells, leading to higher gain, increased photon emission during avalanches, and greater susceptibility to neighboring cell triggering. This, in turn, raises the likelihood of cross-talks, where one microcell's breakdown induces a breakdown in adjacent cells, creating false signals.

As overvoltage increases, the number of photons emitted by the avalanche process also increases. More emitted photons mean a higher chance that some of these photons will be absorbed by nearby microcells. Additionally, the absorption cross-section of SiPM microcells is sensitive to photons, and at higher overvoltages, the detector becomes more susceptible to triggering a secondary avalanche from even lower-energy photons.

Thus, higher overvoltage increases both the likelihood of photon emission during the avalanche and the absorption of these photons in nearby cells, leading to a rise in cross-talks.[4]

3. External cross-talks in detectors with liquid scintillators

In applications such as liquid xenon detectors for rare-event searches (e.g., dark matter detection), cross-talks can degrade the energy resolution of the system by producing additional light events that interfere with the actual detection of particles. The same effect was found during the construction of the TAO detector. [5] The focus is on understanding two types of cross-talk: internal (within a single SiPM) and external cross-talk (where photons escape one SiPM and trigger avalanches in neighboring ones). The article emphasizes that optical cross-talk is a critical issue in SiPMs, particularly in settings where multiple SiPMs are positioned in close proximity, such as in detectors for nEXO and JUNO-TAO experiments. Cross-talk contributes to noise by causing false signals, which reduces the accuracy of photon counting and affects overall detector performance.

The experimental setup for measuring external cross-talk involves two distinct methods. The first is the counting method, where SiPMs are positioned face-to-face, and the coincident signals (triggered by photons escaping one SiPM and causing an avalanche in the other) are measured. This setup directly quantifies the amount of external cross-talk. The second method is the reflection method, which employs a highly reflective film attached to the surface of the SiPMs to measure how much external cross-talk can be reflected back into the SiPM array. This method provides an alternative approach for estimating the degree of cross-talk noise.

The method of measuring external cross-talk, which is generated as a result of the departure of photons as a result of recombination of a photoelectron and a hole into a layer of optical window material, consists in conducting a series of measurements of noise single-electron spectra for cases where the photosensitive surface is SiPM:

1) Optically connected to glass or non-reflective material: This setup helps measure the baseline noise performance of the SiPM when it is connected to materials that do not reflect light back towards the detector. It establishes a reference for comparison with other setups.

2) Located in air: This configuration measures the SiPM’s performance when not optically coupled with any material. It helps in understanding the SiPM’s intrinsic noise characteristics without any external influences.

3) Optically connected to a reflective coating (e.g., Mylar): Mylar or other reflective materials can bounce light back towards the SiPM. This setup helps in studying how reflected light impacts the noise characteristics.

3.1 Results and analysis

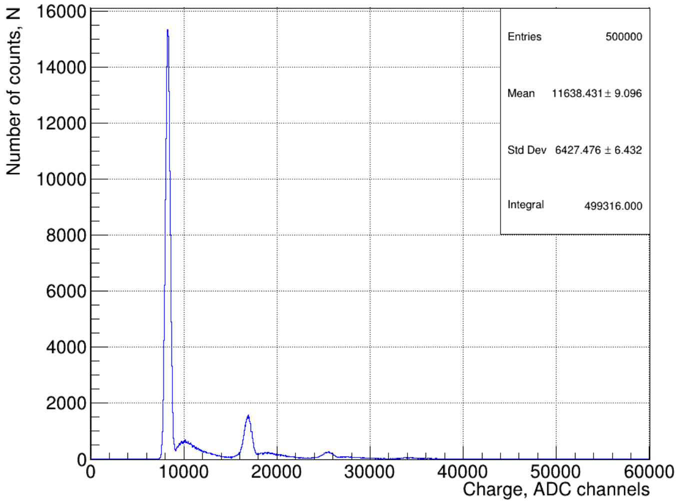


Figure 7. A typical noise spectrum, in which the first three peaks (excluding the zero peak) are well resolved, reflects the presence of cross-talk. This spectrum corresponds to the case where the SiPM is in optical contact with glass.

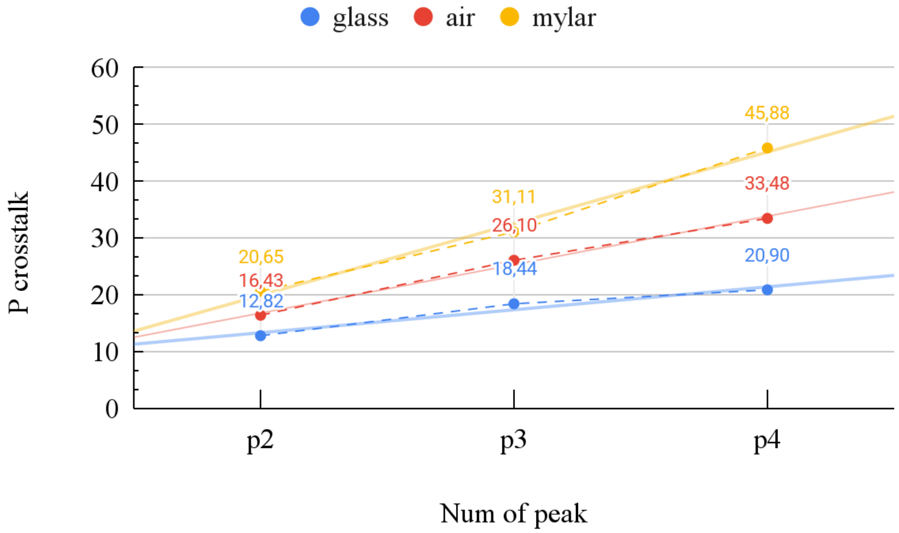


Figure 8. Probability of cross-talks of cascading events successively generating photoelectrons in two (p2), three (p3) and four (p4) cells for cases of optical contact of a photosensitive SiPM surface with glass (glass), air (air) and a mirror reflector (mylar).

Note that there is a variation in the level of cross-talk depending on the configuration of the experimental setup. The lowest probability of cross-talk is observed when the SiPM is in optical contact with glass. This is due to the fact that the generated light quanta escape into the optical window material of the SiPM. The optical contact with glass reduces the reflection coefficient at the interface between the two media. Consequently, the probability of cross-talk is decreased, as evidenced by the experimental data.

In the configuration with a reflective coating, an increase in the probability of cross-talk compared to the air configuration is observed. This is due to the fact that Mylar reflects a significant portion of the emitted photons back towards the SiPM surface, thereby enhancing the likelihood of cross-talk events.

3.2 The dark count rate (DCR) in a SiPM

The DCR is determined by counting the number of pulses above the threshold and dividing by the time interval. This gives the count rate in units of counts per second (cps). By varying the trigger threshold, it is possible to measure how the dark count rate changes depending on the signal size. Higher thresholds typically reduce the dark count rate since small noise signals are excluded.

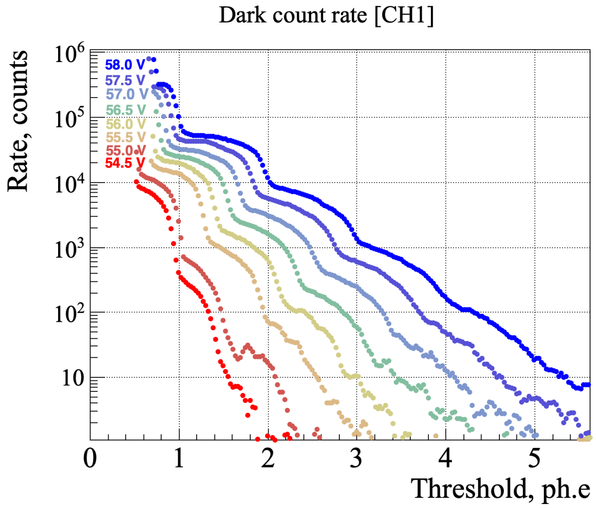


Figure 9. Typical graphs showing the dependence of the dark count rate of the Hamamatsu SiPM on the signal registration threshold for various voltages, ranging from 54.5 V to 58.0 V in increments of 0.5 V.

As a result of the dark count scan, curves were plotted as a function of the trigger threshold, showing the correlation of count rates at different voltage values for the three experimental configurations.

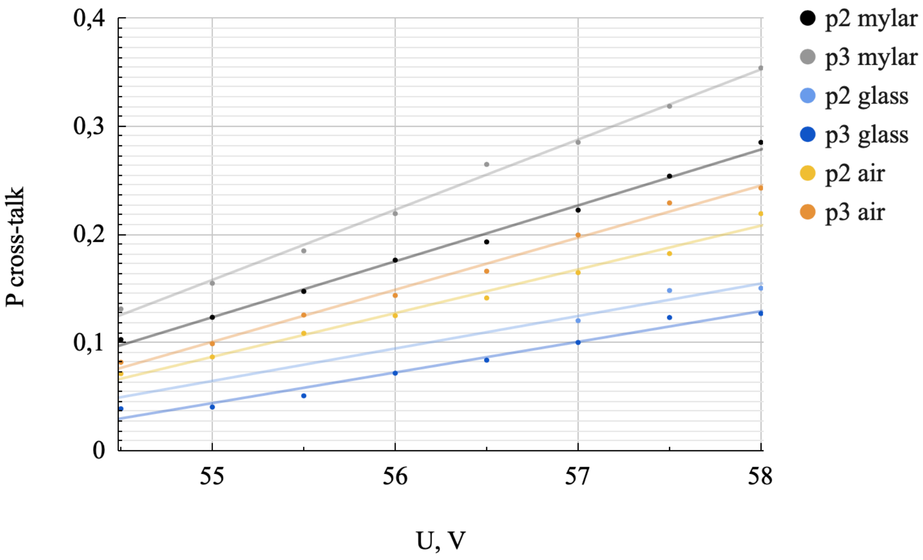


Figure 10. Probability of cross-talks of cascading events successively generating photoelectrons in two (p2) and three (p3) cells for cases of optical contact of a photosensitive SiPM surface with glass (glass), air (air) and a mirror reflector (mylar).

U, V	58,0	57,5	57,0	56,5	56,0	55,5	55,0	54,5
Mylar	35,38	31,84	28,50	26,46	21,91	18,47	15,47	13,09
Air	24,27	22,90	19,93	16,58	14,34	12,53	9,88	8,17
Glass	12,67	12,30	10,00	8,36	7,16	5,07	4,03	3,87

From the obtained distributions and the table data, it can be concluded that Mylar shows the steepest decline as voltage decreases of probability of cross-talks, indicating a significant sensitivity to changes in voltage. Air also exhibits a decreasing trend, but the rate of decline is more moderate compared to Mylar. Glass has the least sensitivity to changes in voltage, with its values showing the slowest decline across the voltage range.

4. Conclusion

Optical cross-talk is a key characteristic of SiPM which is a main source of the excess noise factor and could significantly impact the detector performance. The external optical cross-talk, cross-talk photons escaped from SiPM, could dominate the overall OUT for some types of SiPMs and become an important aspect that requires full understanding.

Several approaches have been applied to measuring external cross-talk, where similar correlations have been observed. As a result, the cross-talks probabilities for MPD 3x3 mm and SiPM S13360-6050CS 6x6 mm produced by Hamamatsu were obtained, which amounted to about tens of percent. The contribution of external cross-talks depending on the light reflection coefficient from the inner surface of the SiPM optical window material is investigated, and the dependence of external cross-talks on overvoltage is determined.

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Lastly, I hope that this internship marks the beginning of a long-term collaboration with JINR, and I look forward to the possibility of future cooperation and contributions to the scientific community.