Hardware Camp for Fast and Low-light Detection

MPPC CHARACTERIZATION EXPERIMENTS

Study the Speed of Light in Cable & Muon Rate at Distinct Angles

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1 Introduction

Facing the challenge to introduce a solid-state photodetector into different fields of photon detection, from medical to high-energy physics applications, a lot of efforts have been made to develop new multi-pixel photon counters (MPPC). The MPPC is a solid-state photodetector also known as the silicon photomultiplier (SiPM). It is a photon-counting device consisting of multiple avalanche photodiode pixels connected in parallel and operating in the Geiger mode. When photons enter a pixel while it operates in Geiger mode, the pulse output from the pixel is constant regardless of the number of photons. This means that each pixel provides only the information on whether or not it received one or more photons. The output signal from the MPPC is proportional to the number of excited pixels. Details of the operational characteristics of a SiPM can be found in the literature.

MPPC is an opto-semiconductor with outstanding photon counting capability and low operating voltage and is immune to the effects of magnetic fields. The S13360 series are MPPCs for precision measurement. The MPPCs inherit the superb low afterpulse characteristics of previous products and further provide lower crosstalk and lower dark count. They are suitable for precision measurements, such as flow cytometry, DNA sequencer, laser microscope, and fluorescence measurement, that require low noise characteristics.

2 Theorical and Scientific Background

2.1 Theory

MPPC

Operation principle

- **Photon counting**
  Light has a property in both a particle and a wave. When the light level becomes extremely low, light behaves as discrete particles (photons) allowing us to count the number of photons. Photon counting is a technique for measuring the number of individual photons.

  The MPPC is suitable for photon counting since it offers an excellent time resolution and a multiplication function having a high gain and low noise. Compared to ordinary light measurement techniques that measure the output current as analog signals, photon counting delivers a higher S/N and higher stability even in measurements at very low light levels.

- **Geiger mode and quenching resistor**
  When the reverse voltage applied to an APD is set higher than the breakdown voltage, saturation output (Geiger discharge) specific to the element is produced regardless of the input light level. The condition where an APD operates at this voltage level is called Geiger mode. The Geiger mode allows obtaining a large output by way of the discharge even when detecting a single photon. Once the Geiger discharge begins, it continues as long as the electric field in the APD is maintained.

  To halt the Geiger discharge and detect the next photon, an external circuit must be provided in the APD to lower the operating voltage. One specific example for halting the Geiger discharge is a technique using a so-called quenching resistor connected in series with the APD to quickly stop avalanche multiplication in the APD. In this method, when the output current due to Geiger discharge flows through the quenching resistor, a voltage drop occurs and the operating voltage of the APD connected in series drops. The output current caused by the Geiger discharge is a pulse waveform with a short rise time, while the output current when the Geiger discharge is halted by the quenching resistor is a pulse waveform with a relatively slow fall time.

Structure

Figure 25 shows a structure of an MPPC. The basic element (one pixel) of an MPPC is a combination of the Geiger mode APD and quenching resistor, and a large number of these pixels are electrically connected and arranged in two dimensions.

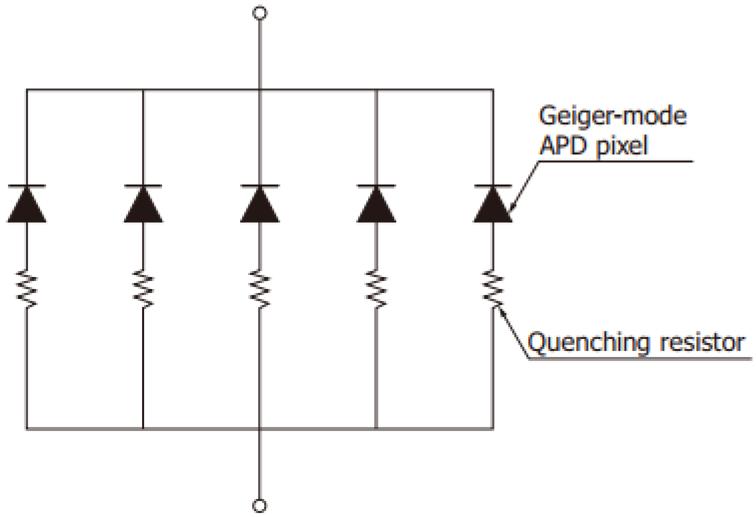


Figure 1: Structure of MPPC's photon counting

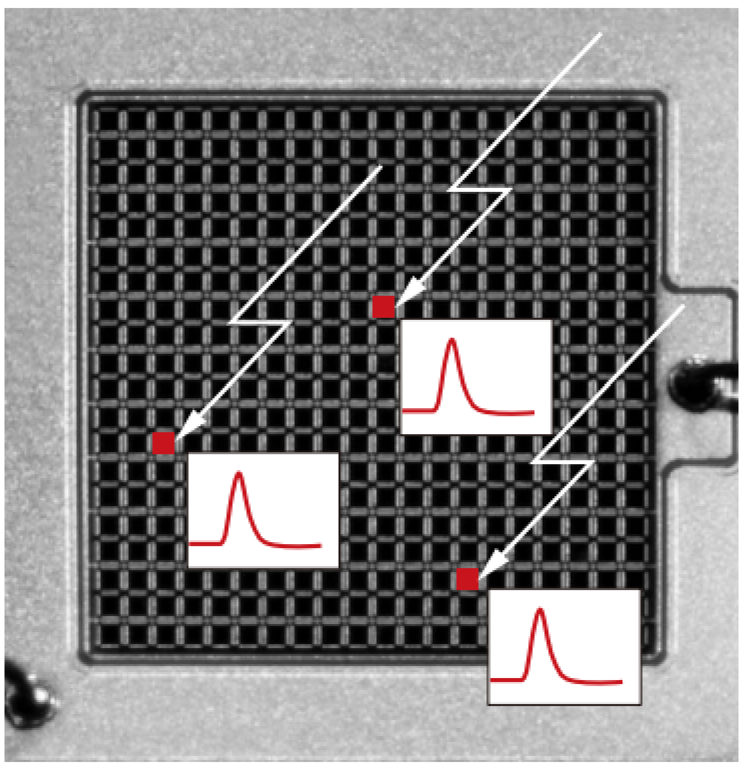


Figure 2: Image of MPPC

Basic Operation

Each pixel in the MPPC outputs a pulse at the same amplitude when it detects a photon. Pulses generated by multiple pixels are output while superimposed onto each other. For example, if four photons are incident on different pixels and detected at the same time, then the MPPC outputs a signal whose amplitude equals the height of the four superimposed

pulses.
Each pixel outputs only one pulse and this does not vary with the number of incident photons. So the number of output pulses is always one regardless of whether one photon or two or more photons enter a pixel at the same time. This means that if the number of photons incident on the MPPC increases and two or more photons are incident on one pixel, the linearity of the MPPC output relative to the number of incident photons is degraded. This makes it essential to select an MPPC having enough pixels to match the number of incident photons.

- Observing pulses

When light enters an MPPC at a particular timing, its output pulse height varies depending on the number of photons detected. Figure 3 shows output pulses from the MPPC obtained when it was illuminated with the pulsed light at photon counting levels and then amplified with a linear amplifier and observed on an oscilloscope. As can be seen from the figure, the pulses are separated from each other according to the number of detected photons such as one, two and so on. Measuring the height of each pulse allows estimating the number of detected photons.

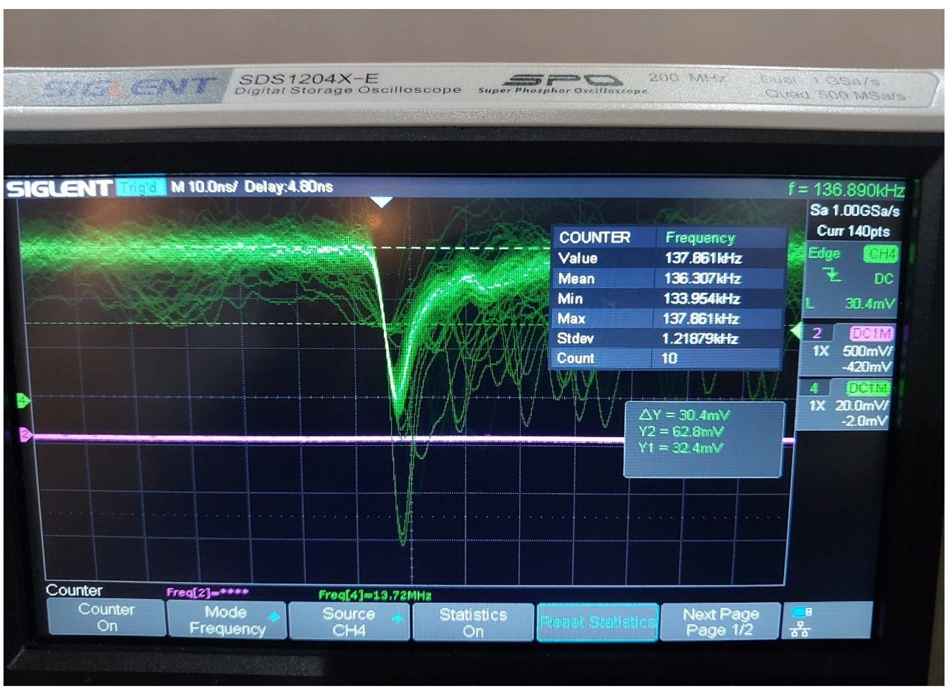


Figure 3: Output pulses from the MPPC

Features

- **Low afterpulses** When detecting photons with an MPPC, signals delayed from the output signal may appear again. These signals are called afterpulses. Compared to our previously marketed products, new MPPCs have drastically reduced afterpulses due to use of improved materials and wafe process technologies. Reducing afterpulses brings various benefits such as a better S/N, a wider operating voltage range, and improved time resolution and photon detection efficiency in high voltage

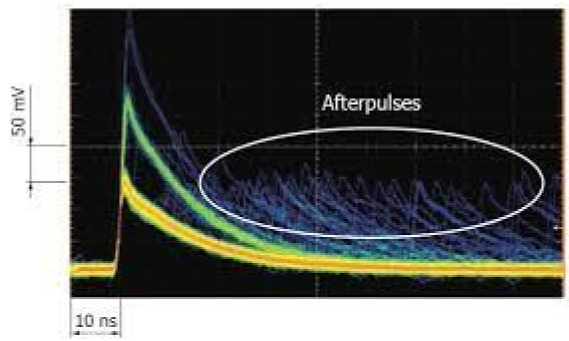


Figure 4: Crosstalk Effect

- **High photon detection efficiency** The MPPC has a peak sensitivity at a wavelength around 400 to 500 nm. The MPPC sensitivity is referred to as photon detection efficiency (PDE) and is calculated by the product of the quantum efficiency, fill factor, and avalanche probability. Among these, the avalanche probability is dependent on the operating voltage. Our 25 µm pitch MPPC is designed for a high fill factor that vastly improves photon detection efficiency compared to our previous types. Using this same design, we also developed 10 µm and 15 µm pitch MPPCs that deliver a high-speed response and wide dynamic range as well as high photon detection efficiency. The fill factor of 50 µm and 100 µm pitch MPPC is the same as that of previous types, but increasing the overvoltage improves photon detection efficiency.

Pixel pitch (μm)	Recommended overvoltage (V)		
	Previous products S12571/S12572/ S12576 series	S13360 series	S14160 series
10	4.5	-	5
15	4	-	4
25	3.5	5	-
50	2.6	3	-
75	-	3	-

$$V_{ov} = V_{op} - V_{BR} \quad \cdots\cdots\cdots\cdots \quad (2\text{-}1)$$

V_{ov}: overvoltage
V_{op}: operating voltage
V_{BR} : breakdown voltage

Figure 5: Recommended overvoltage

- **Low crosstalk** The pixel that detects photons may affect other pixels, making them produce pulses other than output pulses. This phenomenon is called crosstalk. Hamamatsu has drastically reduced the crosstalk in precision measurement MPPC by creating barriers between pixels.

Figure 6: Caption

Characteristics

- **Gain**
  - Definition

  The MPPC gain is defined as the charge (Q) of the pulse generated from one pixel when it detects one photon, divided by the charge per electron $q = 1.602 \times 10^{-19} C$.

$$M = \frac{Q}{q} \tag{1}$$

  M: Gain.
  The charge Q depends on the reverse voltage (V_R) and breakdown voltage (V_{BR}) and is expressed by equation 2.

$$Q = C \times (V_R - V_{BR}) \tag{2}$$

  C: capacitance of one pixel.
  Equations 1 and 2 indicate that the larger the pixel capacitance or the higher the reverse voltage, the higher the gain will be. On the other hand, increasing the revers voltage also increases the dark and afterpulses. So the reverse voltage must be carefully set to match the application.

- **Linearrity** As the reverse voltage is increased, the MPPC gain also increases almost linearly. Figure 7 shows a typical example.

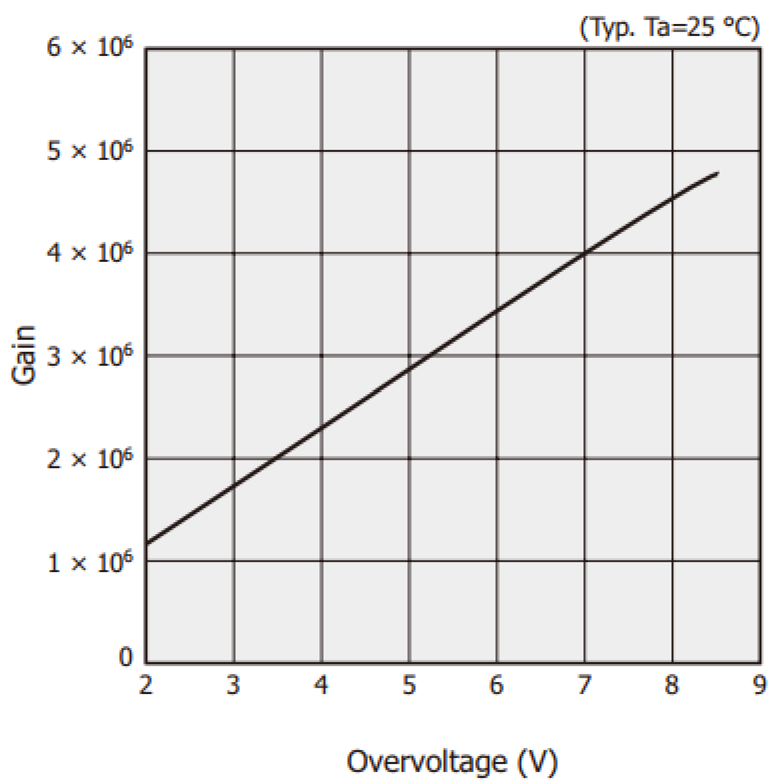


Figure 7: Gain vs. overvoltage (pixel pitch: 50 μm)

Dark Count Rate

In the MPPC operation just the same as with APD, pulses are produced not only by photon-generated carriers but also by thermally-generated carriers. The pulses produced by the latter are called the dark pulses. The dark pulses are observed along with the signal pulses and so cause detection errors. Thermally-generated carriers are also multiplied to a constant signal level (1 p.e.). These dark pulses are not distinguishable by the shape from photon-generated pulses [Figure 8].

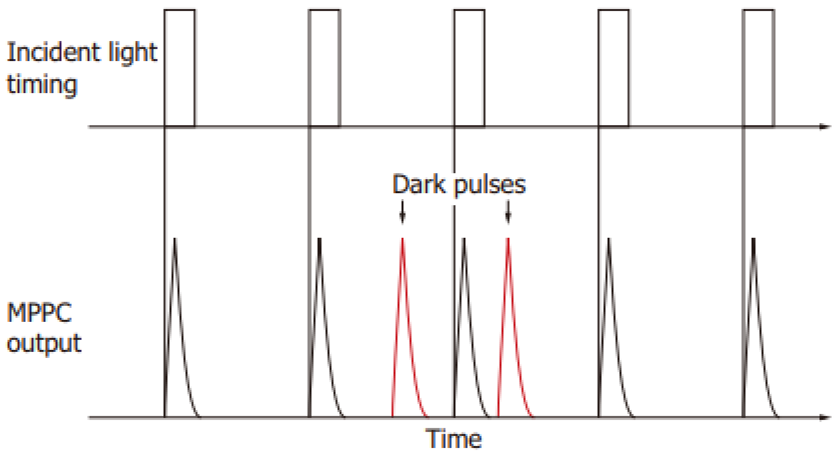


Figure 8: Dark pulses

The number of dark pulses observed is referred to as the dark count, and the number of dark pulses per second is termed as the dark count rate [Unit: cps (counts per second)]. The dark count rate of Hamamatsu MPPC is defined as the number of pulses that are generated in a dark state and exceed a threshold of 0.5 p.e.

Light in optical fiber

Fiber optics is a technology that uses glass or plastic fibers to transmit light signals over long distances. The light in fiber travels in the form of an optical wave, which is confined within the core of the fiber by total internal reflection.

The light in fiber can be described in terms of its wavelength, frequency, and intensity. The wavelength of the light determines its color, with shorter wavelengths appearing blue or violet, and longer wavelengths appearing red or orange. The frequency of the light determines its energy, with higher frequencies corresponding to higher energies.

In fiber optics, light signals are typically generated by a laser or an LED and then sent through the fiber using a series of optical components such as couplers, splitters, and amplifiers. The light signals are then received by a photodetector, which converts them back into electrical signals for processing by electronic devices.

The ability of fiber optics to transmit light signals over long distances with very little signal loss has made it a critical technology for telecommunications, internet connectivity, and other applications where high-speed data transmission is required.

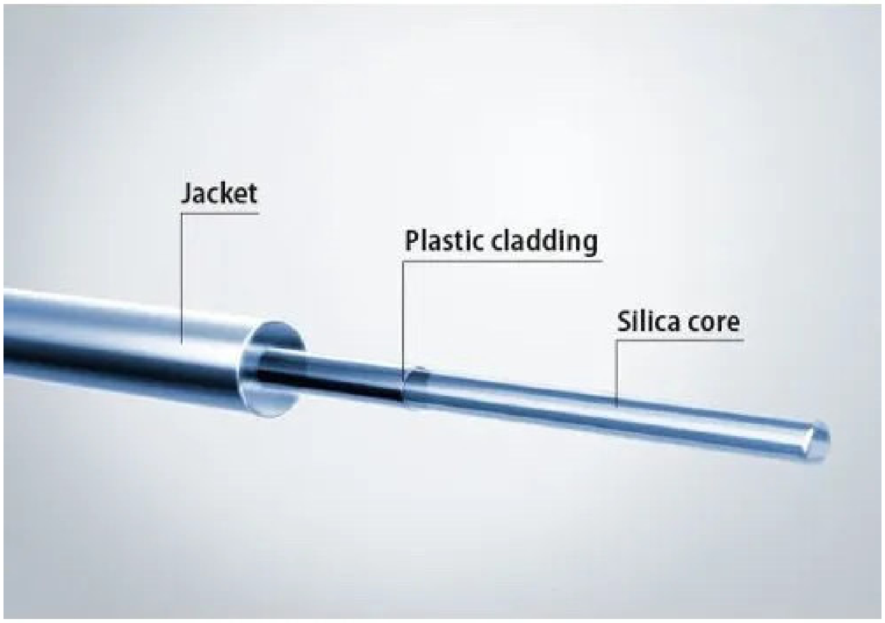


Figure 9: Optical Fiber

Cosmic rays

2.2 Material

Hardware

- Power Supply
- Signal Generator
- MPPC
  - Type: S13360-1325CS
  - Serial: 12482
  - Vbreakdown from manufacturer: 51.85V
  - Voperator: 56.85V (=Vbreakdown + 5V)

- LED
- Optical fibers
- Oscilloscope
- Scintillator bars (25cm x 2.5cm x 1.3cm)
- Amplifier
- NIM modules:
  - Discriminator
  - Scaler
  - Coincidence

Software

We use Origin for plotting and fitting the data

2.3 Purpose

Examination of $V_{breakdown}$

- Determining the VBR of MPPC initially is practically beneficial and recommendable.
- Most MPPC characteristics are dependent on V_{over}(= $V_{operation}$ - $V_{breakdown}$)

Studying the Speed of Light in Cable

- Determine the speed of light in a given optical fiber.
- From the obtained data, find the Refractive Index of that material

Cosmic Ray Detection

- Calculate muon rate in different scintillator's angle.
- Obtain the muon counts distribution.

3 Method

3.1 Examination of $V_{breakdown}$

Set Up

The system to calculate the breakdown voltage is visualized below:

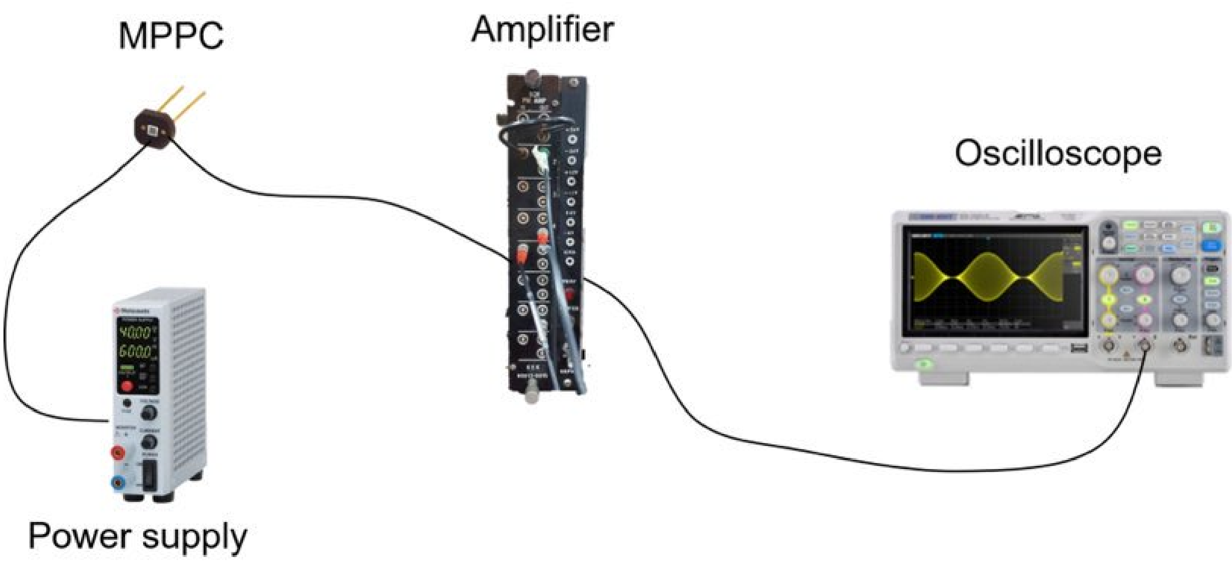


Figure 10: Examination of V_{BR} schematic

A dark box consisting of an MPPC and a low-pass filter is connected to the Power Supply. After that, the signal will go through the Amplifier and directly to the Oscilloscope. We then alter the *Vertical* and *Horizontal Scale*, as well as the *Trigger* button to adjust and find the pulse. We will measure the distance from the base to the peak of certain pulses.

The pulses of 1 photoelectrons are common, there are also some belong to 2 photoelectrons, but 3 or higher is rare.

Also, it is recommended to compare or calibrate the characteristics of MPPCs at the same V_{over} (= V_{OP} - V_{BR}).

3.2 Speed of Light in Cable

Set Up

The system to setudy the speed of light in optical fiber is visualized below:

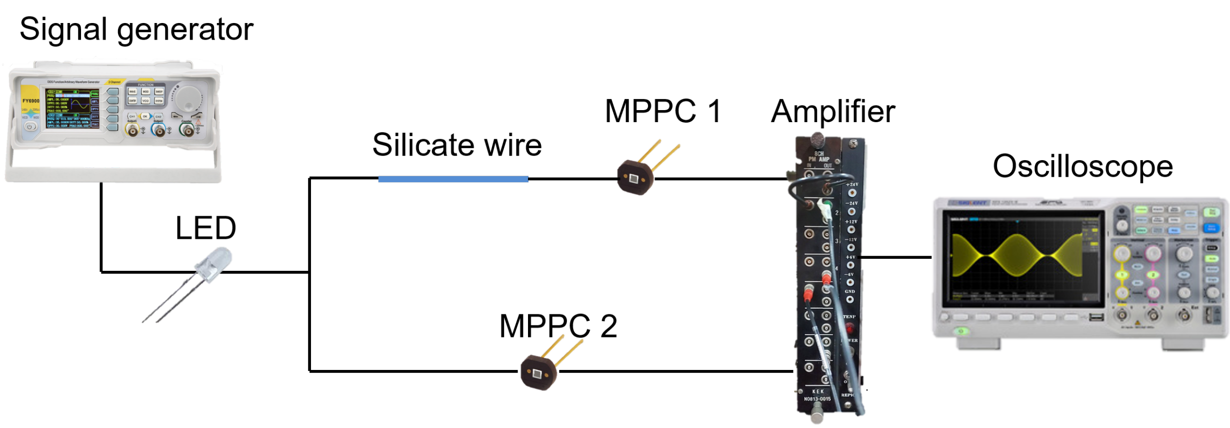


Figure 11: Studying the speed of light in cable circuit schematic

The LED is covered in order to prevent noise from external environment. The legs of the

LED are conencted to a power supply and the other side is put into an optical fiber which is bifurcated in the middle. Two MPPCs are joined at the end of two fibers, in respective. Then, the signal will go through an Amplifier and directly into the Oscilloscope.

We will change the length of one fiber later to measure the difference in the arrival time of the two signals.

3.3 Cosmic Ray Detection (Muon Rate Counting)

Set up

Our overall system for cosmic rays detection, also known as muon rate counting, is visualized below:

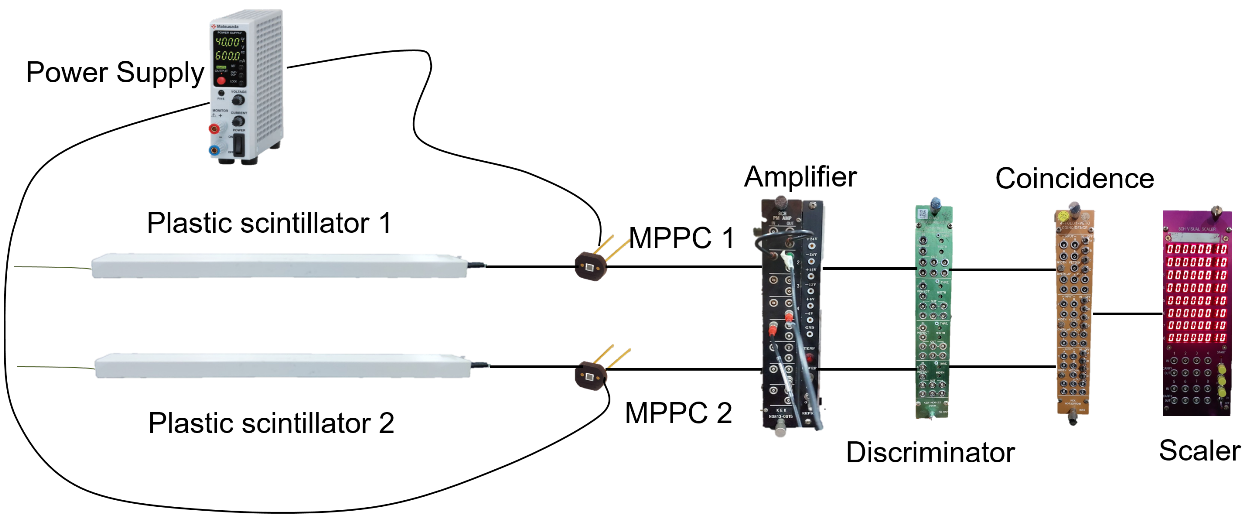


Figure 12: Muon counting circuit schematic

We have 4 scintillators stacked on each other with 2 in the middle are the separators so we don't show it on the schematic. Two optical fibers are led in 2 top and bottom scintillators and then mounted onto the MPPC board. But for the most accurate experiment, we need to put the scintillators in the wooden box and sealed it in order to reduce photon leakage which can cause false signals.

Since the output signal from the MPPC is too small, we connected the MPPC with an amplifier to amplifie the output signal up to 100 times. We then connected to the discriminator to set the threshold in order to make sure that what we count is a muon and reject others particle. The digital output is then used for coincidence which will return a signal is 2 outputs are present and this signal will be send to the scaler and counted as 1.

But due to the fact that our discriminator, coincidence, and scaler is not working, we are forced to use an alternative for these 3 devices, which is an oscilloscope although it can not be precise and efficient like the system of 3 devices above.

As the cosmic ray detector was ready to operate. We recorded the count on the oscilloscope in 15 minutes interval for 5 times on each angle between the scintillators and the vertical axis. The angles we have chosen in our experiment are 0, 15, 30, 45, 60, and 75 degrees.

4 Result

4.1 Examination of $V_{\text{breakdown}}$

Applying the formula

$$Q = N_{\text{fired}} * C_{\text{pixel}}(V_{\text{operation}} - V_{\text{breakdown}})$$

We can see that MPPC gain (Q) is proportional to the difference between the bias voltage applied to the MPPC (V_{OP}) and MPPC's inherent breakdown voltage (V_{BR}).

To find the V_{BR}, we conduct several mesurements to take the data and plot the graph between Q and V_{OP}, and at the gain-voltage plot's x-intercept (at which Gain = 0), V_{OP} thus corresponds to the V_{BR}.

We have the regression line function: Amp = a*V + b. At V_{BR}, obviously, Amp = 0 (no pulse). Therefore, we can just extend the regression line until it traverses the vertical axis (Voltage), the intersection point will be the V_{BR}.

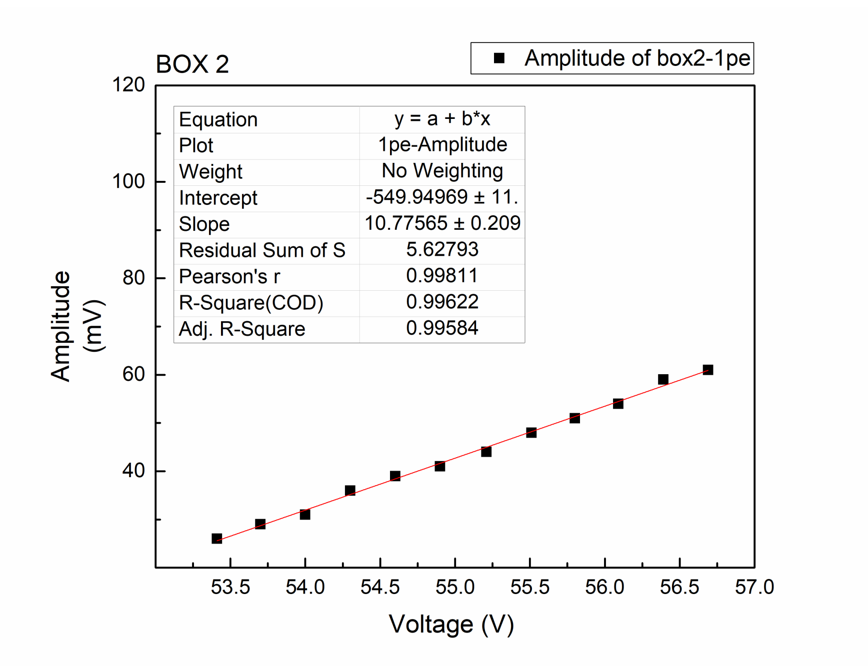


Figure 13: Box 2 - The Relation between Supply Voltage and Pulse Amplitude - 1 p.e

Table 1: Data Analysis Table

Intercept [b]		**Slope [a]**	
Value	Standard Error	Value	Standard Error
-549.95	11.56	10.78	0.21

In this experiment, we measure the V_{BR} is:

$$Amp = a * V + b = 0 => V = \frac{-b}{a} = \frac{-(-549.95)}{10.78} = 51.04V$$

This is the plot for the data of 2 photoelectrons pulses:

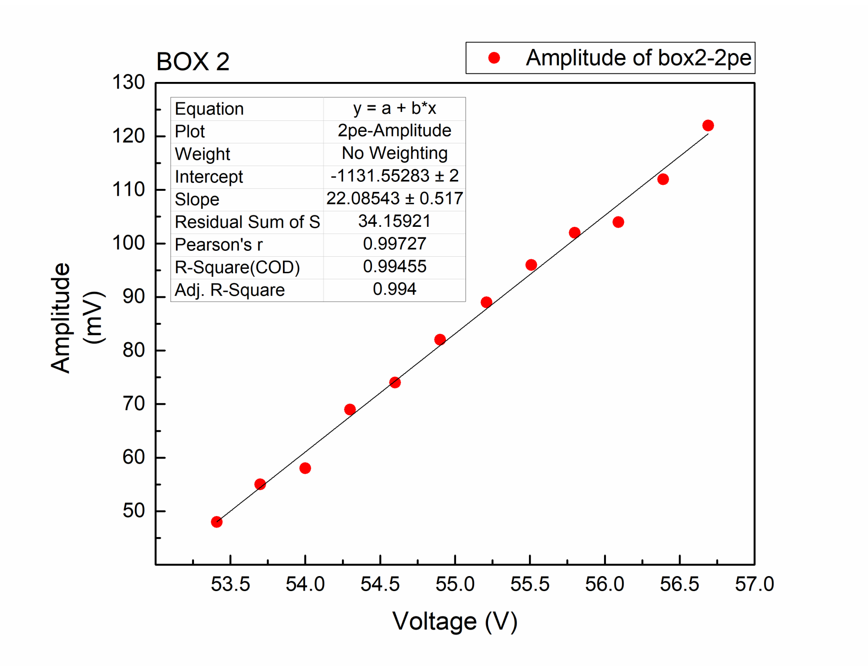


Figure 14: Box 2 - The Relation btwn Supply Voltage and Pulse Amplitude - 2 p.e

These are the data and plot to compare between the amplitude of 1 p.e pulse and 2 p.es pulse:

Table 2: Data from Box 2

Voltage from supply [V]	**Amplitude 1p.e [mV]**	**Amplitude 2p.e [mV]**
56.99	53	104
56.69	51	102
56.39	47	91
56.09	45	87
55.8	44	80
55.51	39	77
55.21	37	69
54.9	32	63
54.6	30	58

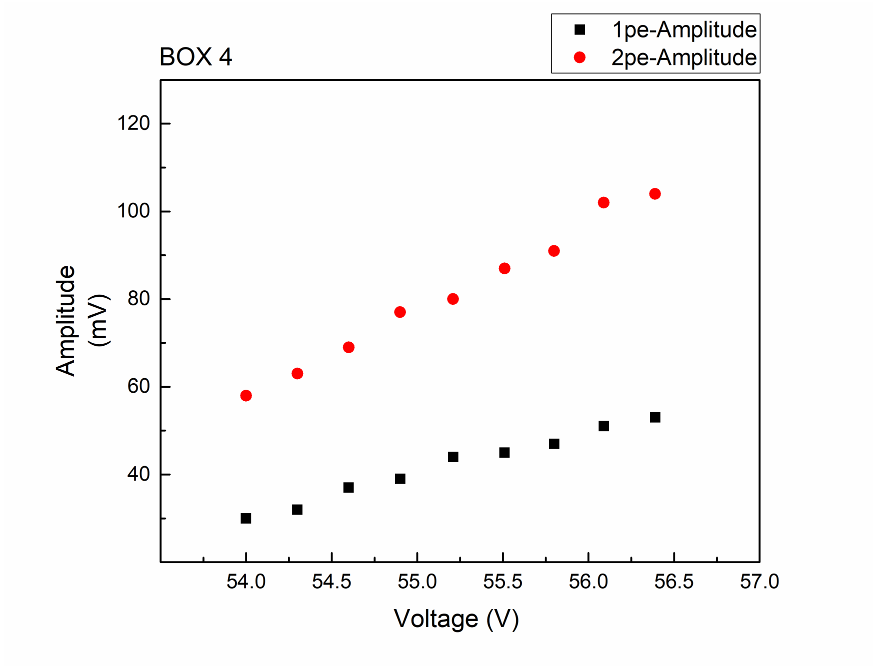
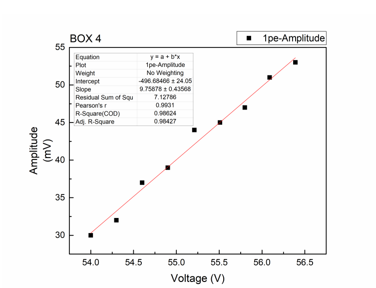


Figure 15: Box 2 - Amplitude of 1 p.e pulse v.s. 2 p.es pulse

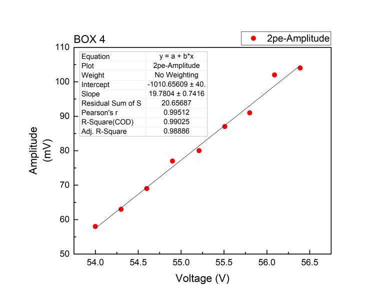
As the consequence of the mentioned formula: $Q = N_{\text{fired}} * C_{\text{pixel}}(V_{\text{operation}} - V_{\text{breakdown}})$, it can be seen that N_{fired}*C_{pixel} always >1, Q is then proportional to V_{OP} - V_{BR}, that means Q increases leads to the increase of V_{BR}. Therefore, we observe the higher the voltage, the signal's amplitude on the oscilloscope increases.

In MPPC, the signal's amplitude is proportinal to the number of detected photoelectrons. In particular, the output amplitude is double when the number of detected photoelectrons is double. In other words, there is a linearity in the realationship between them. The signal's amplitude of 2 p.es has to be higher than that of 1 p.e.

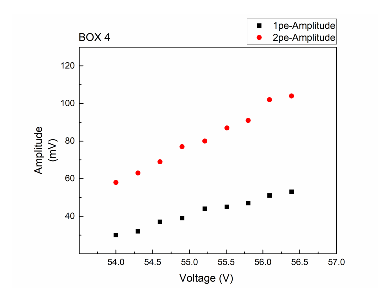
We conducted the experiments with 2 boxes of MPPCs, so the figures below are visualized the data we get from the other box:



(a) 1 p.e



(b) 2 p.es



(c) 1 p.e v.s. 2 p.es

Figure 16: Plot of data from the other box

Discussion

Based on our research, it appears that the breakdown voltage of the Multi-Pixel Photon Counter (MPPC) is significantly influenced by the voltage applied to it. Specifically, our data indicates that a higher applied voltage leads to a higher breakdown voltage. However, it is worth noting that our measurements were subject to an approximation error of approximately 3%, and the standard deviation was found to be insignificant.

It is important to acknowledge the limitations of our study. We only focused on the breakdown voltage of one type of MPPC and under a restricted range of conditions. Therefore, our findings cannot be generalized to all MPPCs or all possible operational conditions. Further research is necessary to investigate the breakdown voltage of different types of MPPCs under various conditions.

4.2 Speed of Light in Cable

This is the pulse we got from the Oscilloscope with 2 fibers at the same length:

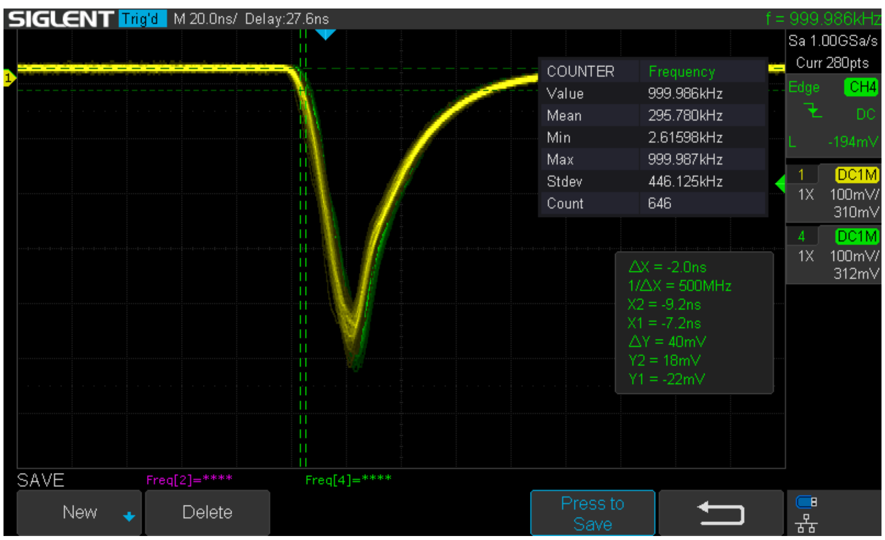


Figure 17: Time Difference of Pulses with Same Length of Fibers

We set the generator at: AMPL: 4V, PULS: 30ns, FREQ: 1000kHz.

Due to the fact that 2 fibers with the same length, in same material, with speed of light is constant, the signals will hit the MPPCs at the same time. As a result, we got the pulses on the Oscilloscope nearly overlap each other.

However, we think there may be some error belong to the set up or the tools, a small difference in time between 2 signals still present, which is equal to 2ns. Base on this measurement, we will substract all of the results we get in the later experiments (when we change the fiber's length) with 2ns.

The figure below is visualized for the case when kept one fiber unchanged and extended the other one with 4.2m-long fiber (same material):

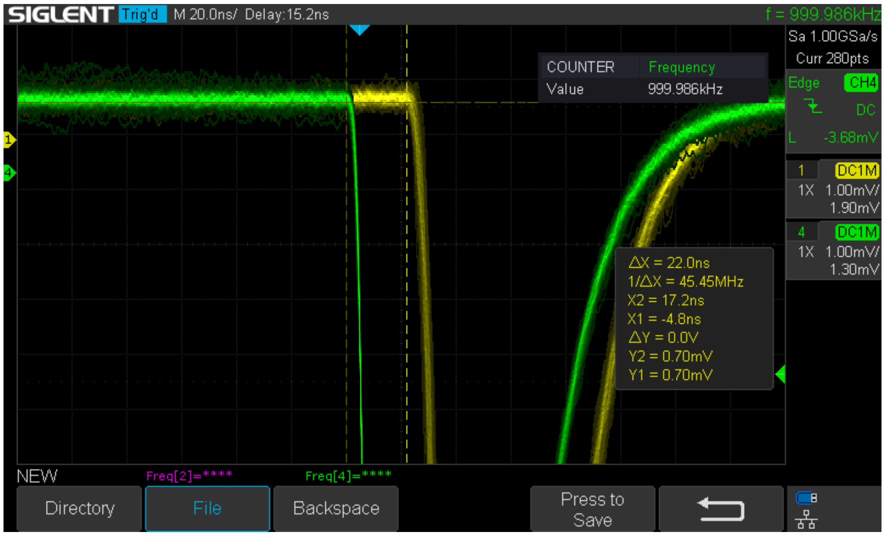


Figure 18: Caption

We set the generator at: AMPL: 4V, PULS: 30ns, FREQ: 1000kHz.

Since the lengths of fibers in this case are not equal, there is an actual difference between the arrival time of the 2 signals.

We called Δ t is the gap difference between 2 pulses.Using relationship of velocity, time, and distance. We could find the speed of light in the silica fiber:

$$v_{\text{light}} = \frac{L}{\Delta t} = \frac{4.2m}{22ns - 2ns} = 2.1 * 10^8 (m/s)$$

Then, we calculated for the Refractive Index:

$$n = \frac{c}{v_{\text{light}}} = \frac{3 * 10^8}{2.1 * 10^8} = 1.43$$

The true value for Silica fiber Refraction Index varies from 1.40 to 1.55. So that means our measurement outcome is quite compatible to the range.

When comparing the outcome from each measurement, we observed that there is no significant flutuation among them. That indicates our result was presiced.

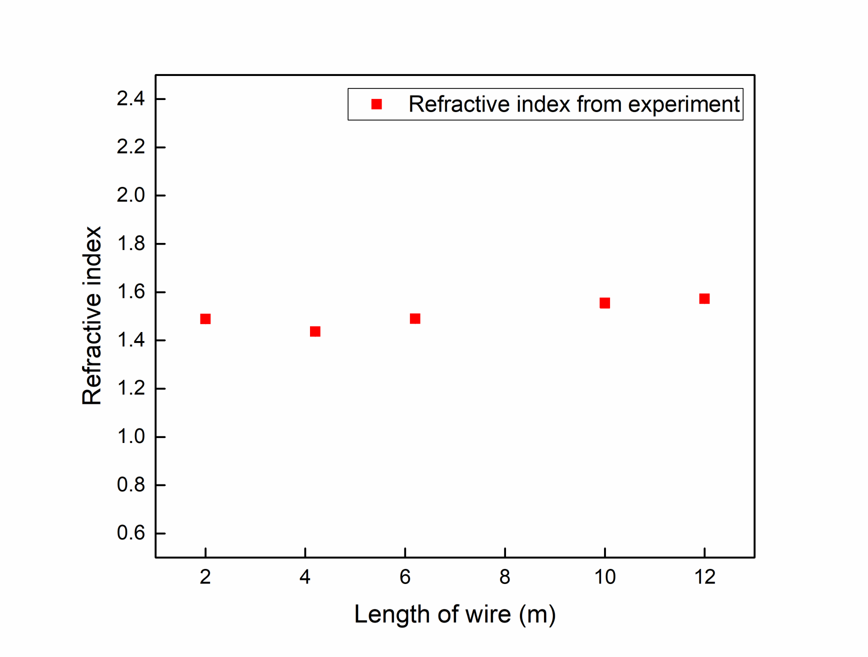


Figure 19: The Precision btwn Measurements

Obviously, as the length of the fiber increases, the longer it takes for light to reach the MPPC. As can been seen below:

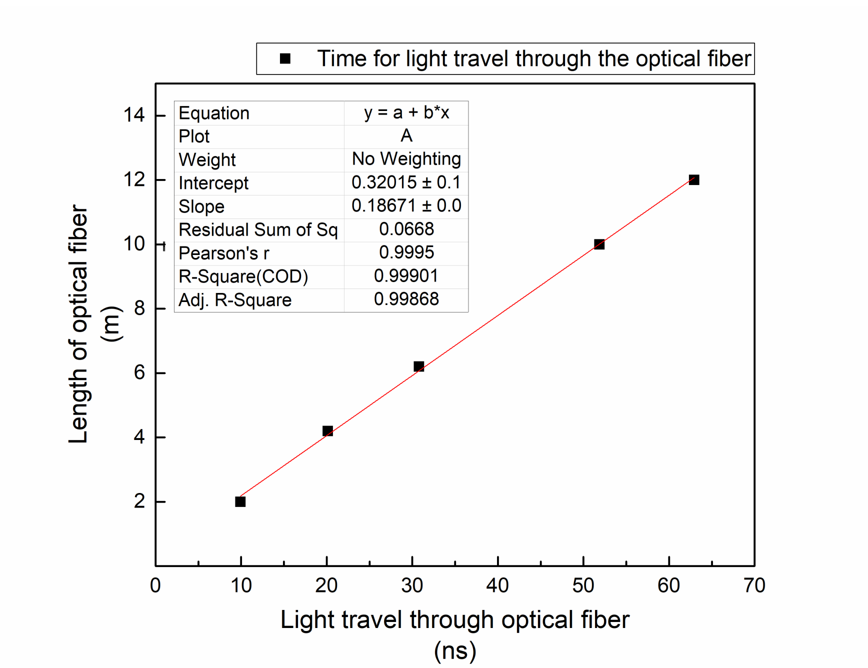
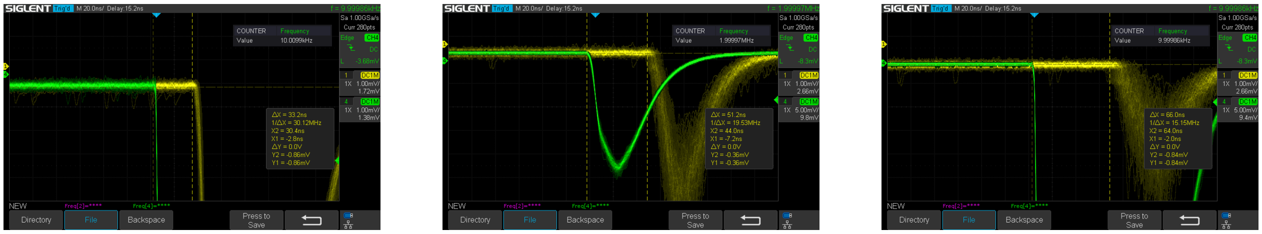


Figure 20: Travel Time of Light among Individual Lengths

The figures below are for illustrative purpose, we carried out the same procedure and alter the length of one fiber, with different AMPL, PULS, and FREQ from the generator, the outcome remained the same.



(a) 6.2m fiber - 6V - 1000kHz - 50ns

(b) 10m fiber - 6V - 2000kHz - 30ns

(c) 12m fiber - 9V - 10kHz - 50ns

Figure 21: Plot of data from the other box

Discussion

Our investigation has determined that the time it takes for light to travel through an optical fiber is directly proportional to the length of the fiber. In fact, the relationship between the time for light travel and fiber length is linear.

The slope of this linear relationship corresponds to the velocity of light in the optical fiber, which we have measured to be 0.1867 meters per nanosecond. With this value, we are able to calculate the refractive index of the optical fiber.

It is worth noting that our measurements have shown that the refractive index remains nearly constant regardless of the length of the fiber being tested. Therefore, we can conclude that the refractive index is a fundamental property of the optical fiber and is independent of its length.

4.3 Cosmic Ray Detection (Muon Rate Counting)

Set Up with Our "DIY" MPPC Circuit Board

Below is the figure of our MPPC board that we have soldered:

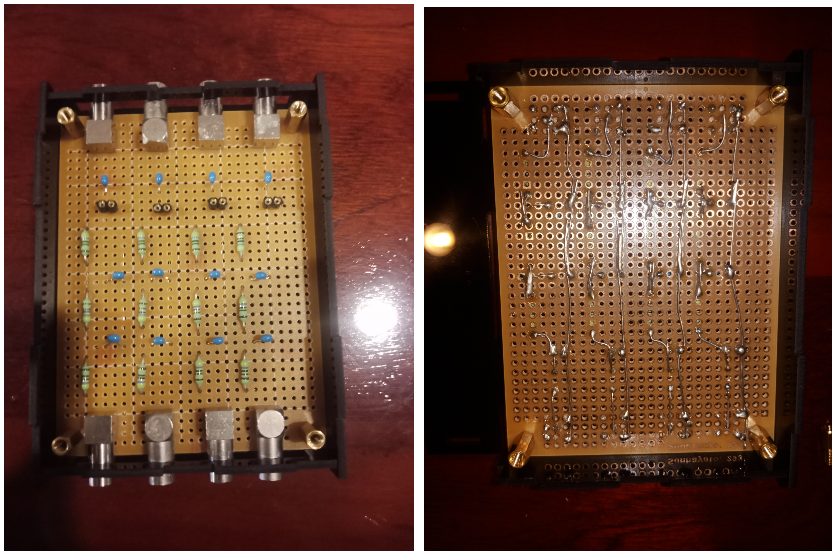


Figure 22: MPPC circuit board. Left: Front face, Right: Back face

As the board needs structural support and frame for shielding, we use black plastic pieces provide to make a box like the figure above.

Figure 23: Complete MPPC circuit

After that, we the MPPC board in aluminum tape to make a Faraday cage for shielding as you can see in the figure above.

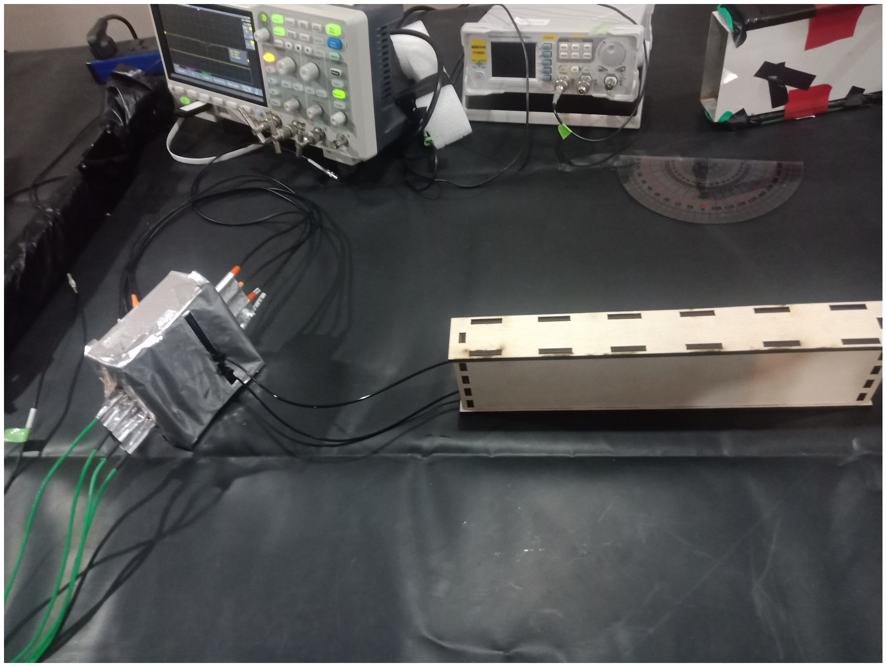


Figure 24: MPPC and scintillator setup for muon detection

As you can see in the figure, we connected the MPPC board with the oscilloscope instead of the system of 3 devices discriminator, coincidence, and scaler as mentioned in the previous section.

We then covered the whole MPPC & Scintillators system with black nylon to make sure that external light wouldn't disturb the measurement

With the detector was ready for collecting the data, we were able to record the muon count for 5 15-minute intervals for 6 angles which are 0, 15, 30, 45, 60, and 75 degrees as the procedure before.

Data Analysis

After getting the data of the muon rate at different angles, we then took the mean of it at those angles and change the unit of angle to radian for convinient. Next, we use Origin software to plot the data and fit it with Gaussian distribution.

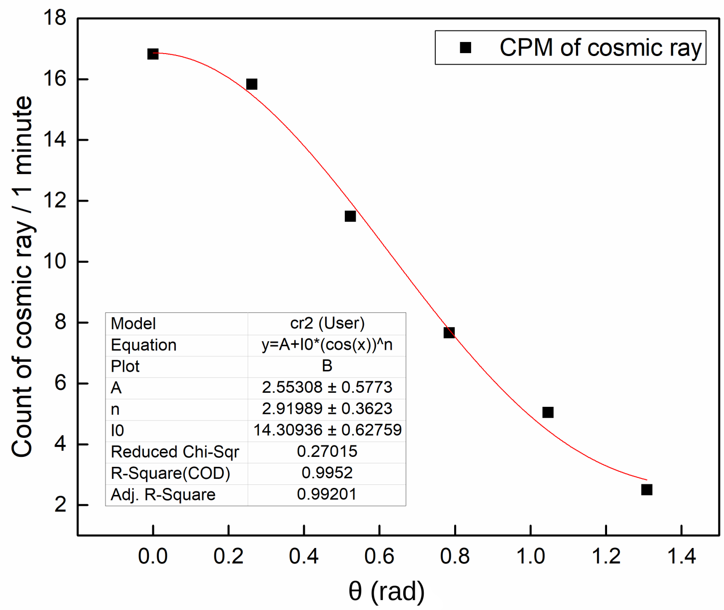


Figure 25: Relation between the angle of scintillator and counts of cosmic rays per time

This figure shows that our data is fitted quite well, returning parameters as shown in the plot. According to this result along with the size of the scintillators being *25cm x 2.5cm*, the Muon count rate for each angle is:

Table 3: Data table

$\theta(rad)$	Muon count rate (count/minute)	Muon count rate per area ($count/minute/cm^2$)
0	16.82 ±4.10	0.27 ±0.07
0.262	15.83 ±3.98	0.25 ±0.06
0.523	11.49 ±3.39	0.18 ±0.05
0.785	7.67 ±2.77	0.12 ±0.04
1.047	5.04 ±2.24	0.08 ±0.04
1.308	2.50 ±1.58	0.04 ±0.03

Discussion

For the goodness of the fit, the R-square returned by Origin is about 0.9952 and the reduced Chi-square is about 0.27, which is indicate that it is an excellent fit into Gaussian distribution to the observed data. This convinces us to believe that our work on measuring muon rate was correct since the higher the angle between the scintillators and the vertical axis, the lower number of muons interact with the scintillators. However, if we look at the distribution, we still can notice some variation. The reason for this is that we probably didn't consider a small time interval. If we consider a longer period of time, the counts of cosmic rays may be more stable, thus reducing the error.

5 Conclusion

5.1 MPPC

Multi pixel photon counters are novel type of solid state photodetectors with significant advantages such as a high gain,fast timing, compactness and insensitivity to magnetic field. All of them make MPPC very attractive in application that relative to nuclear and high energy physics.

5.2 Examination of $V_{breakdown}$

The breakdown voltage is an important parameter to examine in Multi-Pixel Photon Counters (MPPCs) because it determines the maximum operating voltage of the device. If the operating voltage exceeds the breakdown voltage, the MPPC will experience an electrical breakdown, which can cause permanent damage to the device.

5.3 Speed of Light in Cable

The refractive index of the window material in an MPPC (Multi-Pixel Photon Counter) is a measure of how much the speed of light is reduced as it passes through the material. The refractive index of an optical medium that gives the indication of the light bending ability of that medium. The refractive index can be seen as the factor by which the speed and the wavelength of the radiation are reduced with respect to their vacuum values: the speed of light in a medium is $v = \frac{c}{n}$, and similarly the wavelength in that medium is $\lambda = \frac{\lambda_0}{n}$, where λ_0 is the wavelength of that light in vacuum. This implies that vacuum has a refractive index of 1, and assumes that the frequency ($f = \frac{v}{\lambda}$) of the wave is not affected by the refractive index.

5.4 Cosmic Ray Detection (Muon Rate Counting)

Muon tomography, or muography, stands out as a non-invasive technique for the scanning of big objects internal structure. It relies on the measurement of the direction changes or absorption of atmospheric muons when crossing the studied object. Overall, the combination of high sensitivity, fast response time, and durability make MPPCs a good choice for detecting muons in high-energy physics experiments.

5.5 Project Hindrance

The project faced several hindrances that affected the accuracy and reliability of the results. Firstly, the room temperature had an impact on the natural properties of the material under investigation, which led to variations in the data. Secondly, noise from other instruments in the vicinity created interference, which affected the readings obtained from the equipment. Additionally, it was not possible to create a total Faraday cage, which is necessary to isolate the equipment from electromagnetic interference. Furthermore, the scintillators used to detect Muon particles could also detect other sub-particles, leading to potential errors in the readings. The time allocated for the experiments was limited, which prevented the team from conducting long enough experiments for stable measurements. In addition, instrument errors also contributed to the difficulties encountered during the project. However, the biggest hindrance was the team's own inexperience. In fact, for most of us, this is the first time we work with these sorts of these tools and equipment, coupled with the fact that our knowledge in this field is very limited, caused us some troubles while performing the hands-on act.

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