Hardware Camp for Fast and Low-light Detection
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Single MPPC (Multi-Pixel Photon Counter)

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I Introduction

1 Objectives

As part of the Hardware Camp 2024 for Fast and Low-light Detection, group A has to accomplish 3 main objectives, including (1) examining certain MPPC characteristics, (2) time-of-flight method, and (3) cosmic ray muons.

More specifically, for our experiments, we used Single MPPC to explore its three characteristics of dark count rate, crosstalk and after-pulses by eliminating possibble sources of photon and detecting thermal particles in dark environment. Secondly, with the ToF method, we measure the speed of electrical signals in lemo cables as our tester and measure the speed of light via optical fiber. Lastly, the measurement of cosmic ray muons was performed with the setup of wavelength shifting fibers going through 3 scintillators.

2 MPPC Model

Group A uses the MPPC model S13360 - 1325CS with the following stats:

- Pixel pitch: 25 μm
- Effective photosensitive area: 1.3 mm x 1.3 mm
- Number of pixels: 2668

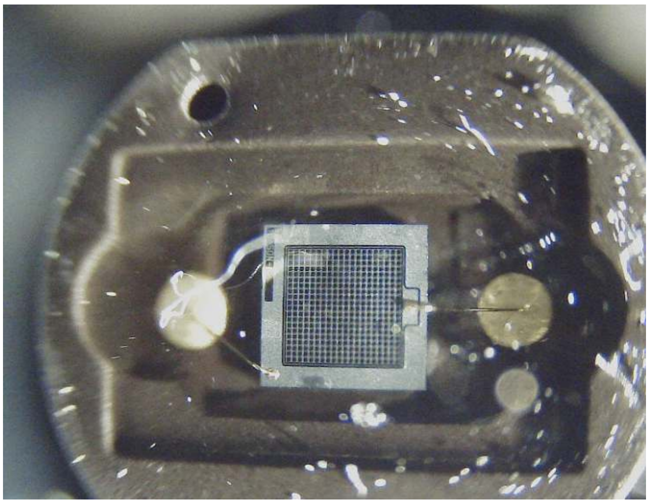


Figure 1: Single MPPC

II Experiments

1 Dark count rate

a Theoretical background

MPPC

In the MPPC operation, pulses are created not only by photon-generated carriers but also by thermally-generated carriers =.The pulses created by thermally-generated carriers are called dark pulses. Since the dark pulses observed with the pulses created by photons can 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.

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. This is expressed as $N_{0.5p.e}$.[1] Since the carriers are generated by thermal and so cause the dark count rate formula depends on temperature variable.

$$N_{0.5p.e}(T) = AT^{\frac{3}{2}} exp[\frac{-Eg}{2kT}] \tag{1}$$

Where:

- T : absolute temperature [K]
- A : arbitrary constant
- Eg: band gap energy [eV]
- k : Boltzmann's constant [eV/K]

Crosstalk

When light enters an MPPC pixel, the resulting avalanche of electrons can lead to photon production. Furthermore, some of these secondary photons can enter neighbouring MPPC pixels, leading to signals being picked up in these neighbouring channels. Thus the characteristic crosstalk of an MPPC is an important measurement background that needs to be quantified.

When the dark current is being measured, to a reasonable assumption, all primary signals are caused by the thermal emission of a single electron in a single pixel. Thus, any 2PE signals detected in this mode must be due to crosstalk from the avalanche caused by the thermal electron. By this logic, the probability of crosstalk can be well estimated by taking the ratio of 2PE to 1PE signals in the dark current measurement.

This probability is shown below, with the subscript on the N indicating the threshold setting for detecting 2PE (numerator) and 1PE (denominator) signals:

$$P_{crosstalk} = \frac{N_{1.5p.e}}{N_{0.5p.e}}. \quad (2)$$

The $P_{crosstalk}$ has almost no dependence on the temperature.

b Set up

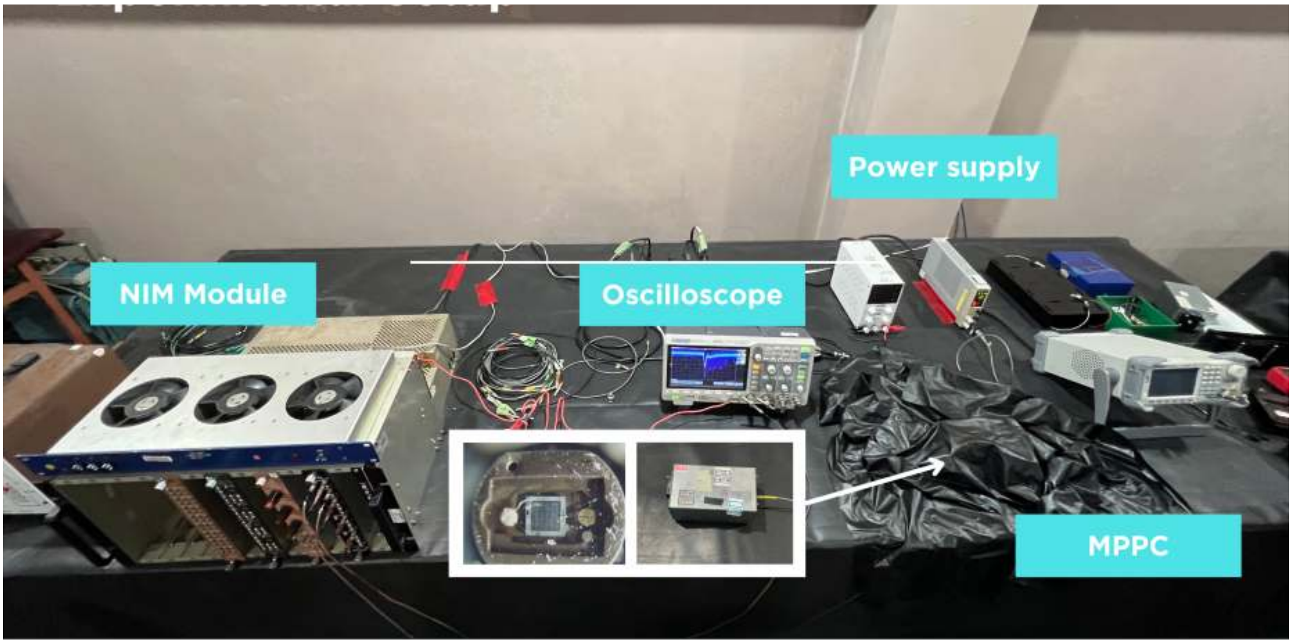


Figure 2: Setup for dark count rate measurements

Our purpose is detect dark current signals from MPPC. We connect devices as following order: connect power supply with MPPC. Then connect MPPC with NIM Module (we need NIM Module due to the signals need to amplify and goes to oscilloscope). The Oscilloscope connected with NIM to detect the signals and express on screen. Cover MPPC by black cloth to minimize photon enters MPPC.

c Procedure

- Cover MPPC with black cloth after connecting.
- Turn on power supply.
- Observe oscilliscope and see if we need to amplify the signals. The mean value on the oscilloscope's screen is dark count rate.
-Amplification using NIM Module.

d Observation

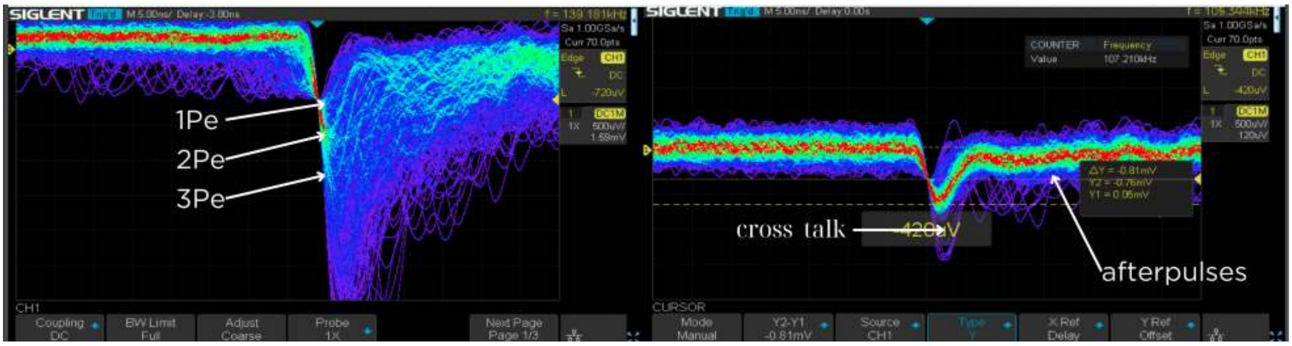


Figure 3: Oscilloscope reading of dark pulses using MPPC model S13360-1325CS

e Measurements

Dark count rate

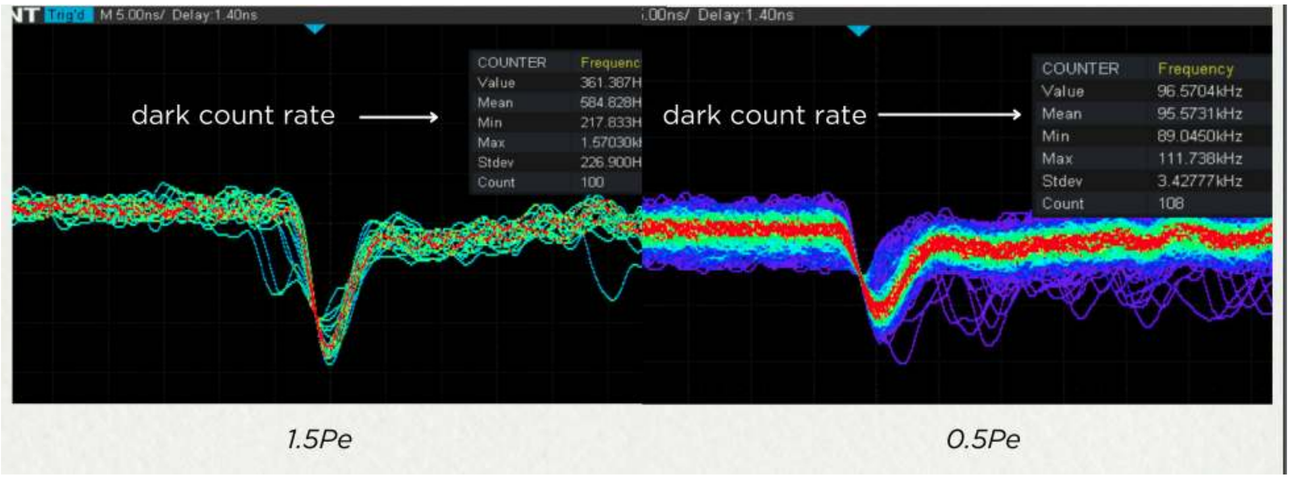


Figure 4: Dark count rate at different threshold

From the above results, the $P_{crosstalk}$ was calculated in fig. 5. At 0.6%, this matches the manufacturer's listed value of ∼1%. In addition, the 1PE rate was close to the listed manufacturer's value of 90kHz. The lower limit of our uncertainty range was slightly higher than this, however the excess in our measuremnt can be attributed to our operating at a higher voltage (57V vs 54.6V), and possible photons leaking through the light-proofing.

Note the relatively high percentage uncertainty in the measurement of the 2PE frequency. Upon review, this can most likely be attributed to an accidental adjustment of the threshold during the measurement, leading to a larger range of values recorded by the oscilloscope than if the threshold was left on one setting. However, the final uncertainty range matched the manufacturer's value well, and so the relatively large error was not a major issue.

	mean rate/kHz	1σ / kHz	Temp/C	Amplitude/mV	Threshold/mV	no. counts
1pe	95.573	3.4278	25	1.25	0.63	100
2pe	0.584	0.226	25	1.9	1.26	100

$P_{crosstalk}$ = 0.006 ± 0.002

Figure 5: Table of results from dark current measurement and resulting $P_{crosstalk}$ calculation.

2 Speed of electrical signals in lemo cables

a Theoretical background

As part of our second major experiment, we measure the speed of electrical signals via lemo cable using the ToF method (before we jump into the measurements of speed of light in optical fiber. Specifically, we observe two signals transmitted by two wires of different lengths on the oscilloscope in order to indicate the delay time between them. Since the long cable is much longer than the short one, we can calculate the speed of electrical signals in this case by dividing the difference in length by the arrival time gap between the two signals or:

$$\delta V = \frac{\delta L}{\delta t} \tag{3}$$

b Setup

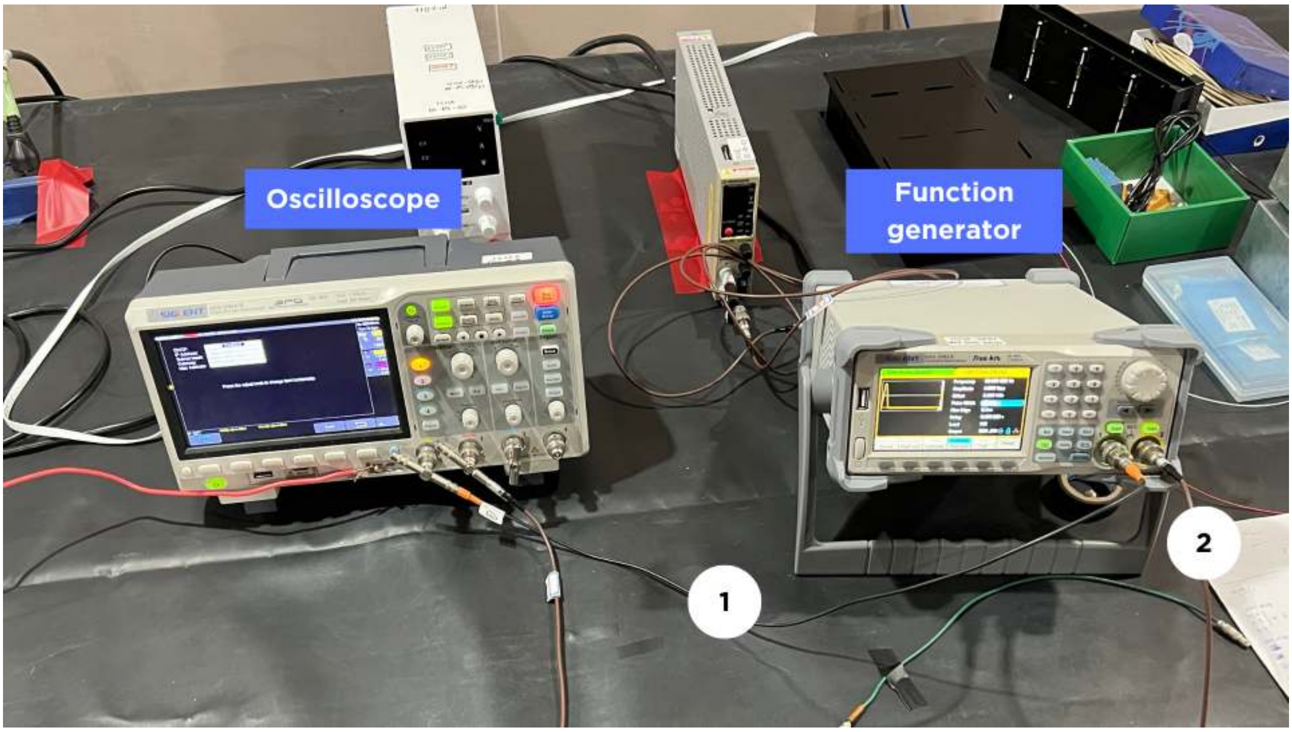


Figure 6: Setup for electrical signal via lemo cables measurements

In this set up, we have 3 main components:

- Function generator: Where we generate waveform signal
- Oscilloscope: Receive signals from the generator and display on screen
- Two cables with different lengths: 1 is the short cable and 2 is the long cable.

c Procedure

Measure the two lemo cables for L

We measure each wire 2 to 3 times and find the average to reduce errors. The following table records the measurements of each wire, their two means, and the final δL that we used.

Llong (m)	Lshort (m)	ΔL (m)
2.018	0.62	
2.0185	0.619	1.39895
	0.619	
2.01825	**0.6193**	

Figure 7: Measurements of cable lengths

The bold numbers are the mean values of two wire lengths and the red number is the final δL that we used for our calculations.

Oscilloscope readings

After transmitting the signals from the function generator through the wires, we get the following readings from the oscilloscope:

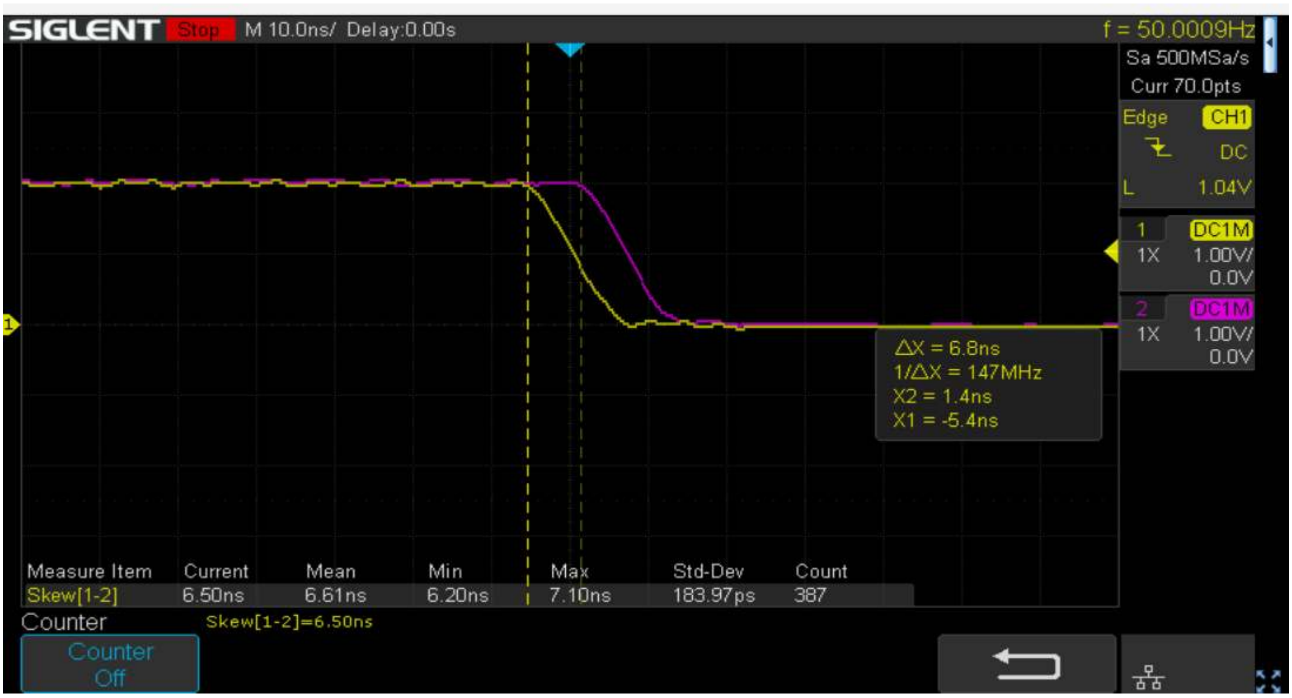


Figure 8: Oscilloscope reading of electrical signals from generator

t (ns)	Δt (ns)
6.8	6.7
6.6	

Figure 9: Time delay between the two signals transmitted through long and short lemo cables

In Figure 8, we have set up the measurements of the time difference between the two signals and get an average t of 6.7 ns (see Figure 9).

Calculations

$$\delta V = \frac{\delta L}{\delta t} = \frac{1.39895}{6.7 \times 10^{-9}} = 218,880,000 \text{m/s} \tag{4}$$

Our expected value is 2×10^8 m/s, so the experimented value is closed to the expected value.

3 Speed of light in optical fiber

a Theoretical background

We will measurement of time taken by an object to travel over a distance through a medium. Using two different length of two wires (with same material) and let photons go through them at the same time, by oscilloscope we can see the phase time. From different length and phase time, easily to calculate the speed of light through the optical fiber by formula:

$$\delta V = \frac{\delta L}{\delta t} \tag{5}$$

The speed of light in the vacuum is about 300000000 m/s, but it will slower because of the index of material it through. We expected speed of light in optical fiber is about 200000000 m/s and the index of material in range 1.57 to 1.67, we can calculate index by formula:

$$n = \frac{c}{V_n} \tag{6}$$

where Vn is the speed of light in material have index n and c is speed of light in the vacuum

b Set up

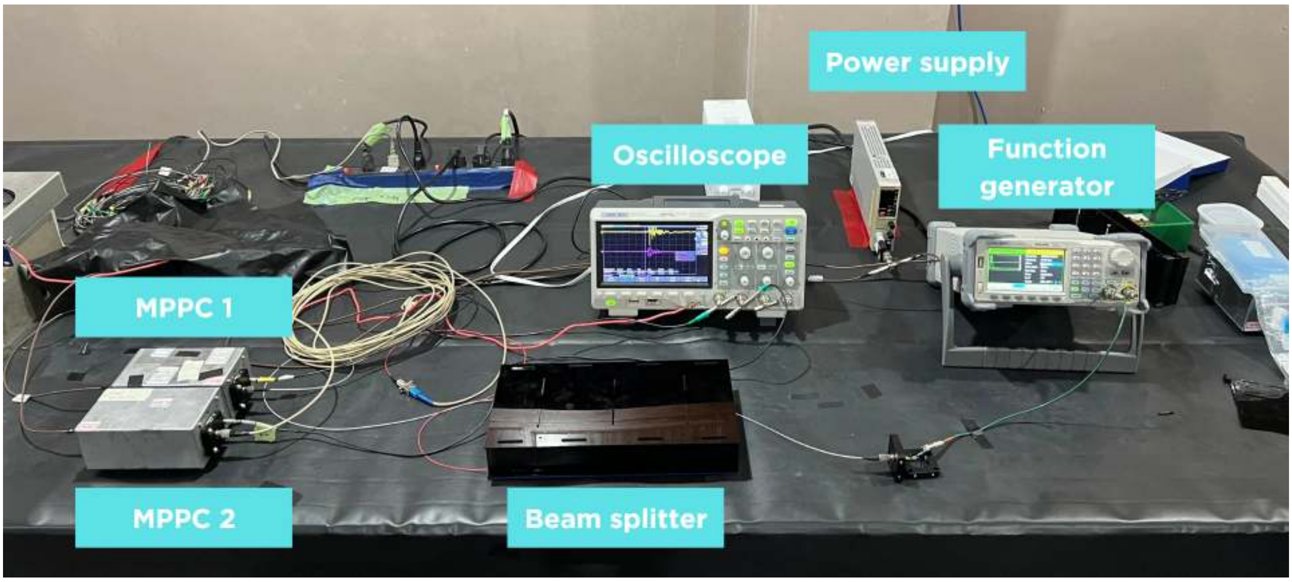


Figure 10: Setup for measurements of speed of light in optical fibers

The LED is covered in order to prevent noise from external environment. The legs of the 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. Two short wires link to the Beam splitter have the same length, we keep one of them as the short length and link the other with a longer wire, it will easier to calculate the different of length that we will discuss deeper in the next part

c Procedure

Finding the offset for precision

Take the offset = 0 as below, it more convenient for measurement the phase time

Measure our cables for L value

Actually the L is different between two long and short ropes. As mentioned in set up part, we keep one of the wire of beam splitter as the short length and link the other with a longer wire, so now the L is only the length of the long wire that we link to the wire of beam splitter. We used 3 different long wire with the length as the table below

Cable	ΔL (m)
1	10.270 ± 0.05
2	4.243 ± 0.05
3	10.140 ± 0.05

Figure 11: Measurements of 3 different lengths of wires

Observe oscilloscope and find t

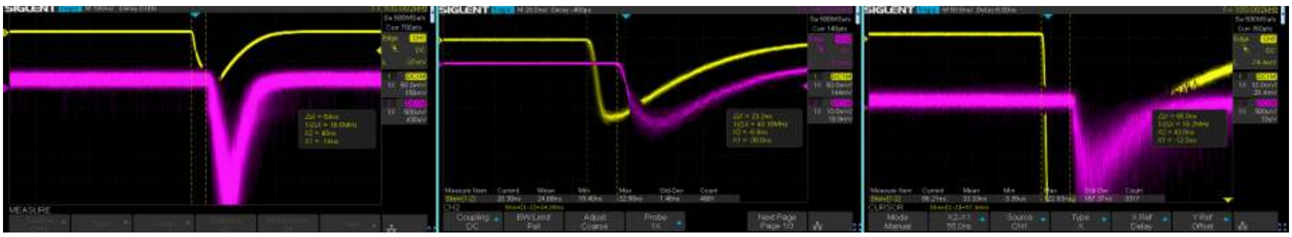


Figure 12: Delay in time of photon signals via 3 different cable lengths

Screen of Oscilloscope show two phase of photon, we can adjust two vertical to measurement the phase of time as showed above, we measurement five times for each cable lengths.

The table of three measurement times:

Cable	Δt (ns)
1	54.0 ± 0.05
2	23.7 ± 0.05
3	55.0 ± 0.05

Figure 13: Time difference among the signal via the cables

Error since 2 cables have roughly similar lengths

Because there are two long copes 10.27m and 10.14m and the different between them just about 10cm, it leading the phase time when we using two long copes is also small. The graph showed below has two close point, we can say that is result of error number:

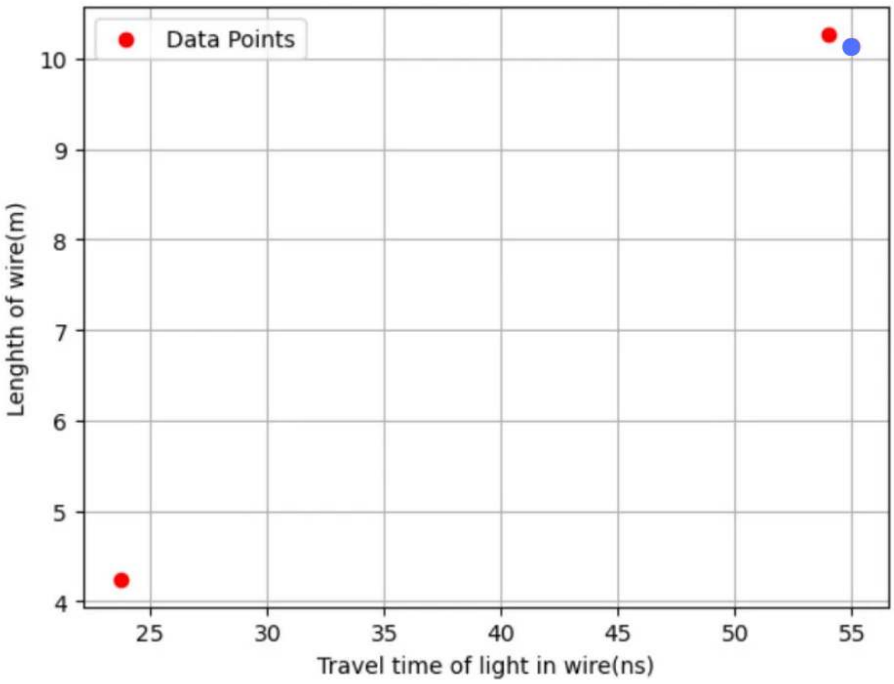


Figure 14: Travel time of light in wire with respect to the length of wire

Result
The table of 3 values of speed of light in three different wires:

ΔL (m)	Δt (ns)	Speed (m/s)
10.270 ± 0.05	54.0 ± 0.05	190,185,185.2 ± 3,521,996
4.243 ± 0.05	23.7 ± 0.05	179,057,665.3 ± 7,554,011
10.140 ± 0.05	55.0 ± 0.05	184,363,636.4 ± 3,352,115

Figure 15: Measurements of change in length and in time and final values of speed of light

Finally the mean value of speed of light in optical fiber is V = 184,535,495.6 ± 2,994,517 m/s

The mean index refraction n = 1.626 ± 0.027 where our expected n between 1.57 to 1.67

4 Muons Counting

a Theoretical background

Cosmic rays are constantly colliding with matter in the atmosphere. Pions are the predominant product of the interaction. Due to the muons travelling at relativistic speeds and length contraction, they can be detected at the Earth's surface before decaying into electron

$$L = L_0\sqrt{1 - \frac{v^2}{c^2}} \tag{7}$$

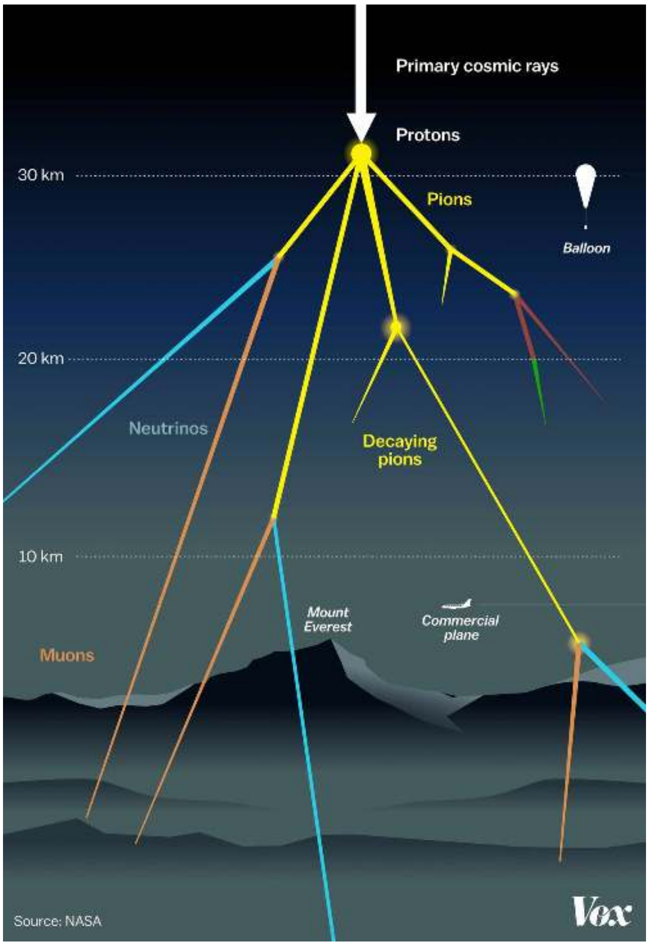


Figure 16: Cosmic ray diagram

In our experiment ,the muon excites electrons in scintillator the electrons de-excite and emit photon, the photo sensor collects and converts photon into electrical signals

The formula to calculate the rate of Muons

$$r_\mu = \frac{hits}{time.Area}(min^{-1}cm^{-2}) \tag{8}$$

b Experimental Setup

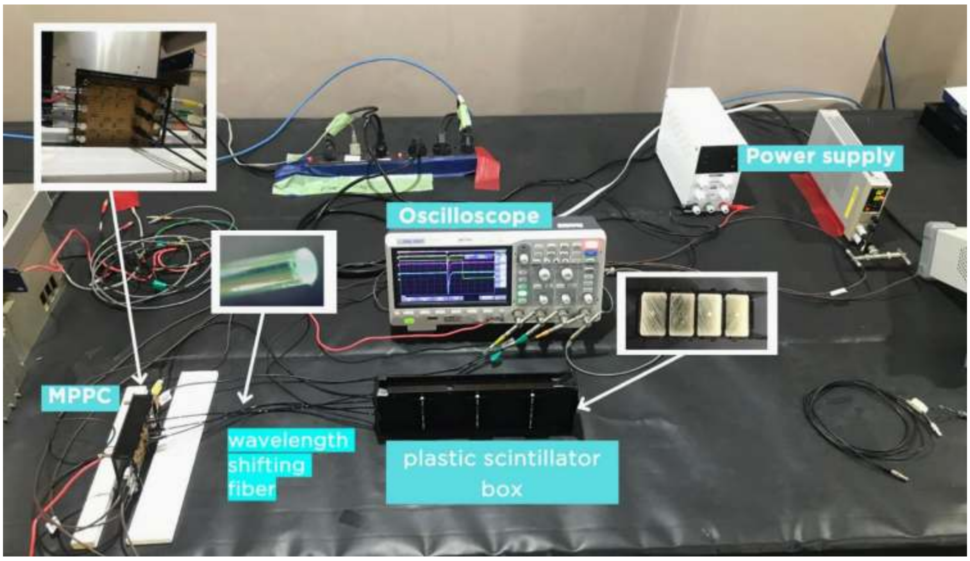


Figure 17: Experimental setup for muon counting

Fixed at a 90-degree angle

In this case, we fixed the plastic scintillator box at a 90-degree angle in the vertical direction of the box with the horizontal plane, and measured the count of Muons in two smaller cases.

In the first smaller case, we measured the count of Muons twice at two time intervals, 5 minutes and 10 minutes, and calculated the rate of muons when receiving coincidence signals of Muons passing through 2 layers of plastic scintillator within the 4 layers of the plastic scintillator box.

In the second smaller case, we continuously measured the count of Muons for 3 hours with each measurement lasting 5 minutes when receiving coincidence signals of Muons passing through 3 layers of plastic scintillator within the 4 layers of the plastic scintillator box.

Changing the angle from 0 to 90 degrees

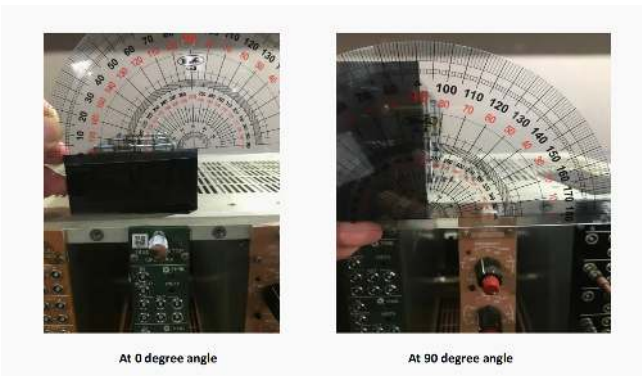


Figure 18: Variations of zenith angle in measurements

In this case, we varied the placement angle of the plastic scintillator box from 0 degrees to 90 degrees relative to the vertical direction of the box with respect to the horizontal plane. We measured the count of Muon coincidence signals passing through 3 layers of plastic scintillator within the 4 layers of the plastic scintillator box, with each measurement lasting 10 minutes. Afterwards, we calculated the rate of muons and plotted a graph based on the received data.

c Observations

Figure 19: The muon signal coming from the two plastic scintillators

Figure 20: The muon signal coming from the three plastic scintillators

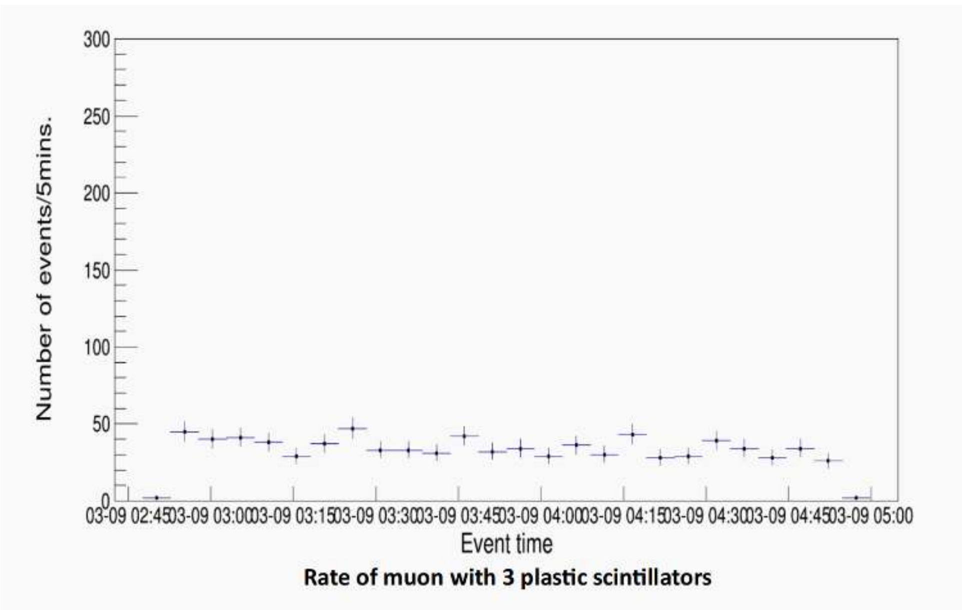
d Results

Time measurement	Hits	Time (min)	Rate of muon (1/min.cm^2)
1	129	5	0.40471
	248	10	0.38902
2	123	5	0.38588
	246	10	0.38588

Figure 21: Rate of muon with two plastic scintillators

Time measurement	Angle (deg)	Hits	Time (min)	Rate of muon (1/min.cm^2)
1	0	3	10	0.00471
2	35	30	10	0.04706
3	40	34	10	0.05333
4	57	61	10	0.09569
5	80	78	10	0.12235
6	85	67	10	0.10510
7	90	68	10	0.10667

Figure 22: Rate of muon with three plastic scintillators changing of angles



In this chart, we kept the system fixed at a 90-degree angle and continuously measured for 2 hours with measurements taken every 5 minutes. The reason why the first and last points deviate significantly from the overall trend is that those two measurement points did not have a full 5-minute interval, so we do not need to consider them.

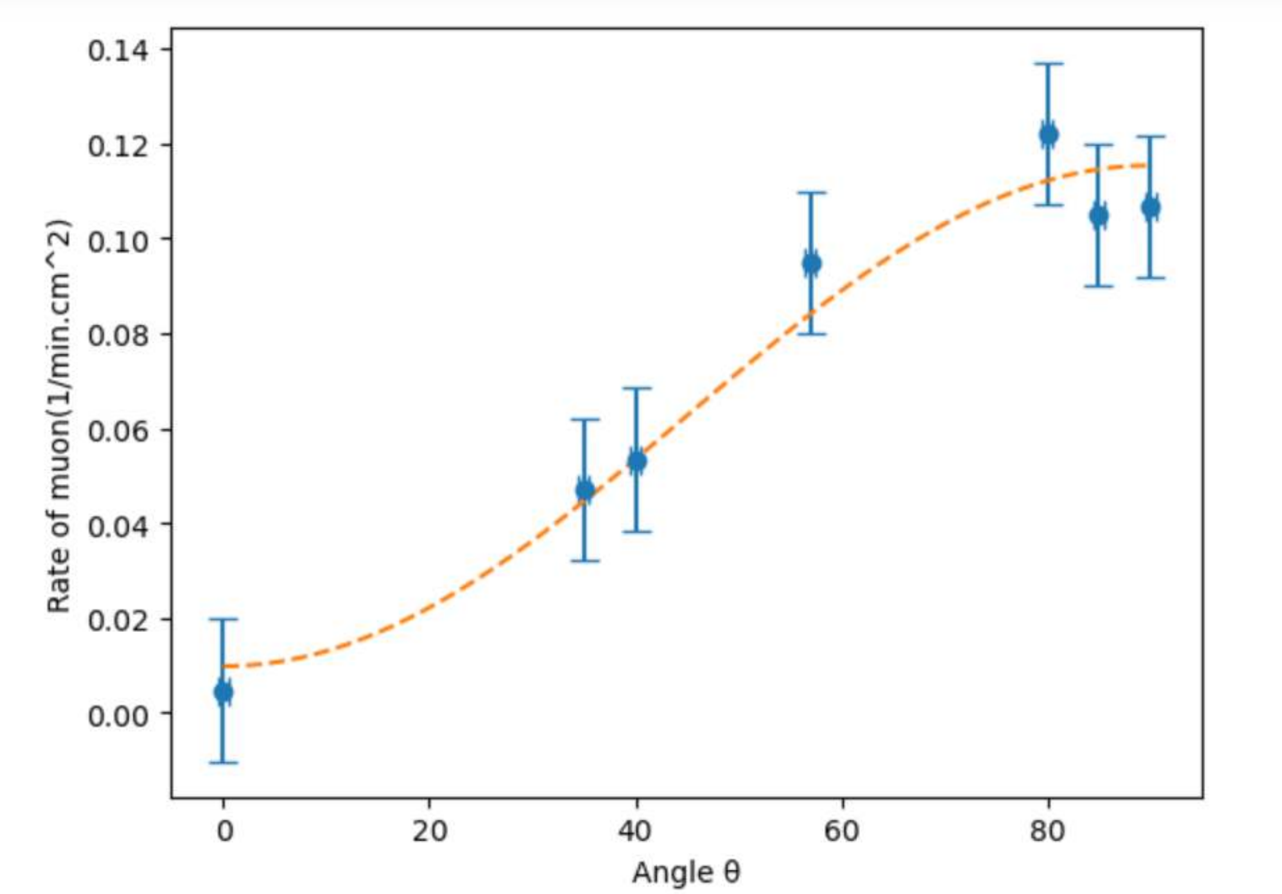


Figure 23: Rate of muon with changing the angle

To fit the curve in this case, we using formula below with A is the factor and b is the background

$$Acos^2(\theta) + b \tag{9}$$

The table of error number is here

Angle	Error number	Rate of muon	Error number
0	0.5	0.00471	0.015
35	0.5	0.04706	0.015
40	0.5	0.05333	0.015
57	0.5	0.09569	0.015
80	0.5	0.12235	0.015
85	0.5	0.10510	0.015
90	0.5	0.10667	0.015

The observation is that as we change the angle of placement of the plastic scintillator box, there is a corresponding variation in the count of Muons. When the angle increases, the muon count also increases

III Summary and discussion

Overall, all of the aims of the experiment were met; characterising the MPPC, measuring the speed of light and electrical signals in particular cables, and building a muon detector. Most of the results met the expected values from theory or datasheet, and any discrepancies can be plausibly explained through experimental setup or statistical error.

If the experiment were to be performed again, there are a number of improvements that we would suggest based on our experiences. Firstly, it would be beneficial to increase the volume of data for the muon counting. This would reduce the statistical error by reducing the effect of random fluctuations in the rate on our calculation of the average rate of muon flux, potentially leading to a value closer to that predicted by the Particle Data Group.

Secondly, in the speed of light/electrical signal experiments, the largest source of error came from our measurement of the wire lengths. This effect could be reduced by using longer cables, or cables that have a greater difference in length. Consequently, the percentage uncertainty from the resolution of the tape measure would be lower, reducing the overall uncertainty of the speed of light or electrical signal calculation.

Furthermore, in the speed experiments it would have been better to align the cursors for measuring the time delay between the signals to a different point on the pulses. In our experiment the very start of the pulse was used, however at a small timescale it is difficult to resolve the exact point due to the pulse being continuous and shallow at the beginning. A better option would have been to measure the height of the pulses, and then set the cursors to the point which is e.g. 10% of that height on the curve. This would result in a more consistent and repeatable measurement.

Overall, we have been able to verify the manufacturer's claims about the performance of the MPPC, and have been able to apply it to a speed of light and muon counting experiment, obtaining reasonable results and thus demonstrating the device's utility and versatility for different applications. In addition we have been able to provide feedback on our experimental setups to make future deployment of the MPPC more effective.

IV Acknowledgement

We wish to register my profound gratitude to Dr. Thanh Dong for the guidance and grace throughout the camp. We would also like to extend special regards to Msc. Shouvik Mondal and Msc. Nguyen Hoang Duy Thanh for such great supporters. With your help, we were able to have a good grasp of what to do and complete the task assigned to us as a team.

We are also grateful to the entire lecturers and professors for organizing and providing us with an informative, delightful, captivating, and entertaining camp like this.

Further on, we want to thank the participants who made this experience much more joyful and indelible. We are looking forward to more similar events in the near future.

V References

[1] Chung Yau Elton ., ”Cosmic Ray Muon Detection using NaI Detectors and Plastic Scintillators”, University of Virginia, Papers with references to CRD 2019

[2] Technical note MPPC Hamamatsu

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