Measuring the Timing Resolution of a Wavelength Shifting Fibre

MATHUSLA 2021

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1 Introduction

This experiment is a step towards the MATHUSLA project which is a CERN initiative to build a large scale detector for exotic long lived particles. As this is a relatively new initiative, the MATHUSLA team is still in the Research and Development (RD) phase of the project and lots of work is being done from institutions around the globe to figure out the optimal detector design. This experiment is performed in contribution to Prof. Miriam Diamond, who is specifically enthusiastic about the cosmic ray path reconstruction aspect of this detector. She is currently investigating a proposed unit of detector which composes multiple layers of WLSF, scintillating tiles and SiPM units. When a particle hits a tile at a specific layer, it will get absorbed by the WLSF and get re-emitted at the end points at lower energies, hence the wavelength shifting. The photons then travel down the fibre due to the total internal reflection of the WLSF, and the signal gets transported to the two SiPMs on both ends. In principal, based on the arrival time of the two signals, we should be able to extrapolate where on the fibre the light pulse was absorbed. However, the current hypothesis is that the WLSF has a direct effect on the timing resolution of the arrival signals which subsequently results in a spatial resolution for the light absorption position along the WLSF. What this project then entails is to investigate various types of WLSF and obtain their respective timing resolution.

2 Background

2.1 Theory

To extract the timing resolution of the WLSF we attach two SiPM detectors on either end of the fiber. In the experiment, we are simulating a cosmic event using the LDDM module. By triggering the LED to pulse at a predefined frequency we can trigger both SiPM modules to only display a pulse that came from the LDDM module. By taking the difference in the pulse's arrival time we can directly measure the delay for the pulse to reach both of the SiPMs. Over a series of measurements of this delay we expect it to statistically map to a Gaussian function as shown below,

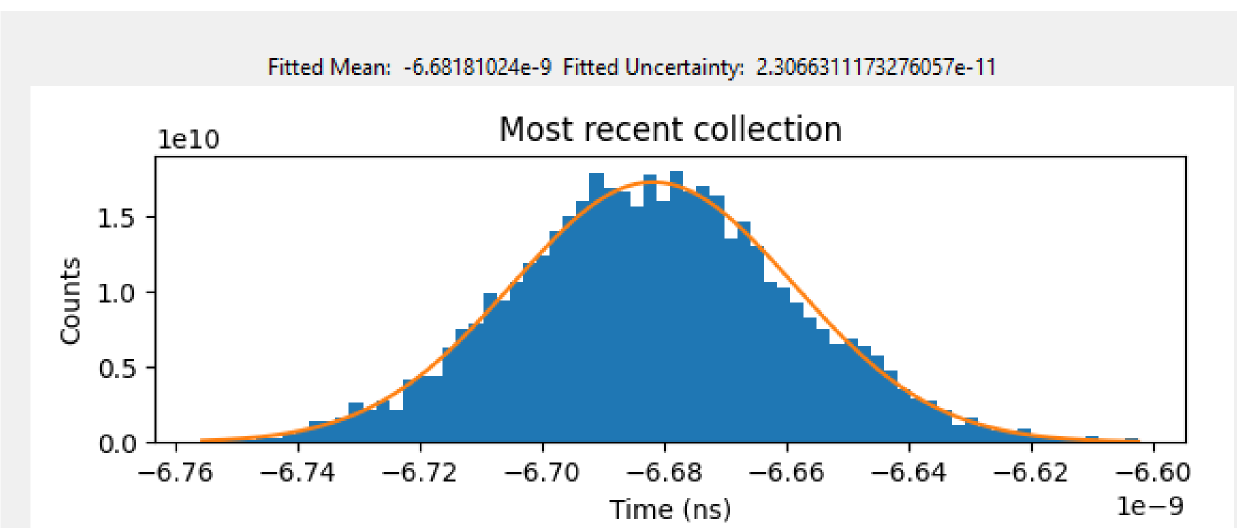

Figure 1: Example timing delay measurement for Y-11J fibre (Normalized w/ 5000 counts).

We take the standard deviation of the Gaussian fit shown in Figure 1 to be the delay's numerical error.

Now that we have the timing resolution at a point, the next step is to move the LED across the WLSF and collect data at each point. Once sufficient data has been collected, a plot of timing resolution versus distance can be created and fit to a linear function. Inverting this function results in the final product of converting the timing resolution of the WLSF to a spatial resolution of the LED pulse. This inverted function then allows you to determine the location of the pulse (within error bounds) by measuring the delay between two SiPM channels.

2.2 Computational

The back-end and front-end code that executes data collection can be pulled from the GitHub repository. The code has been documented to facilitate understanding to encourage improving the code. The flow of the code can be found in Appendix A if one wishes to familiarize themselves with the high-level back-end and front-end processes. The code interfaces with the oscilloscope through PyVISA and executes commands to it in order set-up the necessary parameters to facilitate measurement of the timing delay between two channels. More information on the oscilloscope and the programming guide can be found in Appendix D.2 and D.1 respectively.

3 Experimental Method

3.1 Safety

- This experiment uses SiPMs, which are highly sensitivity photon detectors. They must be operated with caution and **should not be powered on unless placed in the dark box with the lid closed.**
- The detector surface of the SiPMs can be damaged and destroyed easily. Avoid touching them with your hands and any other form of contact.
- Each item in the experiment requires specific operating voltage, follow the specifications in the Set-up section carefully, and respect the order in which the equipment should be powered.
- High voltages are used to operate the equipment in this experiment, **do not touch the experiment or make adjustments to the setup while it is powered on.**
- The oscilloscope in the experiment is shared with another team, thus it is required to cooperate while taking measurements. The oscilloscope can only be used to take measurements for one set-up at a time. Confirm with the other team that you are free to use the oscilloscope before changing anything in the setup.
- The SiPM's have SMA connections that must be handled with care. Use a SMA torque wrench while tightening the connector to avoid damage and ensure proper connection.

3.2 Set-up

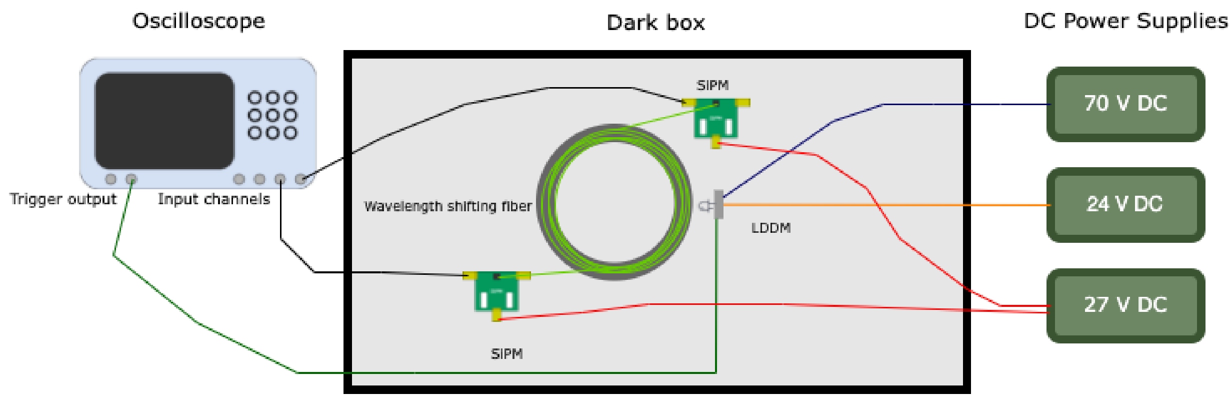

Figure 2: Schematic of apparatus

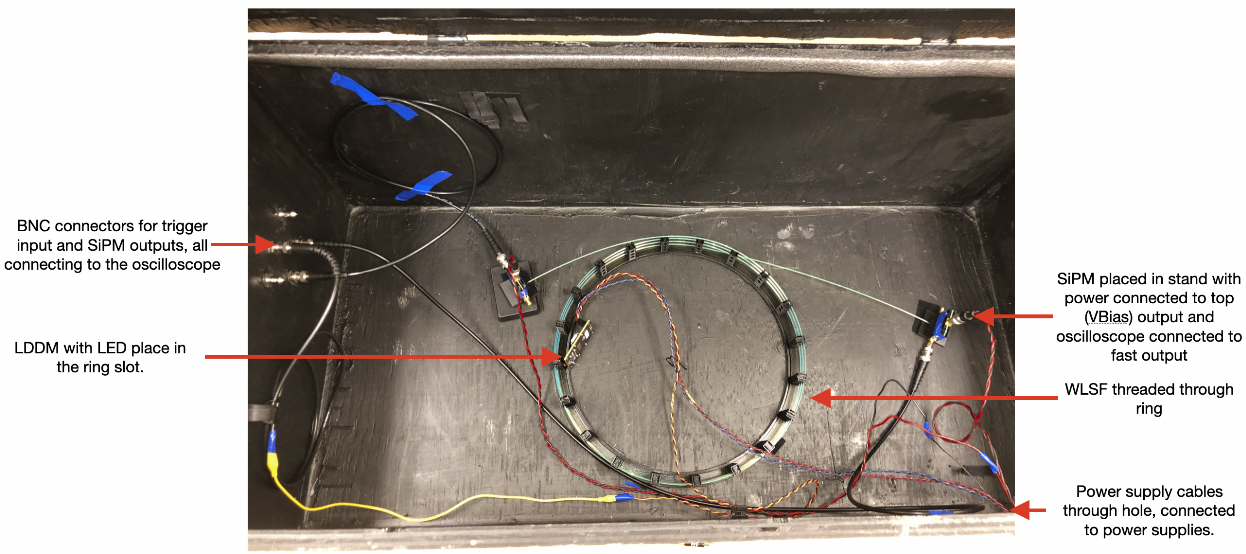

Figure 3: Photo of the experimental set-up in lab.

Figure 2 and 3 outline the major components of the apparatus with respect to the hardware. These components are:

- DC Power Supplies Please refer to Appendix E for more information on these power supplies.
  - The *70V supply* is used for powering the LDDM. The module enables a pulse output that can be varied in length based on it's supply voltage. Hence, a range is offered for this apparatus, which can be found in Appendix C and is approximately 64V-156V. The 70V power supply will have 20A-50A of current drawn from it. Refer to Figure 4 for the respective inputs.
  - The *24V supply* is used to operate the LDDM. The power supply should be operated at no more than 250mV off of the nominal 24V suggestion. The 24V power supply will have approximately 10mA of current drawn from it. Both the high voltage and 24V inputs can be seen in Figure 4.

- The *27V supply* is used to power each SiPM. This power supply may be operated between 25.2V-30.7V, where higher values yield an increased Photo Detection Efficiency (PDE), but also increased dark counts and noise as a consequence. The current draw is negligible, but as a sanity check, one can expect a few mA to be drawn. This voltage is applied to the port labeled Vbias in Figure 5.

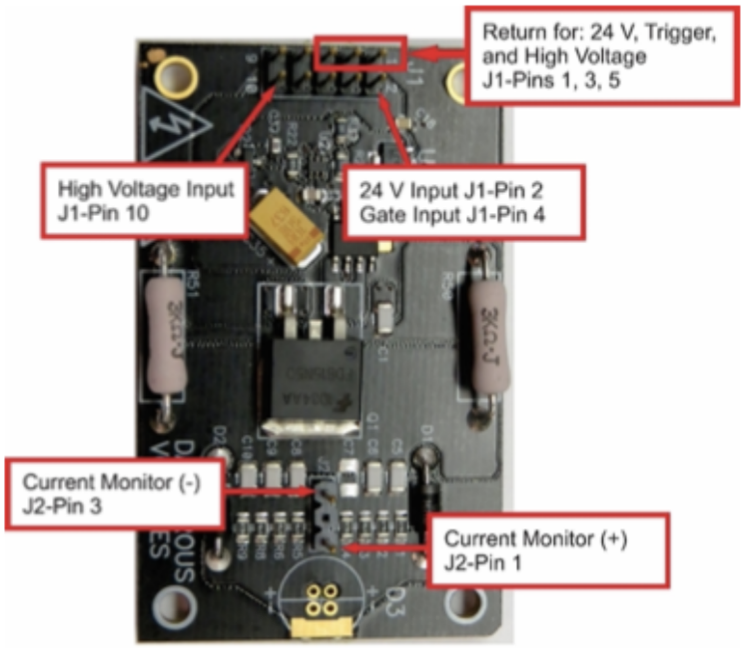

Figure 4: LDDM with labeled parts

- Dark box
  - The SiPMs, at the centre of this experiment, are models 30035 (more information can be found in Appendix B). The specificity here is paramount given the part dictates the test conditions at which the rest of the electronics must operate. Each SiPM takes in light from the WLSF and outputs a pulse to the oscilloscope (light in the range of 400nm-450nm wavelength yields a maximum PDE, so a purple LED is best for operation).

    Each pulse is output along either the standard or fast channels, which are labeled *Sout* and *Fout*, respectively as indicated in Figure 5. The difference between the two channel outputs is that the standard output takes much longer to settle to 0mV. Because of the application and need for precision, a fast output is recommended given that the signals will occupy less of the oscilloscope's time axis, which increases the precision at which timing measurements can be made.

    The WLSF should be fed perpendicular to the SiPM sensor (refer to Figure 5). The SiPMs are placed in custom made stands which have a slot to place the WLSF in. While placing the SiPMs in the dark box, avoid bending the WLSF much to prevent damaging the fiber.

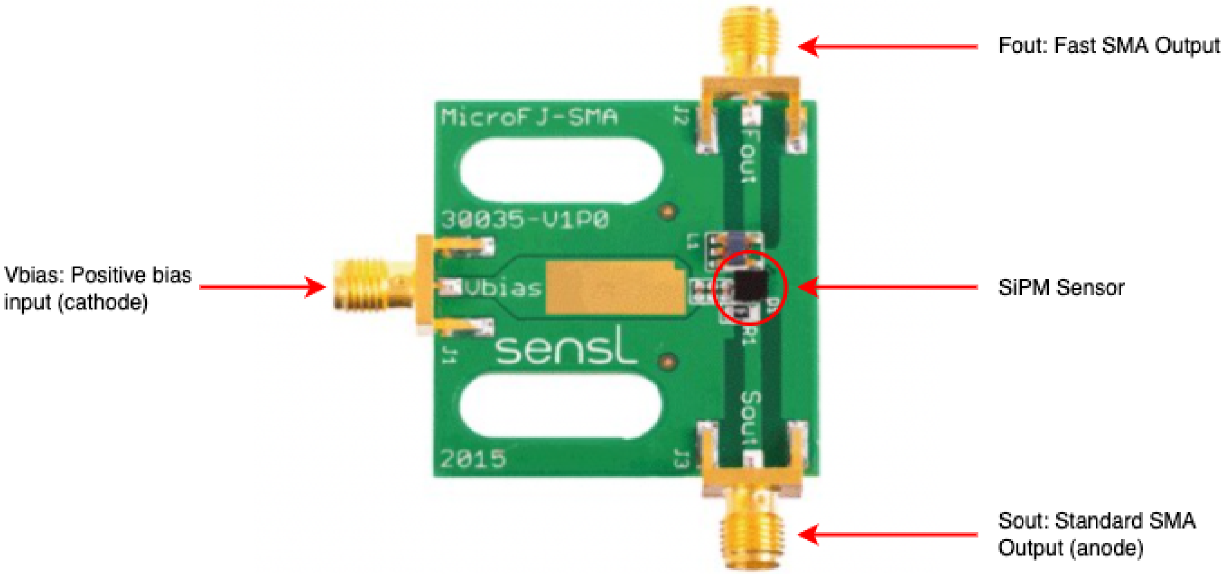

Figure 5: SiPM with labeled parts

Previously mentioned in the *DC Power Supplies* section was the variable voltage that each SiPM may be operated at. This range provides an operational minimum and maximum and should not be exceeded. Operating at a higher voltage yields a higher PDE. Increasing the PDE, however, leads to an increase in Optical Crosstalk (OCT), which can result in accidental triggers within the same SiPM. This means there exists an optimal operational voltage for each SiPM, which is dependent on the experimental setup and conditions. 27V is recommended as a starting point.

– The *LDDM* takes in a trigger and power supply as input to generate a narrow output pulse of light. This output pulse is variable in width and depends solely on the power supply current being drawn; this is summarised below in table 1. The SiPM's pulse width is most closely approximated as 4ns when considering the alternative pulse widths offered by the LDDM. It is therefore recommended to operate at this pulse width.

Varying pulse widths		
Pulse Width (ns)	Current Range (A)	Voltage Range (V)
$\leq$4	20-50	64-156
$\leq$5	5-19.99	36-63.99
$\leq$6	0-4.99	$\leq$35.99

Table 1: Test conditions required for various pulse widths from LDDM

– The *WLSF* is coiled on a 3D-printed ring of 35cm circumference with slots at every 10cm to allow for accurate placement of the LDDM with respect to each SiPM. The distance between the LDDM and each SiPM is an input parameter for future calculations and should be measured with precision.

- Oscilloscope (Please refer to Appendix D for more information on this specific oscilloscope.)

- The *Trigger Output* from the oscilloscope serves to pulse the LDDM at a fixed frequency. Since each SiPM has a microcell recharge time of 45ns, we can place an upper bound on the trigger frequency of 20MHz to ensure pulses are not sent while the SiPM is recharging. 20MHz will far-exceed any the recommended 1kHz-5kHz range, however.
- The *Input Channels* to the oscilloscope each require a connection to an individual SiPM. The channel settings will be discussed later in the software section.

3.3 Data Collection Procedure

In order to collect high-quality data, please follow this flow diagram in Figure 6,

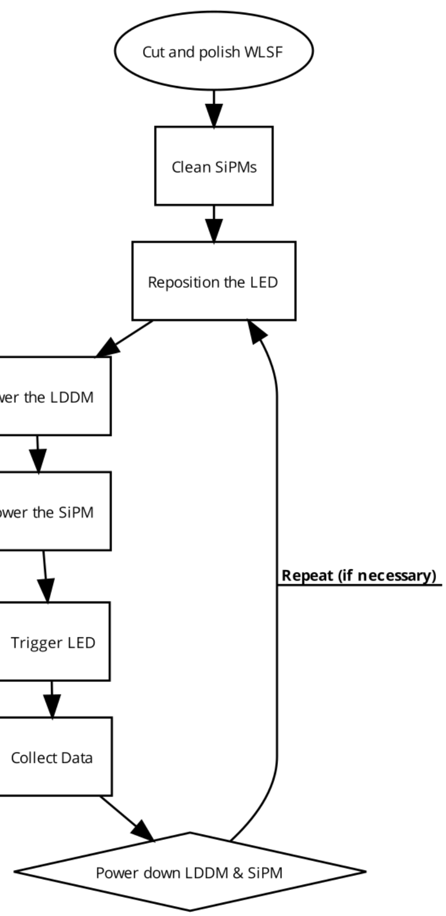

Figure 6: Flow diagram outlining the proper flow of collecting data with the experimental set-up.

Below are the detailed steps to carry out each procedure in Figure 6.

3.3.1 Polishing the WLSF

In order to ensure collection of high quality data and consistent data, the ends of the WLSF must be polished. Refer to Figure 7 below for the parts of the polishing kit.

First cut the fiber using the fiber cutter, replace the blade if needed, as each cutting hole should be used once. Next place the fiber in the polishing disc, which will ensure the tip of the fiber is flat on the surface.

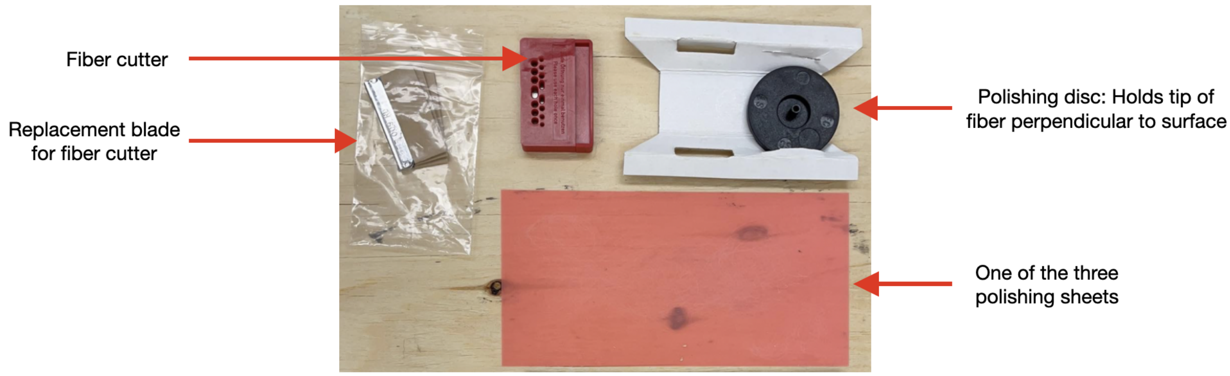

Figure 7: Polishing kit with labeled parts

There are three different polishing sheets, they must be used in order red (pictured above), white and then yellow. Ensure the sheet is placed on a flat surface. Rub the fiber on each sheet making, an '8' figure, which ensures the best results. Make 8-10 rotations on each sheet. An example video of the polishing procedure can be found in this video.

3.3.2 Cleaning the SiPMs

The sensors on the SiPMs must be clean at all times. If needed, a qtip dipped in acetone on it can be used to remove any dirt from the sensors.

3.3.3 Positioning the LED

In order to position the LED correctly, with all components powered off, place the LED along the WLSF by the distance desired. Place the LED into one of the slots in the ring until it is fully inserted to prevent any type of reflection or scattering.

3.3.4 Powering the LDDM

In order to power the LDDM correctly please follow the steps below without deviation,

1. Turn on the 24V power supply.
2. Turn on the High-Voltage Power Supply.
3. Turn on the LDDM trigger on the oscilloscope (either *Wave Gen 1* or *Wave Gen 2*) .

3.3.5 Powering the SiPM

The sensors on the SiPMs are highly sensitive, thus the SiPMs should only be turned on when the dark box lid is closed. To power the SiPMs correctly, you need to provide it with voltage that is greater than the breakdown voltage of the component (25.2V-30.7V Appendix B). Therefore,

1. Set the voltage to 27V as a starting point.

You can verify that the SiPM is on if you see that the dark current (the current drawn when no light source is present within the dark box) reported by the power supply is nonzero.

3.3.6 Powering down the LDDM and SiPMs

Once data collection is done, in order to power down the LDDM correctly please follow the steps below without deviation,

1. Turn off the LDDM trigger on the Oscilloscope.
2. Turn off the High-Voltage Power Supply.
3. Turn off the 24V power supply.

To power off the SiPMs just turn off the power supply voltage. Ensure not to open the box lid until this step is done.

3.3.7 Data Collection

In order to collect data please follow the procedure below,

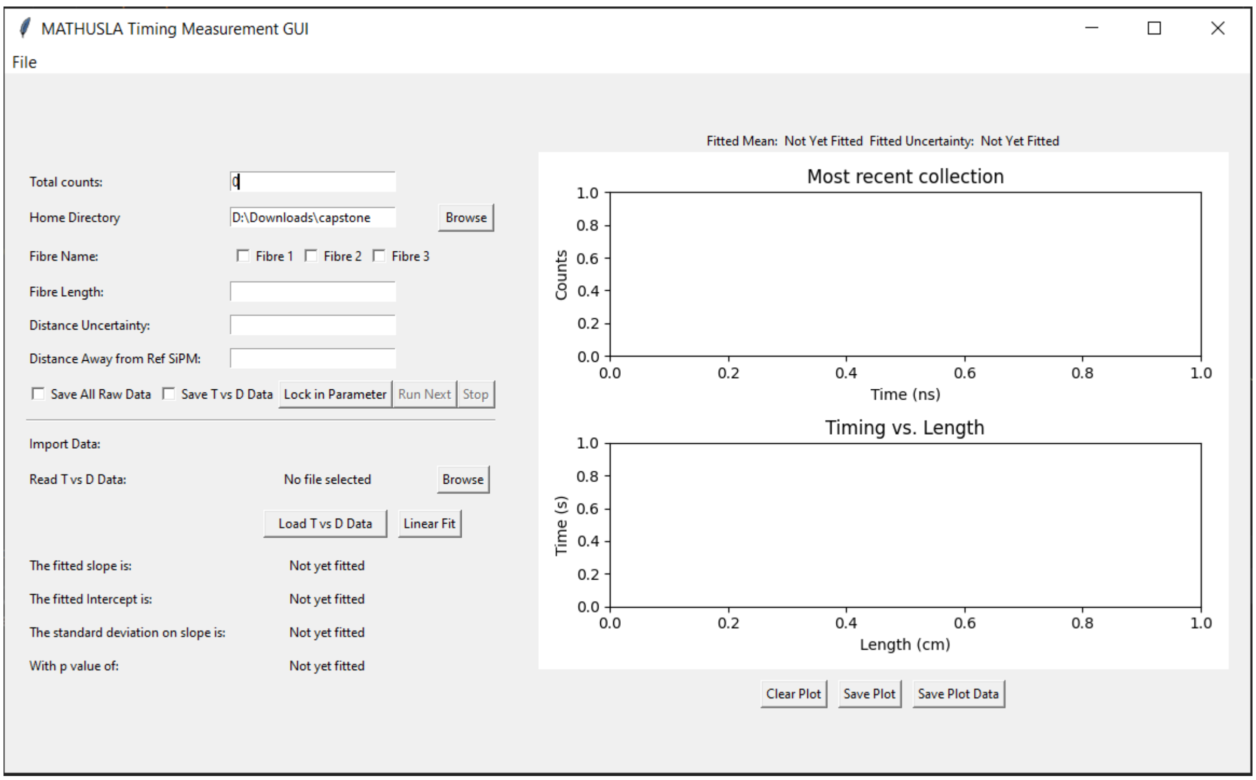

Figure 8: GUI Layout

1. Input required experiment parameters on the left hand side and click **Lock In** to specify the start of a measuring sequence
2. Press **Run Next** to start oscilloscope data collection for one point
3. Press Stop to conclude the run and the save file will save if you check **Save T vs D Data** before the run

Another way to fill in the required experiment parameter is by clicking the **File** menu bar from the top and select **Experiment Profile Builder...** to build an experiment profile and select **Load Experiment Profile** to load existing profiles. Doing this will immediately fill all the required fields based on your pre-written profile.

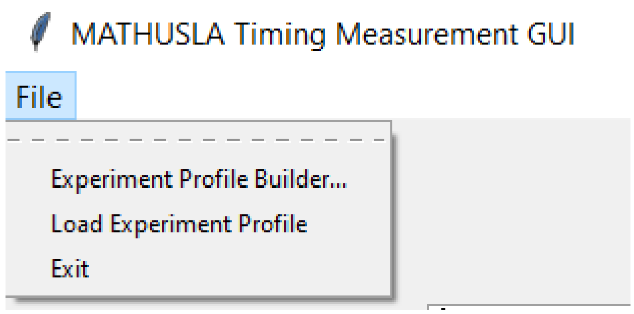

Figure 9: GUI Menu bar

3.3.8 Data Analysis

The GUI also provides some capability for data analysis. First of all, the GUI will fit the histogram collection with a Gaussian function and automatically put that point in the bottom left figure (see fig8) with the fitted uncertainties and mean.

After a reasonable number of points are collected, one can choose to perform a linear fit by clicking the **Liner Fit** button on the left side of the GUI. This will provide all the fitted parameter right below. This linear fit is using the scipy linear regression package and the Gaussian fit is using the norm.fit function from scipy. You can choose to save the graphics by clicking the **Save Plot** button and you can choose to save the point data from the plot by clicking the **Save Plot Data** button.

If the user wishes to load previous data for continuing the experiment or just for basic data analysis, they can do so by first selecting the file to read from by clicking **Browse** and then click the **Load T vs D Data** to load the data into the plot on the bottom right side.

Finally, to achieve the purpose of calculating position and uncertainty based on the timing delay, we need the inverse of this linear plot. One can achieve that by clicking the **D vs T Graph** Button which will give the inverse linear fit with the appropriate uncertainties so that one can calculate the uncertainty given a certain timing delay.

3.3.9 Sample Image

Here is an example in this case we are taking 5000 counts data across 4 position:

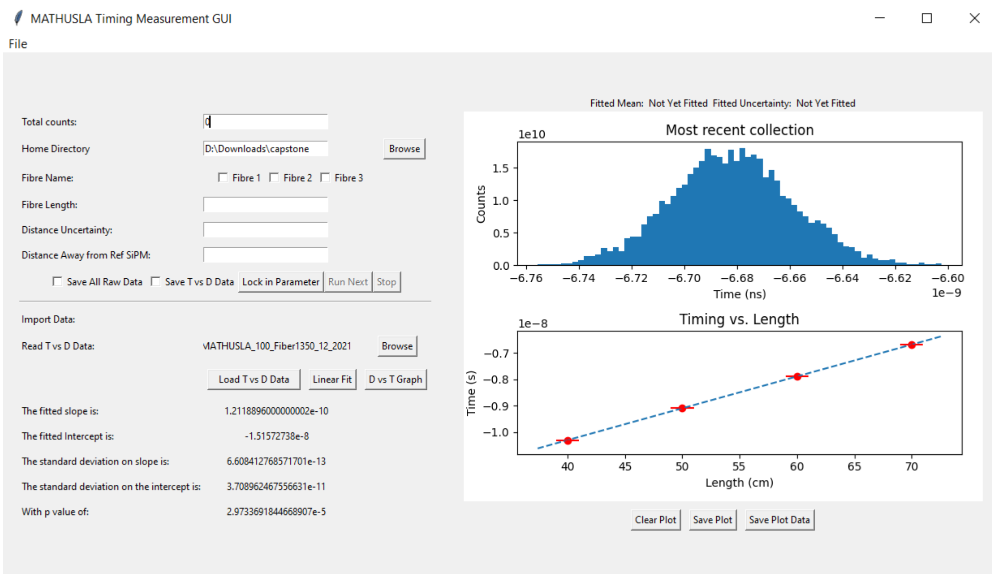

Figure 10: Sample Data Collection and Analysis

We can see here that the 4 data points are fitted and the appropriate errors are given below. We should note that the uncertainty along the y-axis (timing uncertainty) is too small to be seen since they are on the order of 0.5ns whereas the scale is on the order of 10 ns. But they are indeed present, and in fact the linear regression model takes them in as a fitting parameter.

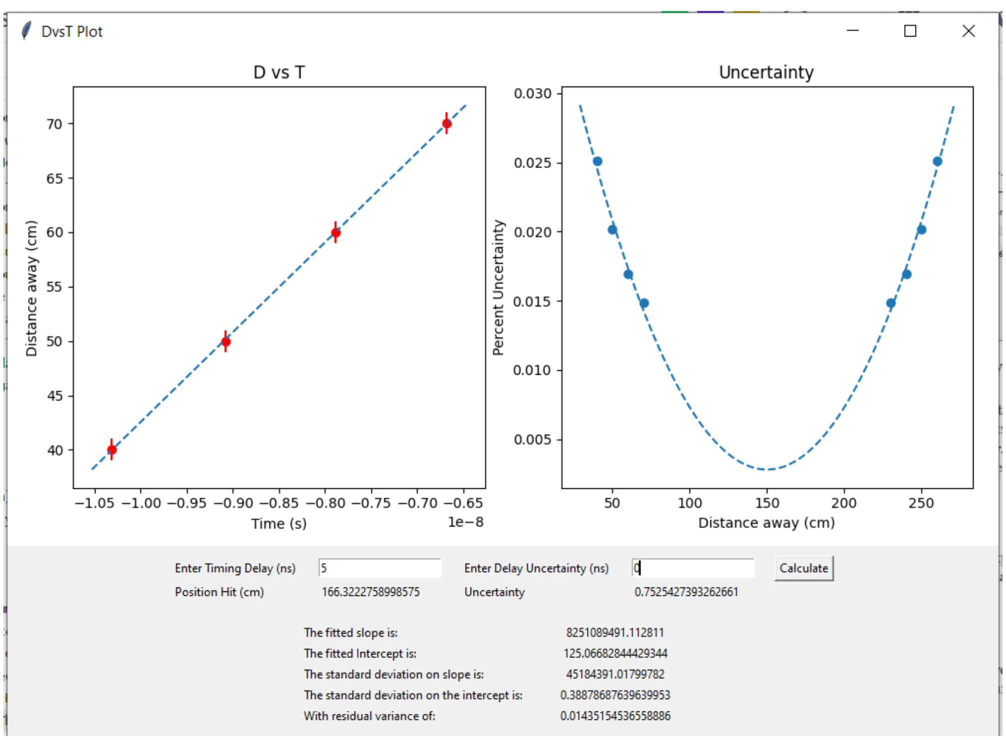

Figure 11: D vs T Graph and Uncertainty Fitting

The attached is then the D vs T graph that one needs to calculate the uncertainty. One can simply input the timing delay on top and obtain a position hit and the calculated uncertainty. In this case, we can see it successfully calculate the position hit which is 166.32 cm with 0.75 uncertainty. Notice that, on the right, it is the uncertainty fitting across fiber position. This is mainly because theoretically uncertainty will be varying as a function of the position of the photon hit due to different level of dispersion of the optical signal. Therefore, to better categorize the uncertainty we provide polynomial uncertainty fitting up to fourth degree since, in general without assumption of symmetry, the uncertainty will most likely look like a kinked or skewed quadratic function instead.

It is worth noting that the calculated uncertainty is a quadrature of the user input uncertainty (uncertainty of the timing delay measurement), the linear regression fit uncertainty (error for the accurate position give in the fiber), and the varying error as a result of dispersion. Notice that the error is not double counted since the second error is a result of the linear regression algorithm rather than the actual measured error.

4 Next Steps

- If the experiment changes and you would like to make an update to this manual, please edit the over leaf document.

A Data Collection Code

For the latest updated code, please see https://github.com/andrijapau/capstone2021.git

A.1 Required Packages and Substructure

1. PyVisa: for engaging with KeySight IO Suite / Oscilloscope
2. numpy: for large data management
3. tkinter: all the basic GUI capability
4. maplotlib: For plotting
5. scipy: for basic data analysis

A.2 Code structure

gui.py is the main function of this GUI application. It initiates the left frame (parameter input frame), the right frame (graphing frame), and menu bar on top, as well as intercommunications such as the Load T vs D data button.

leftFrame.py creates all the widget and spaces in the left frame (parameter frame) as well as any error catching functions

meta_data_handler.py contains all metadata handling capability and connects with **dataAcquisitionHelperFunction.py** to perform scans as well as storing them.

guiHelperFunctions contains all the helper function for initiating the plot on the rightFrame of the GUI.
For detailed documentation: please see the comments in the code.

B SiPM Data Sheet

Below is the relevent information needed to debug the SiPM circuits. More information can be found by following this link: `https://www.onsemi.com/pdf/datasheet/microj-series-d.pdf`.

DATA SHEET
www.onsemi.com

Silicon Photomultipliers (SiPM), High PDE and Timing Resolution Sensors in a TSV Package

J-Series SiPM Sensors

onsemi's J-Series low-light sensors feature a high PDE (photon detection efficiency) that is achieved using a high-volume, P-on-N silicon foundry process. The J-Series sensors incorporate major improvements in the transit time spread which results in a significant improvement in the timing performance of the sensor. J-Series sensors are available in different sizes (3 mm, 4 mm and 6 mm) and use a TSV (Through Silicon Via) process to create a package with minimal deadspace, that is compatible with industry standard lead-free, reflow soldering processes.

The J-Series Silicon Photomultipliers (SiPM) combine high performance with the practical advantages of solid-state technology: low operating voltage, excellent temperature stability, robustness, compactness, output uniformity, and low cost. For more information on the J-Series sensors please refer to the website.

ORDERING INFORMATION

See detailed ordering and shipping information on page 11 of this data sheet.

Table 1. GENERAL PARAMETERS

Parameter (Note 1)	**Minimum**	**Typical**	**Maximum**	**Unit**
Breakdown Voltage (Vbr) (Note 2)	24.2		24.7	V
Overvoltage (OV)	1		6	V
Operating Voltage (Vop = Vbr + OV))	25.2		30.7	V
Spectral Range (Note 3)	200		900	nm
Peak PDE Wavelength (λp)		420		nm
Temperature dependence of Vbr		21.5		mV/°C

1. All measurements made at 21°C unless otherwise stated.
2. The breakdown voltage (Vbr) is defined as the value of the voltage intercept of a straight line fit to a plot of √I vs V, where I is the current and V is the bias voltage.
3. The range where PDE > 2.0% at Vbr + 6.0 V.

Figure 12: Datasheet for the SiPM being used in the experiment.

C LDDM Data Sheet

Below is the relevent information needed to debug the LDDM circuit. More information can be found by following this link: `https://directedenergy.com/wp-content/uploads/2017/09/7675-0017_Rev_A01_PCO-7114_Datasheet.pdf`.

PCO-7114-50-4

Output current range	5 A to 50 A
Pulse width	20 A to 50 A, ≤ 4 ns
	5 A to 19.99 A, ≤ 5 ns
	0 A to 4.99 A, ≤ 6 ns
Rise time	2 ns ±1 ns
Frequency, Max at 50 A, (See SOA graphs below)	Single Shot to 650 kHz
Jitter	≤ 500 ps
Throughput delay	37 ns typical
Housekeeping power required	24 V ± 250 mV, 10 mA
Maximum high voltage input	180 V DC, 25 mA, 4.5 W
Compliance voltage	5 V

Trigger

Trigger input	+5 V
Trigger pulse width	50 ns to 100 ns
Termination impedance	50 Ω

Input connector

24 V input	J1 Pin 2
Gate input	J1 Pin 4
High voltage input	J1 Pin 10
24 V, HV, and Gate returns	J1 Pins 1, 3, 5

Current monitor

Current monitor scaling	20 A/V typical
Current monitor termination	50 Ω
Current monitor +	J2 Pin 1
Current monitor -	J2 Pin 3

Output connector

Four-hole mounting pattern accepts TO-18, TO-5, TO-52, 5.6 mm, and 9 mm packages

General

Size (LxWxH)	6.25 cm x 3.83 cm x 1.0 cm
Weight	15 g (approx.)
Operating Temperature	0 °C to 40 °C
Cooling	Air cooled

Notes

Warranty: One year parts and labor on defects in materials and workmanship.

All specifications are measured when driving a shorted load using the current monitor connection.

Specifications are subject to change without notice.

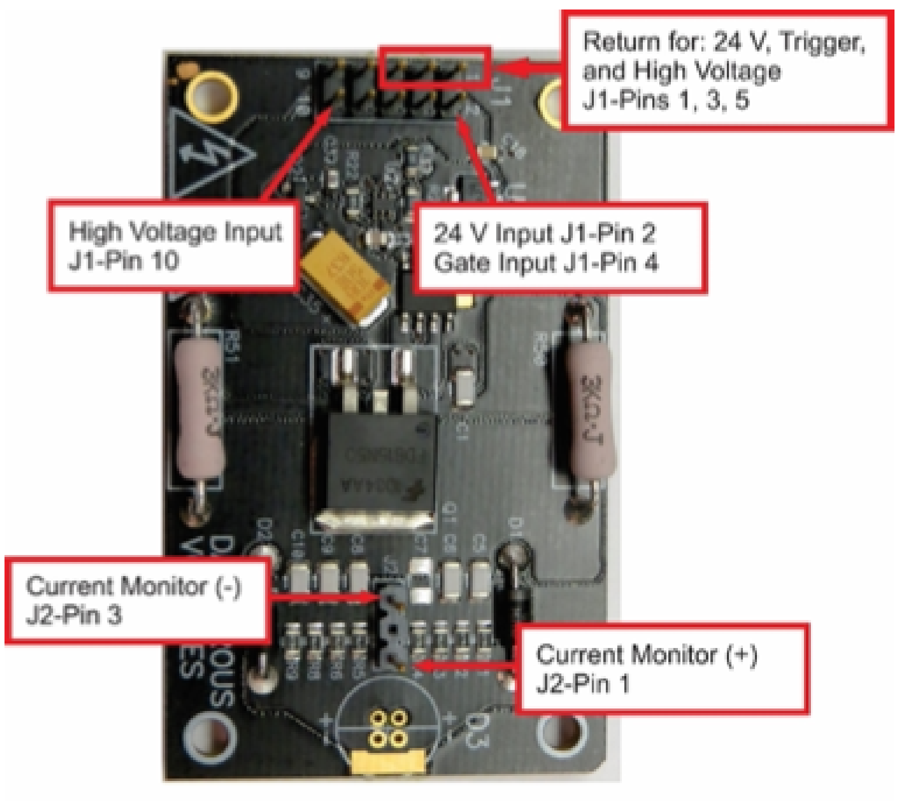

Figure 13: Datasheet for the LDDM being used in the experiment.

D MSOX4154A Oscilloscope

D.1 MSOX4154A Programming Guide

All relevent information on how to program the oscilloscope using Py-VISA can be found by following this url: `https://www.batronix.com/files/Keysight/Oszilloskope/4000X/4000X-Programming.pdf`

D.2 MSOX4154A General Manual

Please follow this url for general information pertaining to the oscilloscope: `https://www.keysight.com/ca/en/support/MSOX4154A/mixed-signal-oscilloscope-1-5-ghz-4-analog-16-digital-channels.html`.

E Keysight Power Supply Manual

Please follow this url for general information pertaining to the power supplies: `https://www.keysight.com/ca/en/products/dc-power-supplies/bench-power-supplies/e36200-series-autoranging-power-supply.html`

F Debugging Tips & Tricks

If the pulses are not producing results you expect please try the following suggestions in order to resolve the problem,

- Double check the SMA connections to the SiPMs
- Ensure the fibre is flush against the SiPM sensor surface
- Make sure the LED is pulsing correctly
- Ensure the LED fits correctly into the hole in the WLSF ring
- Check for significant kinks or defects in the WLSF