SUMMER SCHOOL AT THE IFIC DUNE LABORATORY

Photon collection efficiency measurements of mini-ARAPUCA for the Deep Underground Neutrino Experiment

1. INTRODUCTION

The **Deep Underground Neutrino Experiment (DUNE)** is one of the largest international projects in particle physics. Its primary scientific goals include measuring neutrino oscillations with high precision, determining the neutrino mass ordering, searching for CP violation in the lepton sector, detecting neutrinos from supernovae, and searching for proton decay.

The experiment consists of two detector complexes separated by approximately 1300 km. A high-intensity neutrino beam is produced at Fermilab (Illinois, USA) and directed toward the Far Detector located deep underground at the Sanford Underground Research Facility (South Dakota, USA).

The Far Detector is based on **Liquid Argon Time Projection Chamber (LArTPC)** technology, which combines excellent spatial resolution with precise calorimetric measurements, allowing detailed three-dimensional reconstruction of neutrino interactions.

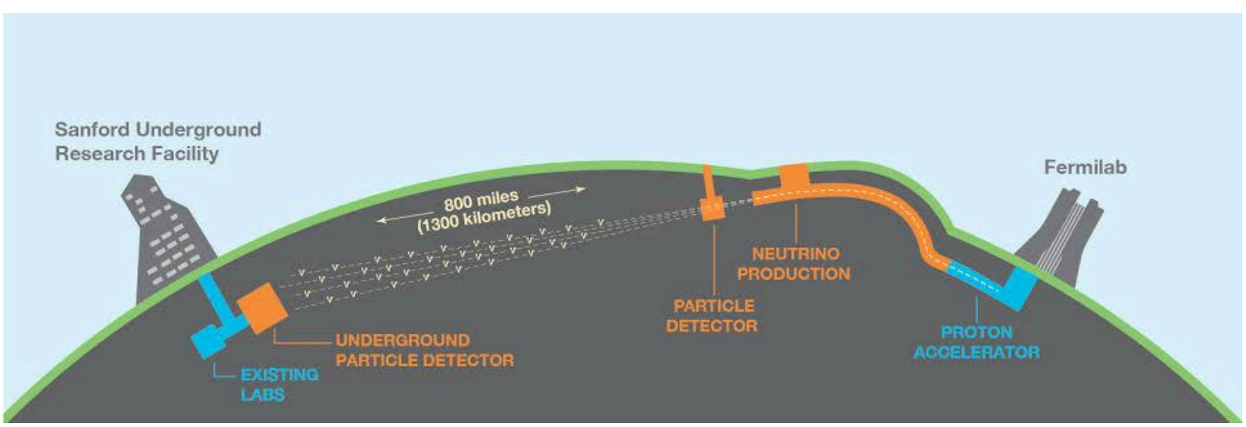


Figure 1. Schematic figure of DUNE experiment layout across 1300 km.

A Time Projection Chamber (TPC) is a particle detector that enables the three-dimensional reconstruction of charged particle trajectories with precise spatial resolution. In the DUNE experiment, liquid argon serves as both the target material for neutrino interactions and the active detection medium.

As charged particles traverse the liquid argon, they produce ionization electrons and vacuum ultraviolet (VUV) scintillation light with a wavelength of approximately 128 nm. While the ionization electrons provide detailed information about the particle tracks, the prompt scintillation light provides the precise interaction time, which is essential for accurately reconstructing events. The efficient detection of this VUV light is therefore a fundamental component of the DUNE detector and is the primary role of the Photon Detection System (PDS).

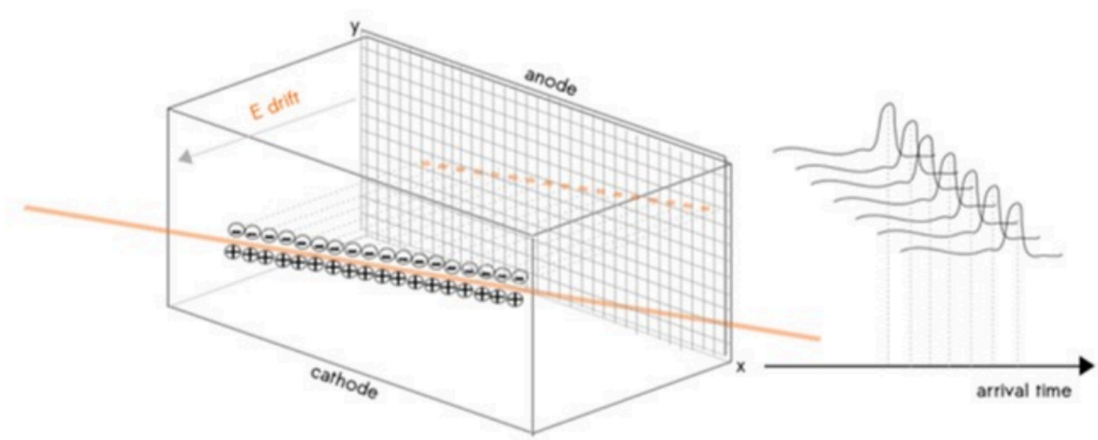


Figure 2 .Operating principle of a TPC: A particle, drawn in orange, ionizes the medium, electrons are drifted by an electric field and generate signals in the segmented anode.

1.1. Photon Detection System: X-ARAPUCAs

Since LAr scintillation light is emitted in the VUV region, specifically at 128 nm, it is challenging to detect it with conventional photon detectors. Therefore, shifting VUV light into the visible and redirecting it to active photo sensors seems a convenient solution. In this context, the DUNE collaboration developed the X-ARAPUCA, a novel device that employs wavelength-shifters (WLS) and silicon photomultipliers (SiPMs) of only a few mm2 . This technology allows for covering large areas at a reasonable cost, making this technology well suited for LAr scintillation light detection in the Far Detector Time Projection Chambers.

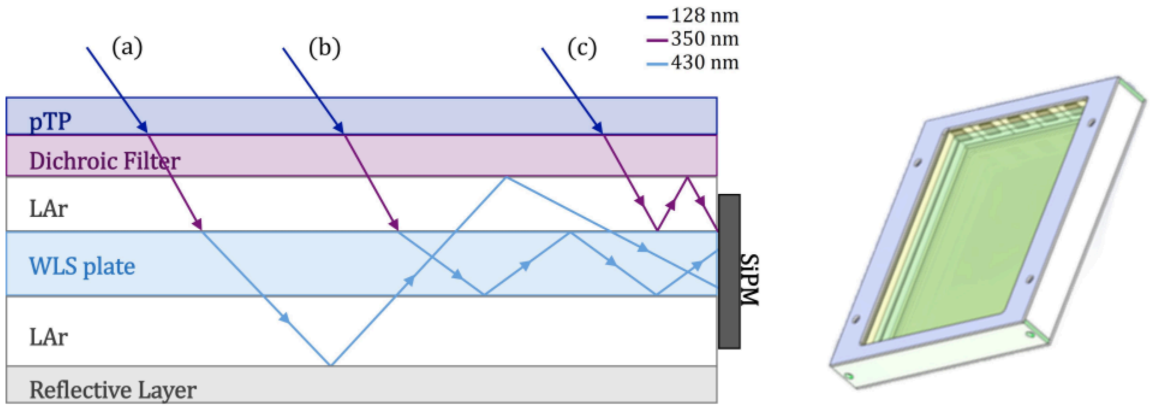


Figure 3. Illustration of X-ARAPUCA.

The objective of this project is to directly measure the light collection efficiency of the X-ARAPUCA, using a prototype built in the lab called mini-ARAPUCA. For that purpose we have in the laboratory an optical box, which can be coupled to a monochromator that produces a wavelength tunable light beam. The light collector is mounted on a linear motorised stage such that it can be displaced horizontally in order to switch between the collector under test and a reference photosensor, which is used for normalization. The setup will be described in the following section.

2. LABORATORY SETUP

Our lab consists of a clean-room that can be used to work with optical sensors under the best conditions as possible. As the sensors are very sensitive to light, it is important to work in dark conditions and it is essential to avoid any dust particles or impurities that might enter our setup.

Inside the clean-room, we have an airtight aluminum box that allows us to create a closed gaseous argon atmosphere (GAr). The importance of working in GAr is to reproduce the conditions in DUNE Far Detector and, more importantly, to eliminate the oxygen gas in the box, as oxygen absorbs light in the 100-300 nm light range.

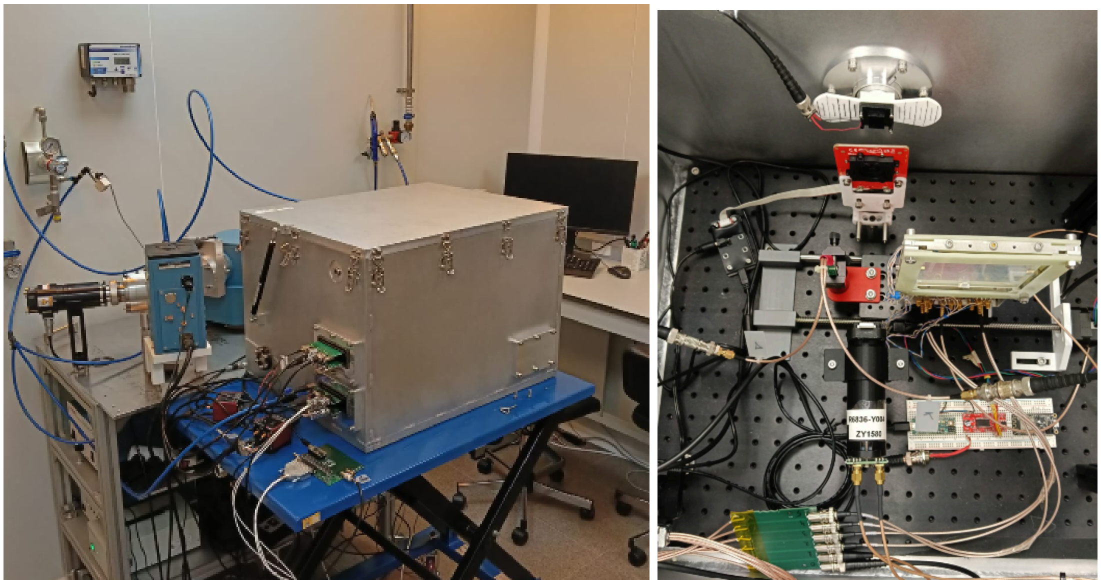
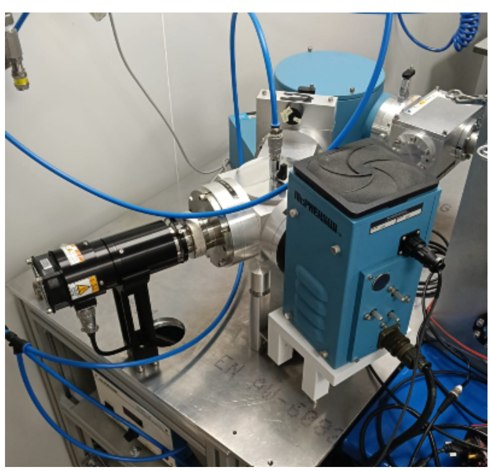
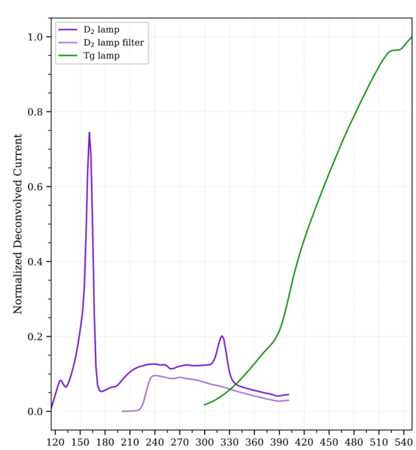


Figure 4. Optical laboratory: Optical box from outside (left) and the inside (right) with different sensors mounted on a linear stage.

The DUNE laboratory at IFIC consists of the following experimental equipment:

1) **Light sources: Deuterium lamp and Tungsten lamp:**
   The laboratory is equipped with two different light sources, each for a different purpose. The Tg lamp (Tungsten) mainly emits light in the 300-500 nm wavelength range so it is used to perform measurements in the visible spectrum. Additionally, as the 500 nm light is visible by the human eye, it can be used to align all components visually. The D2 lamp (Deuterium) emits light in the 100-300 nm range, so it is used for VUV measurements.





a) b)

Figure 5. a) D2 lamp shown on the left and Tg lamp on the right.
b) The light emission spectrum for both lamps.

The light source used can be easily selected by moving a lever that rotates a mirror.

2) **Monochromator (MC):**
The Monochromator is an essential component to this setup, as the light coming from the lamps contain several wavelengths, the MC outputs a beam that is monochromatic with a selected wavelength in the range 110-550 nm. The wavelength of the MC can be easily selected using a Python program in the lab computer.
The Monochromator works by using a diffraction grating of Al with mirror configuration as shown in Figure 6. Two slits are used to select a specific wavelength and they can be tuned between 0.01 and 3 mm.

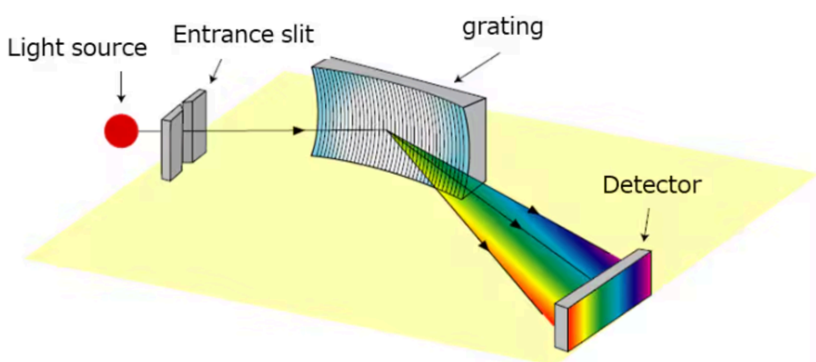


Figure 6. Schematic of diffraction grating in MC.

3) **PMT: Photomultiplier Tube:**
The Photomultiplier Tube (PMT) is one of the most widely used photon detectors in nuclear and particle physics. Its operation is based on the photoelectric effect, whereby incident photons striking a photocathode release electrons. A schematic representation of a PMT is shown in Figure 7.
When light enters the PMT through the optical window, it reaches the photocathode, where photoelectrons are generated. These electrons are accelerated by an applied electric field toward a series of electrodes called dynodes. At each dynode, secondary electrons are emitted, resulting in an electron cascade that amplifies the original signal. Finally, the amplified charge is collected at the anode, producing an electrical pulse.

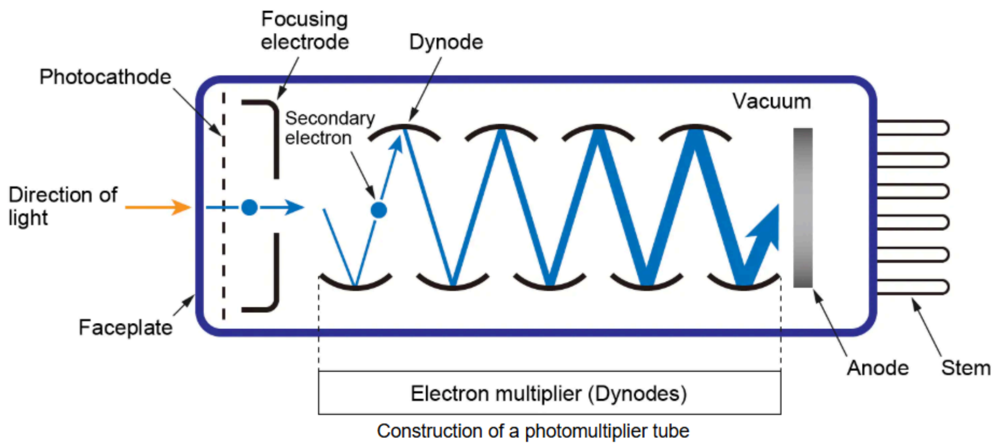


Figure 7. Schematic description of a PMT.

NOTE: The PMT used in this laboratory operates differently from a conventional PMT. All of its dynodes have been electrically short-circuited, preventing the electron multiplication process. As a result, the **PMT operates with no gain**, or with a gain equal to **1**. This means that the current measured at the output corresponds directly to the photoelectrons emitted by the photocathode, without internal amplification.

4) **Stepper motor and linear stage:**
One linear stage with a stepper motor is utilized for different purposes: NEMA 17 with a 17×17 mm size, a step angle of 1.8°, approximately 2000 steps/mm and a supply voltage of 12 V. The stepper can be easily controlled by an Arduino and a Python code, and it allows us to move in the horizontal direction, both the detector sensors or any optical samples which we want to study.

5) **DC source and current read-out:**
Both the PMTs and motors must be biased with a certain voltage. In addition, the PMTs current has to be obtained and read out. To achieve this, a picoammeter Keithley 6485 is connected to the PMT and SiPM. It also includes a ±500 V DC voltage source, so it can be used simultaneously as a current reader and voltage supplier.
On the other hand, motors were biased with R&S HMP4000 Power Supply source. All these devices can be linked to the laboratory computer and controlled easily by Python software.

Figure 8.Keithley 6485 on top and R&S HMP4000 Power Supply below.

Overall, this experimental equipment permits multiple experiments with optical sensors. We will exploit the horizontal movement of the linear stage to directly measure the collection efficiency of the mini-ARAPUCA.

3. MEASUREMENT OF mini-ARAPUCA EFFICIENCY

The main purpose of this measurement is to send a light beam of wavelength 100-300 nm into the mini-ARAPUCA to measure its output current, with special interest in 128 nm light. In order to compute the collection efficiency, we will need to compare this current with the amount of light hitting the mini-ARAPUCA window. This normalization measurement is performed by a PMT placed just behind the mini-ARAPUCA. The setup that allows this measurement is shown in Figure 9:

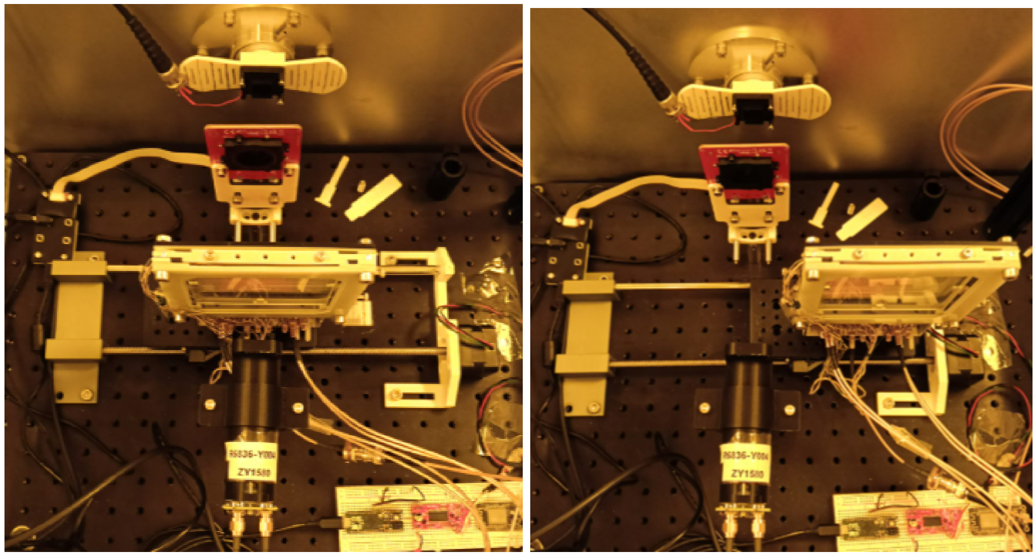


Figure 9. Laboratory configuration to measure mini-ARAPUCA efficiency. On the left, light directly hits the mini-ARAPUCA, on the right, the light hits the PMT.

It must be considered that the mini-ARAPUCA contains 4 SiPM inside, and each produces a signal proportional to the collected light. Comparing these signals with the signals of the PMT will yield a value of the mini-ARAPUCA light collection efficiency.

It is important to notice the different response that the PMT and SiPM have to different wavelength lights, which is shown in Figure 10:

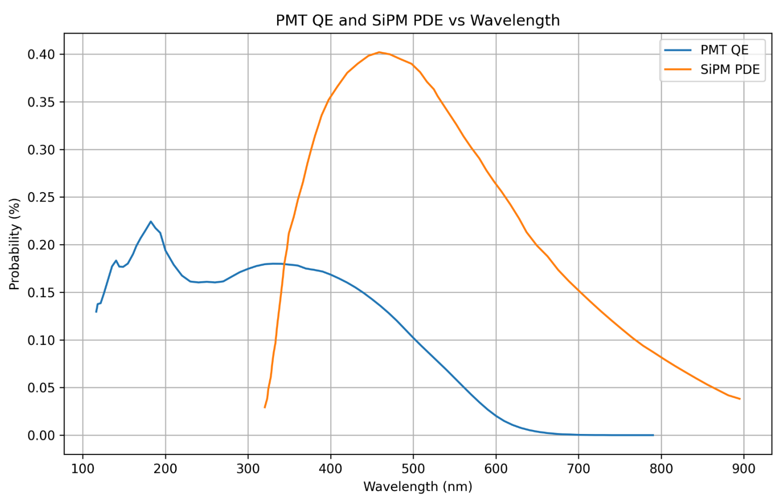
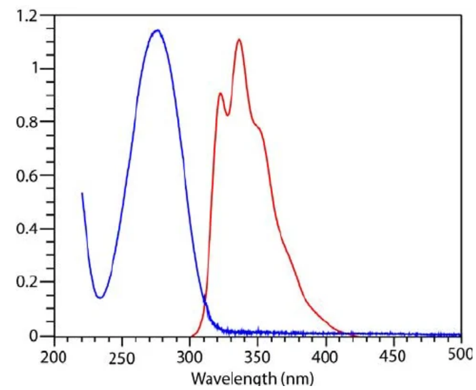


Figure 10. Quantum efficiency of PMT (blue) and PDE (Photon Detection Efficiency) of SiPM (orange).

Check that the PMT is sensitive to light in the 100-300 nm range, while the SiPM cannot detect VUV light. This is where the **ARAPUCA** technology comes into play. As shown in Figure 3, the ARAPUCA contains a layer of PTP (p-terphenyl), which is an organic scintillator that absorbs the light below 300 nm and re-emits light in the 300-400 nm range. Afterwards, the WLS bar absorbs this light and re-emits it in the 400-550 nm range, where the SiPMs can properly measure it.



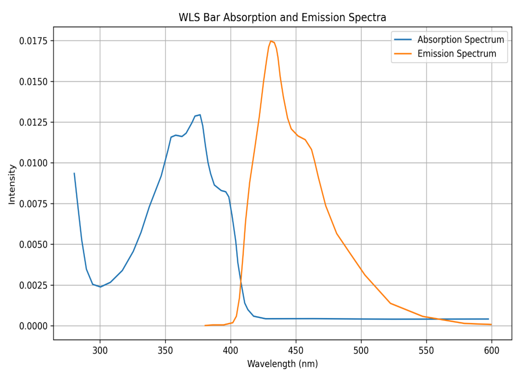


Figure 11. Left: absorption-emission spectrum of PTP.
Right: absorption-emission spectrum of WLS bar.

<u>**IMPORTANT:**</u> The PTP is very sensitive to light, so in order to avoid degrading it, we use an orange light whenever we open the box. Use the switch that has a label with “KAPTON”.

Lastly, we need to consider the important fact that oxygen molecules in air absorb the light in the VUV region. In order to perform a measurement of efficiency we introduce gaseous argon (GAr) into the optical box, because it does not absorb this light. Alternatively, we could work in a vacuum but it is very complicated to work in vacuum, as it takes a very long time to generate and it can break sensitive components.

STEPS OF MEASUREMENT:

In order to create a stable argon atmosphere we perform these steps:

1. Turn on the D2 lamp, to work on the VUV region.
2. Use PMT to measure the 160 nm peak of the lamp. Nothing will be seen at first because of the oxygen in air.
3. Introduce GAr in the box slowly (0.05-0.07 bar). Check that we start seeing light at 160 nm as the oxygen is replaced by argon.
4. Once the light is stable, we can start the efficiency measurement

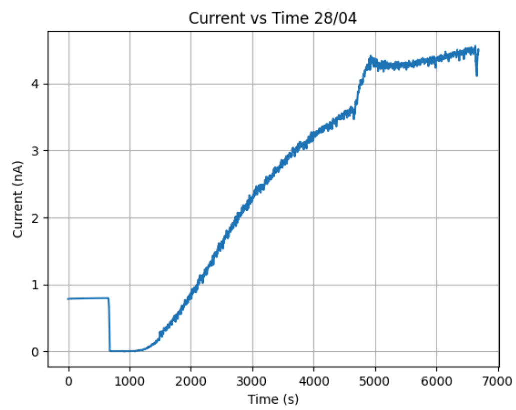


Figure 12. Example of the stabilization of 160 nm light while GAr is introduced.

The efficiency measurement in GAr has the following steps:

1. Select a wavelength
2. Measure light with PMT
3. Move ARAPUCA into beam and measure its output current (4 signals).
4. Remove ARAPUCA from beam and increase wavelength (step 1).

These measurements will be performed on the IFIC laptop using various Python programs already built, mainly “Efficiency_Xabier.py” (see last section). The idea is to first familiarize with the basic operation of all the components, then learn how to create a stable GAr atmosphere and lastly perform an efficiency measurement. This measurement can be performed both with or without the PTP layer, this way we can study the effect of the PTP in the efficiency.

4. DATA ANALYSIS, EFFICIENCY CALCULATION

Once the datafiles are created from the measurements, you will create a Python code (or other language) that reads all the data and computes the efficiency, creating a visual plot. This section will explain how the efficiency is computed.

The collection efficiency of the ARAPUCA at a given wavelength is defined as the ratio of the collected light and the incident light:

$$\varepsilon(\lambda_0) = \frac{N_{col}}{N_{inc}}$$

The incident light (in photons/s) is easily computed from the current measured by the PMT at that wavelength:

$$N_{inc} = \frac{I_{PMT}}{G_{PMT} \cdot QE_{PMT}(\lambda_0) \cdot e^-}$$

Where G_{PMT} is the gain of the PMT (approximately 1) and QE is the quantum efficiency which will be given to you.

Computing the collected light is not as straightforward, because once the light hits the ARAPUCA window, it will no longer be monochromatic. After two WLS phases, a spectrum of light will hit the SiPM inside the ARAPUCA. Because of that, we compute the collected light by using an effective PDE for each SiPM:

$$N_{col} = \frac{I_{SiPM}}{\langle G_{SiPM} \cdot PDE_{SiPM} \rangle_{eff} \cdot e^-}$$

This effective PDE is computed as an average integral over the emission spectrum of the WLS bar which is known from the bibliography. These values will be given to you directly.

<u>TASK:</u> Write a code that takes the currents measured by both the PMT and SiPM and computes the efficiency, all extra parameters will be given. Then plot the efficiency as a function of wavelength for each one of the 4 SiPMs inside ARAPUCA. Compute the total efficiency as the sum of all efficiencies and don't forget to compute the error of the final result.

The datafile to be read will have this format (CSV format):

```
User Tag:
Run start time: 2026-07-09 11:39:30
Keithley 1 label:pmtvuv80
WL Range: 100 to 300 step 10
UNIXTime (s), Wavelength (nm), MUX_CH, Current (A), Current STD
1783590037.171792,100,PMT,1.5958584375e-10,1.941778642367295e-11
1783590069.280337,100,ARAPUCA_CH3,4.5415756458333337e-07,2.604078196269714
3e-09
1783590082.7130241,100,ARAPUCA_CH4,4.6974285416666665e-07,3.39010203103327
95e-09
1783590096.0738115,100,ARAPUCA_CH5,5.269730687500001e-07,3.320135740395025
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6e-09
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1783590187.7203176,110,ARAPUCA_CH3,5.5806094375e-07,3.2494258762706937e-09
. . .
. . .
```

PYTHON PROGRAMS TO BE USED:

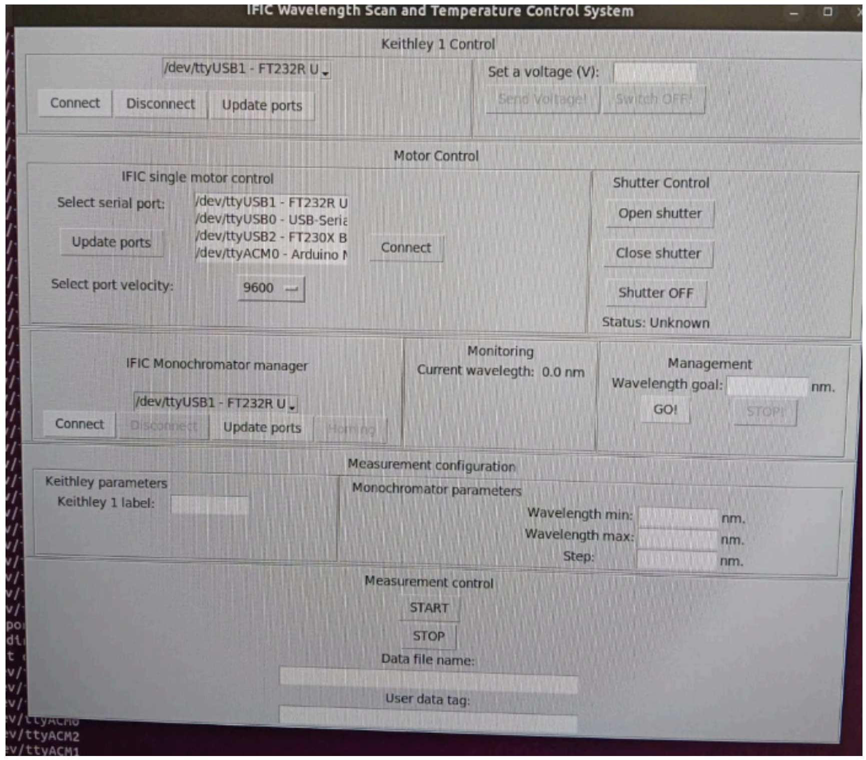
These programs are located in the "device-control" directory of the laptop. Write "python3 + program_name" on the terminal to execute the program:

1. KeithleyControl.py: This program will be very useful to monitor what the PMT of SiPMs are measuring in real time. It connects to the Keithely that reads the measured current every 1.5 seconds and while showing it on screen it also stores the current over time in a datafile.

   This program also allows you to select a voltage to apply a bias to the PMT and SiPMs. We will always apply a voltage of 54.5 V.

2. WLScan_X.py: This program allows you to connect to the Monochromator and choose the wavelength of the light. We will always perform a HOMING every time this program is used, setting the MC at 240 nm.

   Additionally, it can perform several measurements in a given wavelength range so you can measure different spectrums as shown in Figure 13.



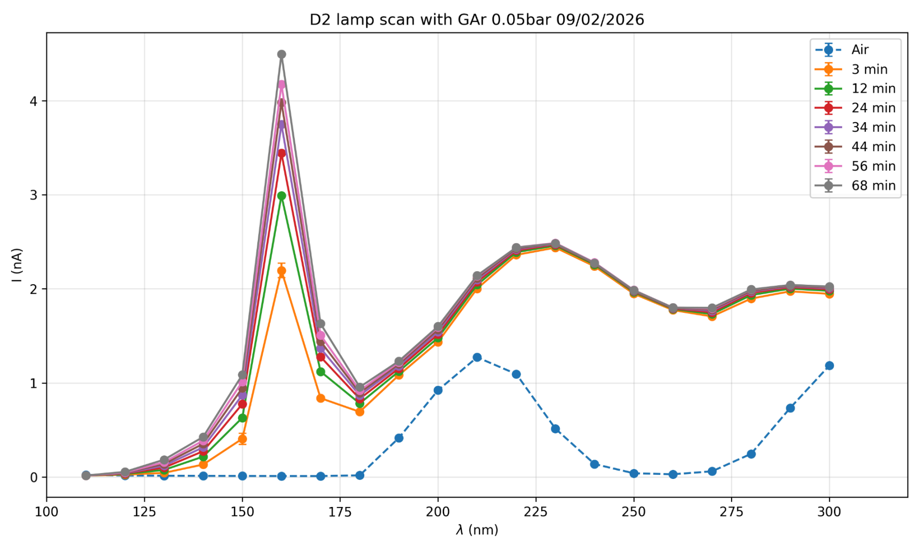
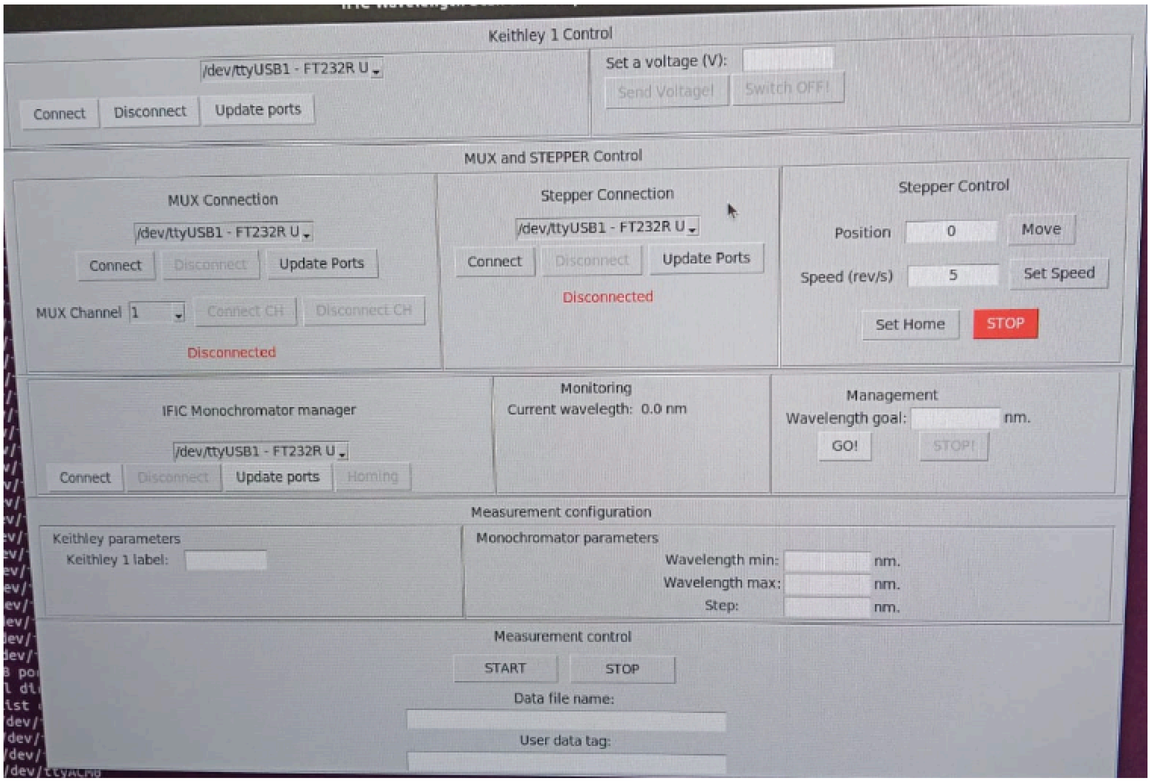


Figure 13. Scan in 100-300 nm range, while GAr is introduced.

3. Efficiency_Xabier.py: This program will automatically perform an efficiency measurement in a chosen wavelength range. It connects to the motors that move the linear stage horizontally and also connects to a MULTIPLEXER (MUX) that is responsible for choosing whether we are measuring the PMT signal or one the SiPM signals.


Keithley 1 Control
/dev/ttyUSB1 - FT232R U
Connect
Disconnect
Update ports
Set a voltage (V):
Send Voltage!
Switch OFF!
MUX and STEPPER Control
MUX Connection
/dev/ttyUSB1 - FT232R U
Connect
Disconnect
Update Ports
MUX Channel
1
Connect CH
Disconnect CH
Disconnected
Stepper Connection
/dev/ttyUSB1 - FT232R U
Connect
Disconnect
Update Ports
Disconnected
Stepper Control
Position
0
Move
Speed (rev/s)
5
Set Speed
Set Home
STOP
IFIC Monochromator manager
/dev/ttyUSB1 - FT232R U
Connect
Disconnect
Update ports
Homing
Monitoring
Current wavelegth: 0.0 nm
Management
Wavelength goal:
nm.
GO!
STOP!
Measurement configuration
Keithley parameters
Keithley 1 label:
Monochromator parameters
Wavelength min:
nm.
Wavelength max:
nm.
Step:
nm.
Measurement control
START
STOP
Data file name:
User data tag:

REFERENCES

[1] **DUNE FD-VD:** https://arxiv.org/abs/2312.03130

[2] **SiPM basics**: this article