TRIUMF Co-op Term Report

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1 Overview

High-precision experiments like PIONEER and nEXO plan on using liquid xenon (LXe) calorimeters to measure the energy of incoming particles. LXe is considered because it is highly dense, has high light yield, and responds quickly. Particles entering LXe will interact with it, causing both scintillation and ionization. Both of these phenomena can be measured to determine the energy of the incoming particle. Electronegative impurities in the LXe will affect the precision of the energy measurement through the absorption of light emitted by scintillation and the attachment of electrons. A *purity monitor assembly* (PUMA) [Fig. 1] was built to accurately measure the level of impurity inside of these calorimeters.

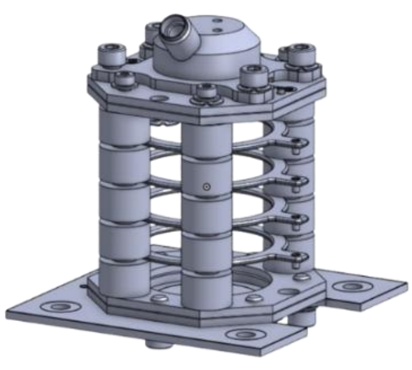

Figure 1: PUMA CAD Model

Electrons are emit from the gold photocathode of PUMA (thickness 10 nm) by a 20 W Hamamatsu Xenon flash lamp.

Signals produced by electrons are measured by PCBs at the anode and cathode; these signals can be related back to the purity of the medium the monitor is in.

Inside of the drift region of PUMA, two grids are mounted [Fig. 2] to separate the anode and cathode from the drift region. Some electrons travelling through the drift region will get stopped at this physical mesh.

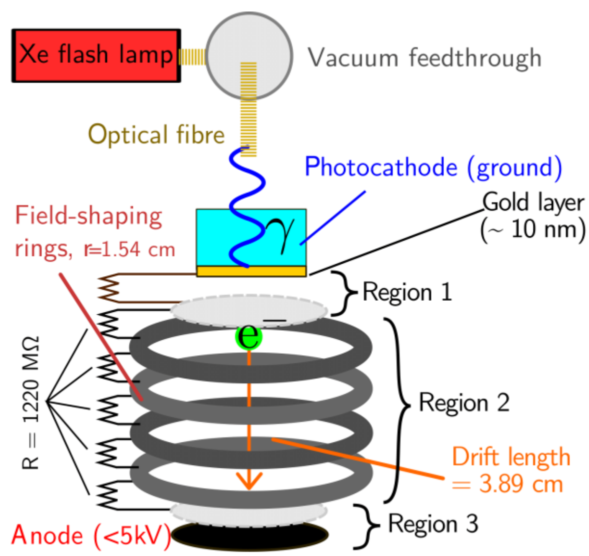

Figure 2: PUMA Drift Chamber[1]

It is important to determine how many electrons pass through the grid, also known as the *transparency* of the grid. PUMA must be calibrated by determining the transparency of the grids mounted inside of it. We define the grid transparency k as:

$$k = \frac{anode\ charge\ [Q_a]}{cathode\ charge\ [Q_c]} \qquad 1$$

The grid transparency is medium dependent. The medium PUMA is in will affect the grid transparency as different media will cause electrons to drift with different trajectories and energies. The grid transparency can be determined independent of PUMA but because it changes depending on the medium, a calibration setup is needed for operation in the same medium as PUMA.

A novel assembly called little PUMA [Fig. 3] has been developed to calibrate PUMA by allowing for precise determination of the grid transparency in various media.

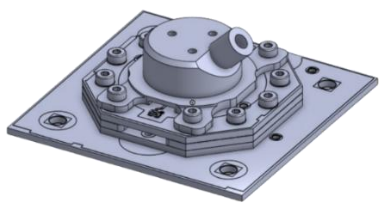

Figure 3: Little PUMA CAD Model

The drift region of little PUMA [Fig 4.] is 1.66 mm, much shorter than the 38.9 mm drift region of PUMA. Electrons emit from the cathode of little PUMA drift through the grid to the anode.

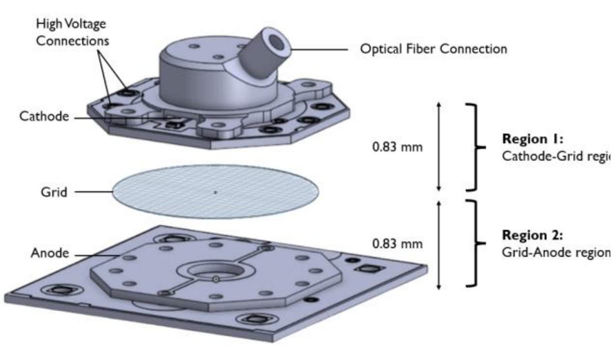

Figure 4: Little PUMA Drift Region

The main goals of this co-op were to perform first tests of little PUMA, as well as develop simulations of PUMA to understand particle behaviour in its drift region.

2 Simulations

Simulations of PUMA were conducted using COMSOL Multiphysics and Garfield++ to verify assumptions and understand particle behaviour in PUMA.

2.1 COMSOL Multiphysics

The electrostatics module of COMSOL Multiphysics was used to generate a field map and mesh containing information about the geometry and potential of PUMA for integration with Garfield++.

Measured voltage/resistance values [Table 1, 2] were taken at McGill and used to modify past co-op's COMSOL simulation of purity monitor to reflect current status.

Resistor	R [MΩ]
R1, R3	1
R4	19.4
R10	99.3
R11	249
R12	201
R13	198
R14	202
R15	249

Table 1: PUMA Resistors – Experimental Values

Region	Voltage [V]	E [V/cm]
Cathode	25.4	156.1
Drift 1	326.6	412.9
Drift 2	265.0	360.5
Drift 3	259.7	353.4
Drift 4	263.7	358.7

Drift 5	326.6	366.6
Anode	130.3	799.2

Table 2: Voltage/E-Field in PUMA

Results of the COMSOL study are shown in Figure 5/6 (potential and electric field).

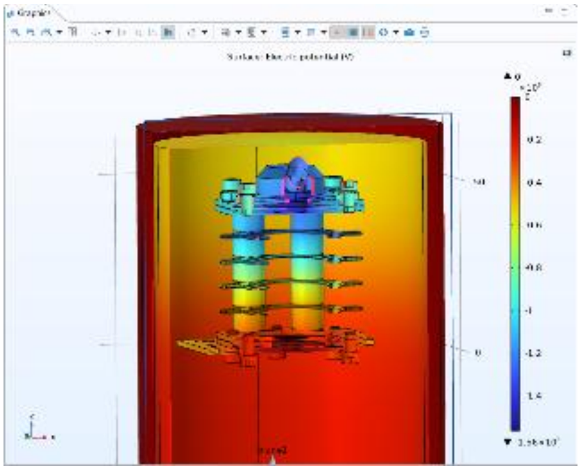

Figure 5: PUMA Potential

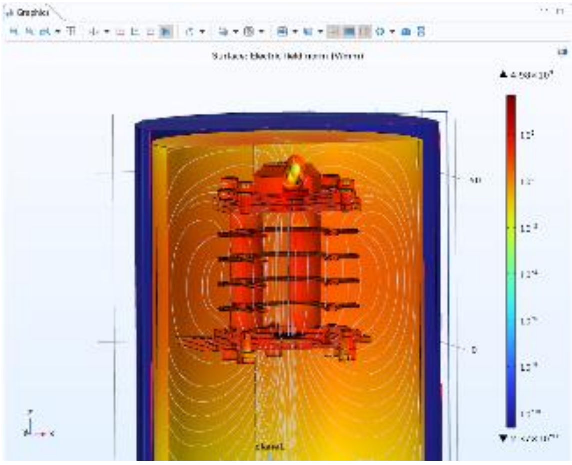

Figure 6: PUMA E-Field

2.2 COMSOL/G++ Integration

Several exports and files needed to be written to be able to export the COMSOL model to be used in Garfield++ (G++). A field map and mesh file were exported directly from COMSOL. *Note:* it is important to include 2nd order elements in mesh export file.

A third file assigning a material to each domain of the COMSOL model is needed for G++ to synthesize it. A Python program[2] was written to generate this file based off the materials associated with each domain in COMSOL. These materials (and their respective indices) are:

- Stainless Steel [0] (PUMA)
- Gold [1] (Cathode)
- Copper [2] (Rings)
- Cuprothal [3] (Wiring)
- Liquid Xenon [4] (Drift Medium)
- FR-4 [5] (PCBs)

2.3 Garfield++ Simulations

Once the model was successfully exported from COMSOL to G++, code was written to better understand how particles behave in the drift region of PUMA.

ELOG entry about running G++ code can be found here.

The simulation[2] was initially conducted in gaseous Argon at atmospheric pressure and room temperature; a second version of the simulation was done in liquid xenon. The medium can be changed easily in G++ by creating a new gas object, loading a new ion mobility file, and generating a new gas table.

The class DriftLineRKF was used to simulate electron drift. DriftLineRKF performs calculation of drift lines based on macroscopic transport coefficients using Runge-Kutta -Fehlberg integration and works well with uniform fields.

Figure 7 is a histogram generated by the G++ program showing the distribution of electron speeds in the drift region of

PUMA. The speed of electrons in the drift region is approximately constant.

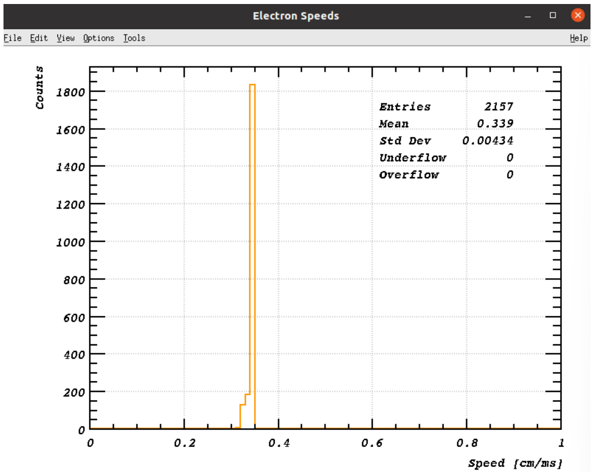

Figure 7: Electron speed distribution in drift region

Further, the TrackHeed class was used to visualize electron drift lines in the drift region when drifting n electrons from the cathode of PUMA. Electrons were drifted from a small circle of radius 0.5 cm centered on the 2.5 cm radius cathode. Figure 8 shows these drift lines with $n = 150$.

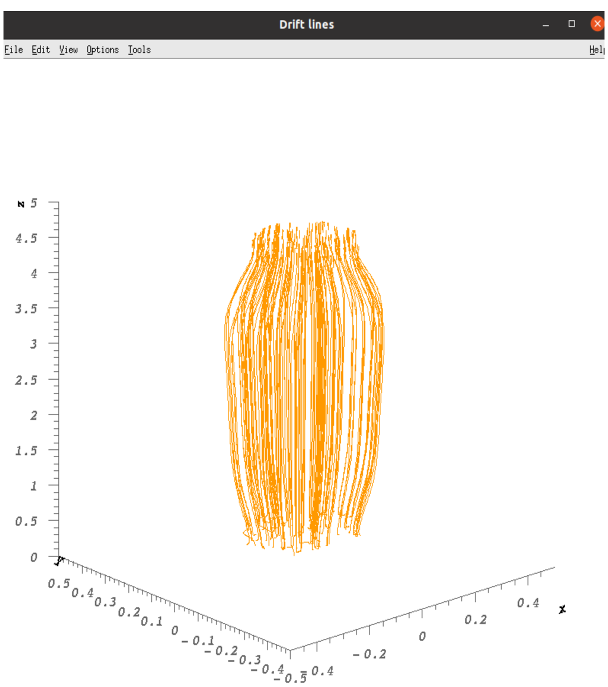

Figure 8: Electron drift lines in drift region [cm]

The G++ simulations found in the GitHub repository[2] can be modified to generate results in various media and temperature/pressure conditions.

3 Vacuum System

A KF-flanged vacuum system was designed and assembled for testing of little PUMA. The purpose of the system was to contain little PUMA, provide connections to the Xenon lamp/power supplies/instruments, and display internal pressure. The system was made to allow for measurement in both vacuum and gas (argon). The system was designed with considerations about little PUMA's geometry.

3.1 Design Process

The design process of the vacuum system proceeded as follows:

1. Consultation with vacuum group regarding necessary components as well as research about available parts
2. Creation of CAD Model (using OnShape) of vacuum system [Fig. 9]
3. Ordering of parts (mainly from Kurt J. Lesker)
4. Thorough clean of all parts using ethanol and Kimwipes
5. Assembly of system [Section 3.3] and connection to turbo pump

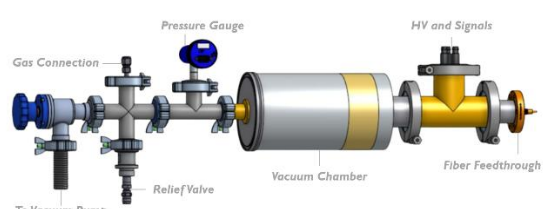

Figure 9: Vacuum System CAD Model

The fiber feedthrough purchased was of 600-micron diameter. Externally, a Xenon flashlamp connects to this feedthrough. Internally, a 600-micron diameter optical fiber is attached to the feedthrough on one end and to the top of little PUMA on the other.

Note: The relief valve [see Fig. 9] was later removed (during vacuum tests only) and blanked due to not being vacuum tight.

3.2 Pressure Gauge Setup

The pressure gauge used to make pressure measurements inside the chamber is the MKS 925 MicroPirani Vacuum Pressure Transducer. In order to log pressure data from the gauge, it was necessary to create an electrical box [Fig. 10] with ports for the required cables. The wiring schematic for the box is shown in Figure 11. Connection of the USB-RS232 cable to the box allows for easy computer integration to collect data.

The MKS logger software (a LabVIEW program) was used to log pressure data, which is written directly to .xls files on the computer connected to the electrical box.

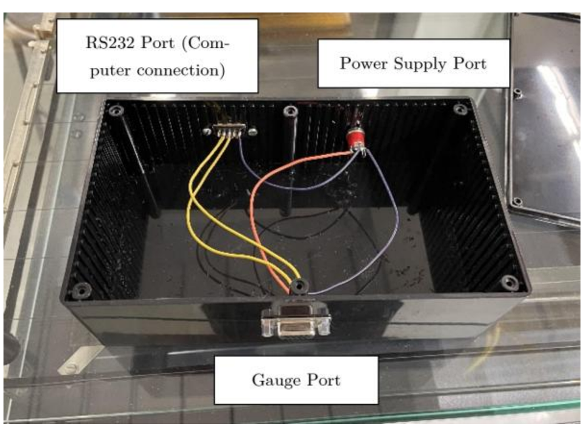

Figure 10: Electrical Box for Pressure Gauge

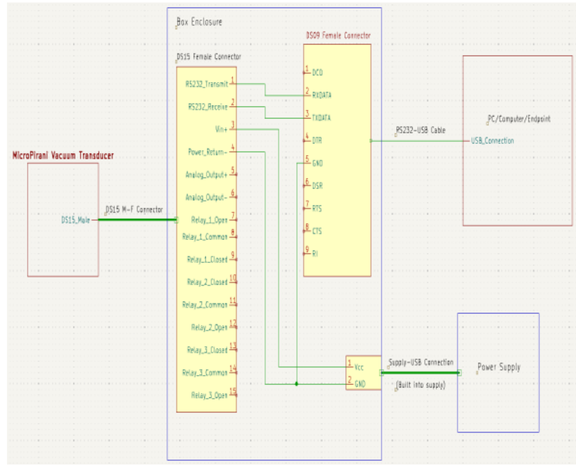

Figure 11: Wiring Inside Fig. 8 Box

3.3 Final Setup

The final setup of the vacuum system is shown in Figures 12-13. Figure 13 shows how little PUMA was screwed onto the vacuum chamber flange and connected to the optical fiber.

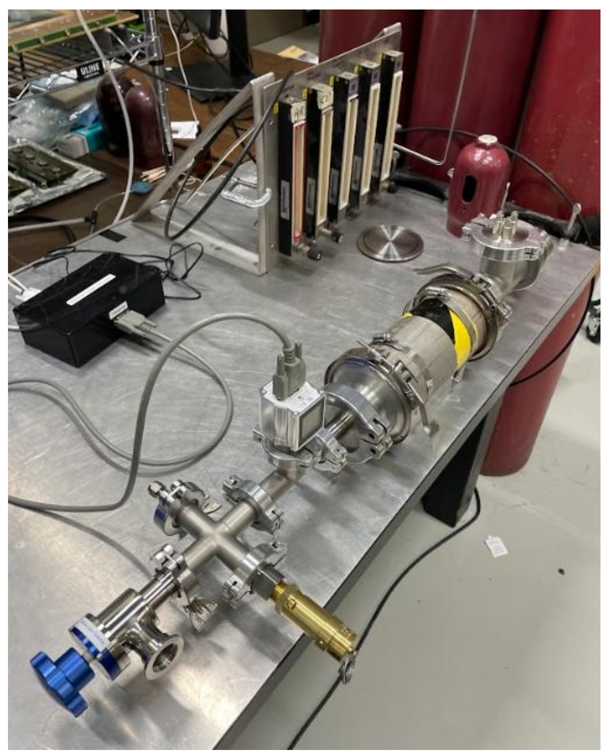

Figure 12: Vacuum System Setup

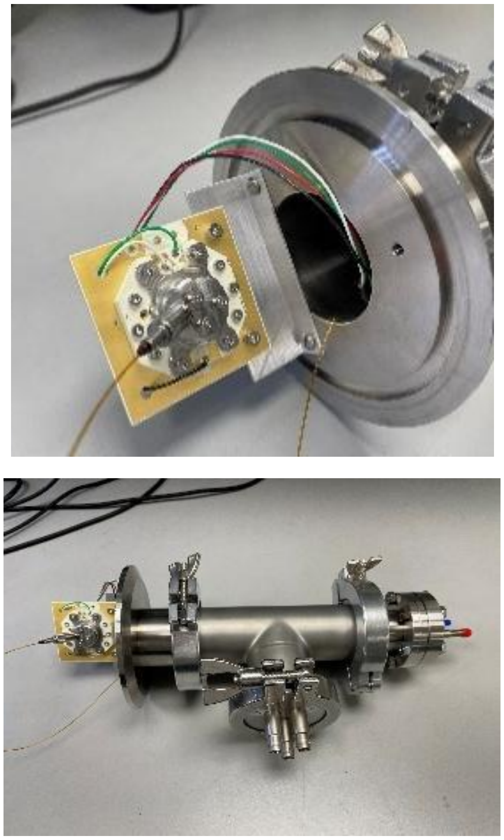

Figure 13: Little PUMA Integration into System

To achieve a good and stable vacuum, a helium leak check was performed before testing began. Probing the system with gaseous helium allowed for determining which connections were loose and causing a leak. Eventually, the leak rate was reduced to < 1 mBar/hour.

Note: While testing, other leaks appeared. Some testing indicated that this was due to outgassing.

Over time and with more runs, outgassing effects were reduced. After pumping the system down to 10^{-3} mBar and then isolating it from the pump by closing the valve, the pressure increase over time would be observed to see how fast the vacuum decreased [Fig. 14].

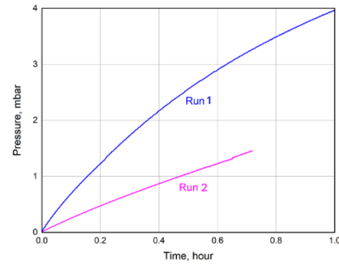

Figure 14 [3]: Pressure in System Over Time

Figure 14 shows that outgassing reduces with pumping time (number of runs); Run 2 (second pump down) saw the pressure increasing at around 1/3 of the speed of the pressure increase during the first run.

4 Testing Phase

Once the vacuum flanges were properly tightened and sealed, the leak was eliminated. Outgassing was reduced with pumping time, and testing *in vacuum* was begun at a pressure of order 10^{-3} mBar.

4.1 Experimental Procedure, Setup

Figure 15 shows the experimental setup for taking data with little PUMA. This includes the vacuum system containing little PUMA, the power supplies and function generator, the oscilloscope, and the amplifier circuits.

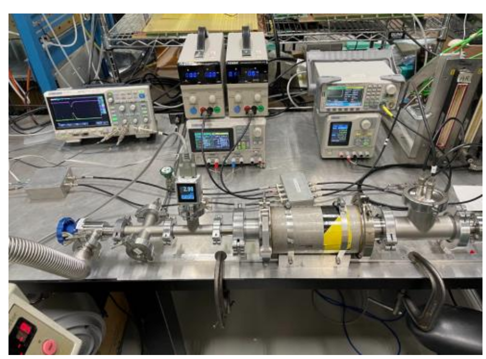

Figure 15: Experimental Setup in PIONEER Lab

A LabVIEW program written by Leonid was used to adjust the scale of the oscilloscope, change number of flashes from the Xe lamp, change the time period of flashes, and begin data collection as well as write signal data to a file.

Experiment runs proceeded as follows:

1. Pump down to stable pressure of order 10^{-3} mBar
2. Run LabVIEW program using a descriptive naming convention
3. Xenon flash lamp sends 10 flashes to photocathode of little PUMA, which emits e^{-}
4. PCBs at cathode and anode of little PUMA capture signal produced by e^{-}; signal sent through an amplifier circuit and written to file
5. Adjust voltage at anode and grid as necessary depending on context of tests; repeat from step 3

An experiment was conducted to determine the transimpedance of the anode and cathode amplifiers accurately; the values were determined by injecting a known charge into the amplifier input.

- Cathode transimpedance = 213 kΩ
- Anode transimpedance = 207 kΩ

The error of these values is ±2%.

When signal data is collected [see Section 4.2], the charge at the anode and cathode can be found by integrating the signal and diving by the previously found amplifier transimpedance. Then, the original goal of finding the grid transparency k can be completed by taking the ratio of the charges [see Equation (1)].

4.2 Analysis + Results (in Vacuum)

Figures 16/17 show collected signals from two runs of testing.

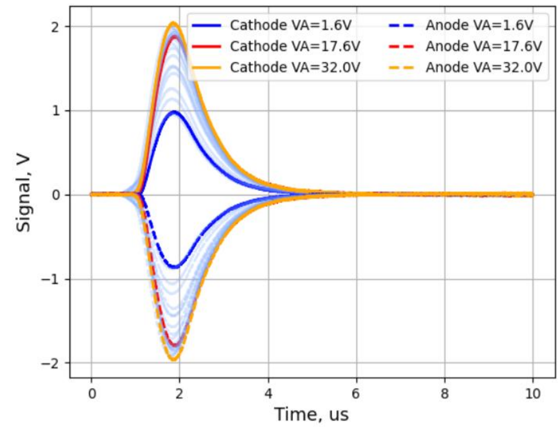

Figure 16: Cathode (solid), Anode (dotted) Signals

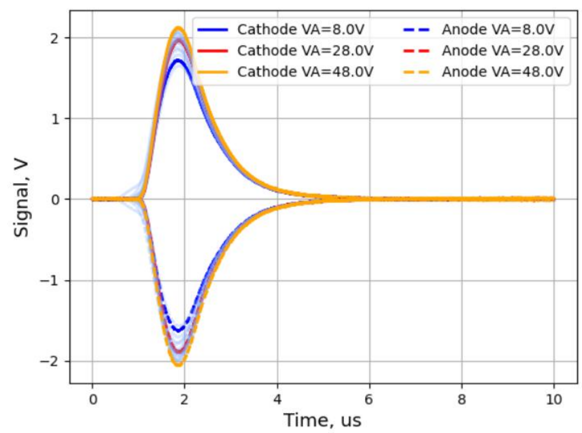

Figure 17: Cathode (solid), Anode (dotted) Signals

Data analysis was performed in JupyterLab using matplotlib and numpy and files can be found in the GitHub respository[2] listed below.

Finding the charge at the anode and cathode as described in section 4.1 allowed for various plots to be made [Fig. 18/19]. In Figures 18/19, the units of the measured signals is pico Coulomb [pC].

The ratio of E-Field in Figure 19 refers to the ratio of electric field in the grid-anode region to cathode-grid region [refer to Fig. 4].

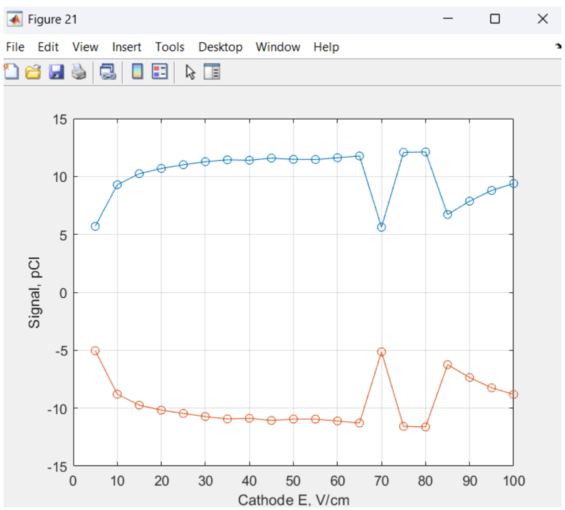

Figure 18: Cathode (blue), Anode (orange) Signals as a function of E-Field in Cathode-Grid region

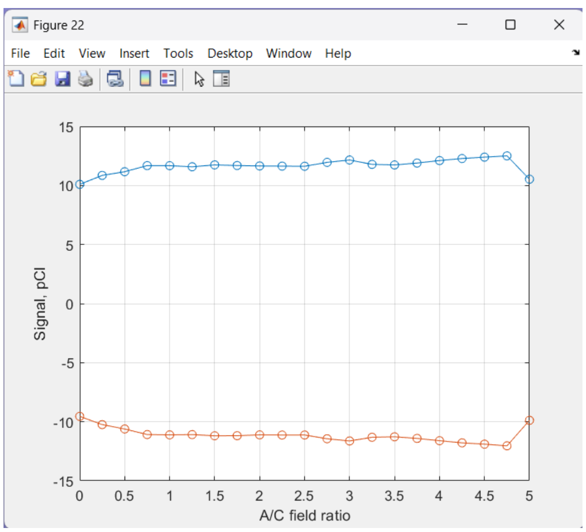

Figure 19: Cathode (blue), Anode (orange) Signals as a function of Ratio of E-Field in Anode/Cathode region

Figure 20 shows a plot of the ratio of charge at anode and cathode (i.e. grid transparency) with the ratio of E-Field in the Cathode-Grid and Grid-Anode regions of little PUMA. The transparency remains close to 1, meaning the majority of electrons make it through the grid with only some getting caught on the mesh.

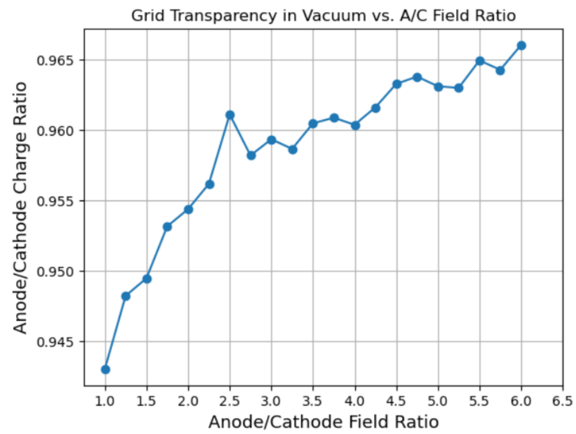

Figure 20: Grid Transparency in Vacuum

As seen in Figure 20, the grid transparency increases as the E-Field in the grid-anode region [refer to Fig. 4] increases. This is expected because more electrons will be pulled through the grid in the electric field is stronger in this second region.

4.3 Obstacle for Argon Data

The pressure gauge described in section 3.2 is not designed to measure over pressure in Argon; it saturates at ~ 13 mBar. Therefore, it is necessary to find a new pressure gauge in order to start measurements in argon gas, which are to be done at 100 - 1100 mBar.

We were able to find a mechanical gauge that read the internal pressure, but only to a precision of 10%. A test was run comparing readings of the original MicroPirani gauge (in saturation) to the actual pressure (measured by the new mechanical gauge) [Fig. 21].

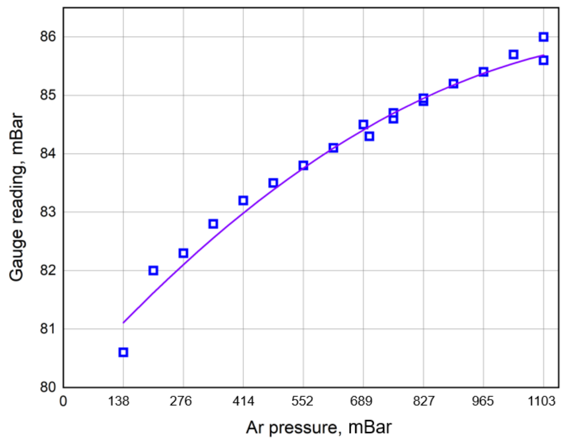

Figure 21: Pressure Gauge Calibration

Adding this new gauge into the system also introduced a new leak in the system. Before Argon data can be taken, this leak must be repaired, and a new pressure gauge with higher precision must be obt ained and added to the system. Then, grid transparency can be determined in argon gas by taking data as described in section 4.1 but at various argon pressures.

5 Next Steps

The immediate next step with little PUMA is to finish testing in argon gas. Everything is set up and ready for this data to be taken, but a new pressure gauge is needed for over pressure, and this needs to be connected to the vacuum system upon arrival. When it is connected, a brief leak check should be performed to ensure the gauge is vacuum safe, and then measurements may proceed.

After little PUMA has been thoroughly tested at TRIUMF, it will be brought to McGill for insertion into the LoLX cryostat, where PUMA is currently being tested. Here, data can be taken with PUMA and little PUMA working in tandem for the first time. In the future, the two assemblies will be integrated into experiments like PIONEER and nEXO to maximize the performance of their calorimeters by delivering a highly accurate value of the impurity level in LXe.

6 References

[1] Pierce Comerford, *LoLX Co-op Term Documentation and Report*, 2024

[2] Simulations code found at this GitHub repository

[3] Plot made by Leonid Kurchaninov