Testing the Quantum Efficiency of MELZ Photo-Multiplier Tubes

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Abstract

Quantum efficiency (QE) and spectral responsivity are measured of a set of photo-multiplier tubes (PMTs) from the Moscow Electric Lamp Plant (MELZ) that were made using the air-transfer process similar to that we have been developing for the Large-Area Picosecond Photo-Detector (LAPPD). We compared the quantum efficiency and the spectral responsivity that was measured with the expected values for the type of photo-cathode used in these photo-multiplier tubes and the printed values for these photo-multiplier tubes. We found that the measured value of the quantum efficiency is close to the expected values for the known photo-multiplier tube.

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1 Photo-Cathodes and Quantum Efficiency

Quantum efficiency is defined as the ratio of the number of converted photoelectrons to the number of photons incident on the window of a photosensitive device. There are many factors that contribute to the quantum efficiency of a photo-multiplier tube. These can include, but are not limited to, the geometry of the tube, and the photo-cathode material.

These photo-multiplier tubes are made using a K_2CsSb photo-cathode, where its spectral responsivity vs. wavelength are shown in fig. 1. Other characteristics typical of this type of photo-cathode can be seen in tab 1.

The geometry of the photo-multiplier tube also has an affect on the quantum efficiency. In the case of the MELZ photo-multiplier tubes, we only have the specifications for one of the tubes, FEU-527. They can be seen in tab. 1.

In measuring quantum efficiency, it is not possible to directly count the number of incoming photons and the number of outgoing photo-electrons. As such, it is necessary to instead measure the power (or intensity) of the incoming light and the current of the photo-electrons.

Below is the derivation for determining the quantum efficiency from the intensity of the incoming light and the measured photo-current.

$$\begin{aligned} QE &= \frac{n_e}{n_\gamma} = \frac{n_e}{n_\gamma} \cdot \frac{et}{et} = \frac{I}{n_\gamma} \cdot \frac{t}{e} \\ &= \frac{I}{n_\gamma} \cdot \frac{th\nu}{eh\nu} = \frac{I}{P} \cdot \frac{h\nu}{e} = \frac{I}{P} \cdot \frac{hc}{e\lambda} \\ &= \frac{I}{P} \cdot \frac{1240(W/A) \cdot nm}{\lambda} \end{aligned} \tag{1}$$

Where n_e is the number of converted photo-electrons, n_γ is the number of incident photons, e is the electric charge of an electron, t is time, I is the current measured out of the photo-multiplier tube, h is Planck's constant, ν is the frequency of the light source, P is the measured power of the light source, c is the speed of light in a vacuum, and λ is the wavelength of the light source.

	Wavelength of Maximum Response (nm)	Responsivity at $\lambda_{\max}$ ($\frac{mA}{W}$)	QE at $\lambda_{\max}$ (%)
Characteristics of K_2CsSb photo-cathode	380-420	100	>30
Characteristics of FEU-527 photo-multiplier tube	410	66	20

Table 1: Characteristics typical of a K_2CsSb photo-cathode and the FEU-527 photo-multiplier tube [1] [3].

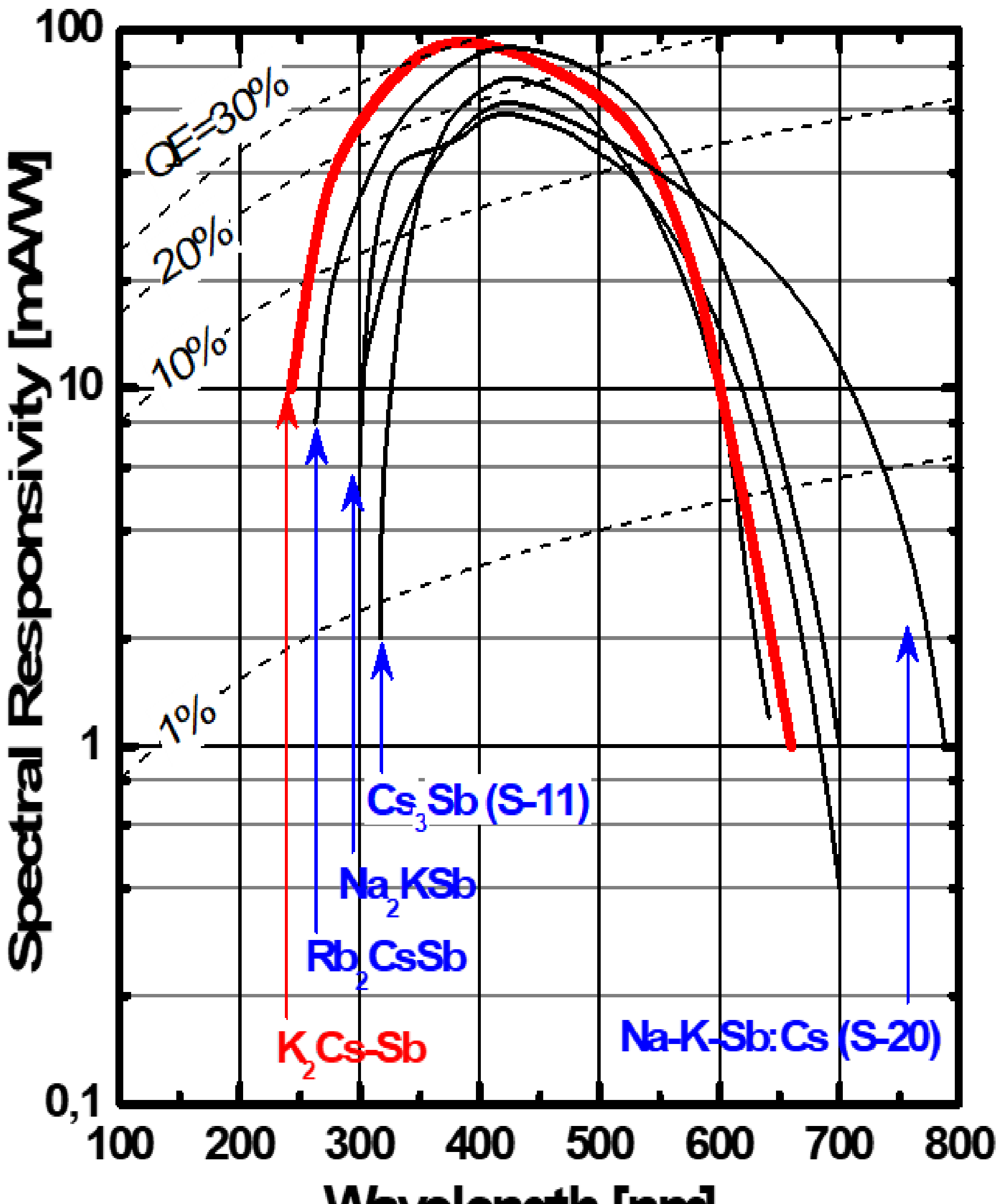

Figure 1: Expected spectral responsivity of various photo-cathodes. K_2CsSb is the alkali used in the MELZ photo-multiplier tubes. [1]

2 Description of MELZ Photo-Multiplier Tubes

2.1 Description of the Cathode-to-Anode Photo-Multiplier Tube

The cathode-to-anode photo-multiplier tube (marked as N5) does not have any dynodes between the photo-cathode and the anode, hence the name "cathode-to-anode".

This photo-multiplier tube has 14 pins on its base. Three of the pins are connected to the photo-cathode, three of the pins are connected to the anode, and eight of the pins are not connected to anything, and as such are called "floating pins" (see fig. 2).

There are two chains of pin sockets used to keep all pieces of metal at a known potential. One chain keeps all of the anode pins and floating pins at the ground and the other chain keeps the photo-cathode pins at the negative potential (see fig. 3).

Since a negative polarity is used, it is necessary to take precautions to minimize the effect it may have on the dark current and to also protect the tube against the potentially destructive voltage gradients across the glass. For this reason, the tube is wrapped in an aluminum guard cylinder which is kept at the photo-cathode potential, keeping the potential inside and outside the tube the same [2]. The yellow wire connects the aluminum guard cylinder to the negative potential. A layer of electrical tape is wrapped around the photo-multiplier tube for safety and also as insulation between the guard cylinder and the magnetic shield (see fig. 4).

2.2 Description of the FEU-527 (ФЕУ-527) Photo-Multiplier Tube

The FEU-527 tube (marked as N198) has fifteen dynodes [3].

This photo-multiplier tube has 22 pins on the base of the tube, in two rows, with 15 pins on the first row and 7 on the second row (see fig. 5).

There is one pin that connects to the photo-cathode of the photo-multiplier tube. The remaining 21 pins are either connected to one of the amplification stages, the anode, the focusing apparatus, or are not connected to anything.

To tie the pins that are not connected to the photo-cathode, a chain of pins, similar to that in fig. 3, was made. This chain can be seen in fig. 6.

Similar to the cathode-to-anode photo-multiplier tube in section 2.1, the FEU-527 has an aluminum guard cylinder for insulation and safety which is kept at the photo-cathode potential (see fig. 6).

Figure 2: The figure on the left is the window of the cathode-to-anode photo-multiplier tube. It admits light, while a layer of photo-cathode inside emits electrons. The figure on the right is the base of the photo-multiplier tube. It has fourteen connector pins.

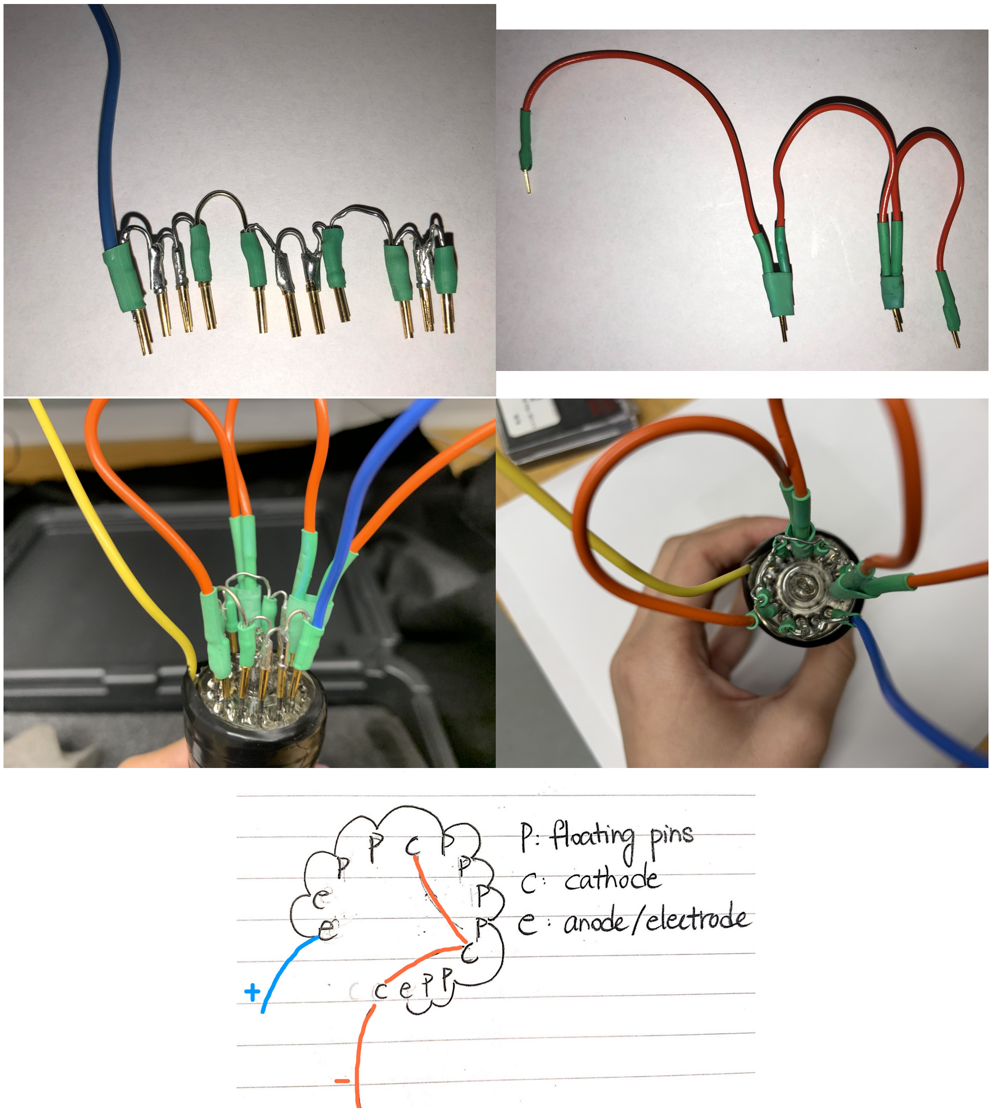

Figure 3: There are 14 pins on the base of the photo-multiplier tube: three pins connected to the photo-cathode, three pins connected to the anode, and eight floating pins that are not attached to anything. The three photo-cathode pins are interconnected by orange wires, with another orange wire being attached, via an SHV cable, to the Fluke power supply. The three anode pins and the eight floating pins are interconnected by a chain of pin sockets and wire that have been soldered together. A blue wire is connecting one of the anode pins to the 500 kΩ resistor. The yellow wire is attached to the guard cylinder at the cathode potential.

Figure 4: An aluminum guard cylinder is wrapped around the tube, keeping the current running inside the tube, not leaking to the nearby glass. Black tape is wrapped up outside the guard cylinder to insulate the photomultiplier tube from the magnetic shield. A yellow wire is attached to the guard cylinder, which would then be connected to the photo-cathode.

Figure 5: The figure on the upper-left corner is the window of FEU-527 cathode-to-anode photo-multiplier tube. It admits light, while a layer of photo-cathode inside emits electrons. The figure on the upper-right is the base of FEU-527. It has two rows, twenty-two connector pins. The figure on the bottom is the side of FEU-527.

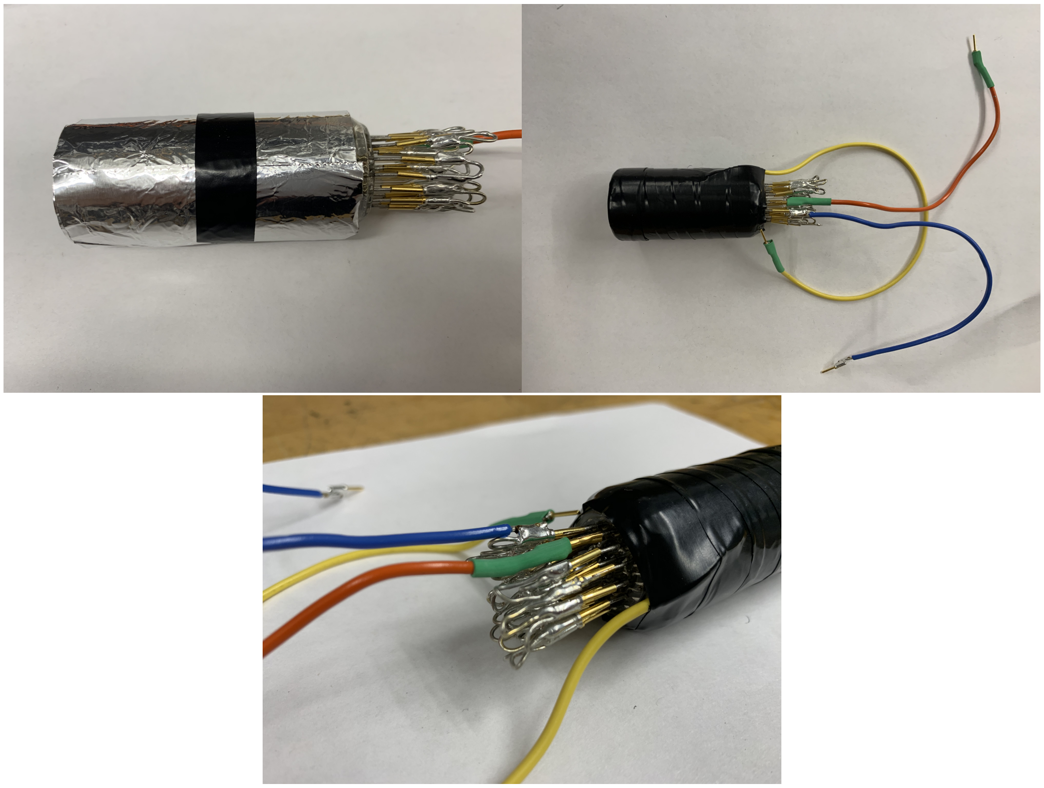

Figure 6: An aluminum guard cylinder is wrapped around the tube to prevent from leakage. A yellow wire is attached to the guard cylinder, so that we could connect it to the photo-cathode. The orange wire is connected to the cathode pins and the blue wire is connected to the anode pins, which is soldered together with the floating pins.

3 Physical Set-Up and Procedure

3.1 The Physical Set-up

The set-up used for measuring the quantum efficiency of the MELZ photo-multiplier tubes is a dark box made out of a brief case with holes cut into it, which is lined on the bottom with foam fitted for the photo-multiplier tube and optical cables, foam blocks set in the holes where the cables run through, foam strips lining the lip of the brief case, and a black felt sheet draped over the case.

A Fluke 415B High Voltage Power Supply is used with a negative output with respect to the chassis-ground, which is at earth ground. The photo-cathode of the photo-multiplier tube is kept at a negative potential.

A 500 kΩ resistor is connected to prevent damage from high currents.

A Prizmatix FC5-LED Multichannel LED Light Source is used as the light source. There are two different set-ups used for shining the light on the photo-muliplier tube window. One involves an external set of cage plates that allow for filters to be added and changed externally (see fig. 7). The other has the optical cable go directly from the light source to the dark box, with filters added within the dark box. The former allows for quicker changing of filters without affecting the interior of the dark box, but also reduces the power such that only a weak filter can be used. The latter allows for a greater range of filters to be used, but does expose the interior of the dark box to ambient light whenever the filters are changed.

The path of the cables, the power supply, photo-multiplier tube, resistor, and the ammeter is diagrammed in fig. 8.

3.2 The Procedure and Safety Considerations

Before approaching the dark box, the high voltage power supply is off and fully disconnected from the photo-multiplier tube, with the coaxial cable wrapped up. The photo-multiplier tube is placed inside of the magnetic shield. The end of the optical cable is positioned to point at the photo-multiplier tube window. At this point, the connections follows fig. 8, and the aluminum guard cylinder as well as the magnetic shield are attached to the photo-cathode potential. The case has foams in the holes and lips, and black felt sheets over it. blocking ambient light. Only at this time do we take the cable from the off power supply and connect it to the photo-multiplier tube via a coaxial cable that comes out of the dark box. Then the power supply is turned on, and, without touching the dark box, we use the Prizmatix to turn the light on and off, and change the voltage on the Fluke power supply to measure the current from the ammeter. The power supply is always turned off while making adjustments in the dark box.

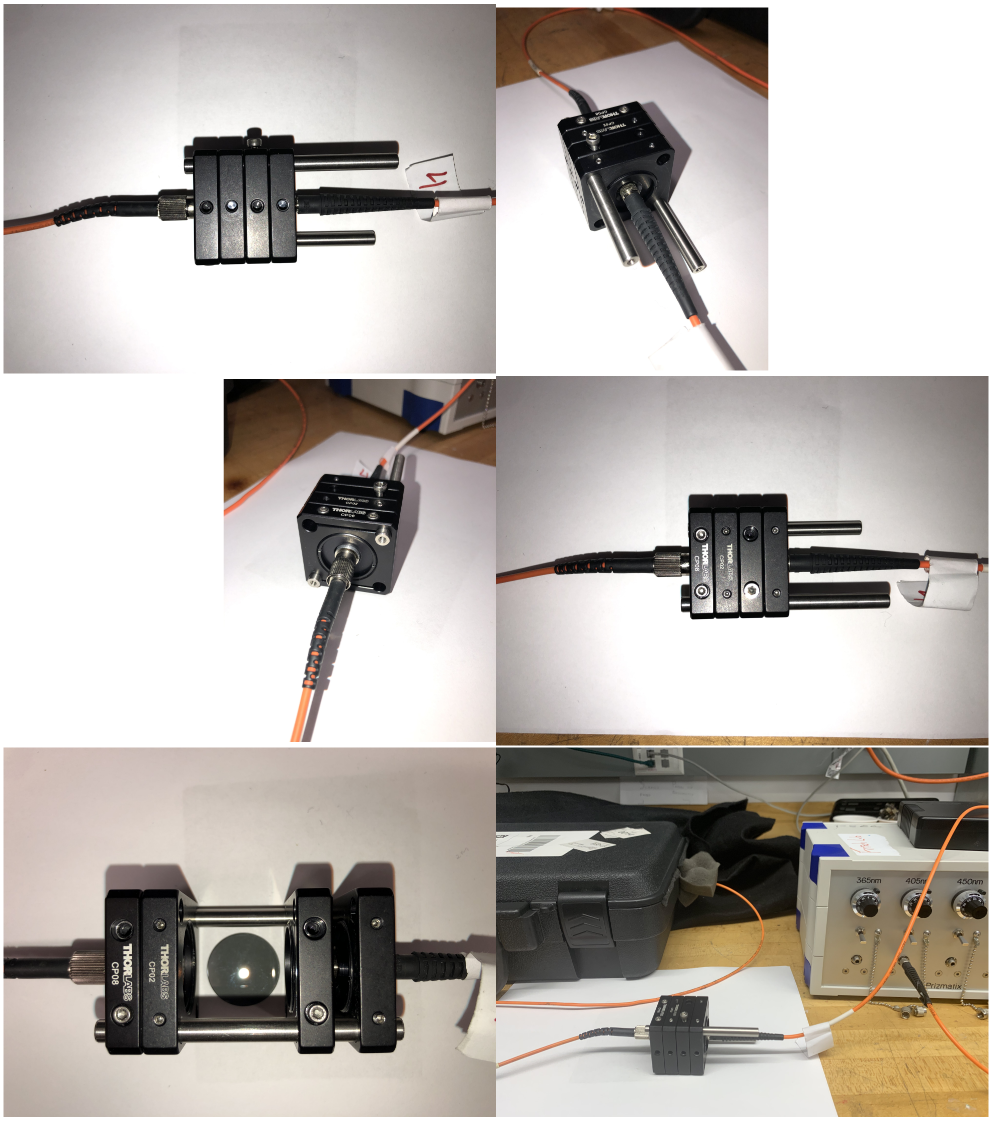

Figure 7: Set-up for adding a filter in the path of the optical cables without opening the dark box. Clockwise from top left: top view, front view, side view, full set-up, expanded view that shows where the filter is placed, and back view. The orange optical cable connects one of the channels of the Prizmatix to the set of four cage plates. The two cage plates in the middle are used for adding filters, while the two cage plates on the side are used to fix the ends of the optical cables. The other optical cable connects the set of cage plates into the dark box, with the end pointing at the window of the photo-multiplier.

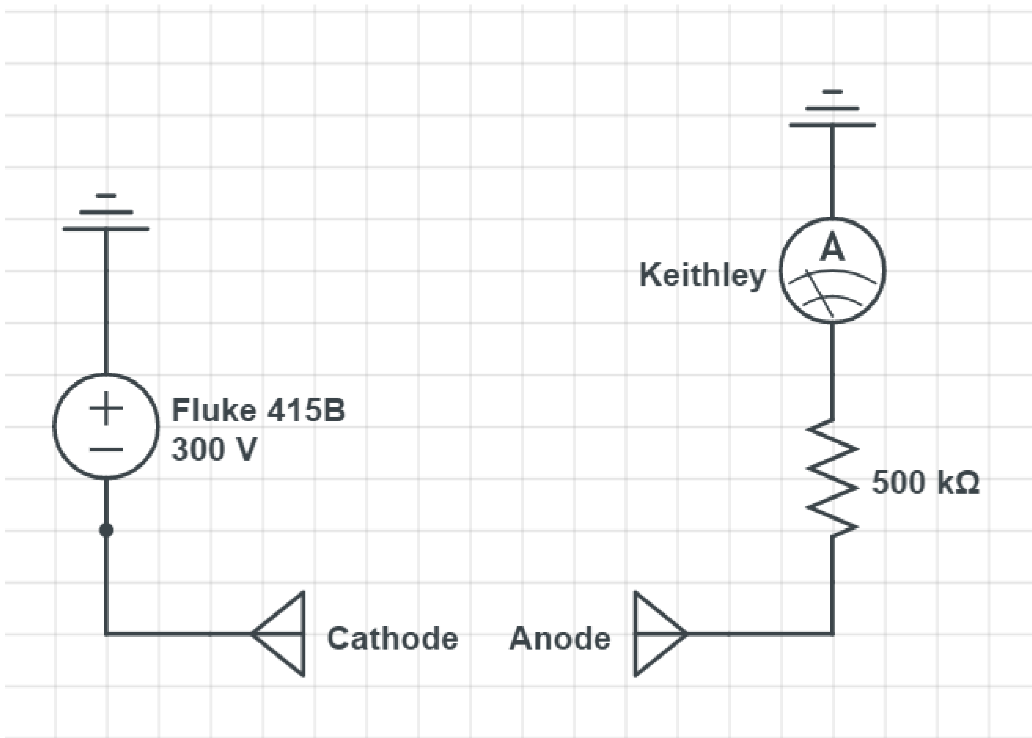

Figure 8: Circuit diagram of the cables, Fluke High Voltage Power Supply, photo-cathode and anode of the photo-multiplier tube, current limiter (resistor), and a Keithley Ammeter. The potential is relative to the chassis-ground of the Fluke power supply, which is at earth-ground.

4 Measuring the Quantum Efficiency of the Cathode-to-Anode Photo-Multiplier Tube

For measuring the quantum efficiency, we used an exterior set of cage plates that allowed us to add filters without opening the dark box (see fig. 7). Using a Prizmatix FC5-LED Multichannel LED Light Source, the quantum efficiency of the cathode-to-anode photo-multiplier tube was tested at four wavelengths: 365 nm, 405 nm, 500 nm, and 535 nm. Keeping the power of the light source at approximately 1-2 nW, the photo-current vs. voltage curves plateaus at different values of photo-current (fig. 9). As seen in fig. 10, the quantum efficiency was found to be highest at 365 nm, and decreases at longer wavelengths.

The 90% plateau-current-voltage vs. photon energy is plotted in fig. 11.

Wavelength (nm)	Photon Energy (eV)	QE (%)	90% Plateau Voltage (V)
365	3.40	15.6	125
405	3.06	8.6	60
500	2.48	2.8	20
535	2.32	0.7	14

Table 2: Table of results from measuring the spectral response of the cathode-to-anode photo-multiplier tube.

4.1 Exposure to Ambient Light

The plateauing photo-current is left overnight and compared with the photo-current measured on the first day, to see the effect of longer time. Since the photo-multiplier tube is exposed to ambient light when adjustments are made, the effect of short exposure to light is also tested by exposing the tube to ambient light for five minutes and comparing the plateauing photo-current.

Longer plateauing time causes decrease in current, but does not affect plateauing photo-current significantly. A five-minute exposure to light results in an overall increase in photo-current, therefore a higher quantum efficiency, but it still falls in the range of uncertainty. Keeping the photo-multiplier tube in dark box for 30 minutes is sufficient to lower the plateauing photo-current to the original value.

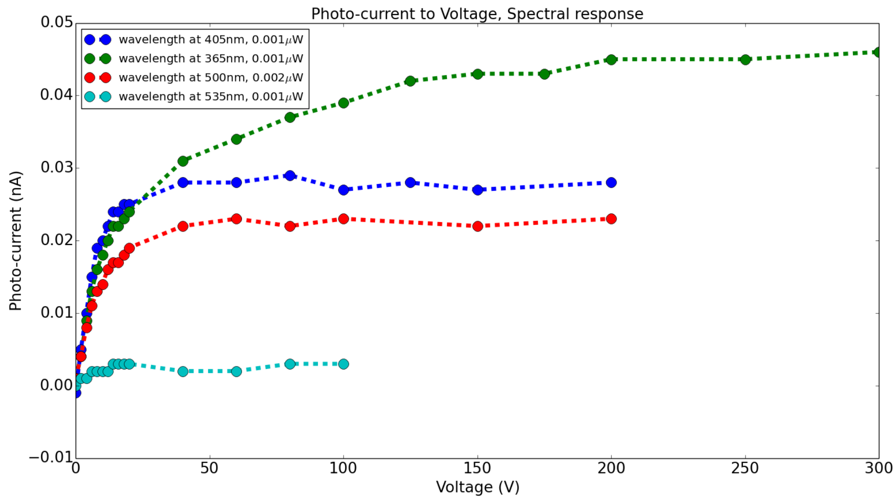

Figure 9: Photo-current vs. Voltage at different wavelengths. The green curve shows the measurements at 365nm, 0.001μW, with photo-current plateauing at 0.046 nA at about 200 V (quantum efficiency is about 15.6%). The blue curve shows the measurements at 405nm, 0.001μW, with photo-current plateauing at 0.028 nA at about 50 V (quantum efficiency is about 8.6%). The red curve shows the measurements at 500nm, 0.002μW, with photo-current plateauing at 0.022 nA at about 40 V (quantum efficiency is about 2.8%). The cyan curve shows the measurements at 535nm, 0.001μW, with photo-current plateauing at 0.003 nA at about 14 V (quantum efficiency is about 0.7%).

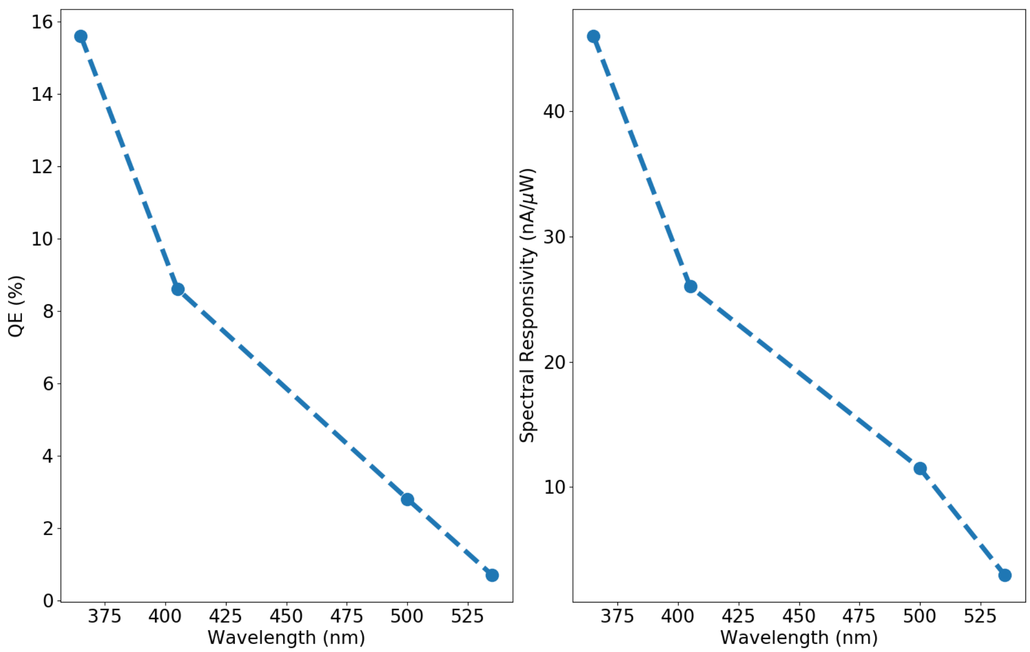

Figure 10: Two plots, one that shows quantum efficiency vs wavelength and the other that shows spectral responsivity vs wavelength. Quantum efficiency is calculated using equation 1. Responsivity is defined as the ratio of outgoing current to incoming power, and is in units of $\frac{nA}{\mu W}$.

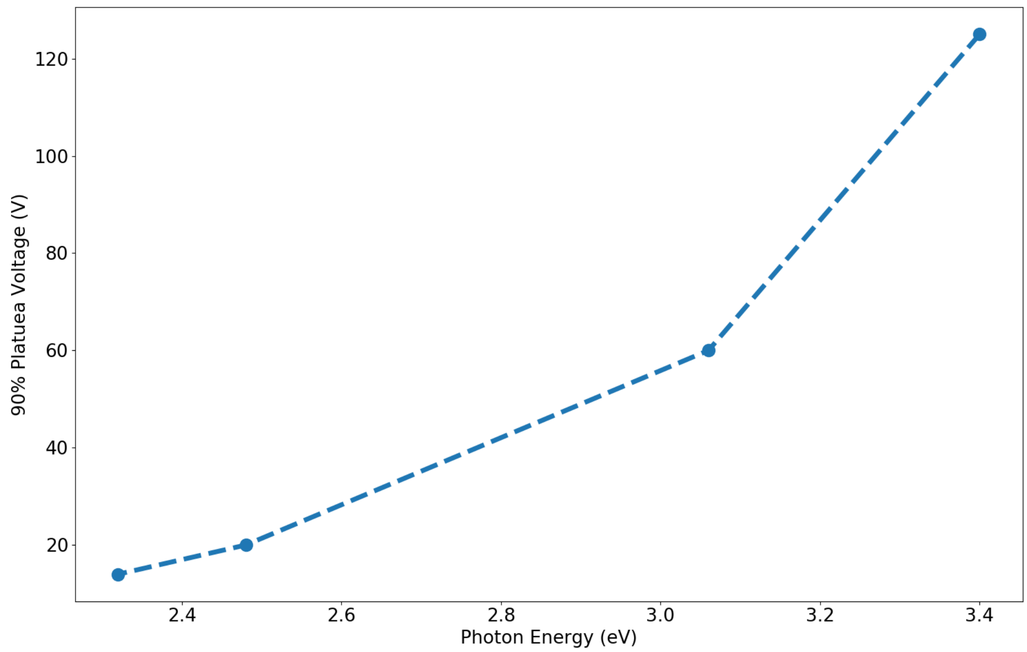

Figure 11: 90% plateau voltage vs photon energy showing how at increasing photon energy, the point at which the current plateaus increases.

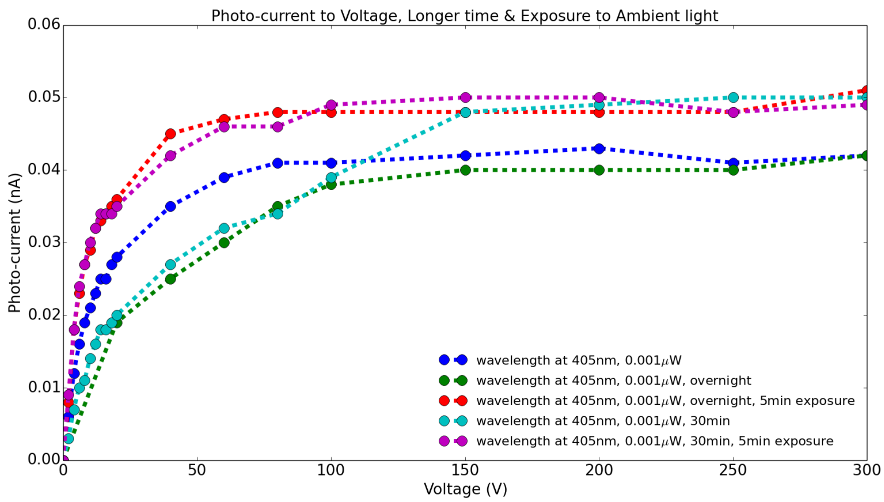

Figure 12: Blue curve shows photo-current vs. voltage at 405nm, 0.001 μW. Green curve shows photo-current vs. voltage after plateauing overnight. Longer plateauing time causes decrease in current, but does not affect plateauing photo-current significantly. Red curve shows photo-current vs. voltage after exposing the tube to ambient light for 5 minutes. A short exposure to light results in an overall increase in photo-current, which raises quantum efficiency, but still fall in the range of uncertainty of power. The cyan curve shows photo-current vs. voltage after keeping photo-multiplier tube in dark with photo-current plateauing for another 30 minutes. Photo-current decreases with time, and 30 minutes is sufficient to lower the plateauing photo-current, close to the original values (blue and green curve). Pink curve shows the effect of another 5 min exposure, which raises photo-current again.

5 Measuring the Quantum Efficiency of the FEU-527 Photo-Multiplier Tube

The first measurement of the quantum efficiency resulted in a quantum efficiency of 40%. This is double the expected value of 20% [3]. As a result, we tried to see what could be causing this discrepancy.

Our hypothesis was that there could be some sort of internal reflection causing the increased quantum efficiency. To test this, we measured the quantum efficiency of the tube at an angle to see how it would change. To take into account how distance would change while putting the tube at an angle, we also measured how distance affects the quantum efficiency. The results of our measurements can be seen in fig. 13.

The distance between the photo-multiplier tube window and the light source has an effect on the quantum efficiency of the tube that is most likely caused by the fact that at a greater distance the light disperses and the actual power of the light is less than measured. This suggests that the most accurate quantum efficiency measurement is at 0 cm from the light source. When the tube was placed at an angle to the light source, the center of the window was 0.5 cm and 1.0 cm from the light source and at an angle of approximately 22° and 39° from the parallel, respectively. Figure 14 shows that the relationship between quantum efficiency and the distance is linear and that the quantum efficiency at the angled measurement fits in this linear relationship, despite being at an angle, which suggests that the angle does not affect the quantum efficiency measurement.

Since there is some sort of dispersal of the light it was important to see by how much did this affect the quantum efficiency. To do this, we measured the intensity of the light at various distances of the Thorlabs detector from the light source. Using these measurements, assuming that at the closest measurement the detector has all of the light on it, the size of the light cone can be determined and used to correct previous measurements of power and quantum efficiency.

To begin, we take our list of powers and use our assumption that at the smallest distance the detector is completely filled to determine what the area of the cross section section of the light cone is at a given power measurement.

$$A_x = \frac{467nW \cdot 0.116in^2}{P_x} \tag{2}$$

Where A_x is the area at distance x from the light source and P_x is the measured power at distance x from the light source. 467 nW is the power measured at the closest measurement and is the assumed actual power from the light source. 0.116 in^2 is the area of the detector measuring the power.

Using A_x, we determine the radius of the cross section of the light cone with

$$r_x = \sqrt{\frac{A_x}{\pi}} \tag{3}$$

Using the data from tab. 3, we determine that the ratio of r_x to x is approximately 0.257.

Distance (in)	P_x (nW)	A_x (in^2)	r_x (in)
0.125	467	0.116	0.193
0.625	348	0.156	0.223
1.125	147	0.370	0.343
1.625	75	0.725	0.480
2.125	46	1.18	0.613
2.625	30	1.81	0.760
3.125	22	2.47	0.887
3.625	16	3.40	1.04
4.125	12	4.53	1.20
5.125	9	6.04	1.39

Table 3: Using the list of power measured at distance x from the light source (P_x) to find the area of the cross section of the light cone (A_x) and the respective radius (r_x).

To find the actual power of the light source, we first find the radius of the light cone at the distance at which the power was measured, x_m. This is found with $r_{x_m} = 0.257/x_m$. Then we find the area of this cross section, A_{x_m}, and multiply that by $P_{x_m}/0.116\ in^2$. The result is the actual power of the light source, P_A.

For the quantum efficiency measurements in figs. 13 and 14, the distance from the light source (x_m) was 0.825 in. and the measured power (P_{x_m}) for the 405 nm quantum efficiency was 1 nW. Using the above method, r_{x_m} is approximately 0.312 in, A_{x_m} is approximately 0.305 in^2, and P_A is 2.63 nW.

Using P_A, we can correct the quantum efficiency. From fig. 13, the quantum efficiency at 405 nm, 0 cm from the light fixture (which in actuality is 0.825 in. from the light source) is 47%. Correcting for the actual power of 2.63 nW instead of 1 nW, the quantum efficiency is 18%.

This correction implies that any quantum efficiency measurements made prior to this needs to be corrected for the geometry of the light cone.

If we assume that the cone is the same for each wavelength, the spectral response for the FEU-527 photo-multiplier tube is much closer to the published value of 20% f)or this tube (see fig. 15.

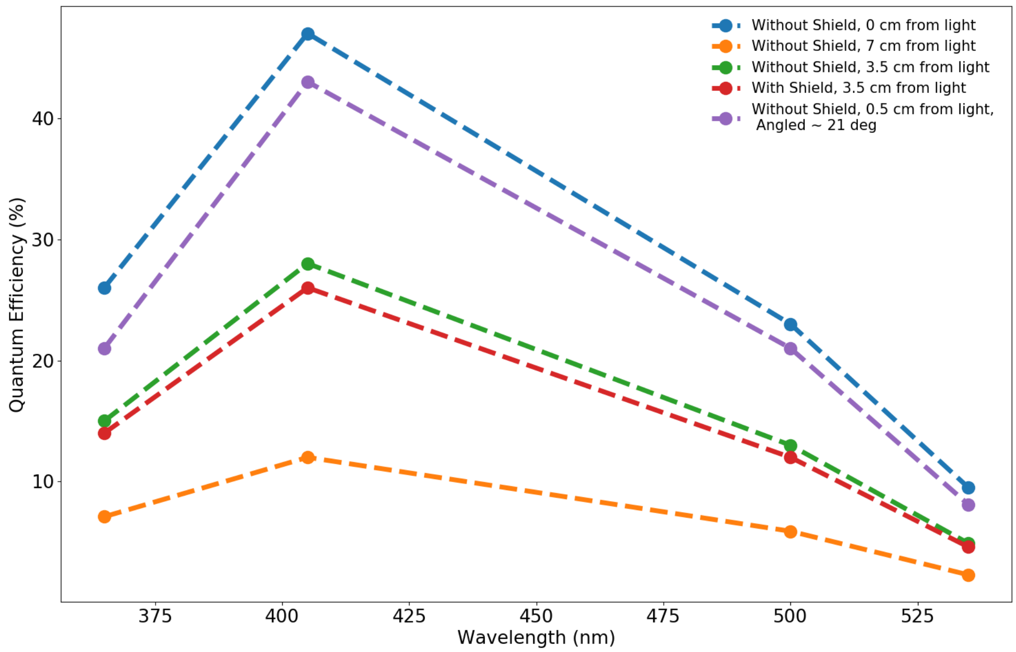

Figure 13: Quantum efficiency vs wavelength at different configurations of the photo-multiplier tube with respect to the light source. Increasing the distance between the light and the photo-multiplier tube reduces the quantum efficiency. Our hypothesis is that a cause of the high quantum efficiency is reflection of light within the photo-multiplier tube. To test this, we moved the tube to be at an angle to the light source. This lowers the quantum efficiency, but not significantly enough for that to be the root cause of the high quantum efficiency.

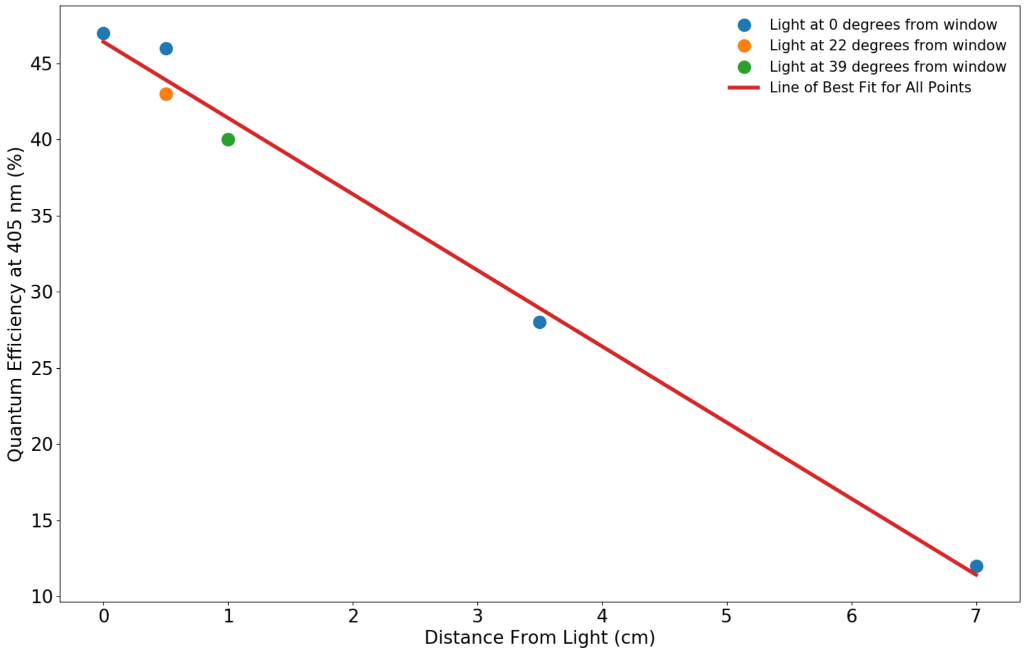

Figure 14: Quantum efficiency vs distance from the light source showing that the relationship is linear, even when the tube is at an angle to the light source.

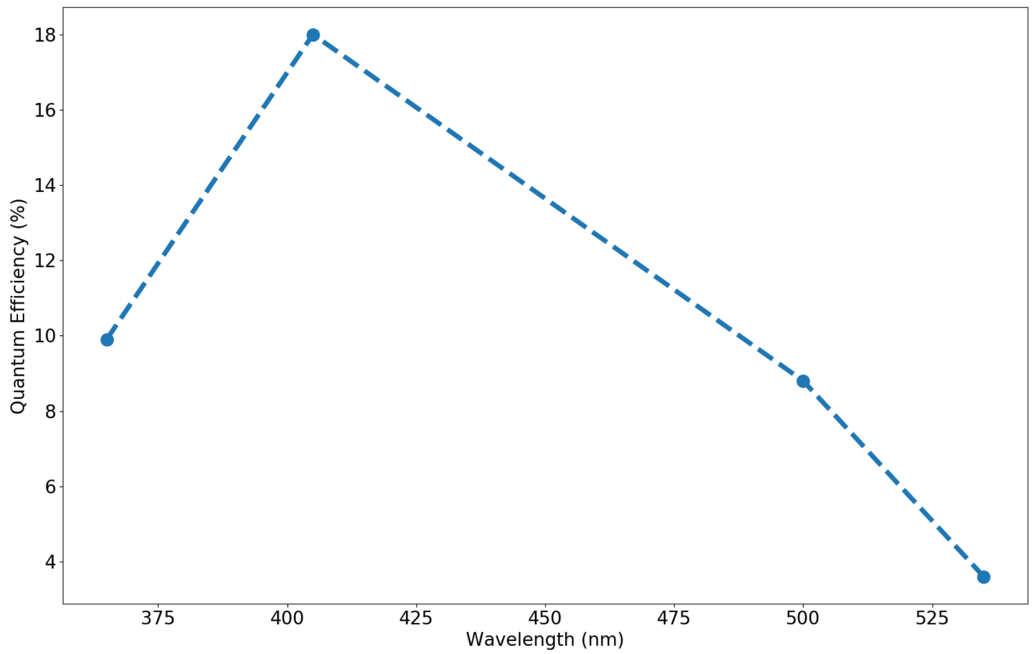

Figure 15: Spectral quantum efficiency after correcting for dispersion of light at increasing distance from the light source.

6 Conclusions

As can be seen in tab. 2 and in sec. 5, the photo-multiplier tubes measured do not agree with the expected values seen in tab. 1, with the cathode-to-anode photo-multiplier tube having a maximum quantum efficiency of 15.6% at 365 nm and the FEU-527 photo-multiplier tube having a maximum quantum efficiency of 18% at 405 nm. This latter quantum efficiency is close to the expected value for this tube [3], but is not consistent with the expected value for a K_2CsSb photo-cathode [1].

7 Acknowledgements

We would like to thank Henry Frisch for guiding us through this project, proof reading our several drafts, and helping us with understanding photo-multiplier tubes; Andrey Elagin for also helping us with understanding photo-multiplier tubes, with building our set-up, and troubleshooting problems when they arose; Eric Spieglan for helping us with building our set-up, and navigating the lab; Evan Angelico for advising us on our project, proof reading our drafts, showing us how to use the soldering iron, and helping us build our set-up; Mary Heintz for helping us navigate the computer systems; Mark Zaskowski for advising us on what materials to use for our set-up; and João Shida for proof reading our drafts.

8 References

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