Effect of anode and cathode luminous sensitivity on photomultiplier tube readings for use in the CHANDLER neutrino detector

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Abstract

In addition to their uses in scientific research, neutrino detectors can be used to monitor nuclear reactor contents from outside and without any prior knowledge of its contents. Building neutrino detectors for this purpose requires developing standards for each component. The MiniCHANDLER detector is designed to use 80 R6231-100 Hamamatsu photomultiplier tubes (PMTs), divided evenly across two faces. Since the PMTs are responsible for converting the light from the scintillators into electrical pulses, knowing how they operate in the detector individually and relative to each other is imperative to knowing how the detector will work as a whole. Hamamatsu provides the cathode luminous sensitivity (CLS) and anode luminous sensitivity (ALS) for each PMT; however, these were measured using a brighter source than the light produced in the scintillators from inverse beta decay. This study examines the correlation between ALS and average pulse height, as well as CLS and the standard deviation of the pulse height distribution using a light source more similar to the light in the detector. We did this by testing four PMTs at a time with different ALS and CLS over a range of voltages using an LED flasher designed to mimic the flashes seen in the scintillator. We found that we can use ALS to predict pulse height with a fair degree of accuracy, although the correlation between CLS and RMS is not as strong as we were expecting. With some additional research, we would like to use ALS and CLS to set standards on what PMTs we should use in the final detector and calibrate the PMTs in the detector accordingly.

1 Introduction

Unlike other by-products of nuclear fission, electron antineutrinos are not normally stopped by the shielding around nuclear reactors [1]. Neutrino detectors can therefore be used to understand and monitor the contents of the reactor without ever needing to know the original core contents. CHANDLER detectors are designed to do this while remaining outside of the reactor using these principles.

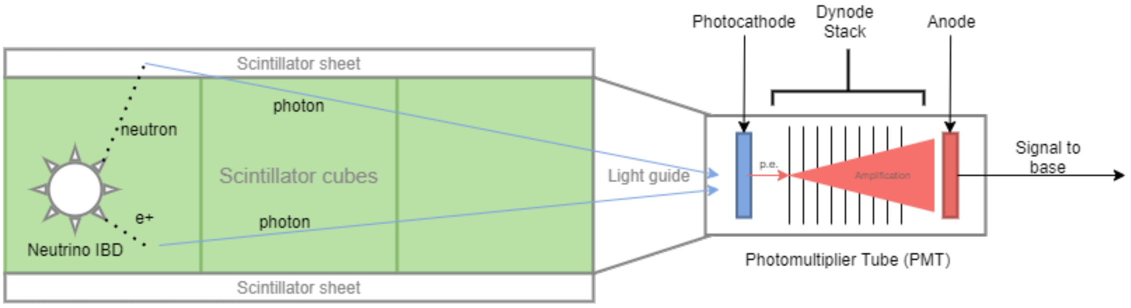


Figure 1: Diagram of how CHANDLER works

Photomultiplier tubes (PMTs) are an essential part of CHANDLER neutrino detectors. The detectors use a Raghavan optical lattice of plastic scintillator cubes with sheets of lithium-6 loaded zinc sulfide scintillator to detect electron antineutrinos [1]. This process produces scintillation photons that travel through the cubes by total internal reflection to the PMTs where they are captured using a photocathode. Photoelectrons produced from the cathode are then amplified using a dynode stack. The dynode stack is a set of dynodes held at progressively lower negative voltages to pull the electrons toward the next dynode. When a single electron strikes a dynode, the energy imparted by it releases multiple more electrons, which then travel to the next dynode and repeat the process. This allows us to take a few photoelectrons and amplify them to a large signal that can be analyzed to determine the properties of the original antineutrino.

The current version, MiniCHANDLER, is designed to use 80 R6231-100 PMTs produced by Hamamatsu; for comparison, the full CHANDLER detector will use 1920 PMTs. Since the CHANDLER detector will use so many PMTs, determining how they will behave before installing them is imperative to understanding how the detector as a whole will operate, in addition to setting standards for future detectors.

In addition to serial number, type, and test date, Hamamatsu provided cathode luminous sensitivity (CLS) and anode luminous sensitivity (ALS) for each PMT. CLS is defined by Hamamatsu as “the photoelectron current generated by the photocathode (cathode current) per luminous flux from a tungsten lamp operated at a distribution temperature of 2856 K” [2]. ALS is measured in the same way but with a filter to reduce the range of light flux from $10^{-5} - 10^{-2}$ lumens to $10^{-10} - 10^{-5}$ lumens. They are measured in µA/lum and A/lum, respectively. Since the PMTs need to capture light on a much smaller scale than that, we wanted to see if ALS and CLS measured by Hamamatsu were still an accurate measure of how they would perform. If this is the case, we could use ALS and CLS as criteria for determining which PMTs to use in the CHANDLER detector. In addition, if we can predict what a given PMT’s readings will be at a certain voltage, we can match pulse height and root mean square (RMS) across multiple PMTs to create more uniform outputs from the detector.

2 Methods

To test the PMTs, we put a frame with five scintillator cubes in a dark box to simulate the detector. An LED flasher was placed on top of the center cube and held in place by a bracket to make sure that it was as close to equidistant from all PMTs as possible. The frame allowed for four PMTs to be tested at a time, so we originally started with four PMTs with ALS ranging from 26.2 to 61.8 and CLS ranging from 125 to 143. Using these four PMTs, we took the average pulse height, RMS of the pulse heights, number of pulses, and outliers at voltages ranging from 800-1300 V.

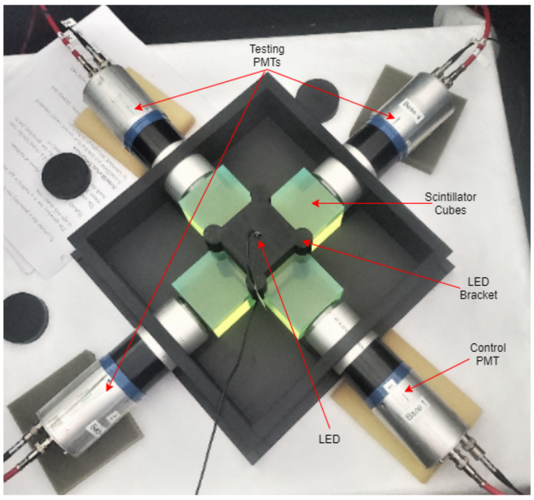


Figure 2: Testing setup in the dark box

During preliminary testing, we noticed that there were some external factors that contributed to readings. Temperature of the room would change the average pulse height readings, so we corrected for that by comparing the pulse height of the control to its expected pulse height at a set voltage. By dividing the control pulse height by the expected pulse height, we could get a drift correction factor to multiply the other three PMTs’ average pulse heights by to adjust for drifting. We also noticed that orientation of the base would affect the readings since the dynode stack is rotationally asymmetric. We corrected for this by marking the same spot on each of the bases and making sure that the mark was facing up; since the PMTs will only fit into the base in one way, this prevents any skewing of the data based on orientation. In addition, any scratches or dust on the cubes would also skew the data, so we used new cubes for testing and handled them with gloves. Lastly, if the PMT had not been used before, we noticed that there was a “burn in” period; because of this, we added an hour-long burn in run before starting the “ramp up” tests that would test the PMTs at 10 V intervals from 800-1200 V.

To see how well we could predict a given PMT’s average pulse height and RMS over a voltage span, we used the preliminary testing data to develop the following formulas:

$$\text{pulse height} \;=\; \text{control pulse height} * \frac{ALS}{\text{control ALS}}$$

$$\text{RMS} \;=\; \frac{\text{pulse height} * \text{control RMS} * \text{control CLS}}{\text{CLS} * \text{control pulse height}}$$

We then used these formulas to calculate a simulated average pulse height and simulated RMS for each PMT to compare to test data. For testing all 87 PMTs, we modified the pulse height formula to account for the external factors in a similar way to how we modified the testing to account for these factors. Since we used a constant control for the tests instead of a control that stepped up with the three other PMTs, we used an averaged best fit line from multiple “ramp up” tests of the control tube. The final pulse height formula was as follows:

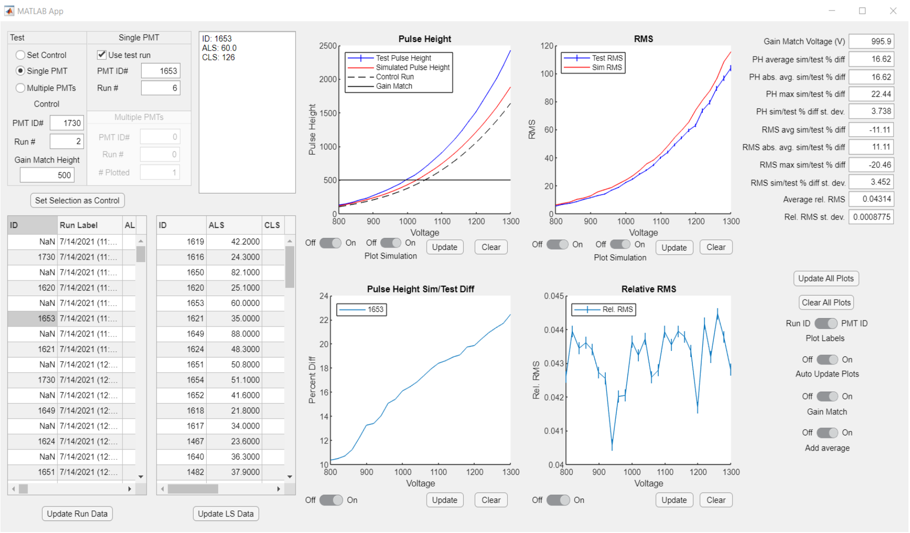
$$\text{pulse height} = \text{average fit} * \frac{\text{ALS}}{\text{control ALS}} * \frac{\text{expected control pulse height}}{\text{test control pulse height}}$$

where the average fit is the averaged best fit line from multiple control "ramp up" tests.

To test the PMTs, we first selected three PMTs and placed them in the dark box, making sure that the front face was against the cube and the orientation mark on the base was upright. The control tube was kept in the same orientation for every test. After making sure everything was in place and putting the lid on the dark box, we ran an hour long “burn in” test with two stages; the first stage was holding the PMTs at 1300 V for 30 minutes, and the second stage was holding the PMTs at 800 V for 30 minutes. After the burn in, we ran a “ramp up” test similar to the preliminary “ramp up” tests but this time using 20 V intervals and going from 800 V - 1300 V.

3 Analysis

To analyze the data, we created a Matlab app that allowed us to compare the simulated and test results, as well as pull important information about each PMT, such as what voltage they would need to match at a certain pulse height.



○ Set Control
● Single PMT
○ Multiple PMTs

Control
PMT ID# 1730
Run # 2
Gain Match Height 500

☑ Use test run
PMT ID# 1653
Run # 6

PMT ID# 0
Run # 0
Plotted 1

ID: 1653
ALS: 60.0
CLS: 126

ID	Run Label	AL
NaN	7/14/2021 (11:...	
1730	7/14/2021 (11:...	
NaN	7/14/2021 (11:...	
1620	7/14/2021 (11:...	
NaN	7/14/2021 (11:...	
1653	7/14/2021 (11:...	
NaN	7/14/2021 (11:...	
1621	7/14/2021 (11:...	
NaN	7/14/2021 (12:...	
1730	7/14/2021 (12:...	
NaN	7/14/2021 (12:...	
1649	7/14/2021 (12:...	
NaN	7/14/2021 (12:...	
1624	7/14/2021 (12:...	
NaN	7/14/2021 (12:...	
1651	7/14/2021 (12:...	

ID	ALS	CLS
1619	42.2000	
1616	24.3000	
1650	82.1000	
1620	25.1000	
1653	60.0000	
1621	35.0000	
1649	88.0000	
1624	48.3000	
1651	50.8000	
1654	51.1000	
1652	41.6000	
1618	21.8000	
1617	34.0000	
1467	23.6000	
1640	36.3000	
1482	37.9000	

Gain Match Voltage (V)	995.9
PH average sim/test % diff	16.62
PH abs. avg. sim/test % diff	16.62
PH max sim/test % diff	22.44
PH sim/test % diff st. dev.	3.738
RMS avg sim/test % diff	-11.11
RMS abs. avg. sim/test % diff	11.11
RMS max sim/test % diff	-20.46
RMS sim/test % diff st. dev.	3.452
Average rel. RMS	0.04314
Rel. RMS st. dev.	0.0008775

Figure 3: Matlab app used in testing

We used this app to plot the simulation and the test to compare them, as well as to calculate average percent differences between the simulations and tests. We also used it to calculate relative RMS:

$$\text{relative RMS} = \frac{RMS}{\text{pulse height}}$$

We used relative RMS to remove pulse height from the calculation, making it a more direct measurement of CLS.

To find the percent difference between the simulated run and the test run, we used the following formula:

$$\text{percent difference} = \frac{\text{test} - \text{simulation}}{\text{test}} * 100$$

$$\text{absolute percent difference} = \frac{|\text{test} - \text{simulation}|}{\text{test}} * 100$$

We then recorded the average percent difference and average absolute percent difference for RMS and pulse height. Using this data, we were able to come up with the following distributions:

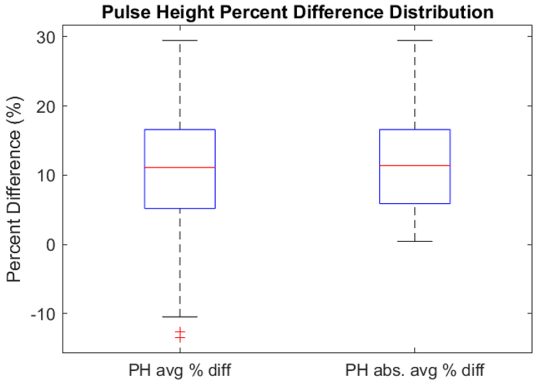


Figure 4: Pulse height simulation/test percent difference distribution

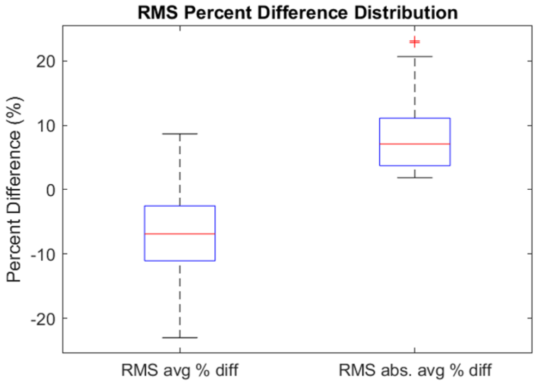


Figure 5: RMS simulation/test percent difference distribution

From these plots, we can gather that our simulation differs from the test by 11.88 percent on average for pulse height and about 8.33 percent for RMS. This inaccuracy could be caused by additional factors that we haven't taken into account in our simulation, inaccuracy in the simulation formula, or something else entirely. Looking for these factors is one of the next steps we plan on taking.

For ALS and CLS, we expected to see a correlation between ALS and pulse height at a set voltage, as well as for $1/\sqrt{CLS}$ and relative RMS. We did see a correlation between ALS and pulse height but not as much of a correlation for CLS and relative RMS. In the future, we'd like to look into why that is and if we can still use CLS as a measure of PMT performance for our detector.

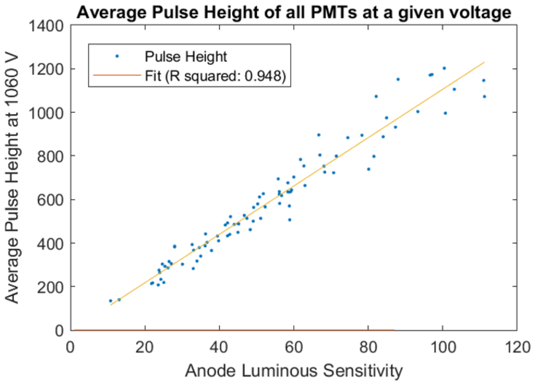


Figure 6: ALS effect on pulse height

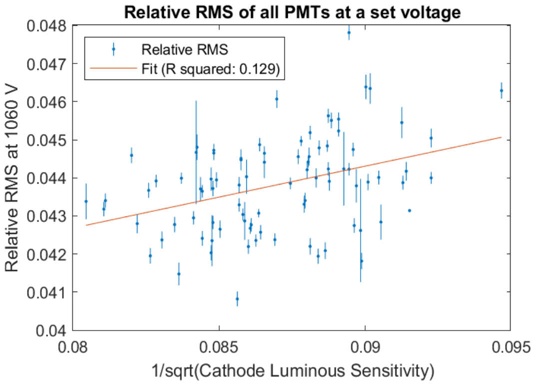


Figure 7: CLS effect on relative RMS

4 Conclusion

We can approximate pulse height and RMS with an average absolute percent difference of 11.88% and 8.33%, respectively. ALS does correlate with pulse height but CLS does not necessarily correlate with RMS, so we will need to look more into why that is before we can definitively say that we can use CLS as a measure of PMT performance. We would like to use both numbers as a criteria for ordering PMTs for other CHANDLER detectors. So far, it looks like we can do that for ALS, but we will need to research CLS more before we can determine if we can use it or not.

5 Acknowledgements

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References

[1] A. Haghighat et al., "Observation of Reactor Antineutrinos with a Rapidly Deployable Surface-Level Detector," Phys. Rev. Applied, vol. 13, no. 3, p. 034028, Mar. 2020, doi: 10.1103/PhysRevApplied.13.034028.

[2] Hamamatsu Photonics K.K., "Photomultiplier Tubes: Basics and Applications," Hamamatsu, 4th ed. 2017.