CHARACTERIZATION OF LARGE DIAMETER PMTS FOR KAON CERENKOV DETECTOR

Catholic University of America Nuclear Physics Internship Final Report

Abstract

The 12GeV upgrade at the Jefferson Laboratory allows for unique new opportunities to study hadron structure through kaon production in Hall C, a threshold aerogel detector was constructed at the Catholic University of America. It uses the emission of Cerenkov radiation at different indices of refraction ranging from 1.03 to 1.01 to distinguish pions, kaons, and protons. An important aspect of this detector is the collection of very small amounts of light, in particular as the aerogel refractive index decreases. The Hall C aerogel detector uses the Photonis XP4500 large-diameter photomultiplier tubes (PMT) in order to detect these small traces of light. The purpose of this project is to explore the performance of alternative large-diameter PMTs and compares them to that of the XP4500. The PMT uniformity across the photocathode was characterized through scans along the surface of the PMT with a low-intensity, focused LED, thereby creating a 3D image of the gain at each section. The method of scanning consists of a two axis step motor moving an LED light source on a 100 x 100 grid parallel to the face of the PMT, with 30 pulses of light from the LED at each step. The step motor scans with a resolution of 1.2 mm. Scans conducted in this manner result in high resolution images which pick up most sensitive/non-sensitive spots on the photocathode. In this presentation I will present the results of the characterization and performance test of the XP4500 and comparison to alternative large-diameter PMT models.

Derek Boylan

Derek.j.boylan@gmail.com

Introduction

The purpose of this experiment was to investigate the gain and uniformity of different PMTs that are available to be used in the Cherenkov radiation detector built by The Catholic University of America and housed in Hall C of Jefferson Laboratories (J-Labs). In order to do this, the PMTs were scanned along their photo cathode, and the average number of photoelectrons received along a 100 x 100 grid of the face were recorded.

Photomultiplier tubes (PMTs) are vacuum-tight light detectors compromised of a photo-cathode face, multiple dynodes, an anode, and a source of high voltage, all of which convert photons into a stream of electrons (current). The front-facing photo-cathode in the PMTs at Catholic University create a flow of electrons when struck by light due to the low work function and the high voltage running through the system that allow for the photo electric effect to easily create a small amount of current when struck by photons. This current is then amplified through a series of dynodes which create a cascade of electrons that increases exponentially with an increase in the number of dynodes and linearly with an increase in their gain. Finally the anode collects the current of electrons and transmits it [1].

Photomultiplier tubes have a few key properties of interest to this experiment, primarily gain and uniformity. The gain of the PMT is defined as the ratio of the number of electrons received at the anode to the number of electrons emitted from the cathode after the photo electric effect knocks off electrons from the cathode from the energy of an incoming photon [1]. The uniformity of a PMT is essentially the difference between the gains of the PMT across the entirety of the PMT. While uniformity cannot be summed up by a single calculated number, pictorial graphs depicting the gain at each point of a certain resolution on a PMT's cathode can help identify portions of the

PMT which should be avoided, or possibly help determine whether a PMT cannot be used in an experiment at all. The uniformity of a PMT is especially important when used in detectors where the position of the incident photons matters for determining what kind of particle it is. For example, in Cherenkov detectors, the angle at which the Cherenkov radiation is emitted determines what particles created that radiation at a certain refractive index of material.

Photomultiplier tubes are widely used in the experimental physics world, in small scale experiments where a light detector is needed, and in large-arrays in the world's most massive particle detectors. Their ability to detect single photons, in addition to their relative simplicity makes them one of the best light detectors for physicists. PMTs are commonly used in detectors such as Cherenkov detectors and calorimeters. For this experiment, the PMTs were tested for performance in a Cherenkov detector, which requires a PMT able to detect very low intensities of light and also have a similar gain across the entire surface of the PMT to detect photons across the entirety of the PMT face.

The specific type of detector that these PMTs are being tested for is a threshold aerogel Cherenkov detector. These detectors utilize the eponymous phenomenon of Cherenkov radiation in order to identify particles. When a charged particle travels faster than the speed of light, it emits Cherenkov radiation in the form of photons, which can happen in certain media, such as water, or in the case of the Jefferson Lab detector, aerogel. This radiation follows the law $\cos(\theta) = \frac{1}{(n\beta)}$, where θ, the Cherenkov angle, is the angle at which the radiation deviates from the velocity of the particle, n is the refractive index of the material through which the particle travels, and β is the velocity of the particle in units of the speed of light($\frac{v}{c}$). The threshold for a particle to emit radiation is where $\theta = 0$, or in other words, where $\beta = \frac{1}{n}$. Since a

Cherenkov detector is able to measure the Cherenkov angle, and momentum is measured via a magnetic spectrometer, then it goes to follow that the mass can be calculated, thus identifying the particle [2].

Threshold aerogel detectors have two main components: a radiator which produces photons from the incident charged particle via its refractive index, and a photo-detector which detects the photons [2]. Along with these components, the necessary infrastructure to house the radiator and photo-detector and to transport the photons must be included. In the case of Jefferson lab, Silica aerogel is the radiator in the threshold aerogel Cherenkov detector, and Photonis XP4500 PMTs are the photo-detector. Therefore, PMTs are an integral part of Cherenkov detectors such as the one at Jefferson Laboratories and serves an important role in identifying particles and advancing the field of nuclear physics. The goal of this experiment is to determine whether the Hamamtsu R1584 PMT ought to replace the Phtonis XP4500s in the Cherenkov Detector.

Materials and Methods

Characterization of the following PMTs:

Figure 1: Photonis Model XP4500/B, Serial 09641

Figure 2: Photonis Model XP4572/B/D1

Figure 3: University of Virginia PMT - Hamamatsu R1584 - http://www.hamamatsu.com/us/en/R1584.html

Other materials

- LED 470 nm wavelength
- Two axis motor
  - http://www.velmex.com/bislide_model_display.asp?id=19http://www.velmex.com/bislide_model_display.asp?id=19
- High Voltage Power Supply
- Coda programming to translate signal from PMT
- Anti-Magnetic Shielding
- Dark box and black cloth
- Optical fiber
- PS Octal 300 mHz Discriminator model 708
- PS Quad gate generator model 794
- Lecroy 2249A channel ADC http://www.fnal.gov/projects/ckm/jlab/2249a-spec.htm

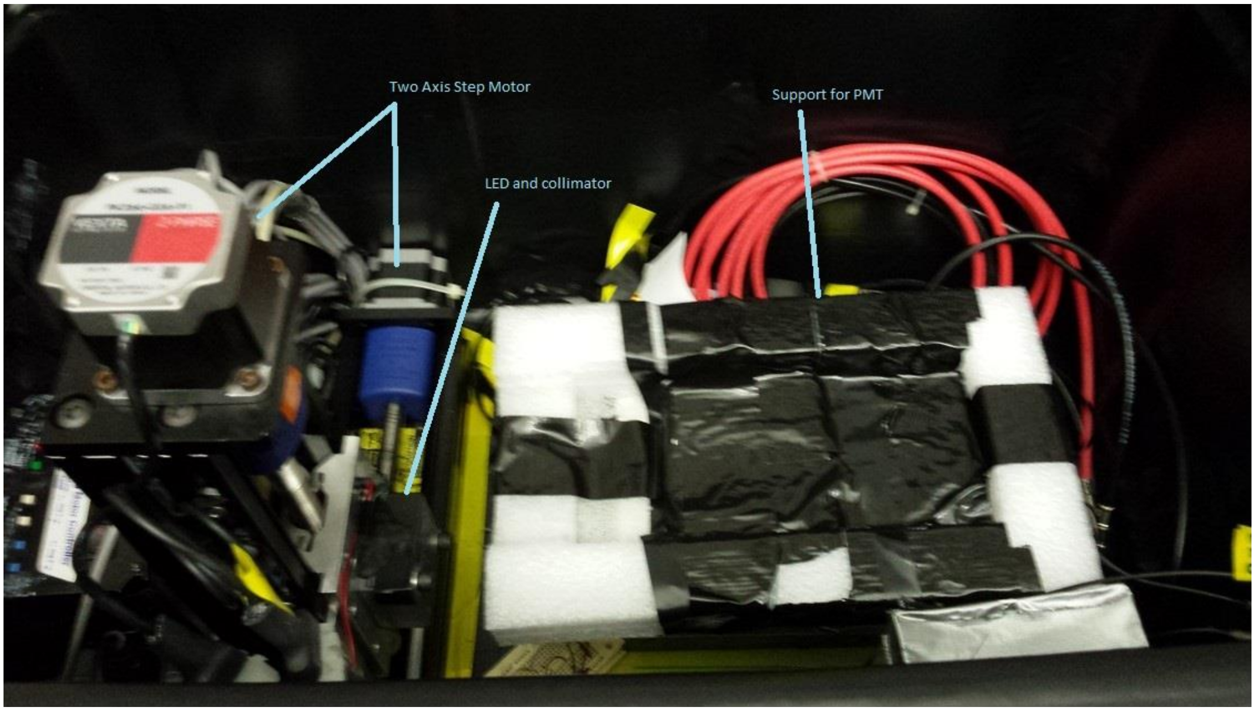

Figure 4: Experimental setup. All equipment secured in a light-tight dark box with dark cloth to cover it.

The two axis motor is set to move in a 100 x 100 grid, moving 1.125 mm each step in that grid. At each point, the collimated LED equipped to the stepper motor blinks a total of 30 times. The LED signal was lined up with a PS Quad gate generator model 794 which created a gate, through which the signal could be interpreted by a Lecroy analog to digital convertor. At each blink, the analog to digital convertor integrates the current received from the PMT and thus alters the measure to charge. However, it gives the measure in counts, where each count is equivalent to 0.25 pC. The measurements interpreted by the analog to digital convertor were recorded by a Data Acquisition (DAQ) computer by a program called CODA, created for the Jefferson Laboratories National Accelerator Facilities. This data was then plotted into graphing software to depict the gain across the photocathode. The Stepper motor moves with a step distance of 0.0025 mm with every motor turn, and the resolution of our setup is set to move 450 turns for each 30 pulses of the LED, giving the scan a resolution of 1.125 mm. The total distance that each axis covers is 112.5 mm, which means that it is just under the 120 mm effective area of the

Hamamtsu PMT tested (the effective area of the two Photonis PMTs was unstated). While this means that not every single edge of the PMT can be plotted, enough of the PMT is covered with a high enough resolution that the uniformity of each PMT is clearly shown. The setup thus described existed prior to this experiment and was used to conduct other experiments in the past. In addition to the former setup, in this experiment, a foam support was constructed to hold a PMT in the same spot over numerous different scans, thus increasing the ability to compare different PMTs. An optical fiber that extended the collimator was also removed from the setup because on the round faced XP4500 PMT, the fiber would curve at the center of the PMT if not given ample space, at which point the LED intensity becomes low to the point where it loses the precision it should have near the edges of the PMT.

The first attempt at scanning a PMT in this experiment came with a myriad of problems. The first PMT scanned was the Photonis XP4500/B, as this was the PMT currently being used in the CUA-constructed Cherenkov radiation detector at J-Labs.

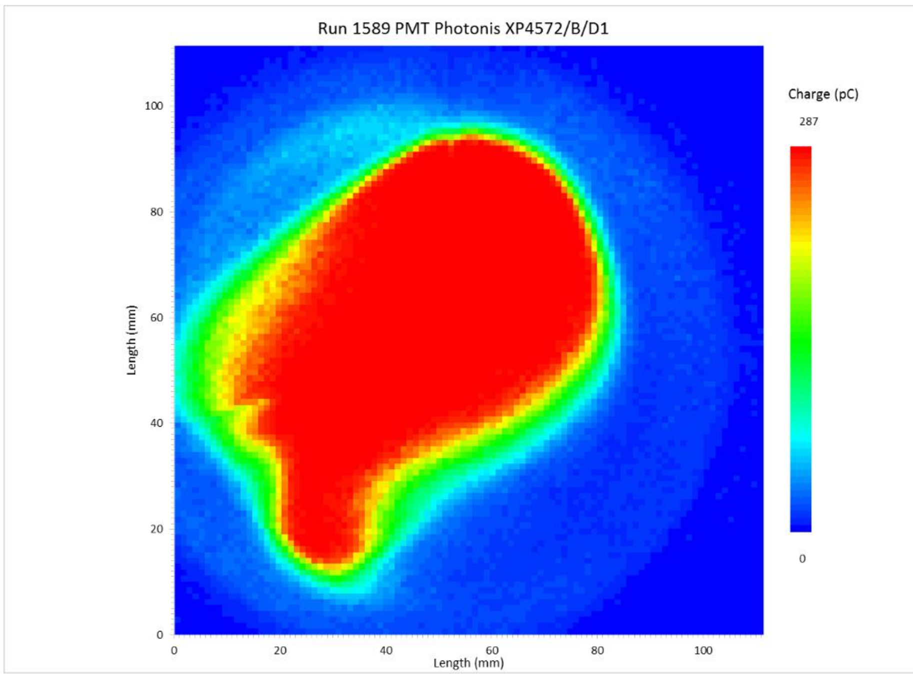

Figure 5: Run number 1589, taken on 07/03/14, with Photonis XP4500/B PMT in 100 x 100 grid with 30 LED blinks at each point. Taken at -1.7 kV high voltage.

After this incident, the intensity and high voltage was decreased to see if a more uniform structure could be determined, but that also proved fruitless, and returned a non-uniform structure. In addition, the PMT was rotated 180 degrees to see if the same shape that existed in the previous scan would also exist in scan 1589.

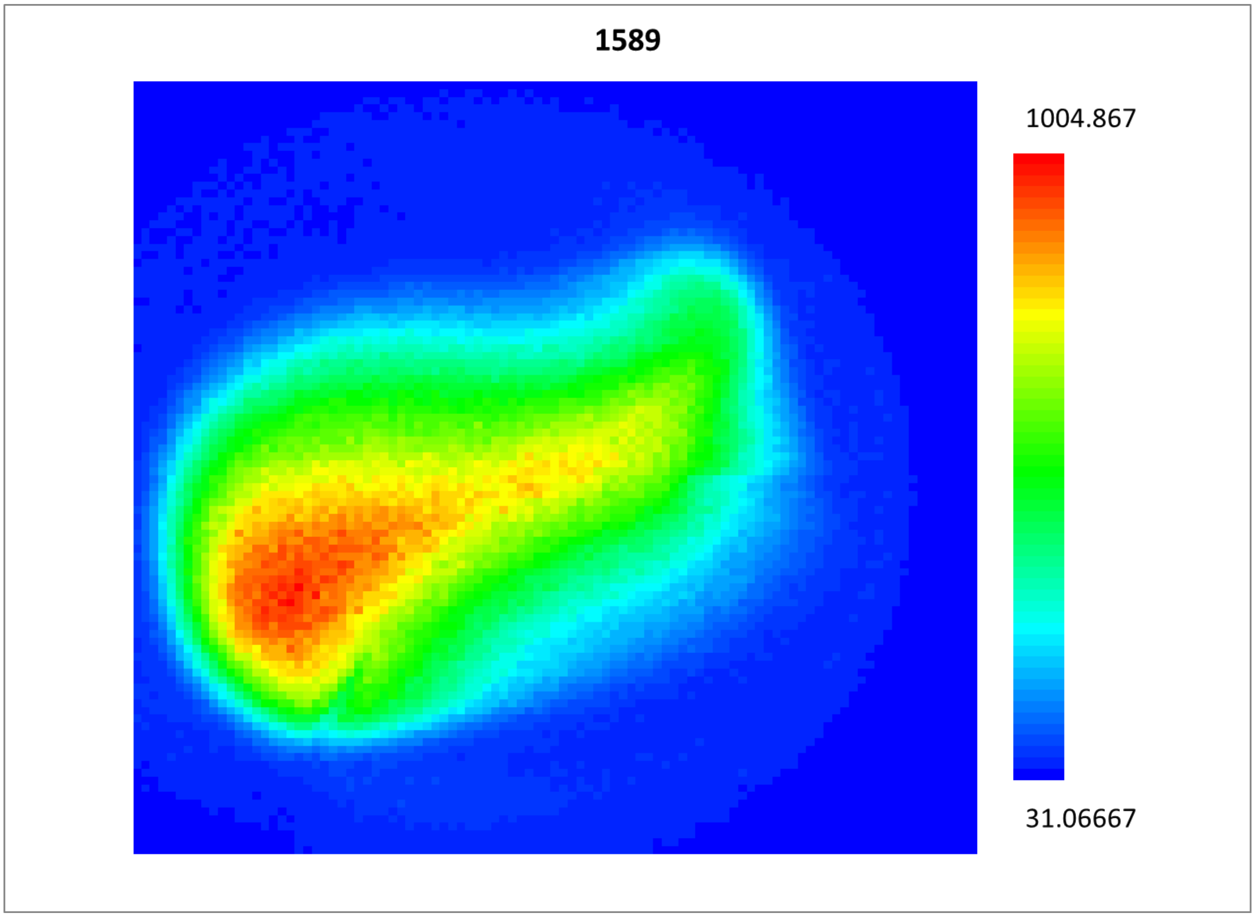

Figure 6: Run number 1594, conducted on 07/03/14 with XP4500/B PMT at -1.5 kV, rotated 180 degrees from previous scan. Units are arbitrary as it was not converted since the scan did not reveal any information save for the fact that something about the scanning method/setup was not correct.

After two failed attempts at scanning the XP4500, a different PMT, the Photonis XP4572/B/D1 was tested as this had been previously scanned and could thereby used to troubleshoot the problems with the scanning procedure. Results from this scan yielded similar results to the XP4500, and thus concluded that the PMT was not the problem with the poor uniformity.

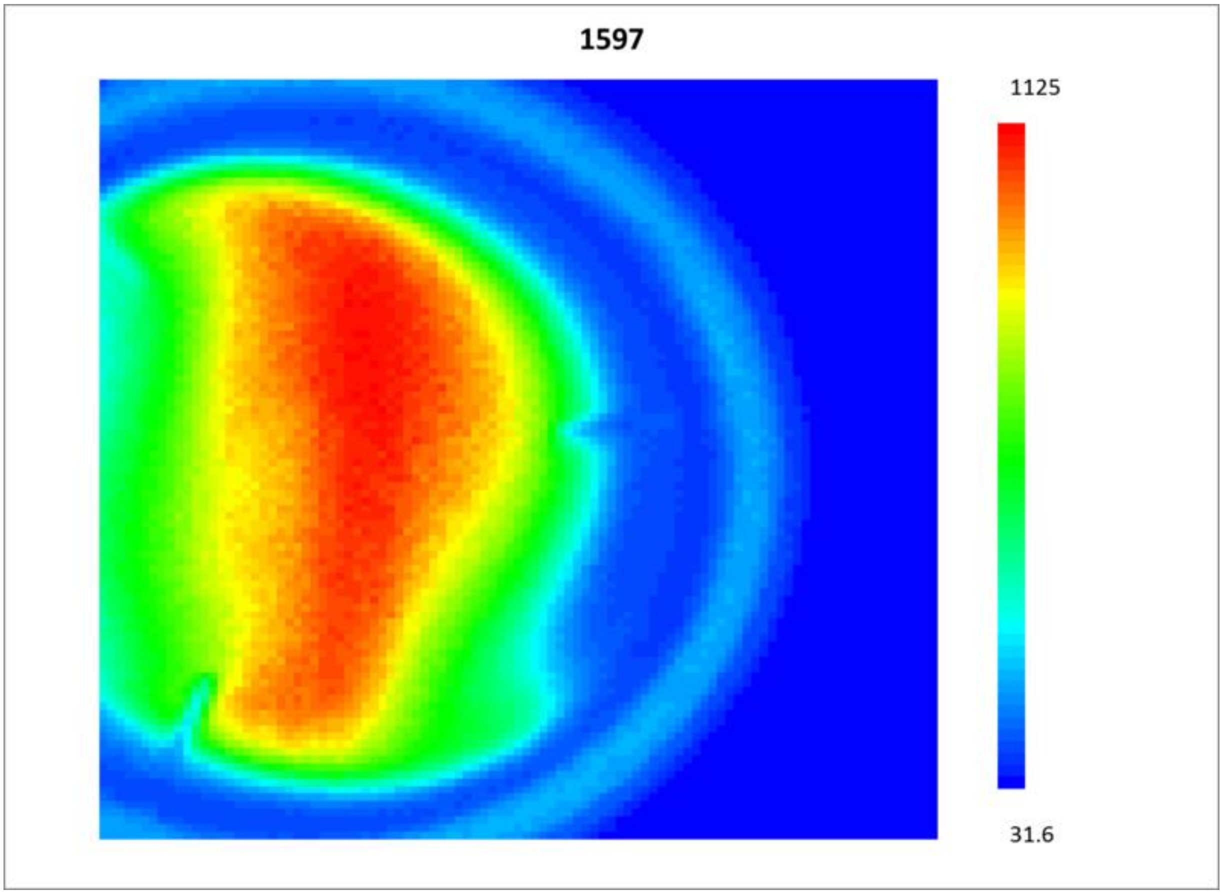

Figure 7: Scan of previously scanned/optimized PMT (Photonis XP4572). -1.7 kV. Optical fiber removed.

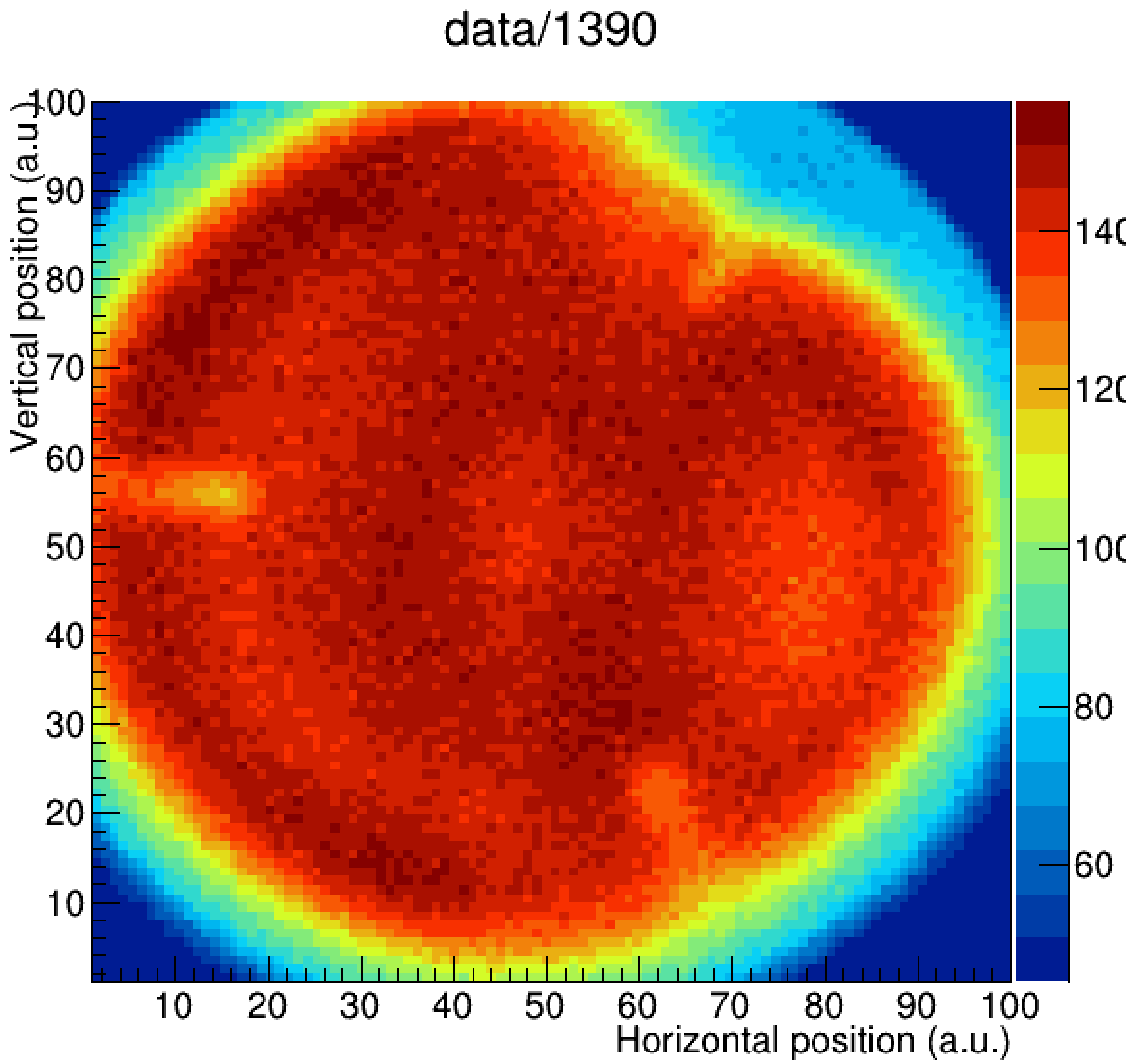

Figure 8: The scan conducted previously of the Photonis XP4572. Much more uniform than the scan previously shown. Form this scan, and scan 1597, it is clear that the PMT is not broken, unless it broke within February 2014 and July 2014. Scan created by Marco Carmignotto.

After the previous scanned demonstrated something was wrong with not the PMTs but the setup, three more scans were conducted at a lower resolution and rotated approximately 90 degrees each time to see if the PMT kept the same non-uniform appearance in different positions.

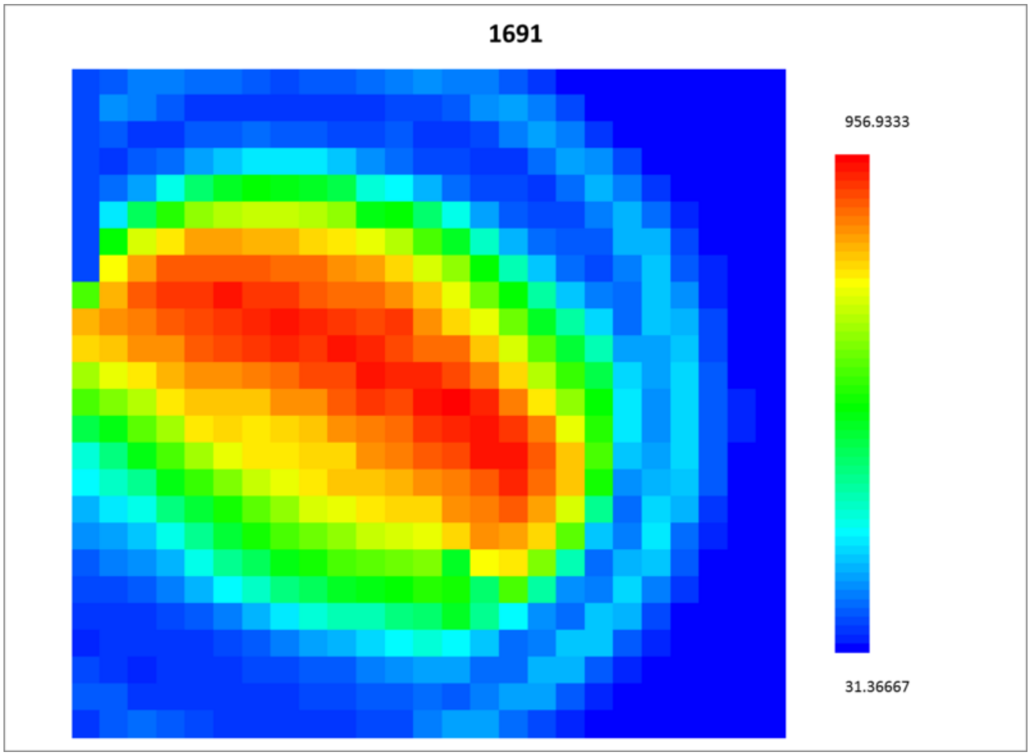

Figure 9: Lower resolution scan of XP4572 to troubleshoot fast. Began rotation of PMT to check to see if pattern remained the same.

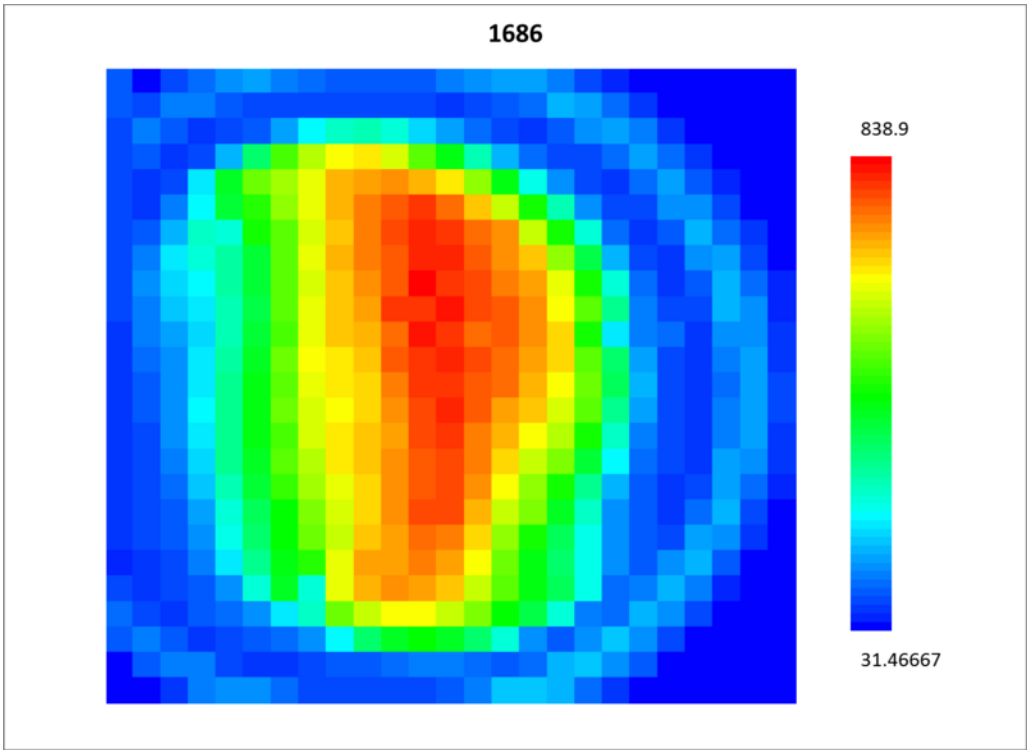

Figure 10: Another rotation of XP4572.

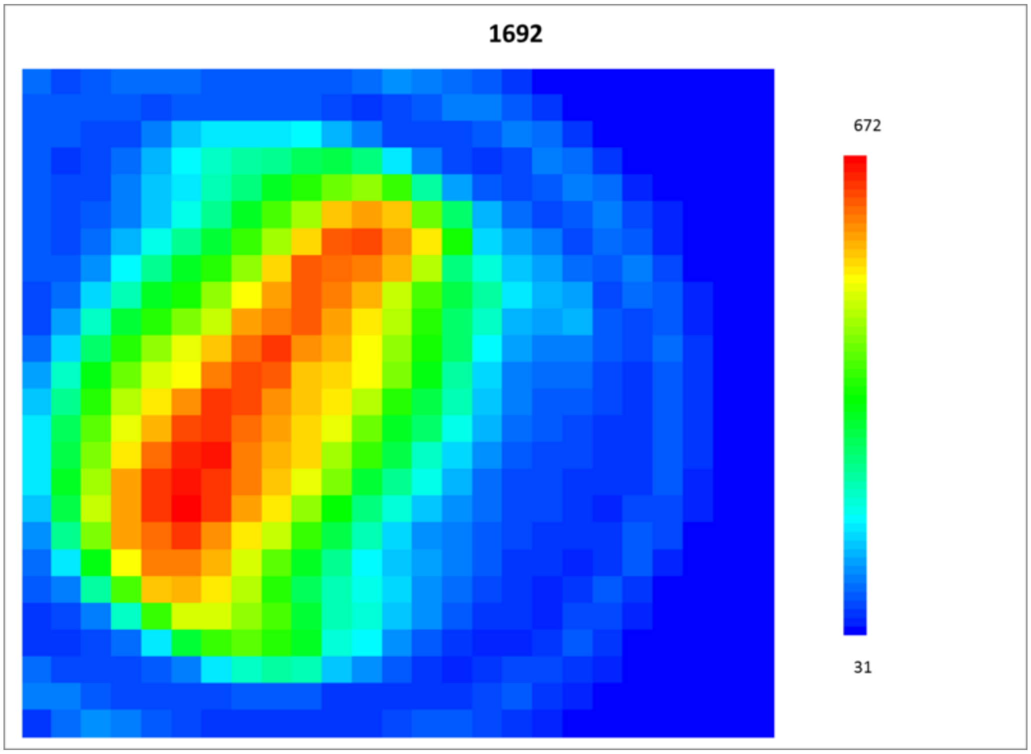

Figure 11: Final rotation of Xp4572.

After this many failed scans, the base of the PMT (which was used for both the XP4500 and the XP4572 was switched out to a different base of the same type. The resulting scans demonstrated a higher level of uniformity, possibly concluding that the erroneous previous scans were caused by a base that could not distribute charge correctly across the PMT, thereby meaning that the PMTs were not broken, but rather the base was unequally distributed.

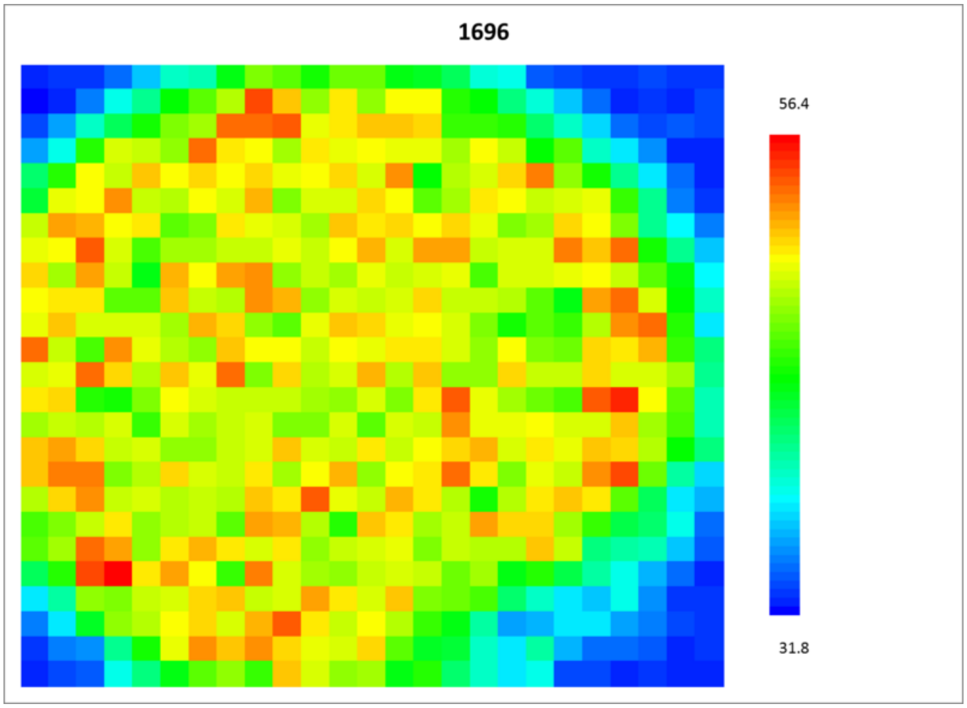

Figure 13: Uniform scan after changing the base of the PMT to one that distributes charge better. While not completely uniform, the scan resembles Figure 8, and not Figure 11, Figure 10, Figure 9, or Figure 7.

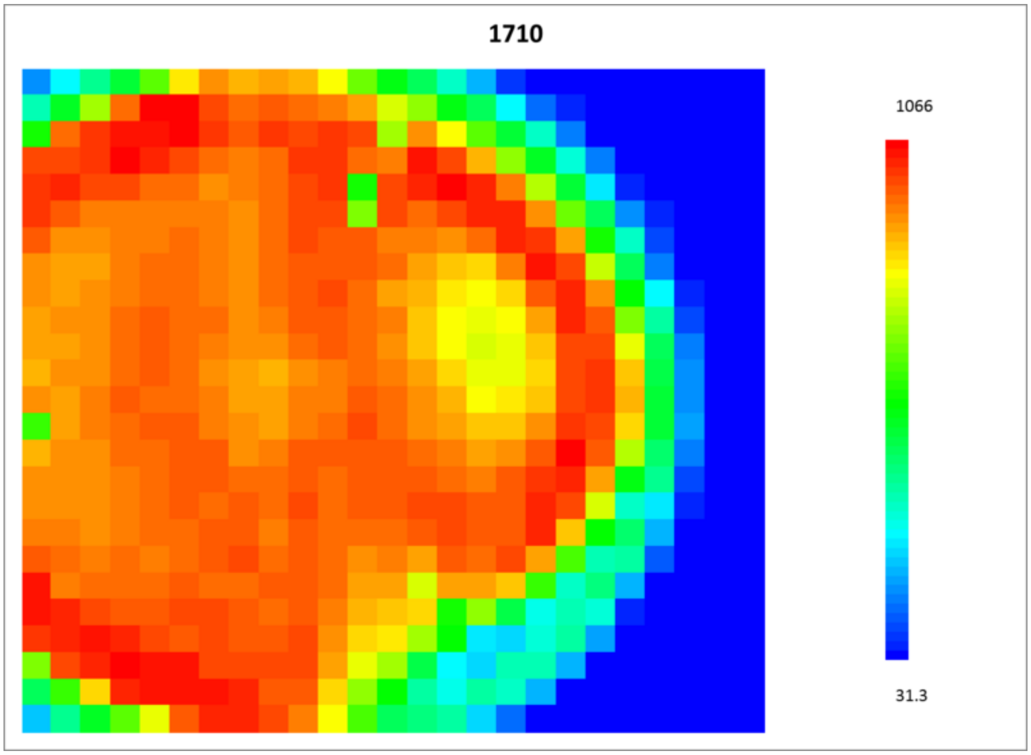

Figure 12: Higher intensity, low resolution scan of XP4572. Demonstrates similar appearance to run 1390.

Following the improvements through a non-broken base, the measurements of the step motor length were calculated and the conversion from counts to charge on the analog to digitical convertor was added to the z axis (the color of the graph). These improvements made the testing apparatus ready to take data for both the XP4500 and the R1584.

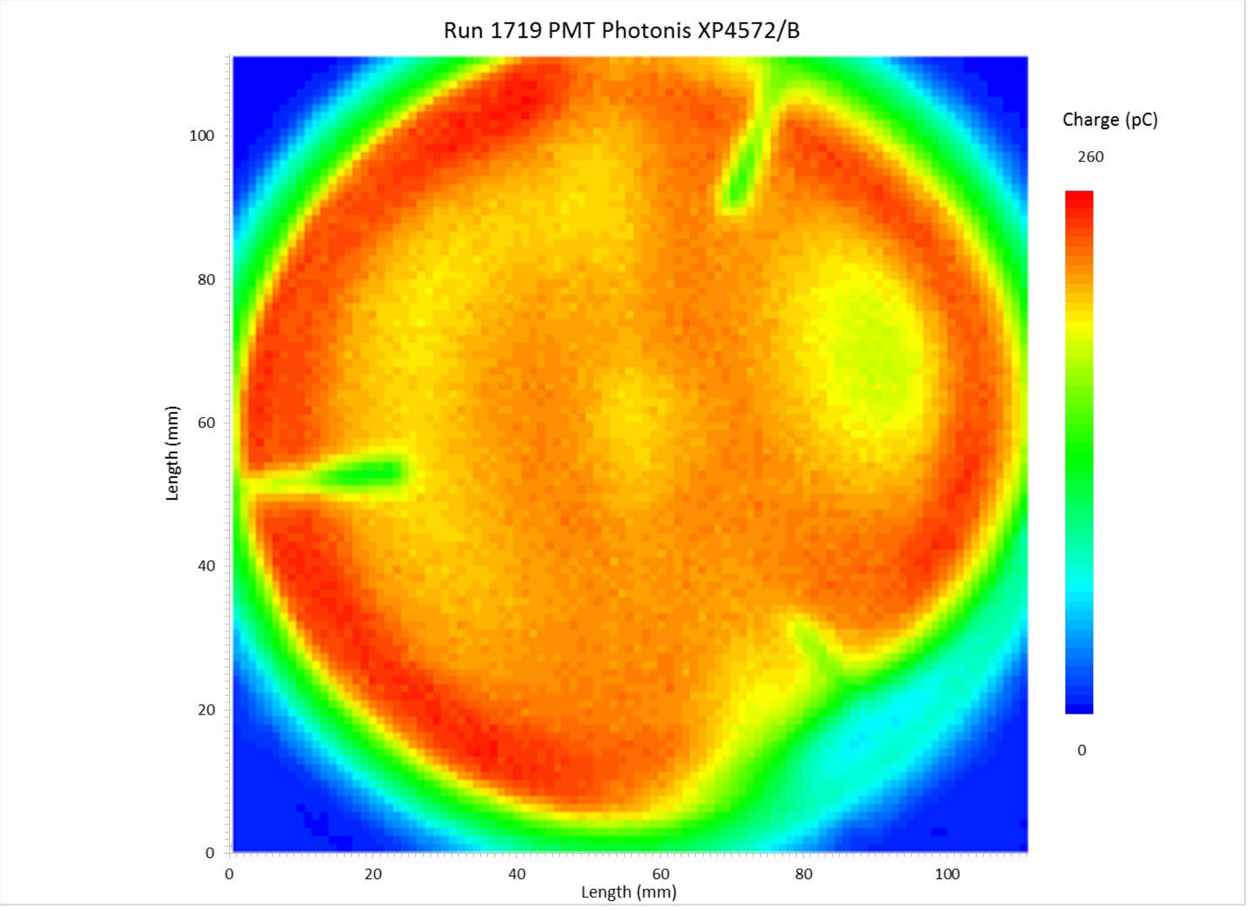

Figure 14: Another higher resolution scan of the XP4572. Almost identical, save for graphing software (which makes different colors) as the one conducted in February 2014 (1390). Temperature axis updated to now include charge, as this graph actually shows useful data. Also, the step motor length increments were calculated and thus plotted on the x and y axis of the graph as well.

While the charge reading of the analog to digital convertor is helpful, the true measure that is more important to the PMT is the number of photoelectrons received, which can be calculated via a gain test. The gain of a PMT is calculated by shining an LED at the lens of the PMT at the minimum intensity needed to convert a photon into an electron from the photo cathode via the photo electric effect. At this intensity, some of the LED blinks will register as only background noise, and some will register as an amplified signal. By creating a histogram of this data, two peaks will appear. One, the pedestal, represents the background noise of the wires and other equipment, read even without a signal from the PMT. The other peak, which can be calculated by a Gaussian curve fit or through a mean calculation at two points on opposite ends of the peak, is the single electron peak, or the amplification of the signal of a single electron passing through the PMT.

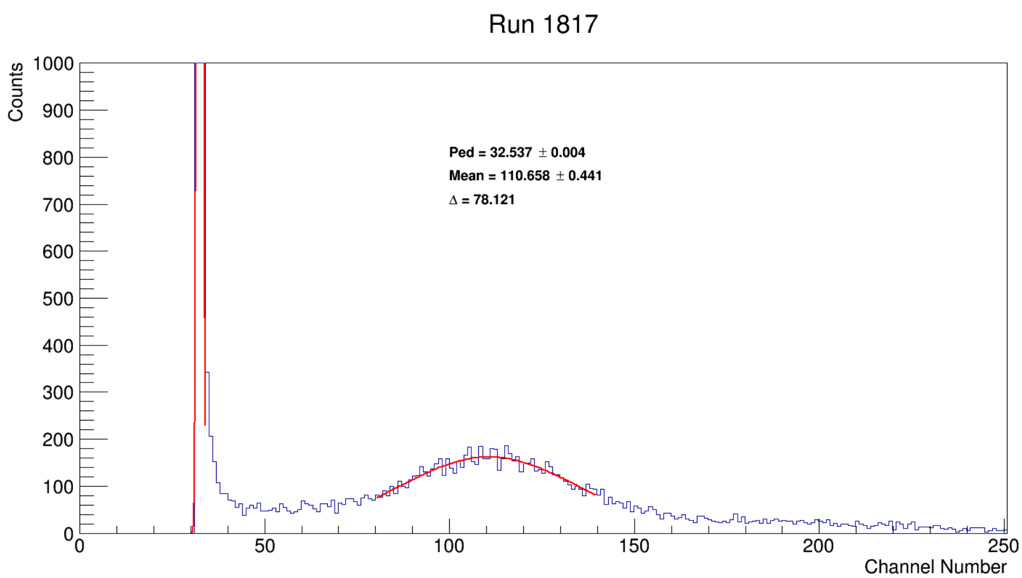

Figure 16: Gain test for the R1584 PMT. With these measurements, the photoelectron count of the PMT. This value is calculated by subtracting the pedestal (Ped) amount from ever measurement and then dividing the resulting value by the difference between the Single electron peak (SEP) and the pedestal.

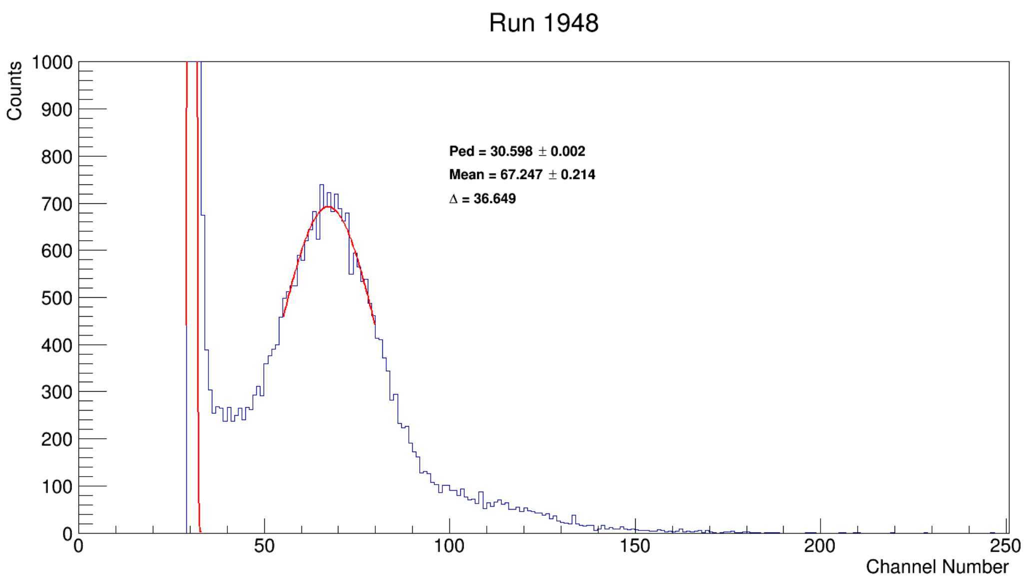

Figure 15: Gain test for XP4500

Results:

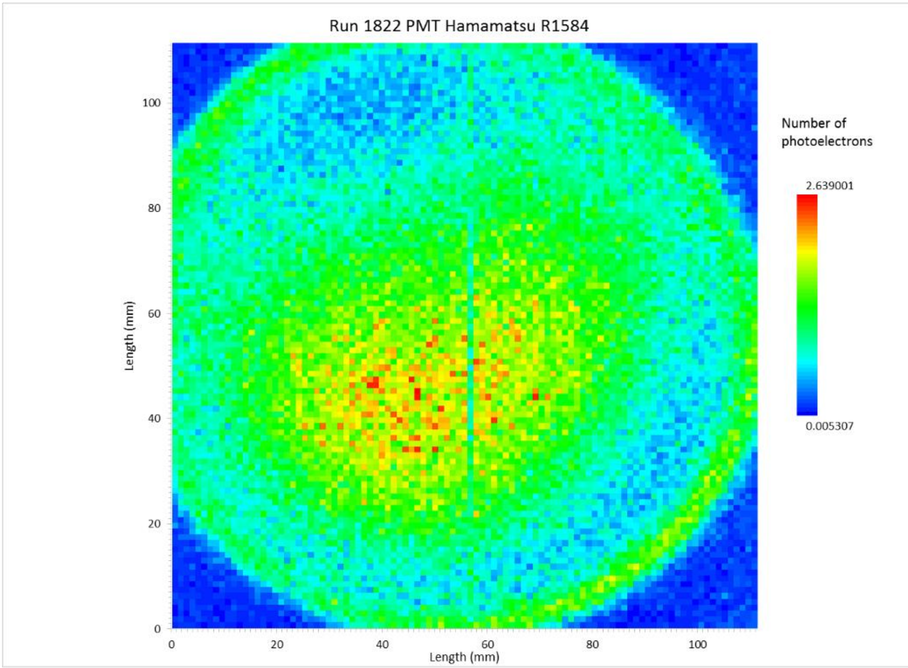

Figure 18: Preliminary scan of R1584. Not the best uniformity. Low number of photoelectrons is due to low intensity of light, and not gain of PMT. High voltage remains the same as the gain test (1817) for this PMT. The blue line of lower numbers of photoelectrons comes from the motor getting stuck at the bottom because of a lack of lubrication on the screw that operates the vertical axis. There is no deformation in the PMT that causes this blue line.

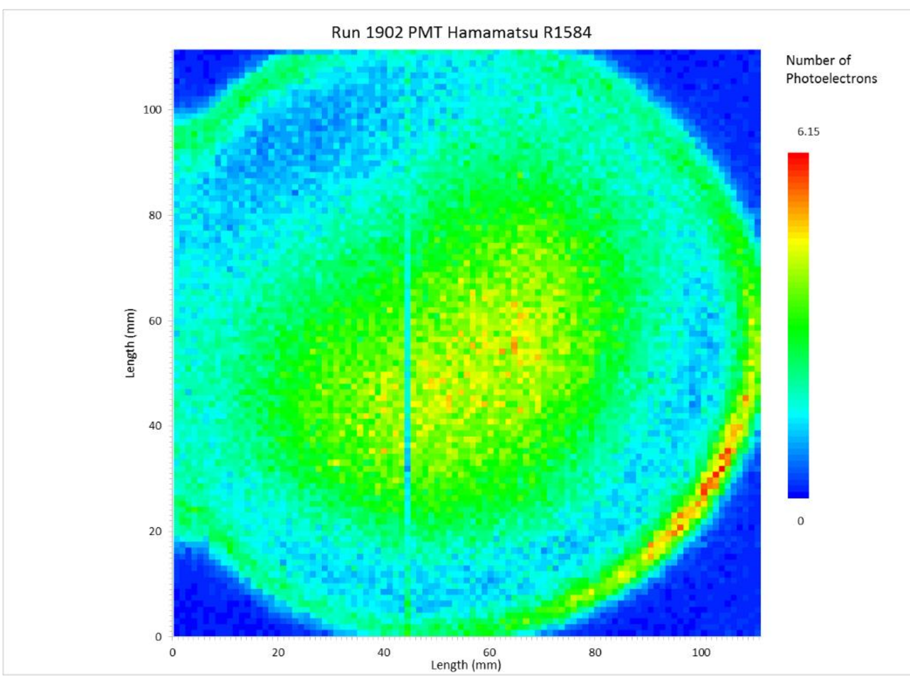

Figure 17: Another scan of the R1584, but this time rotated 180 degrees to see if the shape of the high gain region of the PMT remained the same. What is interesting in these scans is that the outer ring of the PMTs has a high amount of photoelectrons recorded by the anode, whereas other PMTS usually have lower amounts of gain on the very outer edges of the photocathode.

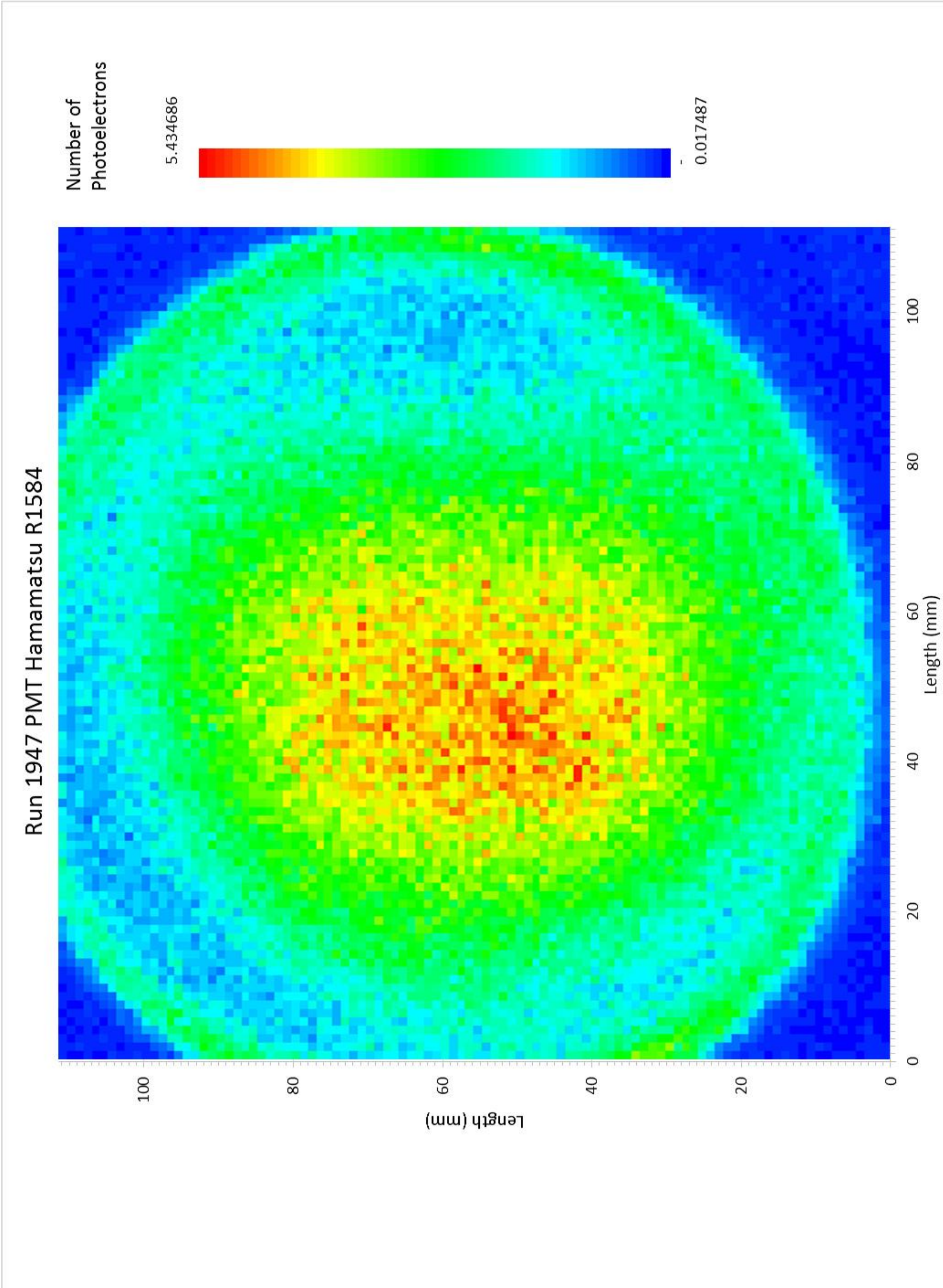

Figure 19: Final scan of the R1584 PMT at 1800 V. This scan had higher intensity from the LED and appeared more uniform than previous scans. In addition, the motor did not stick in the middle of the scan, and therefore is not obscuring any part of the PMT.

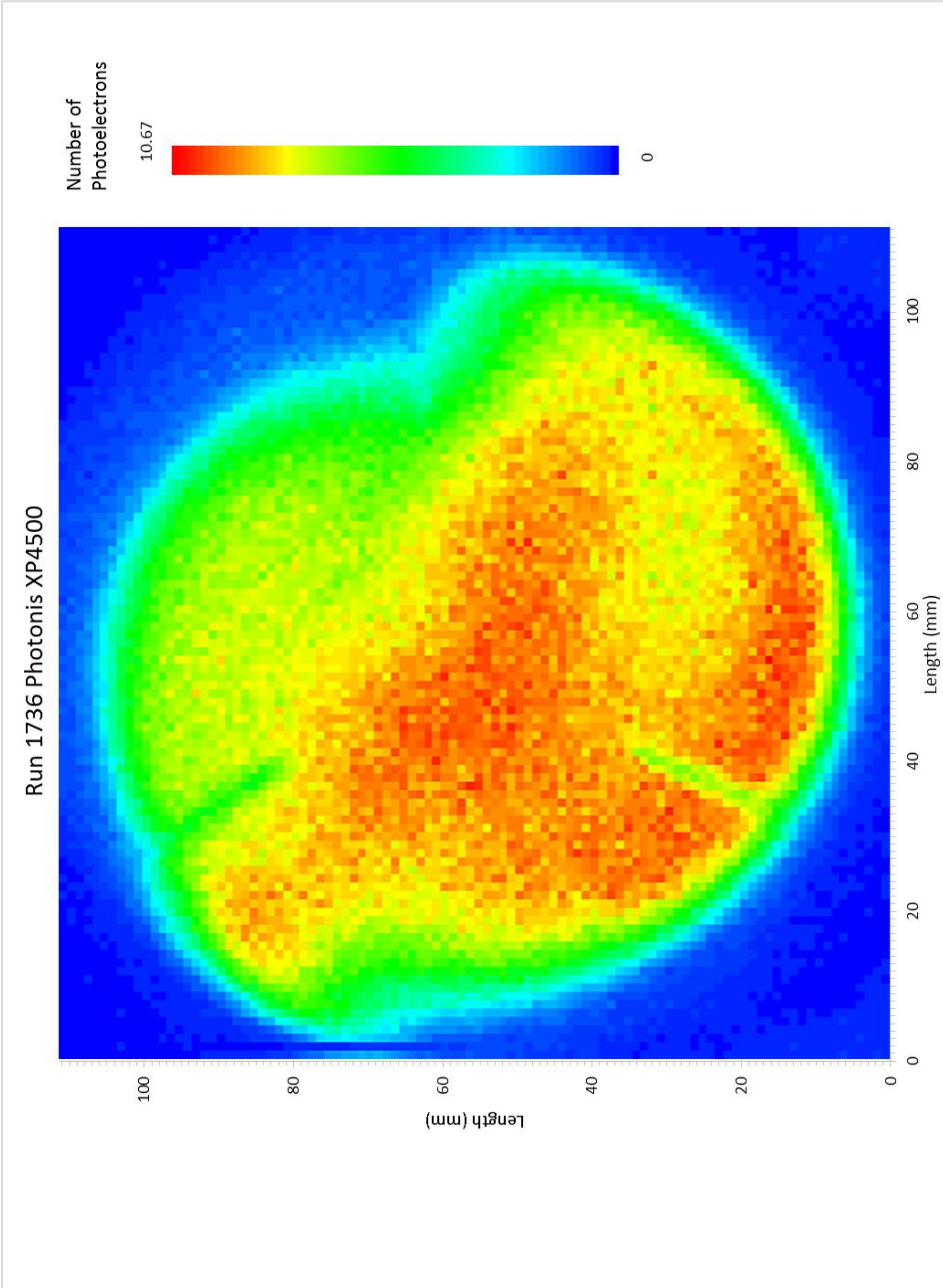

Figure 20: Scan of the XP4500 PMT.

Analysis:

The Hamamtsu R1584 has very good uniformity in the center of the PMT within about a 20 mm radius, but then the gain of the PMT drops significantly outside of that circle, demonstrating that this PMT may not be best for applications that require equal gain across larger distances than 20 or 30 mm. For some reason, the outer edge of the PMT demonstrates moderately high gain as compared to the section 10 mm from the outer radius of the PMT, which has lower gain. This feature is uncharacteristic to other PMTs tested such as the XP4500 or the XP4572. The uniformity of this PMT lends itself to experiments with beams aimed directly at the center of the PMT, rather than experiments where the photon could hit anywhere along the photocathode of the PMT.

The Photonis XP4500/B PMT, even with the improved base, shows a large area of low gain in the topmost region. This could be some sort of deformity in the PMT itself also possible that it could be a problem with the scan since operator error did lead a large strip of the PMT to not be scanned. However, as this did not interfere with the area that showed low gain. The three markings on the edges that point towards the center are existing marks on the photocathode, which prohibit the photoelectric effect from occurring in those places. The very center of the PMT shows moderate uniformity within a ten millimeters radius, and therefore experiments conducted with a limited range would be well-suited for such a PMT. The very outer edge of the PMT has a lower gain than the rest of the PMT, unlike that of the Hamamatsu R1584.

Overall, neither of the PMTs is ideal for situations where uniformity is the most important characteristic of the PMT. The XP4500 has slightly better uniformity, but if any photons hit within the green and yellow section on the face. It is likely that the XP4500 is not working to the full extent that the product is capable of due to the fact that the XP4572 tested earlier in this paper had a much higher uniformity than the XP4500. However, the Photonis R1584 doesn't seem to have any problems, but rather seems to be designed to have the highest gain in the center of the photocathode face. In order to test the results taken in Catholic Universities Scans, a comparison between these results and the results of Donald Day, a physics professor at the University of Virginia, from whence cometh the PMT. Day's tests consisted of covering the UVA photocathode with a material and then placing washers to create circular holes along the face of the PMT. Then, he shined an LED through each of the holes and recorded the collection efficiency at each point (with the assumption being made that the center of the PMT would have a collection efficiency of 1, where all photons would be counted). Day's tested failed to test the very outer edge of the PMT, which means that oddly high gain seen in the CUA tests will not be able to be verified.

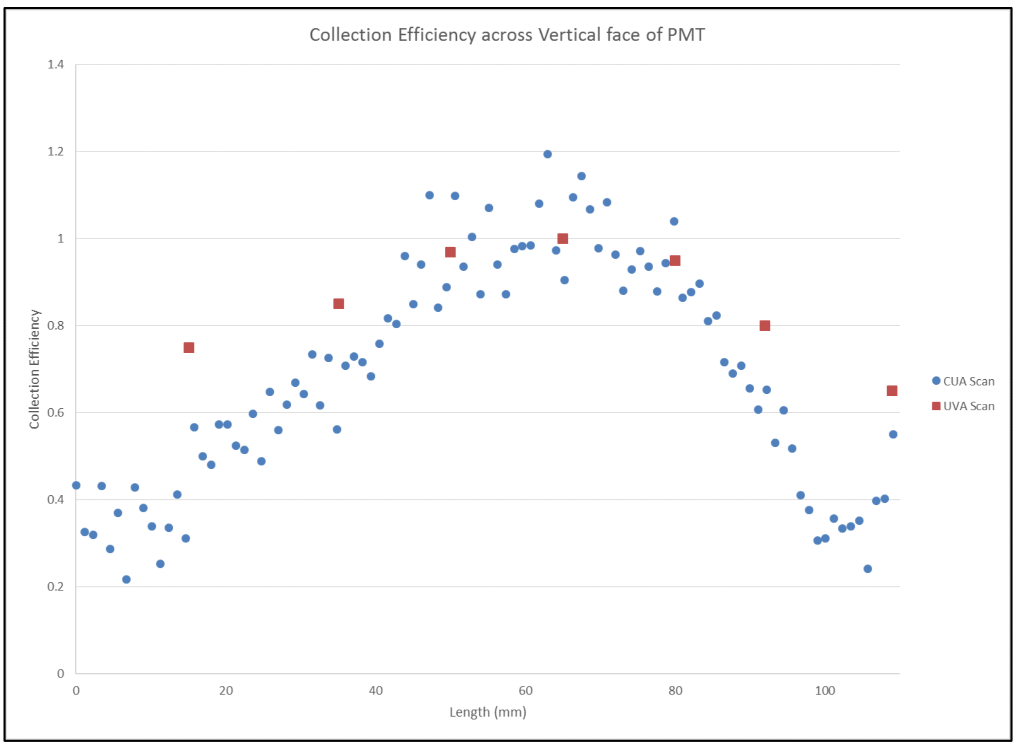

Figure 21: The red squares represent the scan conducted by Donald Day at the University of Virginia. The blue circles represent the data collected by the Catholic University scan.

Day's test showed no indication of a ring on the outer edge of the PMT that had a higher gain than the inner edge, as the Catholic University one did. In addition, the UVA scan did not have the same declination of collection efficiency moving away from the center of the PMT that the CUA scan did. However, both graphs do show a drop off in gain, when moving away from the center of the PMT. While it was speculated that it was possible that the base of the R1584 could have been faulty and not supplied voltage to the entirety of the photo cathode, but that is less likely with the results of Donald Day, as both demonstrate that the photo cathode has a center that has a higher gain than the inner edges of the PMT.

Calorimeter Model:

The following images depict a calorimeter to be put in place in Hall C of Jefferson Laboratory and designed by Catholic University. By no means is this a complete drawing set from which the calorimeter will be built, but it is more just an aesthetic model to demonstrate what the device will look like once completed. For videos of the device rotating, please see: http://www.vsl.cua.edu/cua_phy/index.php/MainPage:Nuclear:Summer2014:PMTCharacterization.

Figure 22: Front face of the Calorimeter with 30 x 36 Lead-Tungsten crystals (PbWO4).

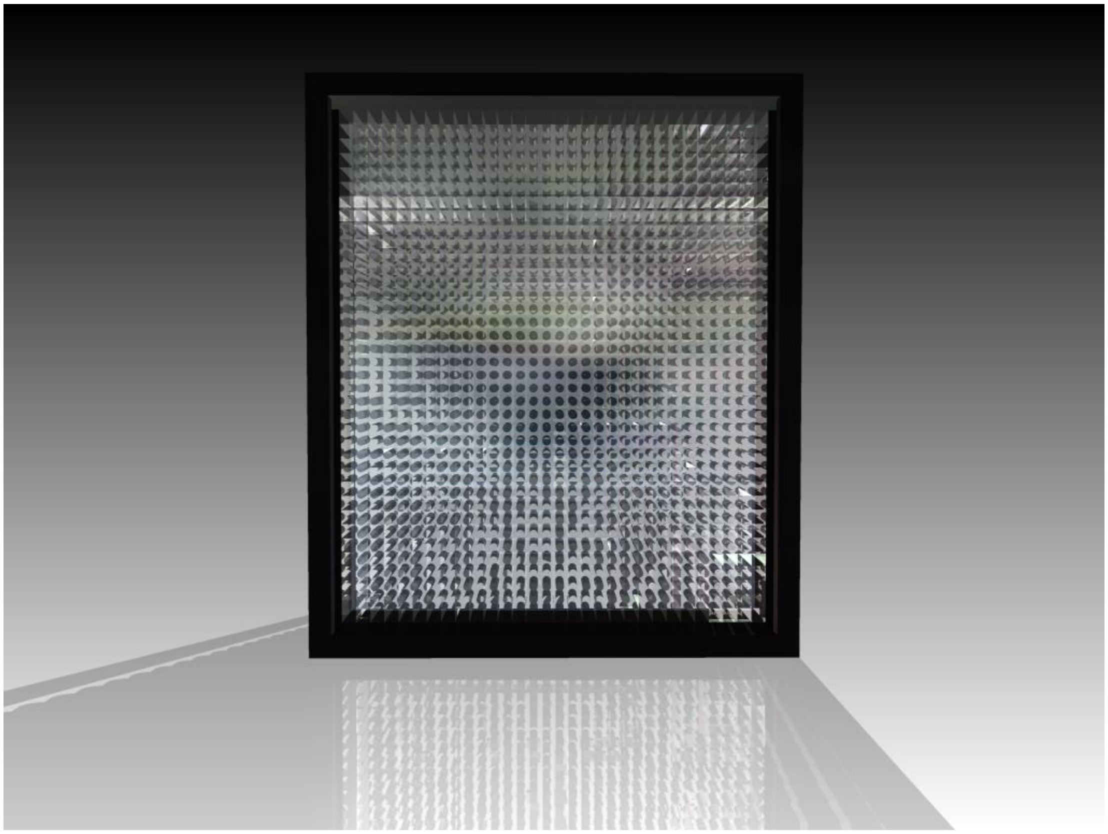

Figure 23: Front face of the calorimeter.

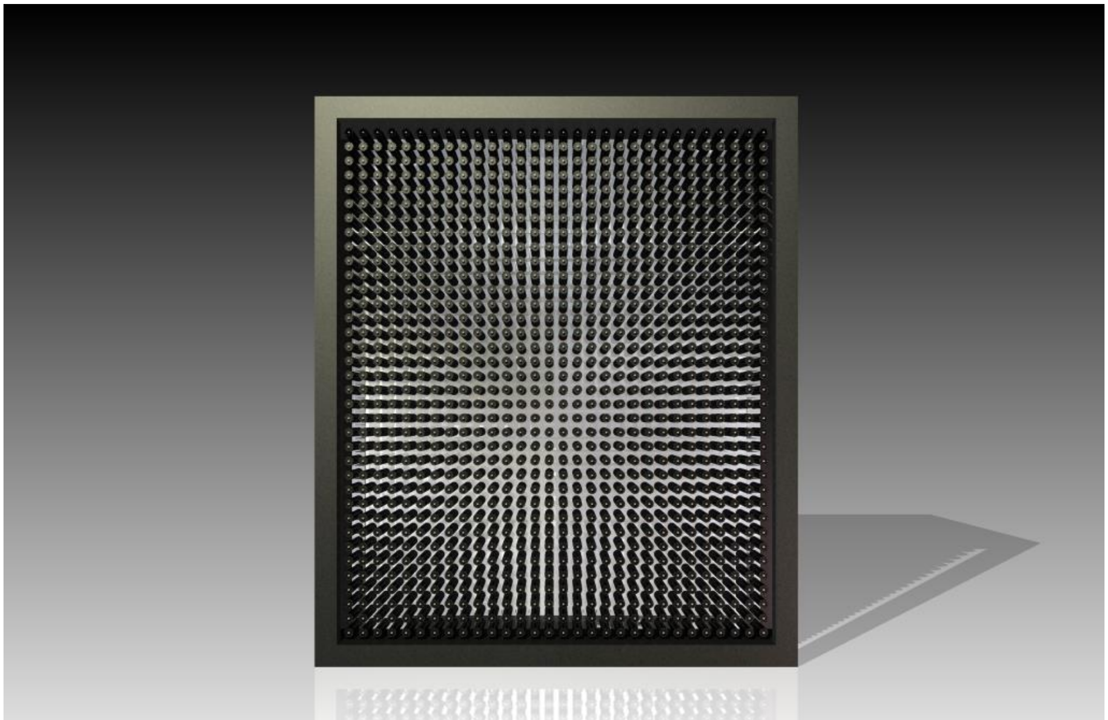

Figure 24: Back face of the PMT, where the individual PMTs are visible.

Figure 25: Front face of the calorimeter.

Figure 26: Back face. Each crystal has one PMT attached.

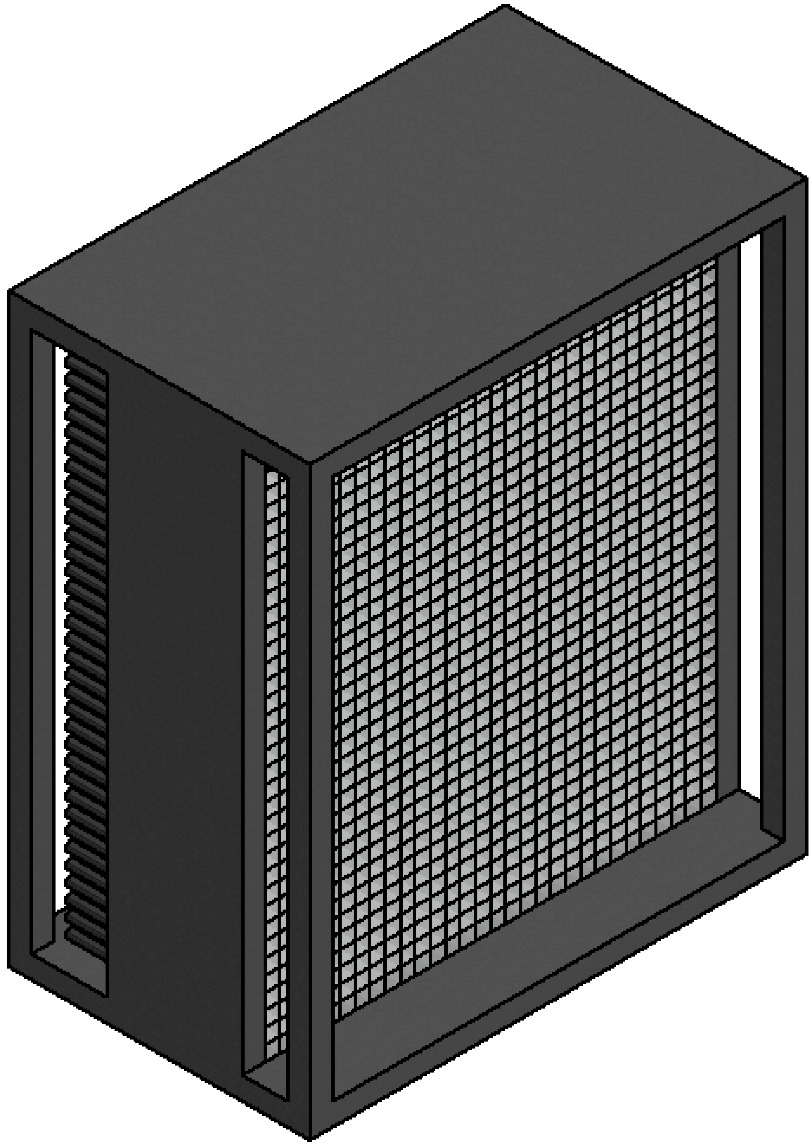

Figure 27: Isometric view of the calorimeter.

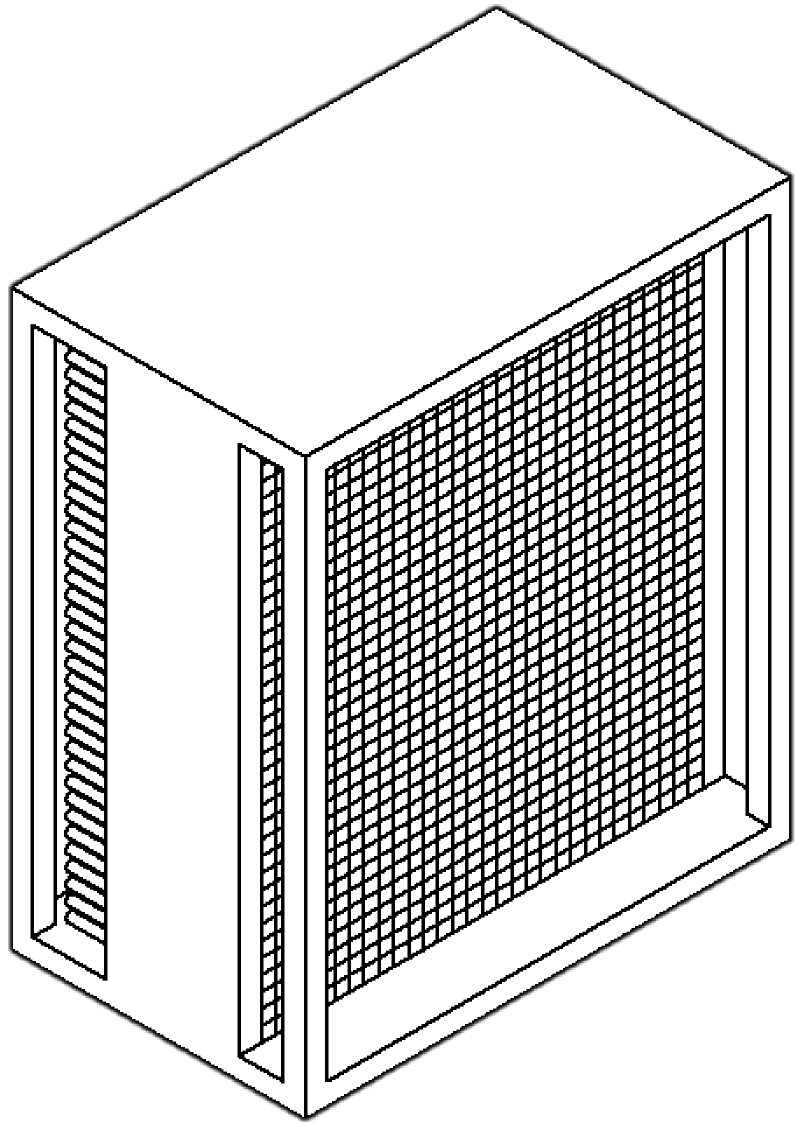

Figure 28: Isometric view without color.

Works Cited

1 Department of Physics, California State University. Photomultipler Tubes. California State University. Available from: http://physics.csustan.edu/Ian/Spectroscopy/LectureNotes/Detectors/PMT.pdf.

2 S. E. Particle Identification [PDF Presentation]. Science and Technology Facilities COuncil; 2011. Available from: http://www2.warwick.ac.uk/fac/sci/physics/staff/academic/gershon/gradteaching/warwickweek/material/detectors/Warwick_week_Pid_Lecture_2011_pdf.pdf.

3 Huber G, Li W, Fischer A. SHMS Heavy Gas Gerenkov June 2012 Update [PDF Presentation]. Newport News, VA 2012. Available from: http://www.jlab.org/Hall-C/talks/06_22_12/huber_cer.pdf.

4 Hlavin N. Kaon Aerogel Cherenkov Detector [PDF]. Presentation. Available from: http://www.jlab.org/Hall-C/talks/06_22_12/hlavin.pdf.