Testing and Characterization of Photomultiplier Tubes and the ANNIE Forward Anti-Coincidence Counter

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Abstract

Photomultiplier Tubes (PMTs) are well known to be one of the essential components of many experimental detectors in high energy physics. Before new models of PMT are implemented in experiments, they must be characterized in order to understand their efficiency under experimental conditions and to determine if there are any dependencies of these efficiencies due to one or more of many possible effects. Two new eleven inch PMTs were tested and characterized to understand their efficiency and performance under various different conditions. Details of the testing procedure and results of testing will be discussed.
The Accelerator Neutrino Neutron Interaction Experiment (ANNIE) Forward Anti-Coincidence Counter (FACC), sometimes referred to as the Forward Veto, is an essential component of the ANNIE detector as it will detect muons which decayed from neutrinos in the ground before the neutrino beam reaches the water tank and therefore allows for the detection of only neutrino interactions within the detector itself. The ANNIE FACC was installed and details regarding its installation will be presented.

Contents

1 11" PMT Characterization

The Japanese company, Hamamatsu, is currently the world leader in the production of PMTs. New 11" PMTs were tested which were designed by ET Enterprises, a subsidiary of Ludlam Measurements, based in Texas, giving further reason behind testing these PMTs in order to support American business. These ET Enterprises PMTs, model number D784KFLB, have a bialkali photocathode with an effective surface area of 800 cm^2 with 12LFSbCs dynodes (12 Linear Focused SbCs dynodes) [1]. These large area ETEL/ADIT 11" HQE PMTs may be used in many different optical experiments (e.g. ANNIE and SNO+). Two 11" PMTs, numbered 120 and 124, were tested out of a number also analyzed at the University of Pennsylvania.

1.1 Experimental Setup

The experimental setup at the University of California, Davis contains a tunable, tri-axial, magnetic field environment composed of three pairs of 1 m^2 copper Helmholtz coils, separated by 0.5 m, contained within a dark room. Inside the dark room, above the PMT is an LED flasher which can be hooked up to a function generator to pulse single photons onto the face of the PMT. The PMT is hooked up to a high voltage power supply and the signal is sent to a Tektronix DPO7254 digital phosphor oscilloscope for readout.

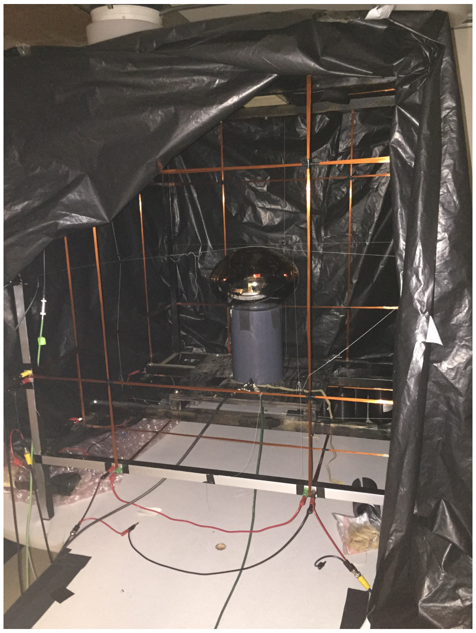
b 

Figure 1: Experimental setup at UC Davis.

1.2 Characterization Procedure for PMT

In order to characterize the PMTs and obtain their operating voltage, 10,000 to 100,000 waveforms were collected with the potential difference in the PMT at a variety of voltages, triggered on an LED pulse of 870 mV, with a width of 30 ns and a frequency of 1 kHz. These waveforms were then analyzed using a fixed integration method in order to calculate the maximum gain of the PMT. This process was repeated for multiple voltages until a gain of approximately 1×10^7 was obtained, with that voltage becoming the operating voltage of the PMT.

1.3 Measurement of Dark Noise

To further understand the PMTs, dark noise measurements, that is, measurements where there was no light incident on the PMT, needed to be taken as a function of time to see the signal the PMT receives as it cools down. This will also help to characterize the amount of background noise received by the PMT, the knowledge of which is essential when analyzing data from experiments.

1.3.1 Experimental Setup and Procedure for Dark Noise

In order to measure dark noise, the signal output from the PMT is sent to a discriminator with the trigger level set to negative 6 mV. The output from the discriminator is sent to a logic pulse unit which sends a TTL pulse to a digital counter, which is then run for approximately ten seconds.
The procedure is as follows. The PMT is placed in the dark room and then set to a voltage. The digital counter is run for approximately ten seconds and the rate of counts is obtained. The voltage is then changed to the next voltage and the process is repeated until the count rates for all the voltages are obtained. The door to the dark room is left sealed and after 30 minutes, another set of measurements is taken. This is repeated until the count rates do not continue to decrease and the only change will be due to statistical fluctuations. It was necessary to obtain the count rates at multiple voltages because this process was occurring simultaneously to the determination of the operating voltage for each PMT.

1.4 Measurement of Effects due to Magnetic Fields

The effects of magnetic fields of PMTs are well know and as such, need to be quantified. Using the Helmholtz coil setup described in 1.1 and a procedure similar to that described in 1.2, the dependence of the PMT was probed. The magnetic field in the X and Y directions were varied independently of each other, with the other and the field in the Z direction both set to zero (in essence, cancelling the Earth's magnetic field except for in either the X or Y direction). The positive X direction is defined as the direction aligned with the bump on the base of the PMT with the Z direction being upward and the Y direction being orthogonal to the other two. Each set of Helmholtz coils has its voltage and current provided by its own low voltage power source. The voltages and currents for each direction were determined by measuring the magnetic field at the point in the center of the bulb of the PMT using a Honeywell HMC5883L 3-axis digital compass IC and adjusting the voltages and currents on the power supplies as necessary in order to obtain the field wanted. The magnitude of the magnetic field in each direction went from -800 mG to 800 mG in increments of 50 mG. This was done for each PMT at their respective operating voltages. This procedure was developed using the procedure used to test the Hamamatsu R11780 12" PMT [2].

1.5 Results

After testing the PMTs at a variety of voltages, it was found that the optimum operating voltages were in fact the manufacturer's operating voltages [1]. These voltages can be found in table 1.

PMT	Voltage
120	1480
124	1270

Table 1: Operating Voltages of PMTs

This conclusion was arrived upon by integrating the area of each individual waveform, dividing it by the resistance (50Ω), and then fitting the resulting histogram's non-zero peak with a Gaussian. The histograms with their fits for PMTs 120 and 124 can be seen in figures 2 and 3 respectively.

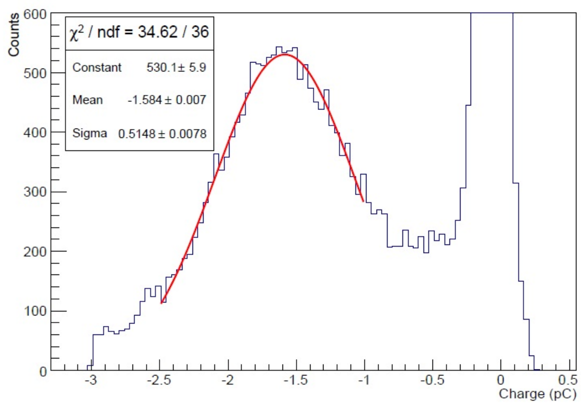


Figure 2: Charge from waveforms for PMT 120.

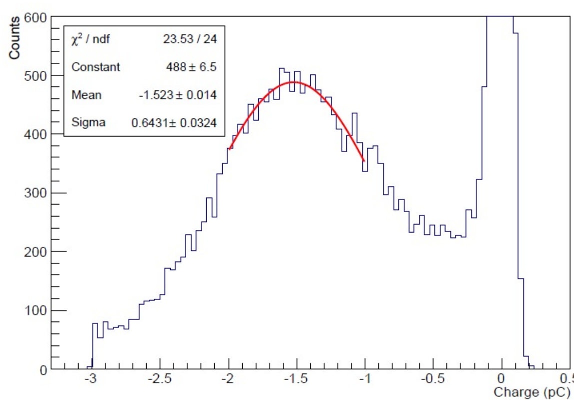


Figure 3: Charge from waveforms for PMT 124.

The gain is obtained from these plots with the mean value of the secondary peak, to which a Gaussian it fit. PMT 120 has its peak at 1.584 pC and PMT 124 has its peak at 1.523 pC. The values of each peak are slightly lower than the ideal value of 1.6 pC, which would correspond to a gain of 1×10^7, but they are close enough to be reasonable and for other operating voltages, these values are much further off from the ideal.

When measuring the dark noise rate for the PMTs, it was found that after approximately two and a half hours of not being exposed to light, the dark noise rate settled down to a uniform rate for that particular PMT, with some statistical fluctuations. These data are presented in figures 4 and 5 as well as in tables 2 and 3.

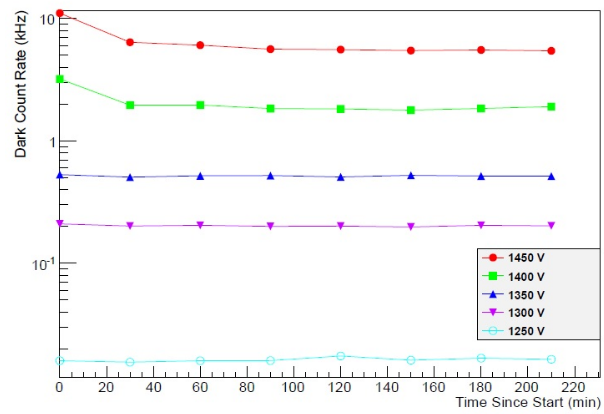


Figure 4: Dark noise rates for PMT 120 as a function of time after light is incident on the PMT face.

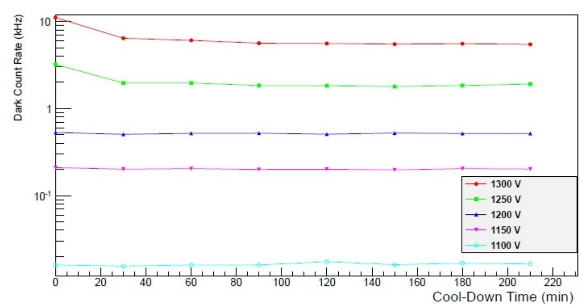


Figure 5: Dark noise rates for PMT 124 as a function of time after light is incident on the PMT face.

	1450 V	1400 V	1350 V	1300 V	1250 V
0 min	10.12	1.98	0.59	0.31	0.078
30 min	8.66	2.03	0.63	0.34	0.095
60 min	6.41	1.79	0.62	0.34	0.093
90 min	6.39	1.72	0.62	0.34	0.09
120 min	5.72	1.70	0.60	0.34	0.09
180 min	5.55	1.67	0.63	0.33	0.10

Table 2: Dark noise rates (in kHz) for various operating voltages of PMT 120 after cooling down for various amounts of time.

	1300 V	1250 V	1200 V	1150 V	1100 V
0 min	11.07	3.21	0.53	0.21	0.016
30 min	6.40	1.96	0.51	0.20	0.016
60 min	6.06	1.96	0.52	0.20	0.016
90 min	5.62	1.84	0.52	0.2	0.016
120 min	5.57	1.82	0.51	0.20	0.017
180 min	5.48	1.79	0.52	0.20	0.016
210 min	5.54	1.84	0.52	0.20	0.017
240 min	5.45	1.91	0.52	0.20	0.16

Table 3: Dark noise rates (in kHz) for various operating voltages of PMT 124 after cooling down for various amounts of time.

The data obtained for both relative efficiency and dark noise rate with the Helmholtz coils controlling the magnetic field are very interesting. They both show that for both PMTs, when the magnitude of the magnetic field is less than 400 mG, there is little effect on the response of the PMT. While statistical fluctuations remain, the values can be considered constant when the magnitude of the magnetic field is below 400 mG. This also means that under the presence of only the Earth's magnetic field and no other external fields, these PMTs have the same efficiency. The values of the Earth's magnetic field measured with the Honeywell probe inside the UC Davis dark room can be found in table 4.

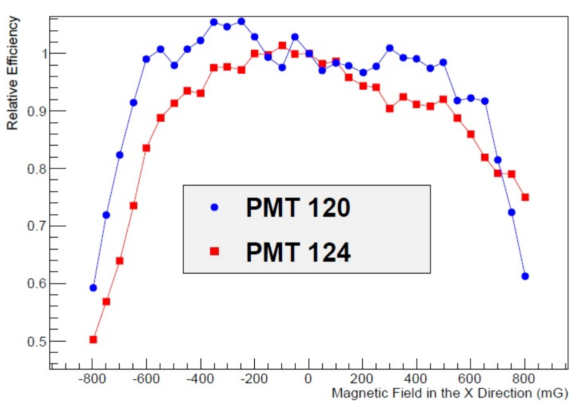


Figure 6: Relative efficiency of PMTs with a variable magnetic field in the X direction and magnetic fields in the Y and Z directions fixed to 0.

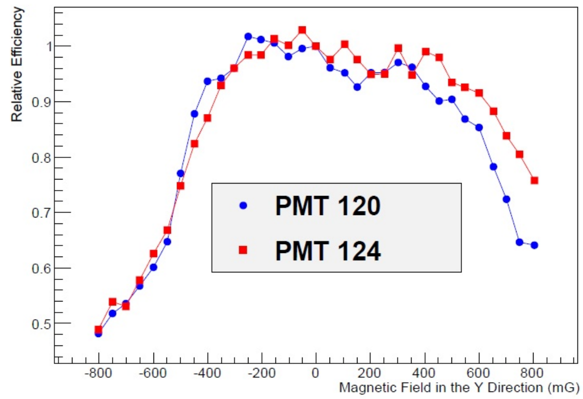


Figure 7: Relative efficiency of PMTs with a variable magnetic field in the Y direction and magnetic fields in the X and Z directions fixed to 0.

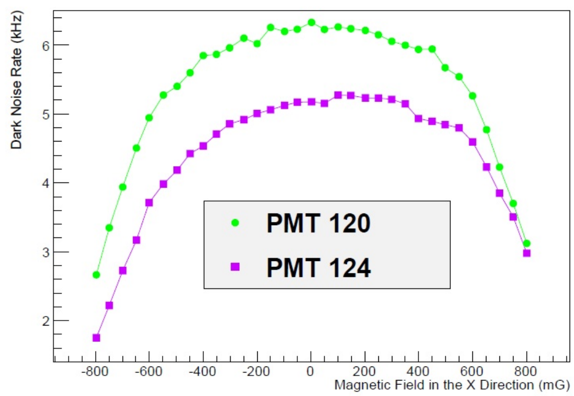


Figure 8: Dark noise rate of PMTs with a variable magnetic field in the X direction and magnetic fields in the Y and Z directions fixed to 0.

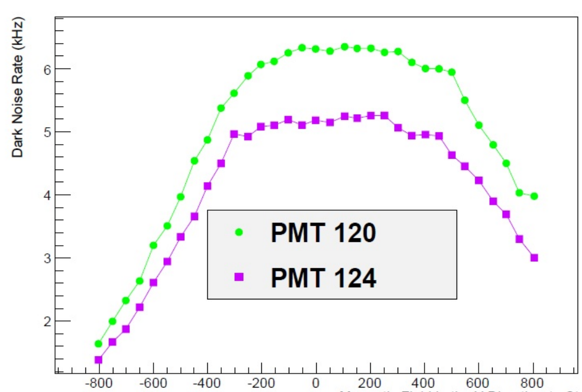


Figure 9: Dark noise rate of PMTs with a variable magnetic field in the Y direction and magnetic fields in the X and Z directions fixed to 0.

	Magnetic Field (mG)
X	187
Y	65
Z	-383

Table 4: Magnitude of the Earth's magnetic field in the UC Davis dark room.

2 The Accelerator Neutrino Neutron Interaction Experiment (ANNIE)

ANNIE is an experiment currently under installation at Fermilab. Its purpose is to study the abundance of final state neutrons from neutrino-nucleus interactions. Measurements of final-state neutron multiplicity will improve understanding of the complex, many-body dynamics of neutrino-nucleus interactions. Also, identifying and counting final state neutrons also provides a useful experimental handle for signal-background separation for future neutrino experiments [3]. The basic design of ANNIE can be seen in figure 10.

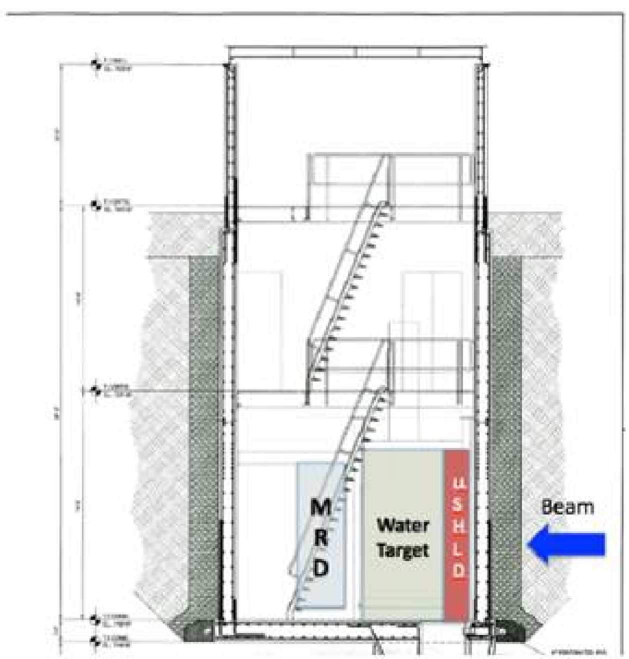


Figure 10: Basic design of ANNIE in SciBooNE hall at Fermilab. The Forward Anti-Coincidence Counter (FACC) is against the wall from which the neutrino beam is incident and the Muon Range Detector (MRD) is on the other wall. A large water tank is placed in between them, inside which is a cube of water doped with Gadolinium.

2.1 Forward Anti-Coincidence Counter (FACC)

An efficient muon rejection counter is needed in front of the water target as muons that come from neutrino-induced events in the rock will obscure data with significant background [4]. This is the purpose of the FACC. The FACC consists of 26 single ended, 10' 6" by 1' 1/8" scintillator paddles which terminate in a readout via a light guide and single 2" PMT. The two layers of 13 stacked paddles are attached to the wall using extruded aluminum struts (15 series Faztek) with custom shaped aluminum straps holding the paddles in place [5] (see figures 11 and 12). A design of the FACC can be seen in figure 13.

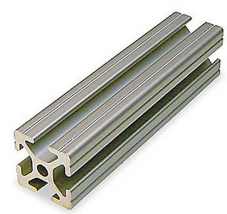


Figure 11: An example of the Faztek material to be used to hold up the structure of the FACC.

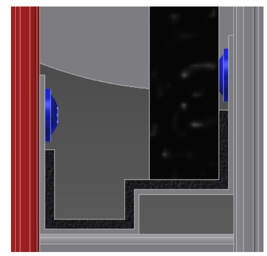


Figure 12: An example of the custom designed aluminum bracket used to support the scintillation paddles.

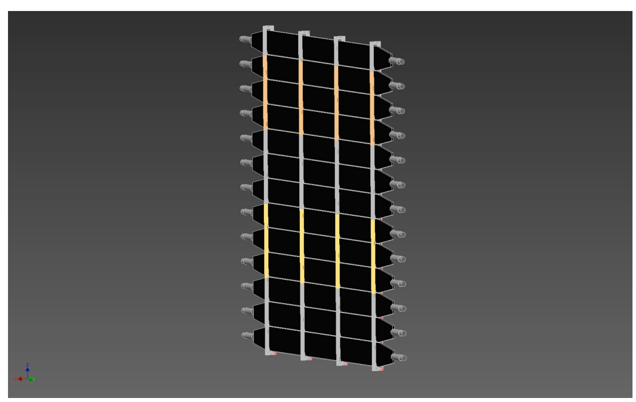


Figure 13: Design of the ANNIE Forward Anti-Coincidence Counter showing 13 horizontal layers.

2.1.1 FACC Installation

Each paddle needed to be tested for light leaks which may have occurred during transportation to SciBooNE Hall. This was done by checking their near and far efficiencies as well as the dark noise rate on both sides. Any light leaks that were found were taped up using electrical tape and the paddle was then retested to ensure that the leak was repaired. The paddle was then carefully lifted into place on the wall. After every pair of paddles was placed, the pair was retested to ensure that no new light leaks formed during installation. Once the first 6 pairs of paddles were in place, a scissor lift was used in order to reach the necessary height to install the paddles [5]. A photograph of the installed FACC can be seen in figure 14.

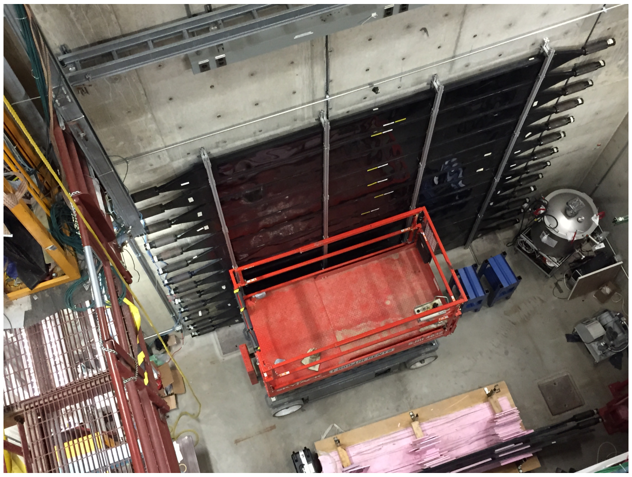


Figure 14: Installed ANNIE Forward Anti-Coincidence Counter.

The installation was very successful and ANNIE is now ready to install the water system and the tank.

3 Conclusions and Further Work

Both projects of characterizing the 11" PMTs and installing the ANNIE FACC were very enlightening. A significant amount of progress was made on both projects, with the installation of the ANNIE FACC being completed. Although only two PMTs were characterized, a procedure was developed which took a significant amount of trial and error, which allows for easier and faster characterization of PMTs in the future. In addition, a new hexagonally shaped dark box is under construction which will allow for the testing of six PMTs simultaneously. This dark box will have a Sr-90 Cherenkov light source in the center, with approximately 7 feet between opposing faces and 8 feet between opposing corners of the hexagon. There will also be two vertical Helmholtz coils which will be used to cancel the Earth's magnetic field in the Z direction. Once completed, this setup will be used to characterize more of the ETEL/ADIT 11" PMTs. Also, once those PMTs are characterized, they will be sealed using an epoxy in order to make them watertight, and then tested in water, so that they may then be used in water scintillation detectors such as ANNIE.

References

[1] Tanner Kaptanoglu, Josh Klein, and Robert Svoboda. *Update on Developments of ETEL/ADIT 11" HQE PMTs*. 2014.

[2] J. Brack et al. "Characterization of the Hamamatsu R11780 12 inch Photomultiplier Tube". In: *Nuclear Instruments and Methods in Physics Research Section A* 712 (2013), pp. 162–173. DOI: http://dx.doi.org/10.1016/j.nima.2013.02.022.

[3] *Letter of Intent: The Accelerator Neutrino Neutron Interaction Experiment (ANNIE)*. Mayly Sanchez: Lead Principal Investigator, Iowa State University. arXiv:1504.01480 [physics.ins-det]. 2015.

[4] I. Anghel et al. "EXPRESSION OF INTEREST: The Atmospheric Neutrino Neutron Interaction Experiment (ANNIE)". In: (2013).

[5] Megan Long. *Installation of ANNIE Front Veto*. 2015.