# Photomultiplier Tube Testing for the MiniBooNE Experiment

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*Abstract*— **The recent discoveries in the neutrino sector in the Standard Model have opened a new frontier in high energy physics. Understanding neutrinos and how they interact is crucial to continuing to verify the Standard Model and look for beyond Standard Model physics. The MiniBooNE experiment is a $\nu_\mu \rightarrow \nu_e$ oscillation search designed to confirm or rule out the neutrino oscillation signal seen by the LSND [1] experiment at the Los Alamos National Laboratory. The MiniBooNE detector, a sphere filled with mineral oil and lined with 8" Hamamatsu photomultiplier tubes (PMTs), uses Čerenkov imaging to identify $\nu_\mu$ and $\nu_e$ interactions. The PMTs are the main detector component and must be well understood. They underwent a series of tests to determine their functionality and figures of merit in order to be placed in the detector, as described here.**

*Keywords*— **Neutrinos, Photomultipliers, Cerenkov detectors, Scintillation detectors.**

## I. Introduction

Recent experimental data indicate that neutrinos oscillate among their different flavors and therefore have mass. Data from experiments looking for the solar neutrino deficit, those looking for the atmospheric neutrino deficit, and the LSND experiment cannot all be explained by the three Standard Model neutrinos. Further checks on these signals are necessary.

The BooNE experiment, now under construction at the Fermi National Accelerator Laboratory, is specifically designed to confirm or rule out the LSND signal. MiniBooNE, the first stage of the BooNE experiment, looks for $\nu_e$ appearance in a $\nu_\mu$ beam created from 8 GeV protons from the Fermilab Booster. $\nu_\mu$'s, $\nu_e$'s, and background events such as $\pi^0$'s are identified in a detector 500 m downstream from the target hall where the $\nu_\mu$ beam is created. The detector is a 12 m diameter sphere filled with mineral oil. It is a sphere within a sphere with an inner light tight signal region and an outer veto region. Neutrinos will be identified in the detector when they interact with a nucleon via a charged or neutral current interaction. The outgoing charged particle produces Čerenkov and scintillation light in the mineral oil. These light signatures are recorded by photomultiplier tubes lining the inside of the detector, and events are later reconstructed from this information.

There are 1280 8" photomultiplier tubes lining the inner signal region of the detector. 241 PMTs in the veto region look for light indicating a charge particle has entered the detector. Of these 1521 PMTs, 1197 are inherited from the LSND experiment. They are Hamamatsu R1408 9 stage, 8" PMTs. 324 new Hamamatsu R5912 10 stage 8" PMTs fill the rest of the detector. Before installing the PMTs in the MiniBooNE detector, they were tested to ensure they are operational, to determine their operating voltages, and to measure their figures of merit. The following sections discuss the results of these tests and the PMT's placement in the detector.

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## II. Testing Setup and Tests Performed

Testing was conducted at Fermilab in a darkroom in air where up to 46 PMTs could be tested in one day. A "winerack" assembly was constructed against one wall of the dark room. Each PMT was secured on its side facing an optical fiber carrying light from an LED flasher. The rack accomadated 30 LSND PMTs and 16 new PMTs held in place using Styrofoam molds.

The PMTs were conditioned in the darkroom for 12-24 hours at approximately 1000 V. After conditioning, PMTs were tested using an automated VXI readout system with a built-in oscilloscope having a maximum capture rate of 10,000 waveforms/90 seconds. The VXI readout system set PMTs at a recommended testing voltage using a serial I/O interface, determined darkrate, and recorded PMT pulse response to an LED flasher. The system allowed for automatic testing of 22 tubes in a single run. The number of tubes that could be tested simultaneously was limited by our use of one multiplexer. A schematic diagram of the system is shown in Fig. 1. Once the testing was complete, the data files were stored for data analysis.

### A. Testing Procedure

There is a trade off between amount of test data that can be taken and the amount of time it takes to perform the tests. For this reason, tests performed are optimized to set operating voltages and determine PMT quality while keeping the testing procedure short.

The testing data were acquired in two modes. In the first mode, the dark currents were collected by recording the noise rates measured at different voltages with no light source. Pulses passing a 3 mV threshold were counted as dark noise and used to determine the dark noise rate. The dark noise was measured at various voltages starting at approximately 1000 V and at increments of 100 V above this to approximately 100 V above the PMTs suggested operating voltage. Suggested operating voltages for the new

PMTs were supplied by Hamamatsu; suggested operating voltages for the LSND PMTs were assumed to be their operating voltage during the LSND experimental run.

After the dark noise rates were recorded, the PMTs were strobed with an LED light source at 450 nm for a duration of 1 ns at 1 kHz to look at light induced waveforms. PMT response to 600-1000 LED flashes piped in through an optical fiber were recorded and used to determine the operating voltage at a chosen gain, to study the charge and time resolutions, and to search for pre- and post-pulsing anomalies.

Responses were triggered off the LED pulse and delayed so that they appear about 40% of the way in time into the scope. This timing allows for adequate determination of the pre-pulse baseline and ample time after the pulse to look for post-pulsing. Light levels were set low enough to allow adequate determination of PMT response to one photoelectron (PE), and high enough to ensure sufficient data events.

LED tests were performed at two different voltages for the LSND PMTs, at LSND operating voltage ±50 volts. New PMTs underwent testing at four different voltages, at -100, 0, +100, and +150 V from the Hamamatsu suggested operating voltage. Multiple tests are necessary for determination of the gain and should be conducted near the nominal operating voltage. The number of tests is as great as needed to determine unknowns about the PMTs while being as few as possible due to time constraints. Using the VXI system, pulse responses were read from the internal oscilloscope, recorded to data files and analyzed off-line.

Testing setups were calibrated and measurement errors determined by taking calibration data. A *rover* PMT which was tested in each possible testing position and a *permanent* PMT which was tested in the same spot in the same way almost every test cycle provided this calibration data.

For each PMT, the 2-4 test data files corresponding to LED response tests taken were analyzed off-line to determine figures of merit for that data file. These figures of merit include PMT functionality and operating voltage, PMT gain, charge resolution, timing resolution, double-pulsing rate and darkrate.

## III. PMT Characteristics: Results of Tests

PMTs were tested to determine their operating voltages and figures of merit. Results are outlined below.

### A. Gain

PMT gain corresponds to the mean number of electrons produced by the phototube in response to one PE. Ideally, one could just read off the gain as the mean of the one PE peak in a plot of the integrated charge of the responses to the 600-1000 LED flashes. The width of this one PE peak then corresponds to the charge resolution. However, the one PE peak for these tests contains responses to 2 and 3 PEs and possibly more. Gain is instead determined by weighting the average response of the PMT – all but null responses to the LED – with the ideal response of a PMT to one PE, determined from Poisson statistics.

$$gain = \left(\frac{1-e^{-\mu}}{\mu}\right)\left(\frac{Q_{tot}}{N}\right) \quad (1)$$

The first term in Eq. 1 is the average number of PEs seen by a PMT for a given light level, $\mu$, excluding zero responses, predicted from Poisson statistics. The second term is what the PMT actually sees: the total charge for all PMTs with response past threshold divided by the number of responses past threshold. Total charge is computed by summing up charge in main PMT pulse for all responses with in-time pulses that pass threshold. Double-pulses are not counted in total charge.

PMTs in the MiniBooNE detector need to have a gain of $16 \times 10^6$ electrons per incoming PE as dictated by MiniBooNE electronics. Operating voltage for each PMT is chosen to pick out this gain. The distribution of operating voltages at which the PMTs will run in the detector is shown in Fig. 2.

### B. Darkrate

Darkrate is the number of pulses larger than 3 mV in one second for a PMT that has conditioned in a light tight environment for $12-48$ or more hours. PMTs should operate at a darkrate below 8 kHz in the main tank and below 4 kHz in the veto. These levels ensure that the electronics can keep up and that this noise does not interfere with signal. Darkrates are measured from several hundred volts below suggested operating voltage up to operating voltage and above. PMTs with darkrates above 8 kHz are re-tested and either improve with more conditioning or are not used in the detector. Darkrate versus voltage plots, or plateau plots, are another indicator of PMT quality. PMTs should operate where they are stable – on the plateau on these plots where darkrate does not change significantly as the voltage increases. For the new PMTs, this is at about 1550 V and above. The LSND PMTs tend to have a less well defined plateaus. They are considered functional if operating voltage is on a steady, not a steep rise.

### C. Charge Resolution

Charge resolution, $\sigma_q$, is determined by extracting the width of the one photo-electron peak also derived from possion statistics. The distribution of charge resolutions for all PMTs is shown in Fig. 3.

### D. Timing Resolution

PMT response to LED pulses is recorded from an oscilloscope triggered by the LED pulses. The amount of jitter in this response corresponds to the timing resolution. To measure this, the time the PMT pulse crosses half max for each of the 1000 LED responses is histogramed. The width of this distribution corresponds to the timing resolution of the PMT. Pre- and post-pulses are not included in this histogram. Timing resolutions do not change significantly when response time is recorded at 10% of the PMT pulse. The distribution of timing resolutions for all PMTs is shown in Fig. 4.

### E. Double-pulsing Rate

Pre- and post-pulsing are expected phenomena with these Hamamatsu PMTs. When it occurs, the main PMT response is either preceded or followed by another pulse or more. Pre-pulsing is thought to occur when the ejected electron from the photocathode skips the first dynode. Prepulses occur at nearly the same time relative to the main pulse because the time it takes for an electron to travel from one dynode to the next is fixed. Pre-pulsing occurs very infrequently (observed on four of the 1240 LSND PMTs) and can come and go. PMTs exhibiting pre-pulsing behavior were not placed in the signal region in the detector.

Post-pulsing is categorized by Hamamatsu as either early post-pulsing occurring between 8-60 ns after the main pulse or after pulsing occurring 100 ns-16 $\mu$s after the main pulse. We are only worried about early post-pulsing because data in the detector is recorded in 100 $ns$ intervals making afterpulsing an unlikely issue for event contamination. Early post-pulsing can occur when an electron accelerated to the first dynode starts a typical cascade and causes another electron to be ejected from the first dynode. This second particle can move around the inside of the PMT dome before settling back to the first dynode and initiating a second cascade. This post-pulse can occur almost on top of the main pulse to many ns afterwards. Post-pulsing can also occur without any main pulse. Unlike pre-pulses, postpulses are spread out in time since there is no typical time for a particle to bounce off the first dynode before initiating a second cascade.

Hamamatsu reports that R5912 PMTs are expected to early post-pulse 3% of the time. Many new PMTs had higher double-pulsing rates than this after conditioning for 12-24 hours. After further conditioning, PMT double pulsing rate was reduced. Based on this, we set a double-pulsing rate limit of 6% for the new PMTs and 3% for the LSND PMTs. The distribution of PMT double-pulsing rates for all PMTs is shown in Fig. 5.

### F. Categorizing PMTs

PMTs with darkrates below 8 kHz, low double-pulsing rates and reasonable charge and timing response are placed in the detector according to their charge and timing resolutions. Placement according to this figure of merit is designed to ensure that PMTs of higher quality are equally distributed around the detector. PMTs chosen for the veto are those with the worst charge and timing resolution but the lowest darkrate. These PMTs are needed only to see light from a passing charged particle and not for particle identification. PMTs with low noise rates are ideal for this.

### G. Calibration Data

Calibration data taken during the course of testing help to quantify errors on these measurements. Table I shows the spread in measurements taken by calibration PMTs which correspond to the errors on those measurements for each PMT.

TABLE I
ERRORS ON PMT FIGURES OF MERIT AS DETERMINED FROM CALIBRATION DATA

| | |
|---|---|
| gain | 0.19 |
| charge resolution | 0.34 |
| timing resolution | 0.13 |
| double-pulsing percentage | 0.60 |

Darkrates decrease as a function of conditioning time. This was seen by a steady decrease in darkrate on the calibration PMT as it moved, day by day, to different positions in the testing room, conditioning more each day. Light level seen by this PMT varied from 0.5 to 1.5 PEs from winerack location to location. Calibration information helped us to understand the error on our measurements as well as to track any changes in the winerack as a function of time.

## IV. Conclusions

The MiniBooNE detector uses Čerenkov and scintillation light signatures from charged particles produced in charged current neutrino interactions to tag the flavor of the incident neutrino. Appearance of electron neutrinos in the muon neutrino beam would indicate neutrino oscillations like those reported by the LSND experiment. The 1280 PMTs in the signal region as well as the 241 PMTs in the veto are the only detector component to resolve these light signatures. The detailed tests performed have allowed us to properly place these PMTs in the detector as well as study properties of the PMTs which will affect our measurement.

## References

[1] A. Aguilar *et al.* [LSND Collaboration], "Evidence for neutrino oscillations from the observation of $\overline{\nu}_e$ appearance in a $\overline{\nu}_\mu$ beam," [hep-ex/0104049].

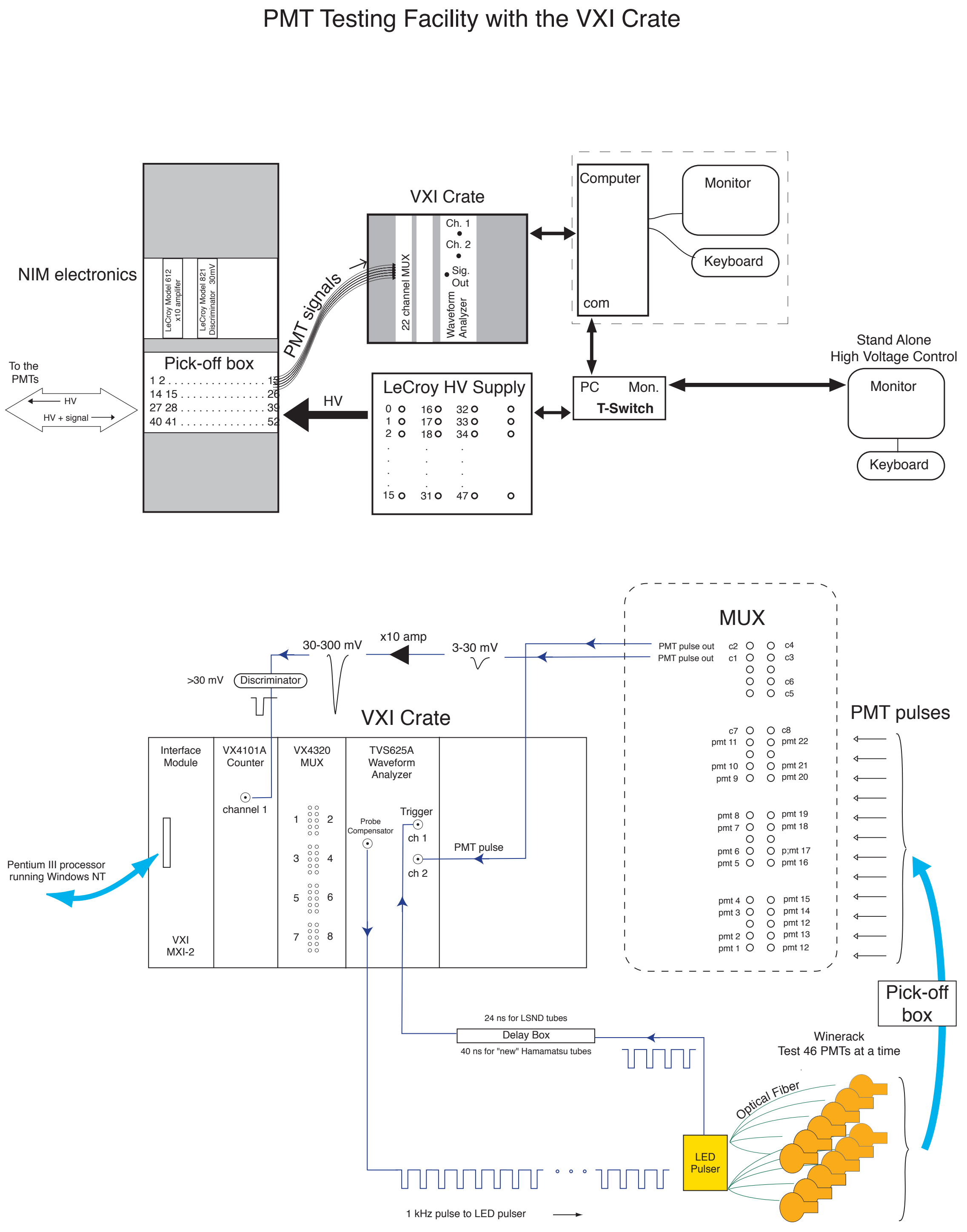


Fig. 1. PMT testing facility with the VXI crate.

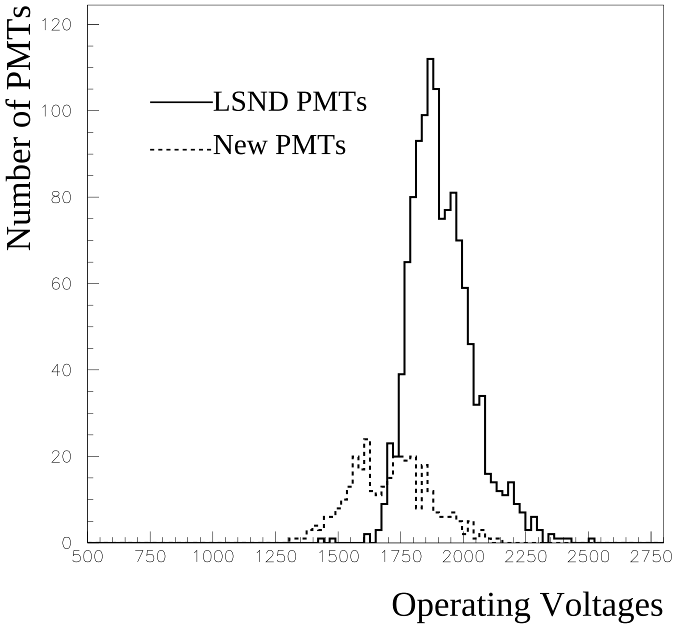


Fig. 2. Distribution of operating voltages for PMTs in the detector

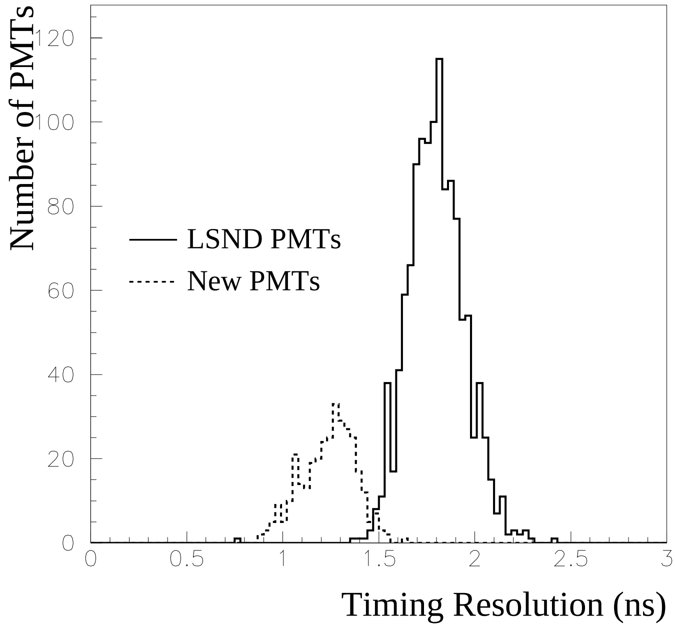


Fig. 4. Distribution of PMT time resolutions.

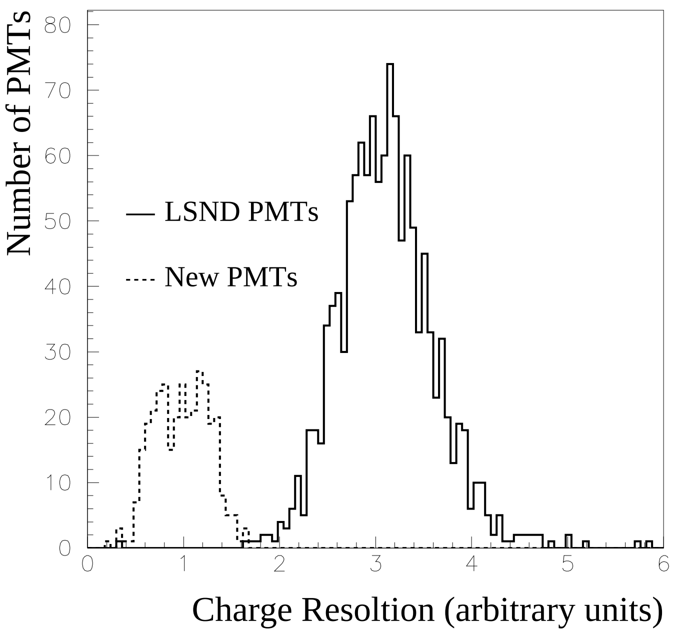


Fig. 3. Distribution of PMT charge resolutions.

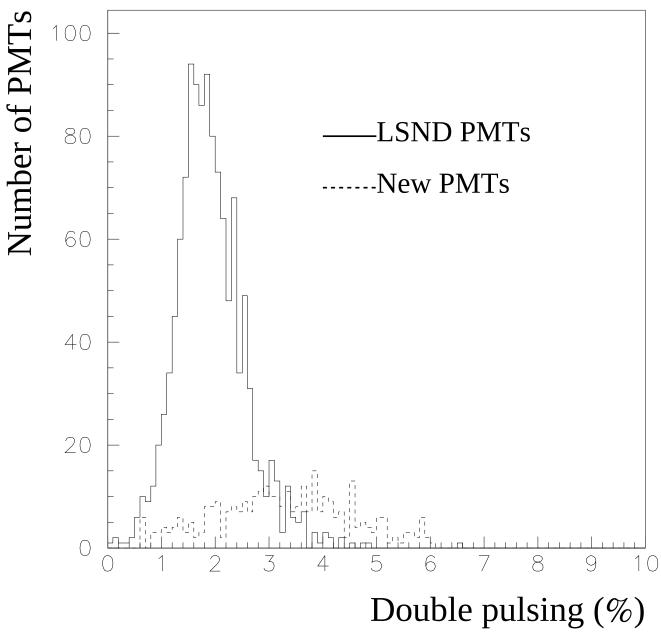


Fig. 5. Distribution of PMT double-pulsing rates.