

Dependence of R11410 PMT Parameters on D1 Field Strength

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Abstract: We evaluate all relevant operating parameters of a Hamamatsu R11410 PMT to the 1% level. This includes dark rate, gain, linearity, and efficiency. Measurement is taken both room temperature and cryogenically at 93 K. We then modify the base PCB to introduce different bias field strengths between the photo-cathode (K) and first dynode (D1). We demonstrate the functional relationship between this bias field $V(K-D1)$, and other device parameters. Of note is the positive correlation between $V(K-D1)$ and total event flux, even when normalized for gain dependence. We analyze digitized events from the PMT to demonstrate that this correlation is a result of PMT misfires rather than changes in efficiency or linearity of the device.

I. PMT INTRODUCTION

We seek to characterize and improve the efficiency of Hamamatsu R11410 PMT's (photo-multiplier tubes). First, an introduction to the basic operating principles of the device.

A. Photon Conversion

R11410's are vacuum tube devices composed of a 3" quartz panel. On the interior surface, a Bialkali photocathode material is deposited in situ after tube evacuation. Given the high sensitivity required by the LZ experiment, R11410's are designed for low background radioactivity requirements in liquid-xenon TPC experiments. This body is thus constructed of stainless steel.

When powered, a PMT is able to generate pulses from light incident on the top surface. Signals as small as single photons are detectable. Photons are massless particles and instead have energies defined by the Planck relation:

$$E_{\lambda} = \frac{hc}{\lambda} \quad (1.1)$$

In general, electrons are bound to the surface of a material due to Coulomb interaction with the nucleus. The strength of this binding force is known as the work function of a material, W . Photons incident upon the photocathode can transfer their energy to the material by giving an electron enough kinetic energy to be ejected. This process occurs through pair production. These are known as photoelectrons. This can only happen if the incident photon has energy of at least W .

R11410's are designed for a spectral response range of $\lambda = 160 - 650$ nm. We can thus estimate the work function value of the Bialkali photocathode using the maximum specified wavelength (minimum energy) as the threshold energy for photoelectron extraction out of the material.

$$W = \frac{hc}{\lambda_{min}} = \frac{hc}{650 \text{ nm}} = 3.06 \cdot 10^{-19} \text{ J} = 1.91 \text{ eV} \quad (1.2)$$

650 nm photons will thus be extracted with no additional kinetic energy. Incident photons with greater energy and smaller wavelength will be extracted with kinetic energy equal to the difference of incident photon energy and work function.

$$KE_{max} = \frac{hc}{\lambda} - W = \frac{hc}{\lambda} - 1.91 \text{ eV} \quad (1.3)$$

This kinetic energy is negligible when compared to the accelerating voltages present in the dynode stages of the device. Photoelectrons can thus be thought to interact similarly with device characteristics regardless of photon wavelength.

B. Electron Multiplication

Past the photocathode, the remainder of the PMT tube consists of 12 electron multiplication dynode stages arranged in interlocking half cylinders. Each dynode multiplies the number of incident electrons through secondary emission. The bias field present within the PMT accelerates those electrons farther down the dynode chain. The number of ejected electrons is dependent on the incident kinetic energy up to a maximal ejection number. The specific functional dependence is discussed in the gain section of this paper.

C. Base Circuitry

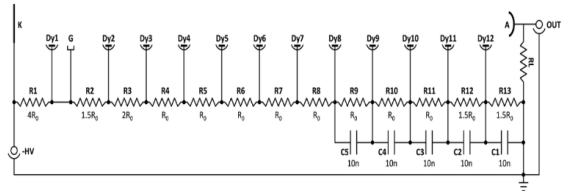


FIG. 1. R11410 Standard Base Configuration. Normally, $V(K)=1500$ V, cascading down to 0V at ground, proportions as determined by R1-R13 values. C1-C5 act as charge banks to mitigate voltage sag.

We present a schematic for a standard bias configuration provided by the manufacturer Hamamatsu. Each resistor acts as a voltage divider, splitting the 1500 V primary bias across all 12 dynode stages. R_0 in standard configuration is $5 M\Omega$, and the sum of all resistors is $18.5 R_0$ leading to a total device resistance of $110 M\Omega$. The nominal bias voltage is 1500 V, leading to a voltage drop across each instance of R_0 of 81.1 V.

$$R_0 = \frac{V_{total}}{\Sigma R} = \frac{1500 V}{18.5 R_0} = 81.1 V \quad (1.4)$$

Thus, referencing Figure 1, $4R_0 = 324.4 V$ is the strength of the bias applied between K and D1 in the standard configuration.

The load resistor is used to probe the current at the anode A and has a value of 50Ω . It is impedance matched at the DAQ module with an additional 50Ω internal resistor. The effective resistance is 25Ω the parallel combination of these two resistors. This value is used to convert between instantaneous anode current and anode voltage.

$$R_{eff} = R_i || R_L = \frac{R_i R_L}{R_i + R_L} = 25 \Omega \quad (1.5)$$

D. Capacitor Depletion

For events with large photon flux, the instantaneous current required to supply enough electrons for dynode multiplication may sag the voltage at the latter dynode stages, interfering with device linearity. Consider Dy12 in Figure 1, as it is the dynode with the highest number of incident electrons. Typically, a quiescent current flows through the resistor chain. Upon a large event, D12 acts as a current source. The process of electron multiplication donates electrons from the dynode material to be ejected. The resistor chain R1-R12 supplies this current. Since the driving voltage remains fixed and stable, Ohm's law tells us that the voltage drop from R1-R12 necessarily increases in order to supply more current. Similarly, the voltage drop across R13 necessarily decreases.

This is known as voltage sag. Device linearity is impacted as voltage sag at D12 inhibits it from being able to similarly multiply subsequent events. For this reason, 5 reserve capacitors are placed in parallel with R(9-13), providing a current source to mitigate these nonlinear effects. They are only necessary at the latter dynode stages.

The capacitor used across Dy12 is a 10 nF capacitor. We can calculate the number of electrons stored within this capacitor.

$$\begin{aligned} 1.5 R_0 &= 121.7 V \\ 10 \text{ nF} \cdot 121.7 V &= 1.217 \mu C \\ \frac{6.2 \cdot 10^{18}}{1.22 \cdot 10^6} &= 5.09 \cdot 10^{12} e^- \end{aligned}$$

To keep voltage sag below 1%, the instantaneous current from a large event should not discharge more than 1% of the capacitor. This is equivalent to $5.09 \cdot 10^{10}$ electrons. When considering a typical gain of $6 \cdot 10^6$, it becomes evident that this reserve capacitor is able to mitigate voltage sag from events up to 10^4 initial photoelectrons large.

E. Efficiency

The PMT characteristic we are most interested in is efficiency. This is the likelihood that any given photon will produce a pulse at the anode of the device. Mechanically, the total device efficiency can be understood as the compound effect of Quantum Efficiency (QE) and Collection Efficiency (CE).

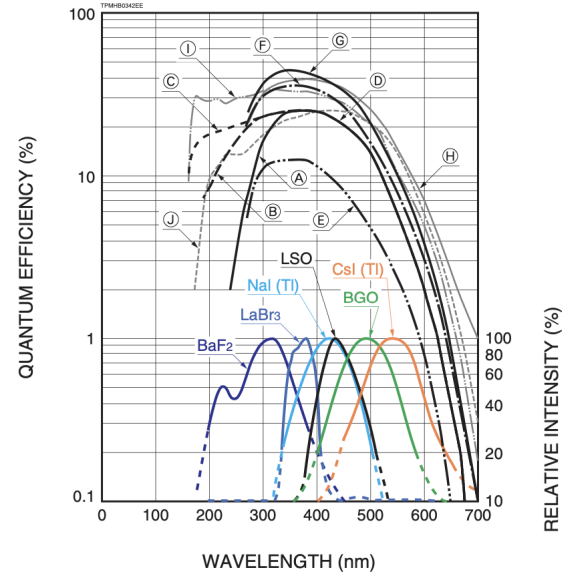


FIG. 2. Wavelength Dependence of PMT Quantum Efficiency. A low temperature bialkali photo-cathode is used in R11410, shown as (I). Xenon scintillation wavelength is 175 nm, just captured by the (I) line with a quantum efficiency near 30%

The QE of a PMT refers to the likelihood that an incident photon will travel through the material and successfully eject a photoelectron. As demonstrated by Figure 2, this is a highly wavelength dependent process. The structure of these QE curves is largely determined by the band gap structure of the photocathode material. QE is a fixed parameter, and photocathode material is matched to the wavelength of the expected experimental light.

The CE of a PMT refers to the likelihood that an ejected photoelectron will be successfully captured by the dynode stages and multiplied into a pulse at the anode. It is determined by the field optics of the device. It is difficult to independently evaluate QE and CE. Given

an incident photon and no produced pulse, one cannot determine whether it was the photocathode or the dynode optics which failed to produce a signal. As such, PMT efficiency are often quoted as the overall efficiency, which is the product of the CE and QE. For this experiment, the photocathode material, bias, and incident wavelength is fixed. Thus QE is held as a fixed parameter, and efficiency changes can be attributed to changes in collection efficiency.

F. Single-Photon LED Pulsing

In order to accurately measure PMT parameters, it is important to have a well-understood source of single photon events. We do so by activating an LED with a very short pulse of 100ns. The LED driving voltage of 2.41V was tuned to ensure only approximately 1 in 10 LED pulses produced a PMT signal. We denote this the single-photon regime.

When driven at sufficiently low power, the number of photons emitted from the diode on every pulse is a process governed by Poisson statistics. There is an expected photon rate correlated with a given power consumption, but each individual emission event is governed by quantum fluctuations and thus uncorrelated, as determines a Poisson distribution.

$$P(k) = \frac{\lambda^k e^{-\lambda}}{k!} \quad (1.6)$$

The Poisson distribution describes the probability of seeing k events in time interval Δt , given the expectation value of λ events in that same time interval. λ is fixed for a given run and is determined by the pulse width and driving voltage of the LED. This is a probability mass distribution, with a normalized sum over all values. This can be seen by recognizing the series expansion for the exponential function.

$$\sum_{k=0}^{\infty} \frac{\lambda^k e^{-\lambda}}{k!} = e^{-\lambda} \sum_{k=0}^{\infty} \frac{\lambda^k}{k!} = e^{-\lambda} e^{\lambda} = 1 \quad (1.7)$$

For each incident photon, the quantum efficiency and collection efficiency will each impact the likelihood of detection by a multiplicative factor. There is an additional factor we denote the optical coupling parameter which details the solid angle of the optical fiber subtended by the PMT face.

For n photons, these multiplicative factors will impact the likelihood of detection through a binomial distribution. Our statistical chain thus combines a Poisson process with binomial processes, each with sub-unity success rate. In the large trial limit, this superposition approximates its own Poisson process, with a modified expectation value. After rough tuning to see PMT pulses 10% of the time, the probability of single, double, and triple

photon events thus is described by Poisson distributions with $\lambda=0.1$:

$$\begin{aligned} P(0) &= e^{-\lambda} \approx 90\% \\ P(1) &= \frac{\lambda e^{-\lambda}}{1} \approx 9\% \\ P(2) &= \frac{\lambda^2 e^{-\lambda}}{2} \approx 0.5\% \\ P(3) &= \frac{\lambda^3 e^{-\lambda}}{6} \approx 0.02\% \end{aligned}$$

To one significant figure, these are the populations that we expect for the single-photon dependent measurements of our experimental apparatus.

G. The Normal Distribution

According to the central limit theorem, the distribution of the mean of a large number of samples will converge to the normal distribution, even if the variable is not itself normally distributed. This probability distribution function is also known as a Gaussian.

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \quad (1.8)$$

Additionally, the Poisson distribution converges to the normal distribution with a large expectation value. When this is the case, the variance and mean of the Gaussian are both equal to the expectation value of the Poisson.

$$\sigma = \sqrt{\mu} \quad (1.9)$$

II. EXPERIMENTAL SETUP

Thusfar, use of the R11410 in the LZ experiment have relied on manufacturer specified base configurations. Hamamatsu optimizes the circuit board parameters for 'general use', with a primary focus on gain and a balanced focus on device linearity and collection efficiency. The LZ experiment is a liquid xenon TPC situated at the Sanford national lab 4000' underground.

A. CE and the First Dynode

Given the single-event statistics of a dark matter search, collection efficiency is the most important parameter to optimize for in LZ. Provided gain is sufficiently high for single photon events to appear above the noise threshold, optimizing for gain is not required. Similarly, provided device linearity is experimentally determinable, nonlinear effects can be calibrated out with a fit function.

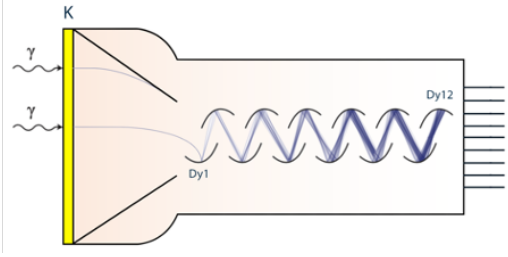


FIG. 3. Schematic of Electron Multiplication in the R11410. Incident photons are labeled γ . After conversion, the top line demonstrates a photoelectron miss, impacting CE. The bottom line demonstrates a photoelectron striking the first dynode and being multiplied through to D12.

Sub-unity collection efficiency arises from ejected photoelectrons which do not successfully make it through the dynode chain. This can happen anywhere along the device, but is predicted to be most relevant between K and D1 for two reasons. First, this section of the device is the one where the most optical funneling occurs. R11410 is a 3" circular PMT at the photocathode, but electrons must be focused through the grid to D1, an area of just 1 square inch. Insufficient field strength may see electrons colliding with the walls of the device, hampering CE.

Additionally, the device is most sensitive to CE deficits at the first dynode because electron multiplication hasn't happened yet. Given a likelihood λ of electron annihilation at any stage and a multiplication factor of α at each stage, the changes of signal annihilation happening at D1 is λ . At D2, that likelihood is λ^α , at D3 it is λ^{α^2} , etc. The optics of the first dynode are most relevant to CE. We thus seek to probe the CE changes observed given different $V(K-D1)$ bias configurations.

B. Cirlex Base Modification

Referring to Figure 1, R1 was desoldered and removed from the Cirlex board. A Mill-max pin was soldered in place, and a second HV coaxial cable attached. The ground pin is left unattached and ground reference remains fixed from the primary HV photocathode control.



FIG. 4. Foreground: modified PMT base in experimental apparatus PATRIC. The left connection is the anode probe. The two right connections are the high voltage supplies. Background: unmodified control PMT.

This allows for independent voltage control of the K and D1. Note that D1 and G are shorted, indicating that the mesh wire grid and first dynode are always biased at the same voltage. The HV cable attached to D1 now becomes the primary current source for the device, and the photoelectron current through K draws negligible current. In all runs, a second PMT with unmodified base is also tested as control.

C. PATRIC

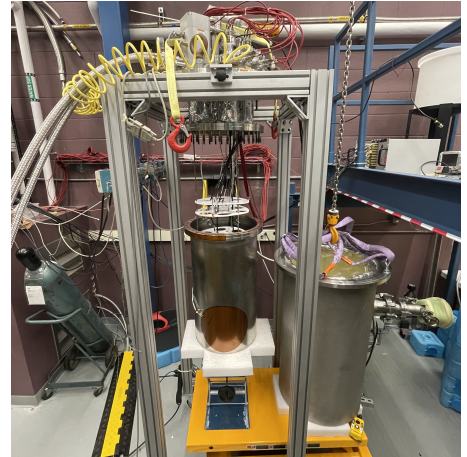


FIG. 5. PMT Array Test Rig in Cryogenics (PATRIC) in loading procedure. At center is the inner vacuum chamber (IVC) with PMT holders inside. To the right is the outer vacuum chamber (OVC). Yellow Kapton circle at center is the IVC heater pad. All ports into PATRIC are at top.

The main experimental apparatus is called PATRIC, acronym for PMT Array Test Rig In Cryogenics. PATRIC consists of two interlocking vacuum chambers, denoted IVC and OVC for the inner and outer chamber, respectively.

PATRIC is cooled by a Cryomech pulse tube refrigerator (PTR) with a CP2800 helium compressor and a thermal exchange head mounted to the top of the OVC. It is able to cool the IVC at approximately 7K/hr. During a cold run, it is run continuously. Thermal equilibrium is achieved using a Lakeshore 336 temperature controller which is connected to two resistive heater elements on the bottom and side of the IVC. Thermometry is done using two thermocouple probes, one at the top of the IVC near the PTR head, and one at the bottom.

A vacuum cart is situated next to PATRIC in order to pull vacuum on the IVC and OVC. A roughing pump and turbo pump are used in conjunction, with the roughing pump bringing pressures down to the millitor level before the turbo pump is tuned on. This system is able to hold pressures down to 5e-9 torr.

IVC is backfilled with N_2 to 2ATM after the cans have been evacuated. This ensures the absence of water in the cans during operation. 2ATM was picked because after cool down, the pressure will be near 1ATM. The steep gradient in vapor pressure of H_2O at 0°C poses an explosion risk and must be avoided. Additionally, cold runs are held at 93.0 K in order to stay sufficiently clear of the 63.0 K condensation temperature of the nitrogen backfill gas. During continuous operation and after proper PID parameter tuning, the lakeshore is able to maintain this temperature set point within 0.01K.

TABLE I. PATRIC Operating Parameters

IVC Temperature	93.0 K
IVC Backfill Pressure (warm)	1ATM
OVC Vacuum Pressure	5e-9 torr
PTR Cooling Rate	7K/hr

D. Optical System

In order to measure the efficiency of a PMT, it is imperative to have a tunable light source, both capable of generating single photon events and large busts or light. To do so, a tektronix AFG 3102 dual channel arbitrary function generator is used. It is operated in pulse mode, with both outputs terminating at 430 nm blue LED's. In a light tight box, the LED's are loosely coupled to a bundle of optical fibers and secured in place using a 3-D printed guide. The loose coupling is to facilitate reaching single photon levels. The fibers pass through external bulkheads into the IVC of PATRIC and deliver light pulses directly to the faces of the PMT's, where they are suspended 8" from the quartz panels.

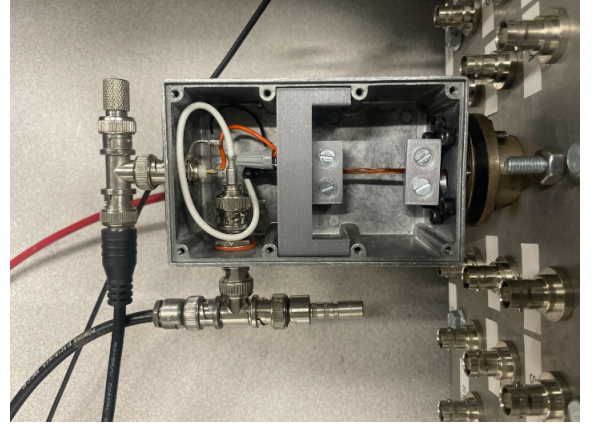


FIG. 6. Fiber Optic Coupling Box. Two BNC inputs (left and bottom) supply voltage to the two LED's. A 3-D printed mount (center - gray) couples the LED's to optical fibers. A 3-D printed strain relief clamp is also mounted to the optical bundle.

For measuring both linearity and single photon efficiency, it is imperative to have precise timing of light pulses. We tabulate the resolution and specifications of the AFG 3102.

TABLE II. AFG 3102 Pulse Wave Characteristics

Frequency Range	1 mHz to 50 MHz
Frequency Resolution	1 μ Hz
Pulse Width	8.00 ns to 999.99 s
Pulse Resolution	10 ps
Edge Transition Time	5 ns
RMS Jitter	200 ps
Output Impedance	50 Ω

E. HV Control System

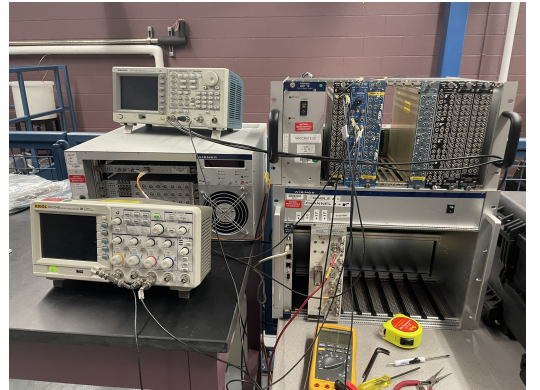


FIG. 7. Electronics Setup. Clockwise from top right: Wiener UE15 NIM Crate with 10x amplifier, Wiener Mpod HV Crate, RIGOL DS1204B 200 MHz Oscilloscope, Wiener SIS3304 ADC, Tektronix AFG 3102 Arbitrary Waveform Generator

In order to bias the PMT's, a WIENER MPOD high voltage crate is utilized, with 2x16 controllable HV channels, and a voltage stability of 10 mV or 0.1% for runs shorter than 24hrs. A trip current of 20 mA was utilized, 25% more than the expected quiescent current of 15.9 mA at a bias of 1750V.

$$I(\text{quiescent}) = \frac{1750V}{110M\Omega} = 15.90 \mu A \quad (2.1)$$

III. DATA PROCESSING

Once biased, signals coming from the PMT are first passed through a Wiener 776 16 channel 10x amplifier to increase the size of the pulses. The amplified signal is then digitized using a SIS3301 ADC. This ADC has a sample rate of 100 MHz and a 12-bit resolution. Acquisition parameters are digitally controlled using XML files specific to each run.

In standard mode, the digitizer will wait until a trigger condition is met, then digitize a signal until a stop condition is met. There are a few notable XML tags that impact the operation of the digitizer.

A. Digitizer XML

<sampling_freq> — The frequency in Hz at which to sample. 100 MHz is the maximum sample rate for this digitizer and the rate used for all acquisitions.

<pulse_thresh_detect> — The mV voltage threshold on the data channel to trigger on as the beginning of a pulse. The digitizer will wait until this threshold is met to begin storing data.

<pulse_detect_pretrigger> — Once the thresh detect trigger condition is met, the digitizer will include this number of samples before the trigger in the stored event data.

<pulse_end_thresh> — The mV voltage threshold at which the end of a sample is marked. If this value is set too low, the digitizer may not appropriately mark the end of a PMT pulse and continue digitizing noise. Thus, this value is set to a few mV above baseline.

<pulse_end_posttrigger> — Once the end thresh trigger condition is met, the digitizer will continue to include this number of samples after the end of the pulse in the stored event data.

<baseline_average_samples> — The number of samples before the beginning of a pulse to average as the baseline value. As mentioned, capacitive coupling can cause the anode BNC line to have electronic noise and baseline drift on the order of a few mV relative to the ground pin. This baseline averaging allows for a new 0 V reference to be set for each pulse individually, normalizing pulse heights and removing noise error.

B. Pulse Characteristics and Reduced Quantities

After being unpacked from raw .dat files, the digitizer output reports trace information from each pulse. It also reports other parameters such as timestamps from each event, and livetime/deadtime information from each acquisition.

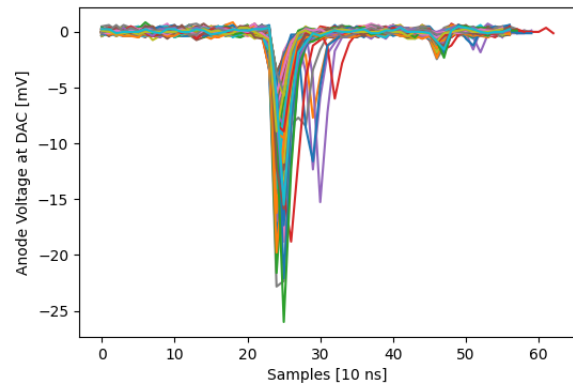


FIG. 8. Example pulse traces from 200 events. Y-axis is voltage measured at ADC. Actual PMT anode values are thus 10x smaller.

We plot 200 pulses from a single-photon calibration experiment. We can see that there is a `pulse_detect_pretrigger` value of 24 as all traces have 24 samples of baseline 0 V signal before the beginning of the pulse. The small peaks around 44 samples are reflection noise from the BNC cabling, which can be confirmed by calculating the signal distance traveled over this 20 sample period. We use $\frac{2}{3}c$ as the speed of signal in cable, and note that our cabling is approximately 20m long, for an out and back signal length of 40 m.

$$\begin{aligned} (44 \text{ samples} - 24 \text{ samples}) &= 2 \cdot 10^{-9} \text{ s} \\ 2 \cdot 10^{-9} \text{ s} \cdot \frac{3 \cdot 10^9 \text{ m}}{\text{s}} \cdot \frac{2}{3} &= 40 \text{ m} \end{aligned}$$

It becomes computationally intensive to store and analyze trace information directly. We thus process the raw data files in python and extract only important pulse parameters (reduced quantities). These include pulse height, pulse area, length of a pulse, peak location, and start timestamps. All further analysis is then done using only these quantities, and the dataset size is reduced by an order of magnitude from the number of samples per pulse to the number of RQ per pulse.

C. Noise Exclusion Height Threshold

For dataset acquisition, a small value of 3.5 mV is used for `<pulse_thresh_detect>`, which enables the digitizer

to trigger on even very small PMT pulses. A side effect of this is that approximately 20% of digitized events are simply line noise. Thus a preliminary noise exclusion cut of 5mV is applied to all data before analysis. It is imperative to make sure that our analysis accounts for this artificial cut threshold.

IV. GAIN

The gain of a PMT is defined as the ratio of the incident to the outgoing device current.

A. Gain Theory

We denote the overall device gain as G . Since the incident current is the photoelectron flux, it is more simply understood as the overall multiplication factor for each electron. Physically, it is the simple product of the secondary emission ratios for each dynode stage. We denote these individual dynode ratios g .

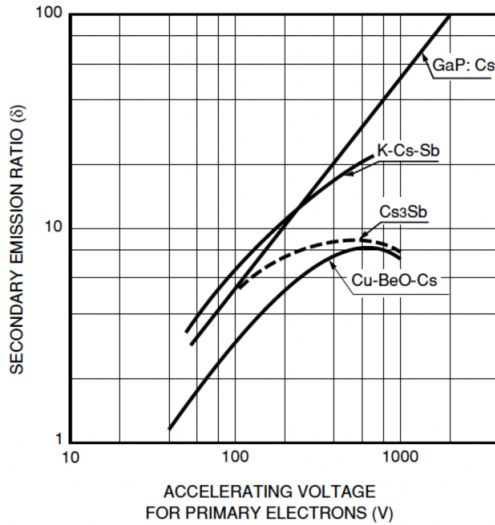


Figure 2-7: Secondary emission ratio

FIG. 9. Secondary emission ratio, applicable to each dynode stage. A roughly linear relationship on the log-log plot implies a power law relationship. The slope of the K-Cs-Sb line allows us extrapolate the exponential term in the multiplication relation.

Hamamatsu provides this secondary emission ratio for various secondary emission materials. The line of interest for the R11410 is the K-Cs-Sb line, a bi-alkali material. This ratio is roughly linear on the provided log-log plot, indicating that each dynode has a voltage-gain functional relationship that is roughly a power law. We can evaluate this dependence from the plot, using the points (60, 4) and (600, 20) and linearizing the power law.

$$\begin{aligned}
 g &= k \cdot V^n \\
 \text{Log}(g) &= \text{Log}(k) + n\text{Log}(V) \\
 \text{Log}(4) &= \text{Log}(k) + n\text{Log}(60) \\
 \text{Log}(20) &= \text{Log}(k) + n\text{Log}(600) \\
 n &= 0.699 \\
 k &= 0.228 \\
 g &= 0.2286V^{0.699}
 \end{aligned}$$

The overall gain of the device G will thus be the product of g over all dynode stages.

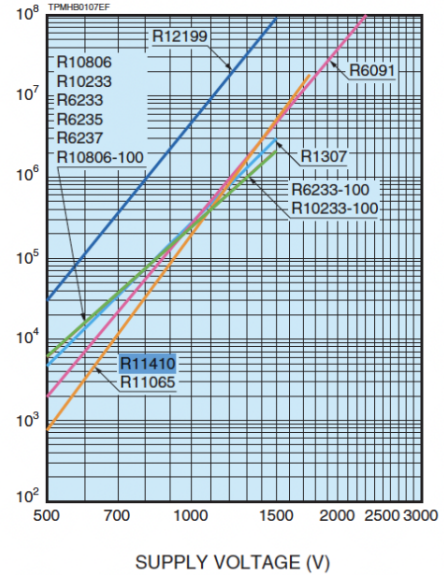


FIG. 10. Dependence of overall PMT gain on supply voltage. A linear dependence on the log-log plot also implies a power law relationship for the entire device bias.

Hamamatsu also provides a functional relationship of overall gain to supply voltage. In the nominal base bias of 1500V, the plot demonstrates an expected gain of $5 \cdot 10^6$, from Figure 10. The primary experiment conducted sweeps the $V(K-D1)$ voltage from the nominal $4R_0 = 324V$ up to 800V. The bias and thus gain and emission ratios of the remainder of the dynode stages remain constant. The increase in gain will be strictly proportional to the change in secondary emission ratio of the first dynode stage.

B. Gain Results

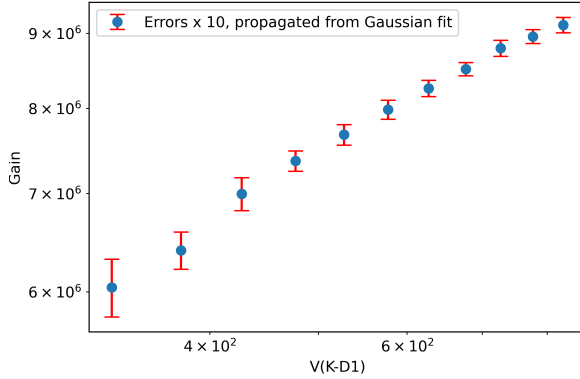


FIG. 11. PMT Gain, Experimental Results. $T = 93.0$ K. The linear relationship on a log-log plot implies a power law relationship as described in the gain theory section. Errors are derived using uncertainty propagation from the covariance matrix of the fit function.

We plot the measured gain values for a spread of $V(K-D1)$ biases. Over the course of a 500 V sweep, the gain of the device increases by 51% from $6.04 \cdot 10^6$ to $9.12 \cdot 10^6$. To determine these gain values, the LED pulsar is tuned to the single-photon level. After applying cuts to exclude dark events, we histogram the pulse area reduced quantity for all pulses.

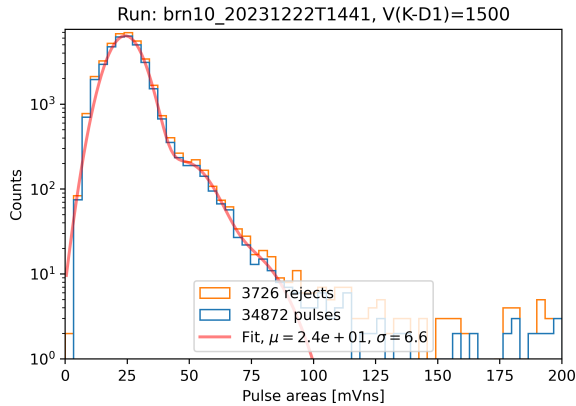


FIG. 12. Pulse area histogram from a cold run with $V(K-D1)=325$ V. $T = 93.0$ K. A triple-Gaussian fit function is used.

The fit expression used in the plot is as follows:

$$(a)e^{\frac{(-x-\mu)^2}{2\sigma^2}} + \left(\frac{a^2}{2!}\right)e^{\frac{(-x-2\mu)^2}{2\sqrt{3}\sigma^2}} + \left(\frac{a^3}{3!}\right)e^{\frac{(-x-3\mu)^2}{2\sqrt{3}\sigma^2}} \quad (4.1)$$

This expression is the sum of three Gaussian distributions, as can be seen from Eq (1.8). An additional amplitude parameter, a , is fit, as the PDF integrates to

1 but we have nonunity counts. Critical to the fit is the fact that the Gaussians have correlated parameters due to the Poissonian origin of these peaks. The second peak corresponds to 2 emitted photo-electrons, and thus has a mean value twice that of the first peak. Similarly the $\sigma = \sqrt{\mu}$ relationship is used as described in Eq (1.9). Lastly, the amplitudes of the three peaks are related by the combinatoric prefactors described on page 3.

For the gain results, the relevant peak is the first peak with the largest amplitude. This peak corresponds to single-photon events, as it reports the average energy delivered to the anode by a single photoelectron. The expectation value of this normal distribution thus corresponds to the average device gain.

$$\text{mVns} \cdot \frac{10^{-3}\text{V}}{\text{mV}} \cdot \frac{1 \cdot 10^{-9}\text{s}}{\text{ns}} \cdot \frac{C}{25\text{Vs}} \cdot \frac{1.6 \cdot 10^{19}e^-}{C} \quad (4.2)$$

Recall that the effective resistance at the anode is 25Ω . Simple dimensional analysis helps convert pulse area [mV ns] at the anode to a number of electrons. The converted single-photon expectation value is used for gain values in Figure 11.

V. DARK RATE

The dark rate is the rate at which a biased PMT in no-light conditions will produce pulses. These are erroneous pulses (rejects). They can be attributed to cosmic rays, radioactive decay, thermionic emission, and bias-induced dark counts.

A. Sources of Dark Rate

Cosmic rays, primarily muons, may interact within the detector and produce high energy gamma rays. Upon striking the PMT, these will be recorded as pulses. The only way to mitigate cosmic ray dark current is through shielding. The LZ experiment is conducted nearly a mile underground in the Sanford Underground Research Facility for this purpose, with the rock shielding nearly all of the cosmic ray flux. This experiment was conducted at ground level. The flux of cosmic ray muons with a minimum energy of 1GeV is approximately $1\text{cm}^{-2}\text{s}^{-1}$.

Radioactive decay can also contribute to the dark rate flux of a PMT. Decay processes which emit gamma rays may strike the photocathode and be recorded as pulses. Due to the high-sensitivity requirements of the LZ experiment, R11410 PMT's are specifically manufactured with ultra-low radiation requirements. In particular, the silica often used for PMT glass casing is hard to manufacture with low activity, and thus stainless steel is used. Similarly, the fiberglass used in traditional PCB's has intolerable levels of radioactivity. A different material, Cirlex, is used, which is manufactured to high radiopurity.

Thermionic emission is the dark current source that is easiest to mitigate. Electrons are fermions, and thus will have energies within the material as described by the Fermi-Dirac distribution. Recall the expression $f(E)$, which describes the probability of finding an electron at an energy E .

$$f(E) = \frac{1}{e^{(E-\mu)/(k_B T)} + 1} \quad (5.1)$$

Dark rate associated with thermionic emission occurs for electrons near the surface of the photocathode which have energies at or equal to the work function of the material. Reducing the temperature of the system thus lowers the energy scale of the system and greatly reduces the likelihood of emission. For this reason the PMT's are operated at 93.0K in PATRIC.

By increasing the strength of the electric field at the photocathode, there is an effective reduction in the work function of the material. This thus makes it easier for electrons to be thermionically emitted. It is this process that will govern the dark rate change over the course of the experiment.

B. Dark Rate Results

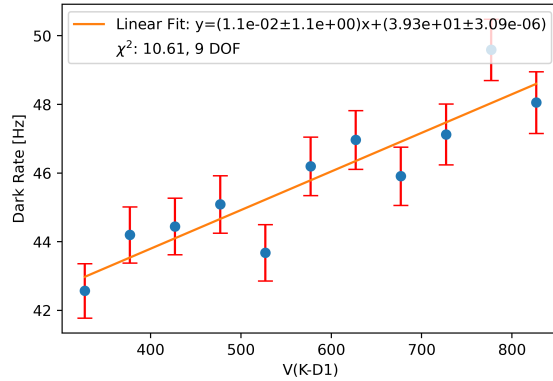


FIG. 13. Dark Rate experimental results, $T = 93.0$ K. Error bars calculated using $\sigma = \sqrt{n}$. 9 Degrees of freedom.

We observe an increase in dark rate by 14% over the course of the dynode sweep. Our statistics correspond to a p-value of 0.306. The relatively poor fit is attributed to the linear model being a crude representation of the functional dependence of the modified work function on bias voltage. The y-intercept of $39.3 \pm 3e-6$ gives an estimate for the non-thermionic dark rate component. This is the muon and accidental-gamma flux of the experimental apparatus.

VI. EFFICIENCY RESULTS

We seek to investigate whether the $V(K-D1)$ bias sweep has any measurable impact on the efficiency of the device. The triple-Gaussian peak fit parameters provide a robust analytical tool for determining device efficiency. Observe that the ratio of incident single pulses to zero-pulses is precisely the lambda parameter.

$$\frac{P(1)}{P(0)} = \frac{\lambda^1 e^{-\lambda}}{1!} \cdot \frac{0!}{\lambda^0 e^{-\lambda}} = \lambda \quad (6.1)$$

Using the peak location, width, and amplitude from the fit, $P(1)$ can be estimated. $P(0)$ is calculated by subtracting the number of non dark rate pulses from the total LED triggers over the runtime (runtime * 10 kHz - accepted_pulses).

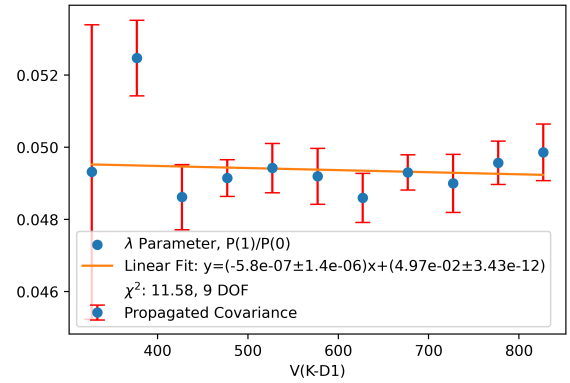


FIG. 14. Efficiency from Gaussian area fit approximation. $T = 93.0$ K. Errors are propagated from the covariance matrix of the triple gaussian fit function. The three σ deviated point at $V(K-D1)=375$ V is attributed to experimental error.

There appears to be no correlation between the $V(K-D1)$ bias and the efficiency of our system, confirming a null hypothesis. The slope of the fit line is nearly zero. The erroneous value at 375 V is attributed to experimental error.

VII. EFFICIENCY DISCUSSION

Another method for evaluating efficiency is to conduct a counting experiment. A greater number of pulses per unit time with the same LED pulse parameters indicates a higher device efficiency. We can compare the incident trigger rate of the PMT for the bias sweep before and after time-based cuts have been applied.

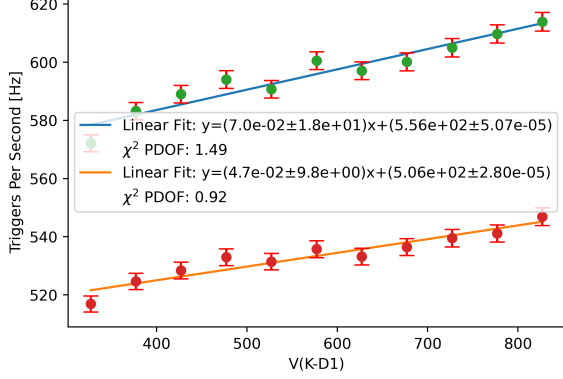


FIG. 15. Trigger Rate Comparison for V(K-D1) Sweep. The blue line is all events, without cuts. It demonstrates Time-Cuts

We see that the cut has reduced the total number of counts per second, in addition to the rate of change increase in triggers. The removal of dark rate events is responsible for the constant reduction. The removal of afterpulses is responsible for the slope difference as afterpulsing is a bias-dependent process. After cuts, we can calculate the fractional increase in triggers over the 475 V V(K-D1) sweep.

$$\begin{aligned} V(324) &= 521.2 Hz \\ V(800) &= 543.6 Hz \\ \frac{V(800)}{V(324)} &= 1.043 \end{aligned}$$

Thus, we report an overall trigger rate increase of 4.3% after a V(K-D1) sweep from 324 V to 800 V. Since we have already demonstrated that it is not the deficiency of the device which is increasing, we seek to determine what the source of these increased counts are.

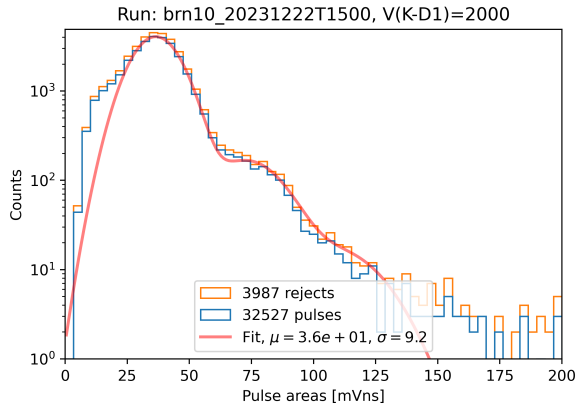


FIG. 16. Pulse area histogram from a cold run with V(K-D1)=725 V. T = 93.0 K. A triple-Gaussian fit function is used.

Compare Figure 16 with Figure 12. The triple gaussian fit hypothesis matches well with observed pulse areas for V(K-D1)= 325 V, but the hypothesis fails for low pulse areas in the V(K-D1)=725 V plot. We attribute this shoulder section to the increased trigger rate seen in figure 15. This accounts for the 'missing pulses' seen in the trigger rate increase of Figure 15.

We attribute these pulses to a side effect of the increased gain from the bias change. This 'shoulder' section is characteristic of PMT's, and represents pulses which miss a stage of multiplication, likely skipping the first dynode. Without the additional resolution from the gain increase, these pulses were obscured by the pulse detection threshold at lower voltages.

VIII. LINEARITY

We present our linearity results. All other dynodes held constant, a 500V increase in bias strength between the Photocathode and first dynode does not impact device linearity within the 3% level at 30 mA.

A. Linearity Introduction

We define device linearity as the ratio of input light flux to signal output size. PMT's are expected to operate linearly for low light intensities corresponding to event peak anode currents of 15-20mA. Past this current, nonlinear regimes driven by the space charge effect and capacitor depletion push the device into a saturated state, clamping any further increase in signal output. For the R11410, Hamamatsu specifies that the devices should remain linear within 2% up to a peak anode current of 20mA and within 5% up to 25mA.

B. Linearity Measurement Technique

In order to measure and evaluate device linearity, it is essential to have a well calibrated light source, ensuring that the incident light flux is known to single-percent levels. Since LED's have strongly nonlinear voltage-intensity responses, the stepped calibration method utilized implicitly removes the need to correct for this non-linearity.

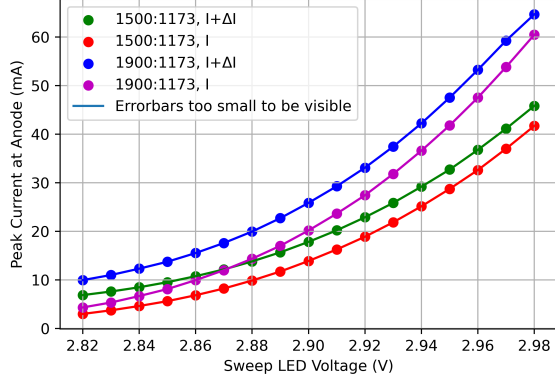


FIG. 17. Linearity measurement bias schematic. $T = 93.0$ K. The control data is shown in red and green. The high-field data is shown in blue and purple. Linearity data is extracted from the difference in current between a set of points.

Two identical LED's are used. The sweep LED (I), is pulsed between 2.82 and 2.98 over the course of a run. This range was selected to access near single-photon pulses at 2.82V and PMT saturating pulses at 2.98V.

The probe LED, (ΔI), is always pulsed at the same voltage, and whose PMT pulse height response (alone) is collected and denoted the baseline. Pulse data is collected and, after data discrimination, pulse heights from a set are averaged into anode currents.

For each 'linearity datapoint', two data sets are taken, one with the sweep LED, and one with both the sweep and probe LED. Linearity of the device at a given voltage V is then defined as how much the pulse height difference between the single-LED set and the dual-LED set differ from the baseline pulse height. If the device is operating linearly and incident light pulses from the two LED's are temporally coherent, adding the probe LED should increase pulse height (directly proportional to instantaneous anode current) by the same amount.

$$L(V) = \frac{I[\text{sweep}(V) + \text{probe}(\text{base})] - I[\text{sweep}(V)]}{I[\text{probe}(\text{base})]} \quad (8.1)$$

C. Linearity Run Parameters

TABLE III. Pulse Parameters

Pulse width	100ns
Pulse frequency	1kHz
Pulse ramp time	5ns

The curve of the lines are simply a result of the LED's nonlinear activation. The steeper curve to the blue and purple trends demonstrate the increased device gain that

is also associated with the 1900:1173 bias voltage regime. We now extract linearity values from these current measurements as described above.

D. Linearity Results

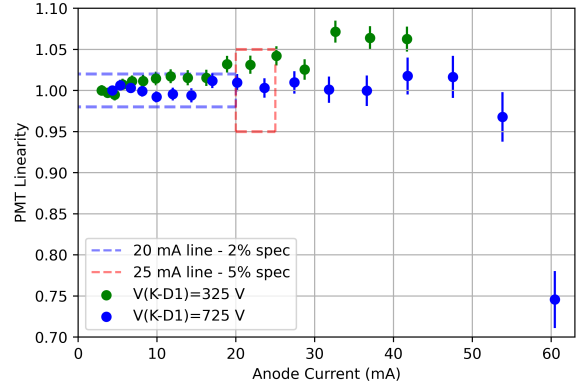


FIG. 18. Linearity results for the control data in green. Results for the high-field data in blue. The two Hamamatsu linearity specs are bounded in blue and in red. All points below 25 mA report a linearity consistent with Hamamatsu spec.

Both the control bias configuration and the test bias configuration have pulse responses within 2% up to 13mA, as specified by Hamamatsu. Notice that the linearity values increase by a few percent before the strongly nonlinear dropoff. This is attributed to the space charge effect. We thus conclude that the proposed bias configuration changes do not induce significant nonlinear effects to device operation.

IX. CONCLUSION

In this paper we demonstrate that the CE (collection efficiency) of the Hamamatsu R11410 is not improved by strengthening the optics of the single photoelectron stage ($V[K-D1]$). The efficiency parameter of the Poisson described single-photon system remains constant throughout the bias sweep. However, the total trigger rate does increase in the left hand shoulder section of the PMT pulse area histogram. This is due to increased resolution past the pulse detection threshold.

We confirm that such a change in dynode bias regime does not detrimentally affect all other relevant device operational parameters. Device linearity remains within the 2% at 20 mA peak anode current specified by Hamamatsu. Device dark rate increases by 6 Hz over the course of the sweep. Gain continues to scale in the prescribed power-law relationship even with increased D1 bias, increasing by 51% over the course of the sweep.

X. APPENDIX

A. Time-Based Cuts

This cut method utilized to eliminate erroneous triggers from our calculation involves histogramming the time between successive triggers for an acquisition. We use coincidence logic between LED pulses and PMT events to discriminate between dark rate events, after pulses, and proper pulses. The AFG3102 arbitrary waveform generator used to pulse the LED's has a timing resolution of 10ps. The SIS3301ADC has a sample frequency of 10ns. The digitizer thus constrains the timing resolution of the experimental setup.

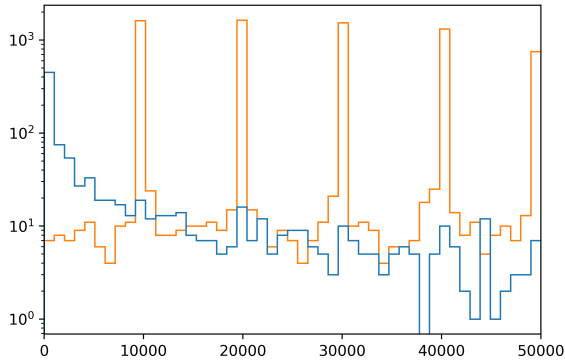


FIG. 19. Event Timing Diff Histogram

We present a histogram of the time between successive PMT pulses, shown up to 50,000 samples. The Poisson nature of the single-photon regime utilized for this experiment means light is not incident on the PMT every LED trigger. As tuned, 90% of LED pulses produce no detectable light. The trigger frequency used was 10kHz, which corresponds to a period of 100us, or 10,000 samples. The primary peaks seen occur at multiples of 100us. These peaks extend well past the 500us point. Only about 20% of the total pulses are shown (6500/31000), with some PMT events occurring after a quiet period of even a few ms.

Events which occur immediately after a preceeding pulse are known to be afterpulses. 100us has not passed for the next LED pulse. As described in the theory section, afterpulses should begin within 200ns of an initial pulse. Thus, a cut of 20 samples was used to tag afterpulses. This can be seen as the tall dark blue bin on the left hand edge of the plot.

Dark rate events are necessarily uncorrelated from the LED trigger timing. They can thus be recognized as the baseline noise along the plot with bin heights 5-10. These

events were selected as events which do not occur within 200ns of an LED trigger (of a multiple of 10k samples). 200ns was selected as it is characteristic of the length scale of an event pulse.

Lastly, consider an event immediately after a dark rate event. Despite having a pulse timing aligned with the LED timing, its diff histogram value would be (100us - dark event timing). This is the reason that only approximately half of the events occurring in the 'dark event' region are tagged as rejects. The rest are actually 'correct' pulses which came immediately preceeding a dark event. The time based cut excludes about 15% of pulses.

B. Gain Normalization

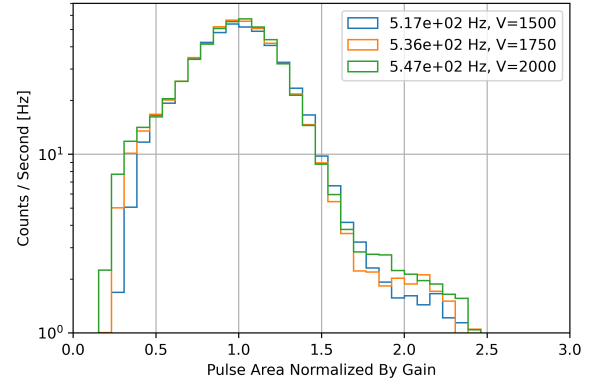


FIG. 20. PMT Gain, Experimental Results

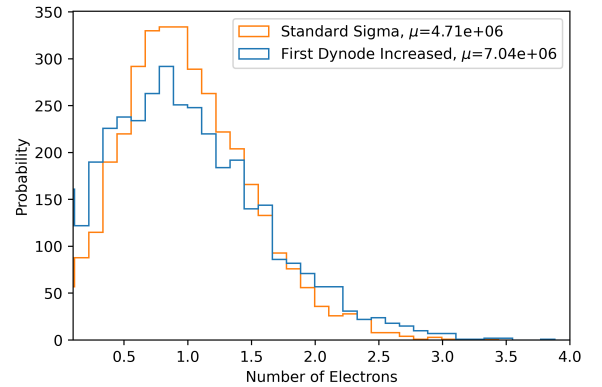


FIG. 21. PMT Gain, Experimental Results