Characterization of Photomultiplier Tubes

Michael Kennedy*, Dept. of Physical Sciences, Suffolk County Community College, Selden, NY;
Garrett Stoddard*, Dept. of Physics, Stony Brook University;
Aiwu Zhang PhD and David Jaffe PhD, Electronic Detector Group, Physics Department, Brookhaven National Laboratory;
Raul Armendariz PhD, Department of Physics, Queensborough Community College, Bayside, NY.
* students

Prepared for the Long Island STEM Hub 5th Annual Celebration, Student and Industry Showcase, Brookhaven National Lab, April 18th, 2017

Testing photomultiplier tubes for two projects

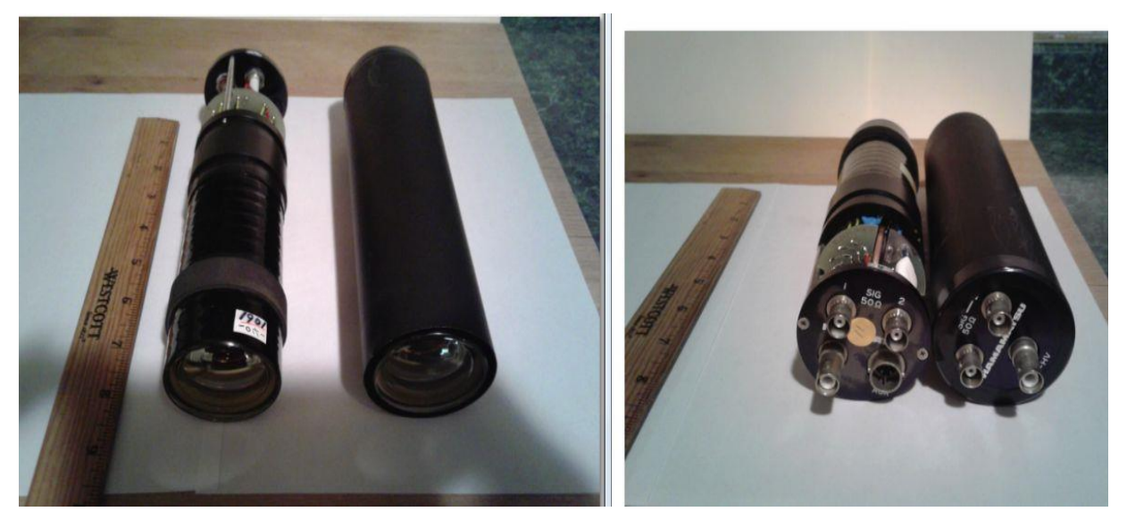
Cosmic ray detectors are being developed using plastic scintillators at Queensborough Community College. To achieve this goal, photomultiplier tubes (PMT) with excellent responses are required. A PMT characterization system has been set up with the electronic detector group in the BNL physics department. PMTs will be evaluated by measuring their gain, relative quantum efficiency, dark rate, etc. The PMTs achieving certain criteria will be selected for the cosmic ray detectors.

Collaborators from BNL Chemistry and Physics have developed a 1 ton detector vessel for water-based liquid scintillator (WbLS) feasibility studies for very large scale (>10000 tons) detectors for particle physics. In these studies, photomultiplier tubes (PMT) with single photon detection capability are required. Various PMTs will be characterized by measuring their gain, single photon-electron resolution (SPE), peak to valley (P/V) ratio, dark count rate, etc. Based on the measurements, satisfactory PMTs will be identified and used for WbLS research.

Accomplishments

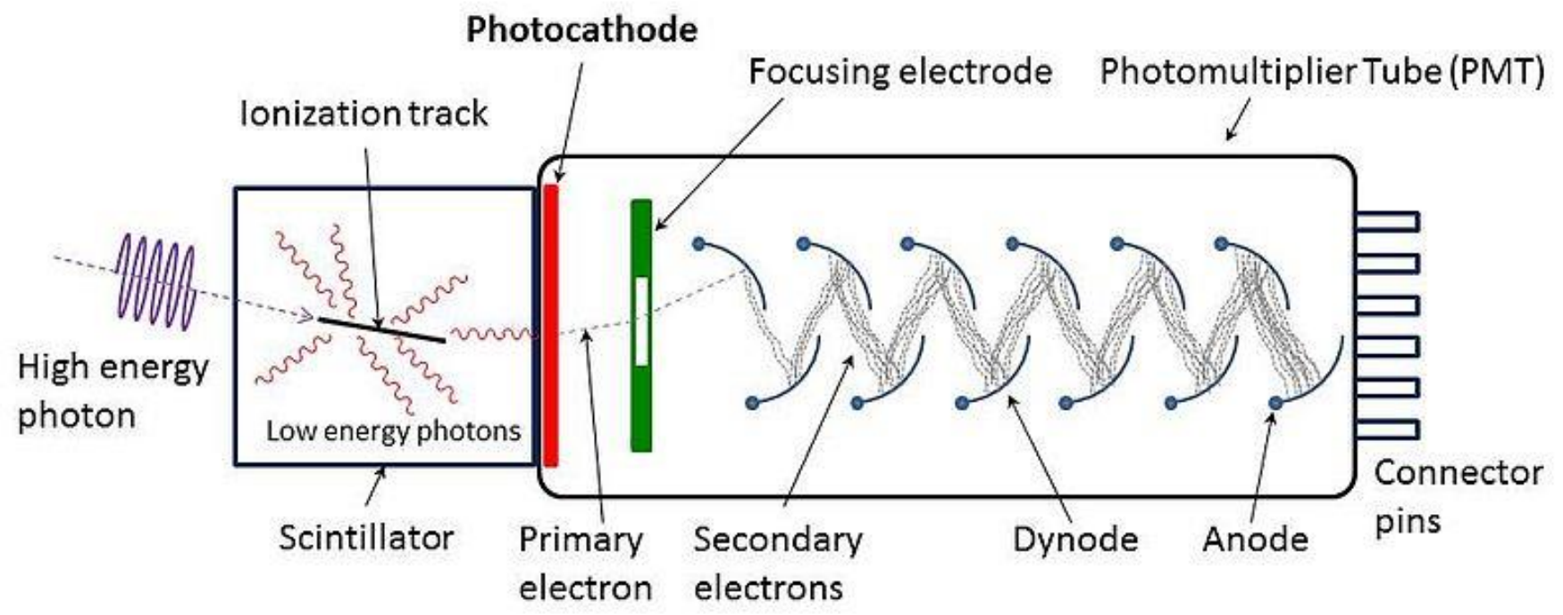
A dark box has been setup which can test 4 PMTs simultaneously at a distance of about 32 inches from a flashing LED driven by a pulse generator set at 1.62 V, 11 ns, frequency 5 to 10 Hz. Four-channel waveforms are taken from a Tektronix DPO 4104 oscilloscope by a LabVIEW program. The daq rate is limited at about 0.7 Hz. It was determined that > 12000 waveforms are needed to get good statistics of the single photoelectron spectrum; one run takes about 5 hours. To measure a gain curve 4 to 5 HV points are measured. Data is processed with s PyROOT program, the single photoelectron spectrum is fitted by a convoluted distribution of Gaussian and Poisson distributions. PMT gain, resolution, and the P/V ratio can be studied. A discriminator and a scaler are used to measure dark count as a function of high voltage.

Hamamatsu H2431-50 PMTs tested.



Dark box setup

Photomultiplier tubes work via the photoelectric effect. Unlike phototubes a photomultiplier tube has dynodes that create an electron cascade which allows for detection of even single photons.



High Voltage Inspection
The HV outputs were tested using three different voltmeters (DVMs); each DVM read a different HV by as much as 18 volts at -1300V; the percent by which each voltmeter reading was different from the HV dial setting was consistent as HV was increased.

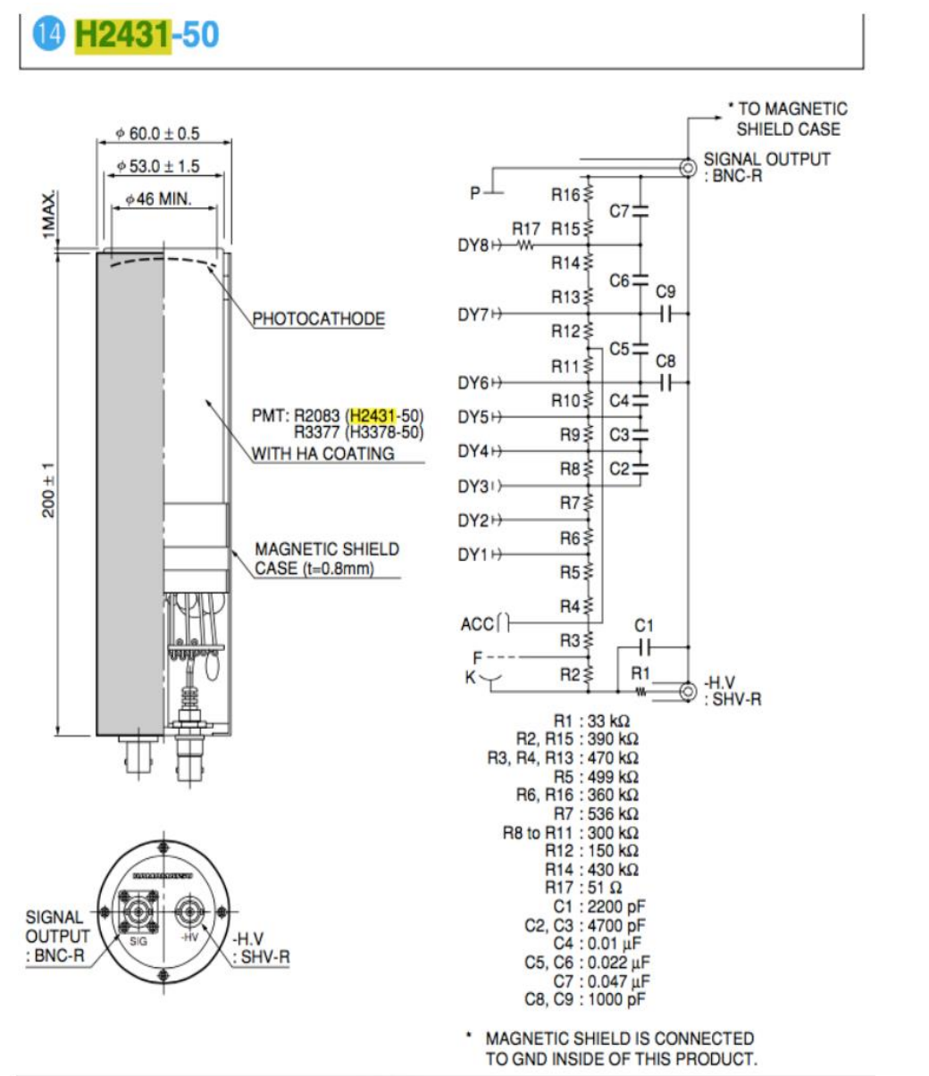
When the HV was set at each -900V, -1100V, and -1300V:
HV1 and HV2 were measured to be within 0.1% of the dial settings.
HV3 and HV4 were measured to be within 0.5% of the dial settings.

Results:
HV set at -900V:
Ch1: DVM1 = -900V, DVM2 = -896V, DVM3 = -910V.
Ch2: DVM1 = -899V, DVM2 = -896V, DVM3 = -910V.
Ch3: DVM1 = -896V, DVM2 = -892V, DVM3 = -906V.
Ch4: DVM1 = -896V, DVM2 = -896V, DVM3 = -907V.

HV set at -1100V:
Ch1: DVM1 = -1100V, DVM2 = -1096V, DVM3 = -1115V.
Ch2: DVM1 = -1100V, DVM2 = -1096V, DVM3 = -1114V.
Ch3: DVM1 = -1094V, DVM2 = -1089V, DVM3 = -1106V.
Ch4: DVM1 = -1094V, DVM2 = -1089V, DVM3 = -1107V.

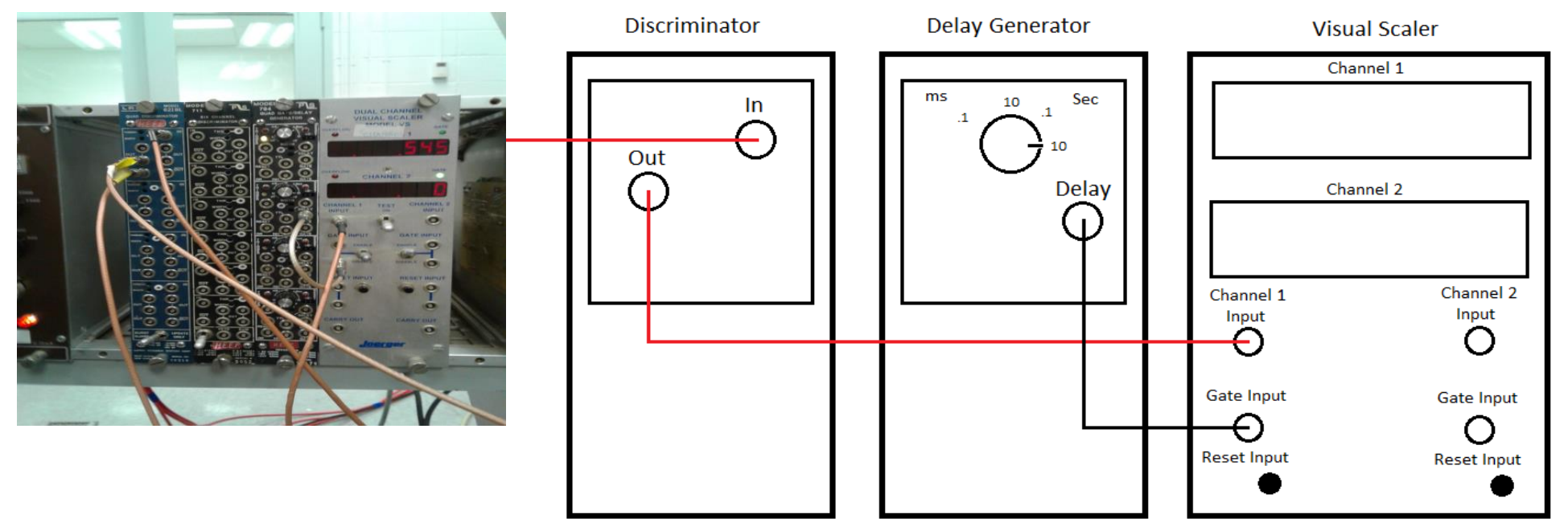
HV set at -1300V:
Ch1: DVM1 = -1299V, DVM2 no good, DVM3 = -1317V.
Ch2: DVM1 = -1299V, DVM2 no good, DVM3 = -1317V.
Ch3: DVM1 = -1292V, DVM2 no good, DVM3 = -1309V.
Ch4: DVM1 = -1292V, DVM2 no good, DVM3 = -1309V.

HV set at -1500V:
Ch1: DVM1 no good, DVM2 no good, DVM3 = -1520V.
Ch2: DVM1 no good, DVM2 no good, DVM3 = -1520V.
Ch3: DVM1 no good, DVM2 no good, DVM3 = -1510V.
Ch4: DVM1 no good, DVM2 no good, DVM3 = -1510V.



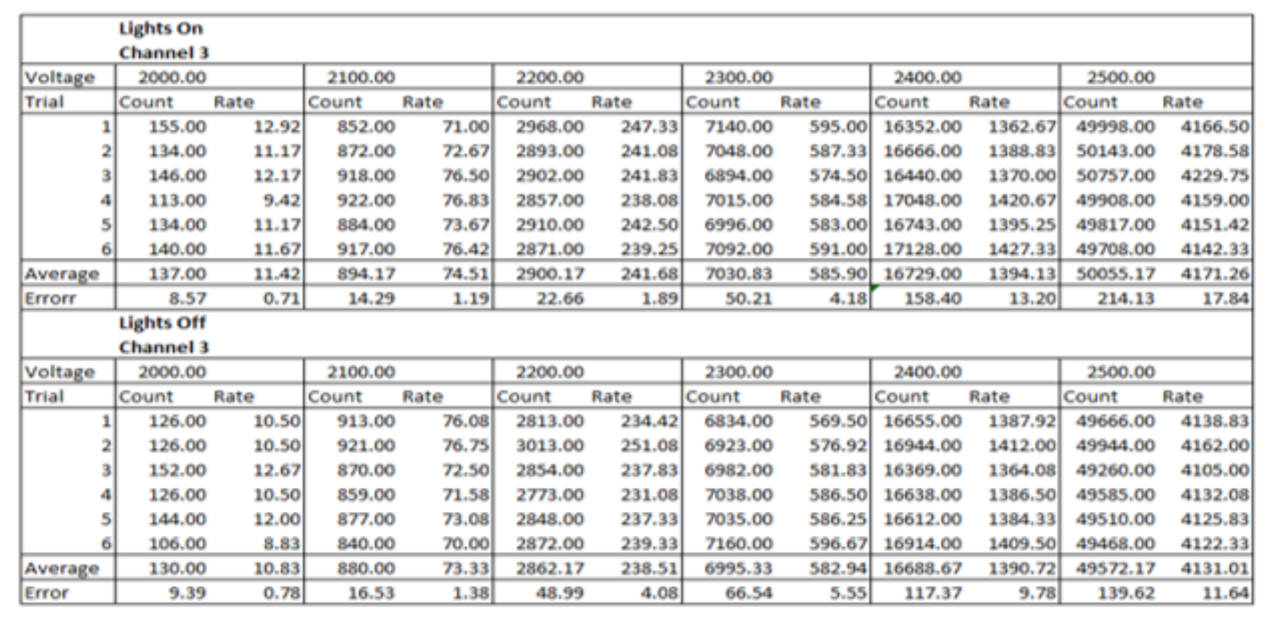
Each PMT uses a voltage divider circuit to distribute high voltage to the electrodes.

Dark box light tightness tests and setup to measure PMT stability

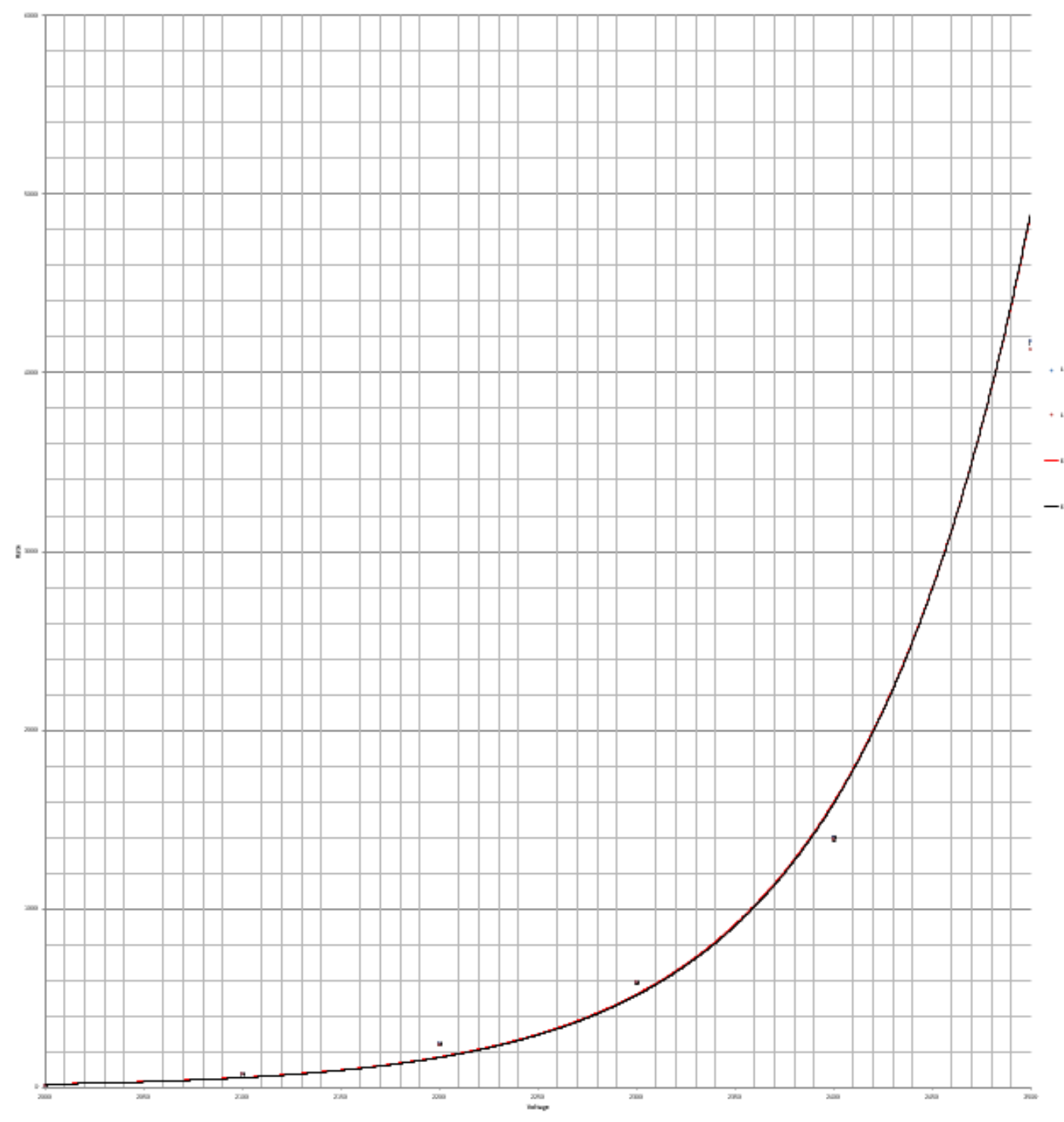


- We tested all four PMTs and only the third seemed to be operating properly, so we used this one. When measured at any voltage, the first, second, and fourth PMT will only register 0-2 counts.
- When timed (using QUAD GATE/DELAY GENERATOR Model: 794 and QUAD DISCRIMINATOR Model 621BL), the time interval for acquiring data was approximately 12 seconds (the device was supposed to make measurements over 10 second intervals, but when measured with a stopwatch, it was almost exactly 12 seconds), so the rate was derived by dividing the total count by 12.
- The Voltage was varied (using HIGH VOLTAGE POWER SUPPLY Model: 456) from 2000 volts to 2500 volts at intervals of 100 volts. A rest period of roughly ten minutes was allowed between testing to allow the count rate to steady.
- After settling at each voltage, six readings were taken with the ceiling lights on and off. These values were recorded in a spreadsheet (shown below) to be used for light leak analysis.
- Error bars were included in the plot but are too small compared to the values on the y-axis to be visible.

- After testing and comparing the count rates at various voltages, the difference in measurements with lights on versus lights off appears to be negligible. Any light leak impacts the data in such a miniscule way that it can be ignored.
- When testing PMTs 1, 2, and 4, we replaced all wires connecting them to our measuring equipment, tested them using multiple inputs to the discriminator, and adjusted the input voltage, all yielding no change in data output.
- Should we conduct future tests, it would likely be beneficial to replace the presumably faulty PMTs in order to truly determine whether or not they are the source of the issue.



	Lights On Channel 3											
Voltage	2000.00		2100.00		2200.00		2300.00		2400.00		2500.00	
Trial	Count	Rate	Count	Rate	Count	Rate	Count	Rate	Count	Rate	Count	Rate
1	155.00	12.92	852.00	71.00	2968.00	247.33	7140.00	595.00	16352.00	1362.67	49998.00	4166.50
2	134.00	11.17	872.00	72.67	2893.00	241.08	7048.00	587.33	16666.00	1388.83	50143.00	4178.58
3	146.00	12.17	918.00	76.50	2902.00	241.83	6894.00	574.50	16440.00	1370.00	50757.00	4229.75
4	113.00	9.42	922.00	76.83	2857.00	238.08	7015.00	584.58	17048.00	1420.67	49908.00	4159.00
5	134.00	11.17	884.00	73.67	2910.00	242.50	6996.00	583.00	16743.00	1395.25	49817.00	4151.42
6	140.00	11.67	917.00	76.42	2871.00	239.25	7092.00	591.00	17128.00	1427.33	49708.00	4142.33
Average	137.00	11.42	894.17	74.51	2900.17	241.68	7030.83	585.90	16729.00	1394.13	50055.17	4171.26
Errorr	8.57	0.71	14.29	1.19	22.66	1.89	50.21	4.18	158.40	13.20	214.13	17.84
	Lights Off Channel 3											
Voltage	2000.00		2100.00		2200.00		2300.00		2400.00		2500.00	
Trial	Count	Rate	Count	Rate	Count	Rate	Count	Rate	Count	Rate	Count	Rate
1	126.00	10.50	913.00	76.08	2813.00	234.42	6834.00	569.50	16655.00	1387.92	49666.00	4138.83
2	126.00	10.50	921.00	76.75	3013.00	251.08	6923.00	576.92	16944.00	1412.00	49944.00	4162.00
3	152.00	12.67	870.00	72.50	2854.00	237.83	6982.00	581.83	16369.00	1364.08	49260.00	4105.00
4	126.00	10.50	859.00	71.58	2773.00	231.08	7038.00	586.50	16638.00	1386.50	49585.00	4132.08
5	144.00	12.00	877.00	73.08	2848.00	237.33	7035.00	586.25	16612.00	1384.33	49510.00	4125.83
6	106.00	8.83	840.00	70.00	2872.00	239.33	7160.00	596.67	16914.00	1409.50	49468.00	4122.33
Average	130.00	10.83	880.00	73.33	2862.17	238.51	6995.33	582.94	16688.67	1390.72	49572.17	4131.01
Error	9.39	0.78	16.53	1.38	48.99	4.08	66.54	5.55	117.37	9.78	139.62	11.64



Though it may be difficult to see, there are two lines plotted above. The red line and data points represent the data that was acquired while measuring with the lights on and the black line/data points represent the measurements under the same conditions with the lights off.

PMT Calculations: understanding PMT signal detection

N_γ	Number of photons incident on photocathode
N_{pe}	Number of photoelectrons emitted by photocathode
$QE = N_{pe}/N_\gamma$	Quantum efficiency of PMT
N_e	Number of electrons emitted by anode
$g = N_e/N_{pe}$	Gain of PMT
$e = 1.6x10^{-19}$C	electron charge
$Q = N_e e$	Charge emitted by anode
$I = \frac{\Delta Q}{\Delta t}$	Photocurrent emitted by anode
I_D	Dark Current emitted by anode

Signal over noise: minimum light detection over PMT dark current

The minimum amount of light detectable by a PMT is determined by its dark current, gain, and quantum efficiency; in order for the PMT anode output I to be above its dark current I_D:

$$I = \frac{\Delta Q}{\Delta t} = \frac{N_e e}{\Delta t} = \frac{N_{pe} g e}{\Delta t} = \frac{N_\gamma QEge}{\Delta t} > I_D,$$

thus:

$$\frac{N_\gamma}{\Delta t} > \frac{I_D}{QEge}\ ;$$

for energy per photon at a given wavelength $E = \frac{hc}{\lambda}$, the incident light power on the photocathode should be:

$$P = \frac{N_\gamma}{\Delta t}\frac{hc}{\lambda} > \frac{I_D}{QEge}\frac{hc}{\lambda};$$

for violet light at $\lambda = 420$ nm, and a PMT with $I_D = 100$ nA, $QE = 0.2$, $g = 2.5x10^6$, the incident light power required for detection is:

$$P_{\text{required}} > \frac{100\text{x}10^{-9}\text{A}}{0.2(2.5x10^6)(1.6x10^{-19}C)}\,\frac{(6.6x10^{-34}\ \text{m}^2\text{kg/s})2.99x10^8\ \text{m/s}}{420\ \text{x}10^{-9}\text{m}}$$

$$P_{\text{required}} > 6x10^{-13}\ \text{Watts}$$

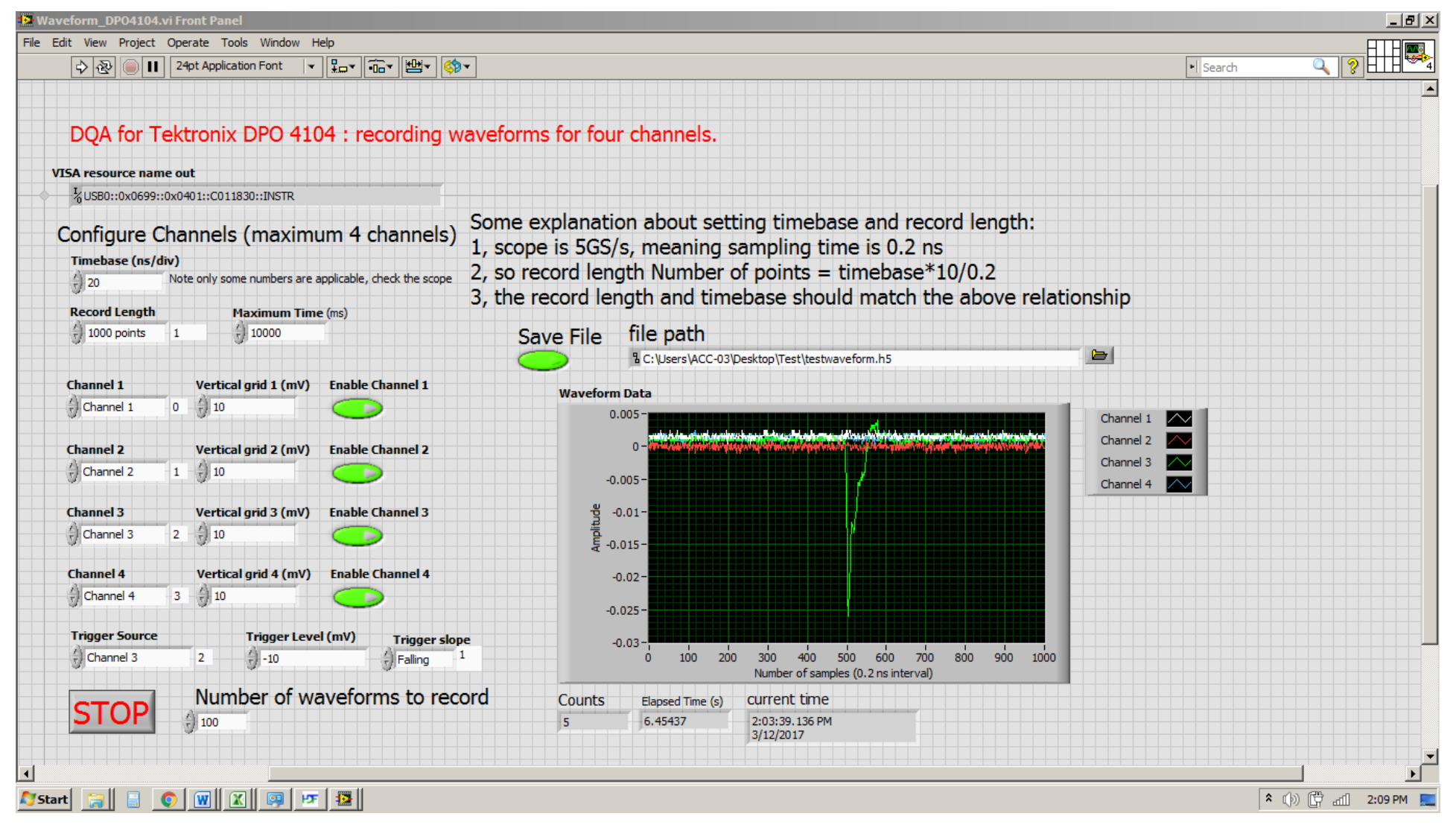
Estimating the single photon peak amplitude on an oscilloscope:

A single photon incident on a PMT photocathode, $N_{pe} = 1$, results in an peak voltage displayed on an oscilloscope terminated in resistance R:

$$V_{\text{peak}} = IR = \frac{\Sigma\Delta Q_i}{\Delta t}R = \frac{R}{\Delta t}\Sigma(N_{pe}ge) = R\frac{ge}{\Delta t};$$

for a gain of $g = 2.5x10^6$, PMT pulse peak distributed over $\Delta t = 10$ ns, and oscilloscope input impedance $R = 50\ \Omega$ the expected peak is:

$$V_{\text{peak}} = \frac{ge}{\Delta t}R = \frac{(2.5x10^6)(1.6x10^{-19}\text{C})}{10x10^{-9}\text{s}}\ 50\Omega = \ 1.7\ \text{mV}$$



DQA for Tektronix DPO 4104 : recording waveforms for four channels.

VISA resource name out: USB0::0x0699::0x0401::C011830::INSTR

Configure Channels (maximum 4 channels)

Timebase (ns/div): 20 — Note only some numbers are applicable, check the scope

Record Length: 1000 points, 1

Maximum Time (ms): 10000

Some explanation about setting timebase and record length:
1, scope is 5GS/s, meaning sampling time is 0.2 ns
2, so record length Number of points = timebase*10/0.2
3, the record length and timebase should match the above relationship

file path: C:\Users\ACC-03\Desktop\Test\testwaveform.h5

Channel		Vertical grid (mV)	Enable Channel
Channel 1	0	10	●
Channel 2	1	10	●
Channel 3	2	10	●
Channel 4	3	10	●

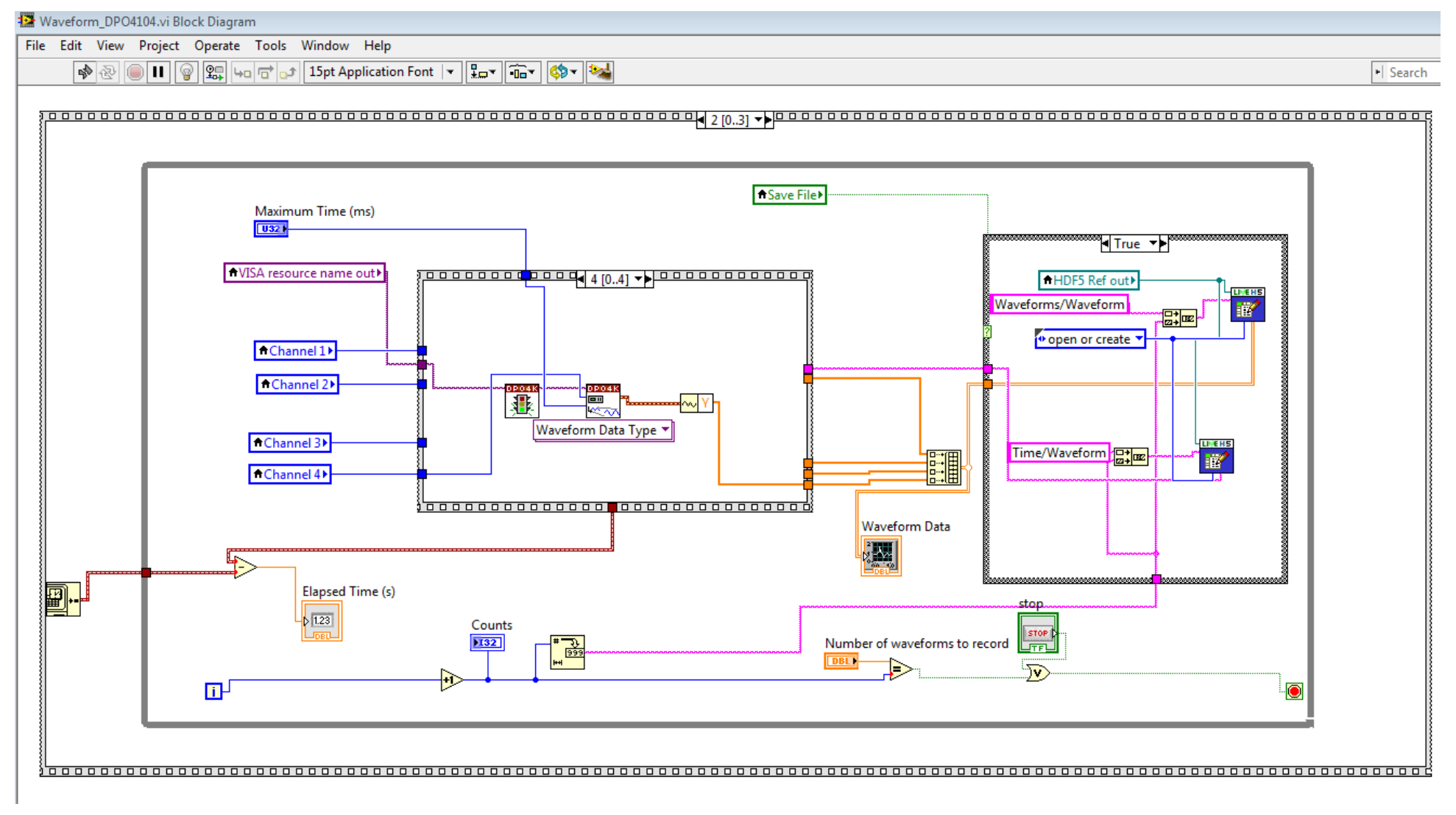
Trigger Source: Channel 3, 2
Trigger Level (mV): -10
Trigger slope: Falling, 1

Number of waveforms to record: 100

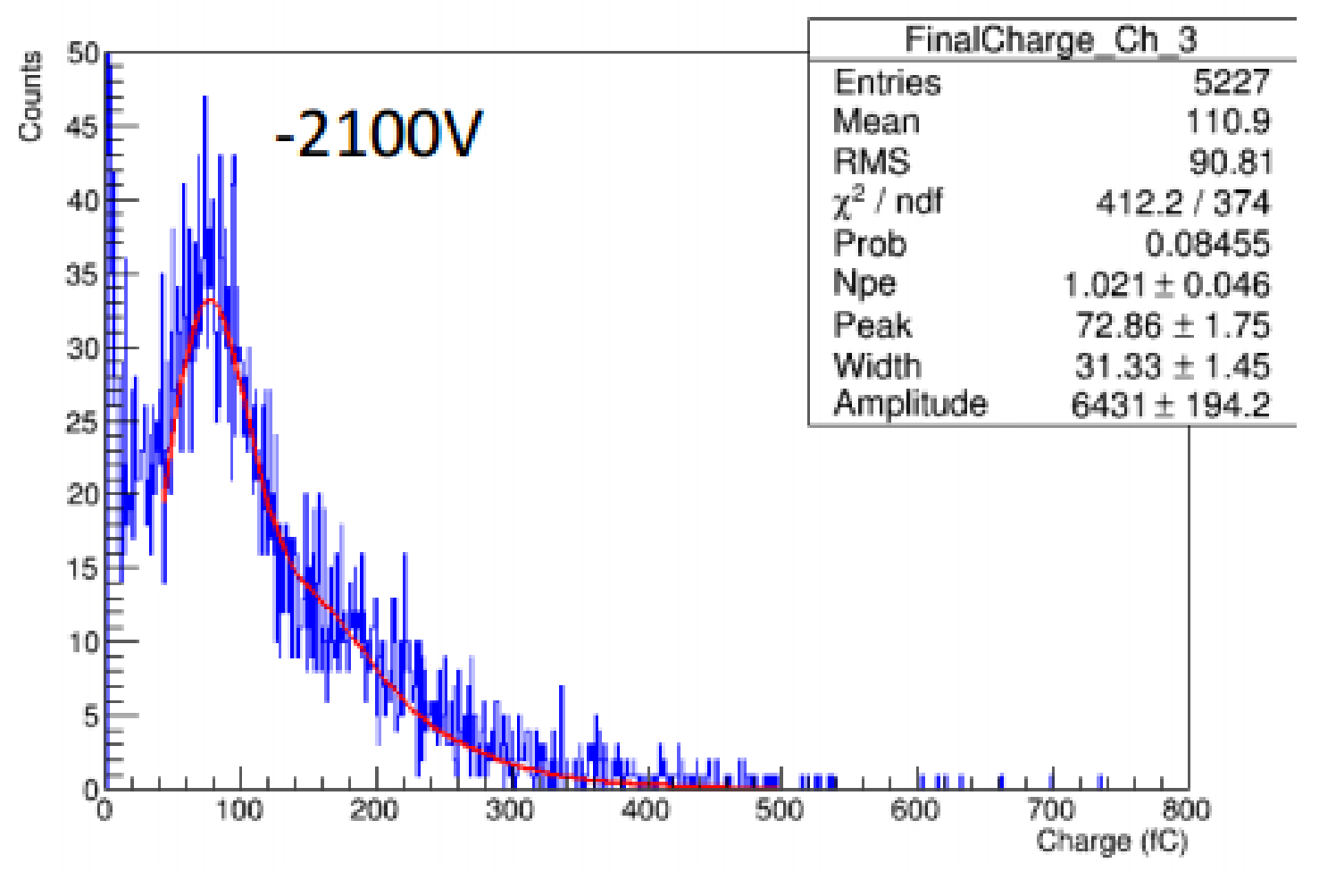
Waveform Data — Amplitude vs. Number of samples (0.2 ns interval); Channel 1, Channel 2, Channel 3, Channel 4

Counts: 5
Elapsed Time (s): 6.45437
current time: 2:03:39.136 PM 3/12/2017

LabVIEW program to control oscilloscope and record data

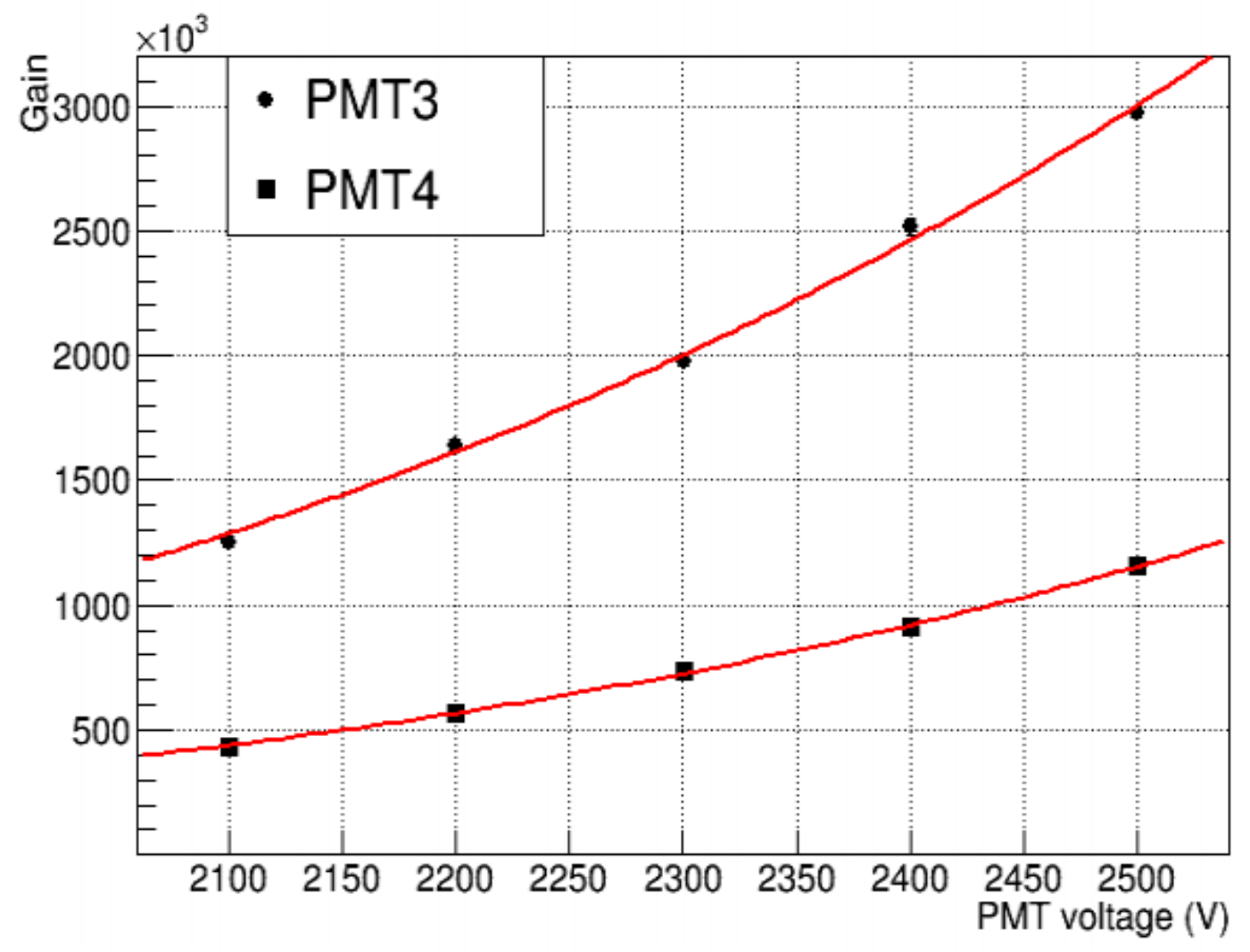


LabVIEW block diagram



FinalCharge_Ch_3	
Entries	5227
Mean	110.9
RMS	90.81
χ^2 / ndf	412.2 / 374
Prob	0.08455
Npe	1.021 ± 0.046
Peak	72.86 ± 1.75
Width	31.33 ± 1.45
Amplitude	6431 ± 194.2

Measured charge distribution at HV = -2100 Volts for 5227 PMT pulse traces; the large peak on the left is the single photon peak at 72.86 femto Coulombs



Measured gain curves for two H2431-50 PMTs

Measuring PMT gain:

PMT gain is measured by flashing an LED on and off and measuring the pulse output on the oscilloscope; the gain can be calculated from the total charge in the pulse Q_{Total}:

$$V_i = IR = \frac{\Delta Q_i}{\Delta t}R,$$
$$\Delta Q_i = \frac{1}{R}V_i\Delta t,$$
$$Q_{\text{Total}} = \Sigma\Delta Q_i = \frac{\Delta t}{R}\Sigma V_i;$$

the oscilloscope sampling period Δt for a horizontal display setting of 20 ns/division, 10 divisions per trace, and 1000 points per trace is:

$$\Delta t = \frac{20\ \text{ns/div}\ x\ 10\ \text{div/trace}}{1000\ \text{points/trace}} = 0.2\ \text{ns},$$

which corresponds to a 5 GHz sampling rate. To remove from each ΔQ_i any spurious charge and/or oscilloscope vertical offset the first 200 points of each trace corresponding to before the LED turns on (dark current) are used to compute a noise baseline, and a 5σ cut is made on each ΔQ_i.

The PMT gain is obtained using:

$$IR = \frac{\Sigma\Delta Q_i}{\Delta t}R = R\frac{ge}{\Delta t},$$

$$g = \frac{\Sigma\Delta Q_i}{e} = \frac{Q_{Total}}{e} = \frac{\Delta t}{Re}\Sigma V_i = \frac{0.2x10^{-9}\text{s}}{50\Omega(1.6x10^{-19}\text{C})}\Sigma V_i$$

$$g = 2.5x10^7\ \Sigma V_i$$

To increase the precision of the gain measurement 10,000 PMT pulses are recorded at each high voltage and a charge distribution histogram is filled and fitted; the single photon peak charge Q_{Total} is extracted from the fit. This process is repeated for each HV = 2000V, 2100V, 2200V …., and a Gain vs. HV plot fitted to an exponential to determine the PMT gain function.

References

1. *Absolute calibration and monitoring of a spectrometric channel using a photomultiplier*, E.H. Bellamy et. Al., Nuclear Instruments and Methods in Physics Research, section A, 339 (1994) 468-476

2. *Model independent approach to the single photoelectron calibration of photomultiplier tubes*, R. Saldanha et. Al., arXiv:1602.03150v1 [physics.ins-det] 9 Feb 2016

Acknowledgements

We would like to thank Dr. Steve Kettell and Dr. Milind Diwan from the Electronic Detector Group at Brookhaven National Laboratory, and Dr. David Lieberman from the Department of Physics at Queensborough Community College.