

Tests of New Extended Dynamic Range PMTs for Auger Project

Arun Tripathi, Katsushi Arisaka, David Barnhill, Christian Howard,
Chris Jillings, Tohru Ohnuki, Predrag Ranin

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University of California, Los Angeles

Abstract

We have performed detailed tests at UCLA on the new extended dynamic range PMTs from ETL, Hamamatsu and Photonis in order to determine whether they meet the specifications determined by the Auger collaboration. Results of these tests are reported in this document.

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1. Introduction

The PMTs being used in the engineering array phase of Pierre Auger observatory are high gain PMTs, designed mainly to detect small signals, of the order of a few photoelectrons. They were not optimized to observe signals over a large dynamic range (1 pe - 10^5 pe). It was, therefore, decided by the Auger collaboration to ask the three companies (ETL, Hamamatsu and Photonis) to manufacture PMTs with reduced number of dynodes, optimized for good linearity over a large dynamic range at low gain. The exact requirements for these new PMTs are described below.

We received these new PMTs over the spring and summer of 2001, and performed tests on them to see if they satisfy our specs. This document describes the tests done and their results.

2. The Specs submitted to the companies

The following specs were provided to the companies for manufacturing the new PMTs in late 2000:

0) PMT diameter:

- Minimum 8", maximum 10".

1) Cathode sensitivity:

- $S_k > 50$ uA/lm
- $S_{kb} > 7$ uA/lm-B
(equivalent to QE > 16% at 420nm)
- QE at 350 nm > 16%
(a special filter should be prepared for this purpose.)

2) Gain and supply voltage:

- Standard operation at Gain = 2×10^5 .
- High Voltage should be less than 2000 V for the gain of 1×10^6 .

3) Dark current and stability:

- PMT should be stable up to Gain = 1×10^6 .
This is defined by dark current behavior by requiring the following (or something equivalent taken at fixed HV points).
 - a) $I_{\text{dark}}(G=1 \times 10^6) < 20$ nA.
 - b) $I_{\text{dark}}(G=1 \times 10^6)/I_{\text{dark}}(G=2 \times 10^5) < 10.0$
 - c) $I_{\text{dark}}(G=1 \times 10^6)$ must be stable in time (no significant fluctuation).

4) Dark pulse and after pulse (measured at $G \geq 1 \times 10^6$):

- Dark pulse rate (> 0.25 pe) < 10 KHz
- After pulse rate per single pe $< 5\%$ (within the gate of 200nsec ~ 5,000nsec from the main signal)

5) Pulse linearity:

- At Gain = 2×10^5 , anode current should be linear within $\pm 5\%$ up to 50mA.

- 6) Single PE resolution (measured at $G \geq 1 \times 10^6$):
- Peak to Valley ratio > 1.2
(for single PE, pulsed light source must be tuned to have 90% pedestal, 10% signal for Poisson distribution of average 0.1 PE.)

- 7) Time resolution for single PE (measured at $G \geq 1 \times 10^6$):
- Transit Time Spread (FWHM) < 10.0 nsec
 - Rise Time (10% - 90%) < 6.0 nsec

Over the spring and summer of 2001, we received the new PMTs from the three manufacturers (ETL, Hamamatsu and Photonis). The major modification was the reduction in the number of dynodes by two. The table below lists the dynode information about the new PMTs:

Manufacturer	PMT Model No.	PMT Diameter	Dynode Information
ETL	D731KB	200 mm	10 dynode stages Linear Focus
Hamamatsu	R5912MOD	200 mm	8 dynode stages, Linear Focus, box first dynode
Photonis	XP1805/D1	230 mm	8 dynode stages Linear Focus, foil first dynode

Table 2.1 Dynode information for the modified PMTs.

3. The Measurements

This section describes all the measurements done on these PMTs and their results.

3.1 Gain and Dark Current

The method used to obtain the gain and dark current is described in [1]. For Hamamatsu and Photonis, the gain curves were normalized using the information provided by the the manufacturers. For ETL, the gain was normalized using single photoelectron spectrum. Dark current was measured after keeping the PMTs in dark for 30 minutes.

The results of these measurements are shown in Figures 3.1.1, 3.1.2, 3.1.3 and 3.1.4. Hamamatsu is generally the quietest PMT and ETL the noisiest. This trend is also reflected in dark pulse rates, described later in the document.

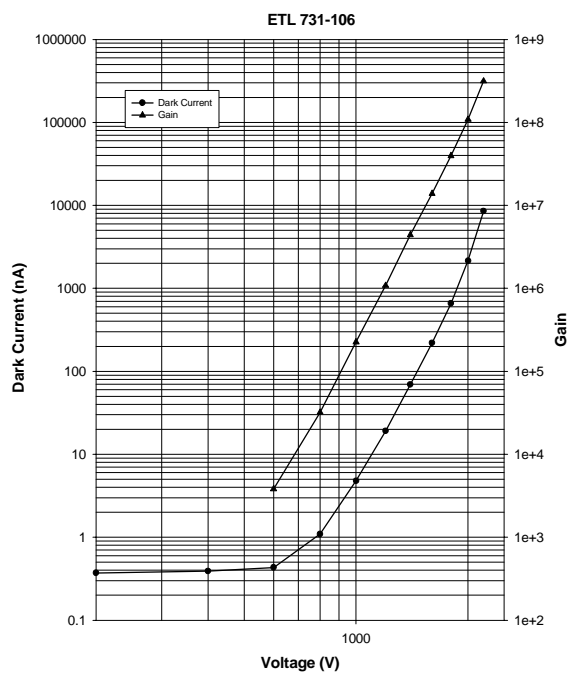
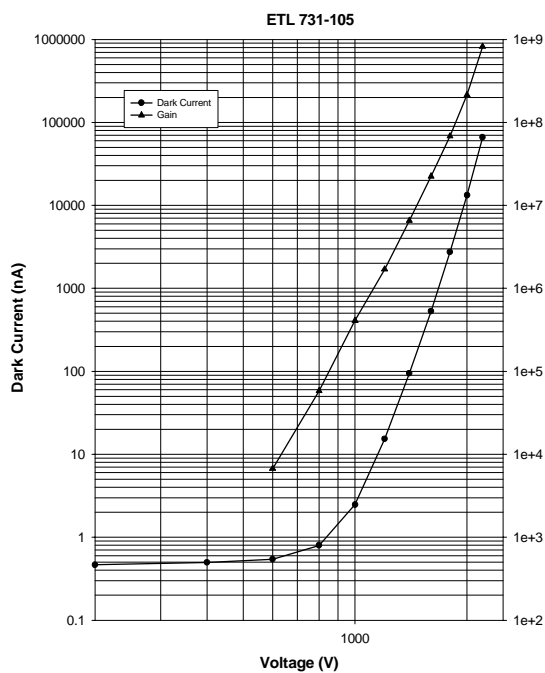
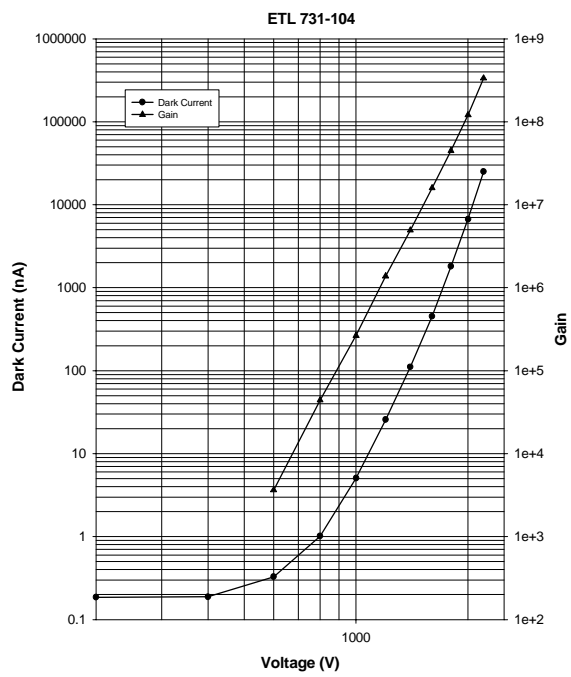
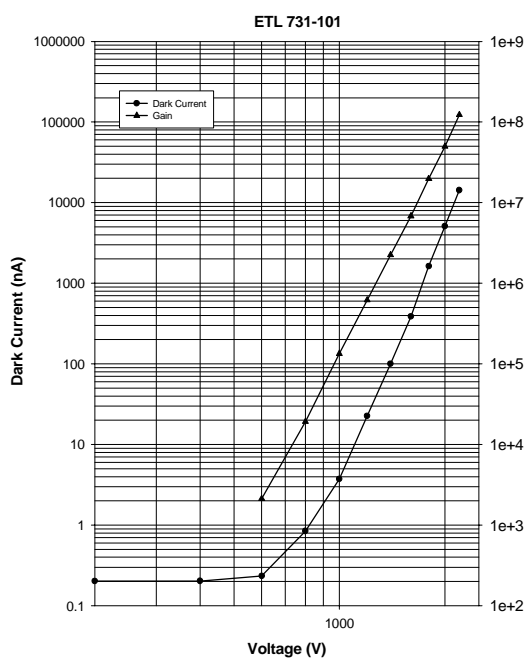


Figure 3.1.1 Gain and dark current curves for ETL731-101, ETL731-104, ETL731-105 and ETL731-106 PMTs.

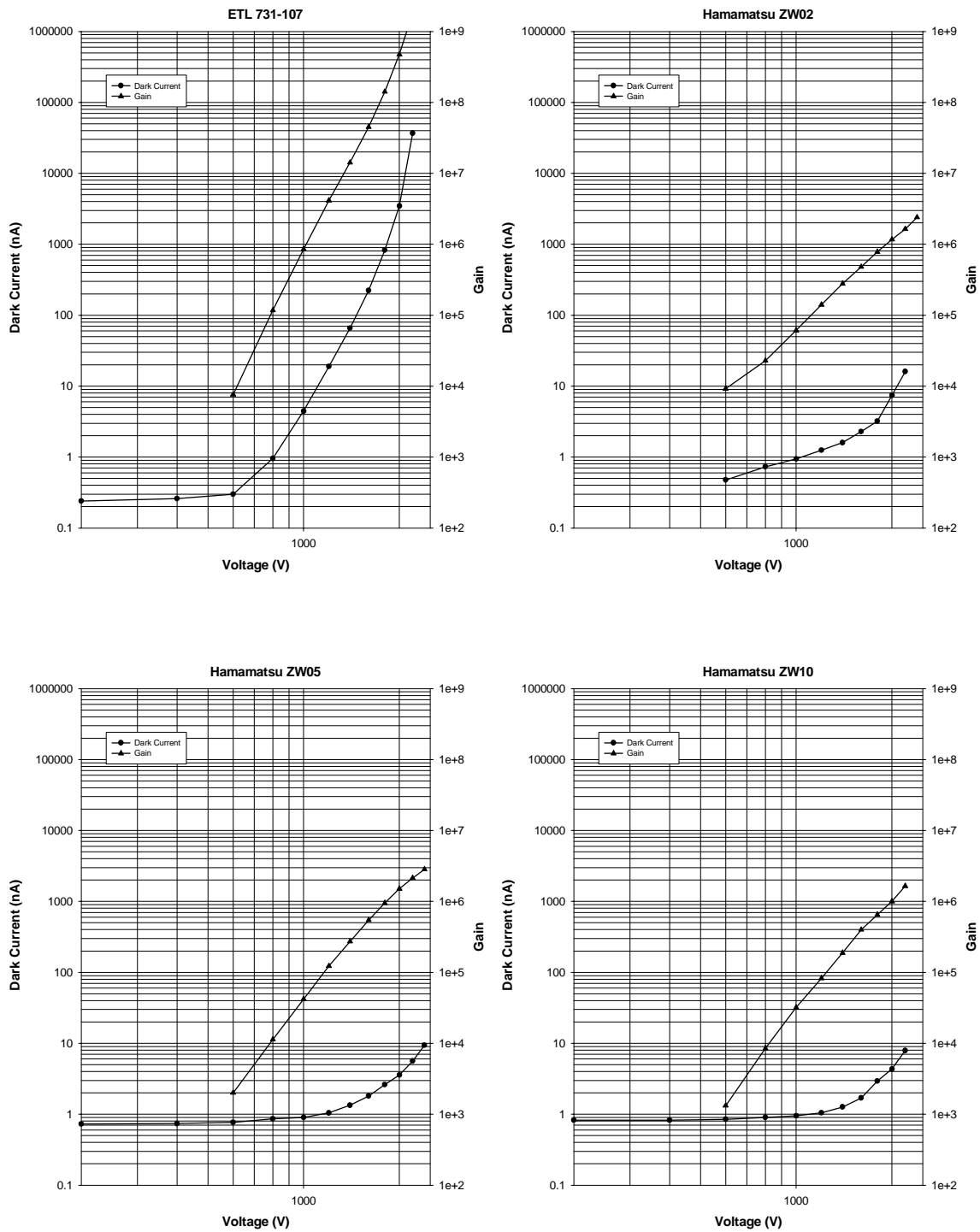


Figure 3.1.2 Gain and dark current curves for ETL731-107, Hamamatsu ZW2, Hamamatsu ZW5, Hamamatsu ZW10 PMTs.

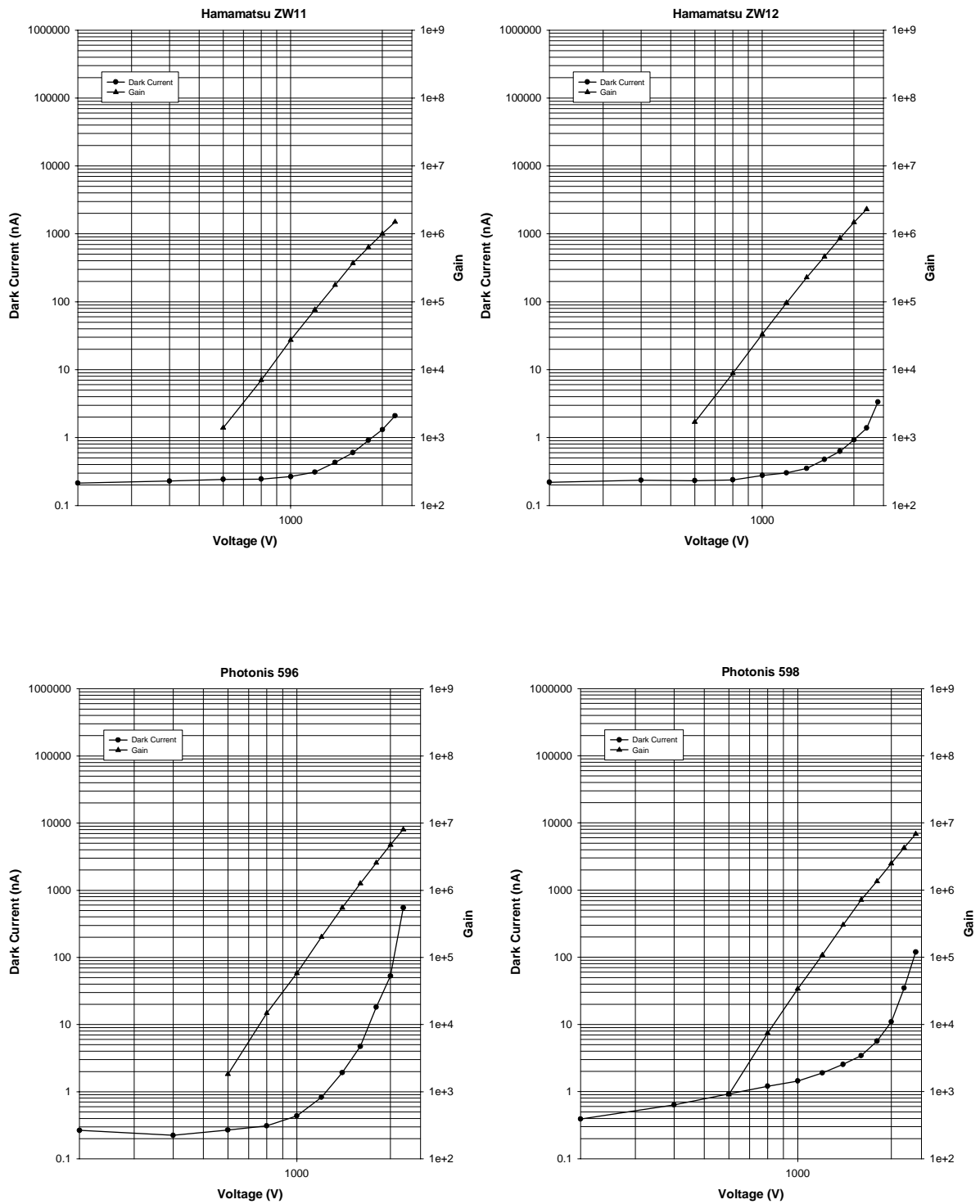


Figure 3.1.3 Gain and dark current curves for Hamamatsu ZW11, Hamamatsu ZW12, Photonis 596, and Photonis 598 PMTs.

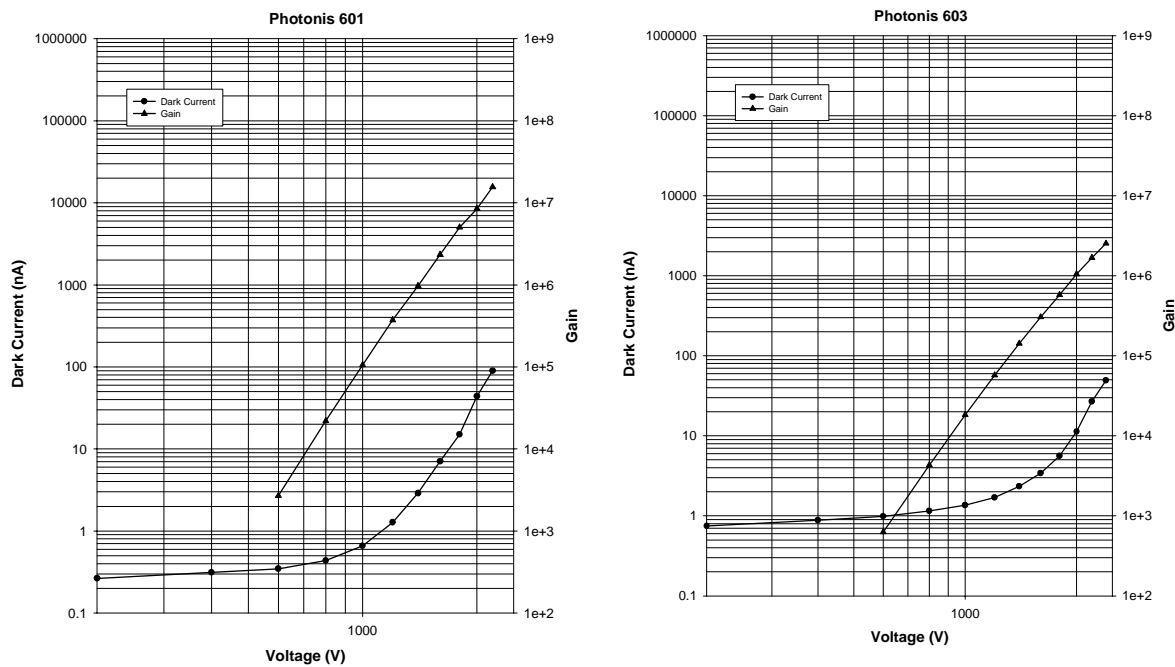


Figure 3.1.4 Gain and dark current curves for Photonis 601 and Photonis 605 PMTs.

3.2 Single Photoelectron spectra

The single photo-electron spectra were measured from the anode signal. Anode signal had to be amplified. We used the amplifier on one of the Hamamatsu bases built by the Orsay group for amplification, because the LeCroy 612A amplifier was too noisy. The single photoelectron spectra were measured at a gain of approximately 10^6 . The results are shown in figures 3.2.1 and 3.2.2.

All the PMTs show a clear single photo-electron peaks, with peak-to-valley ratios of 1.2 or higher. Photonis has the worst peak-to-valley ratio because of foil type first dynode.

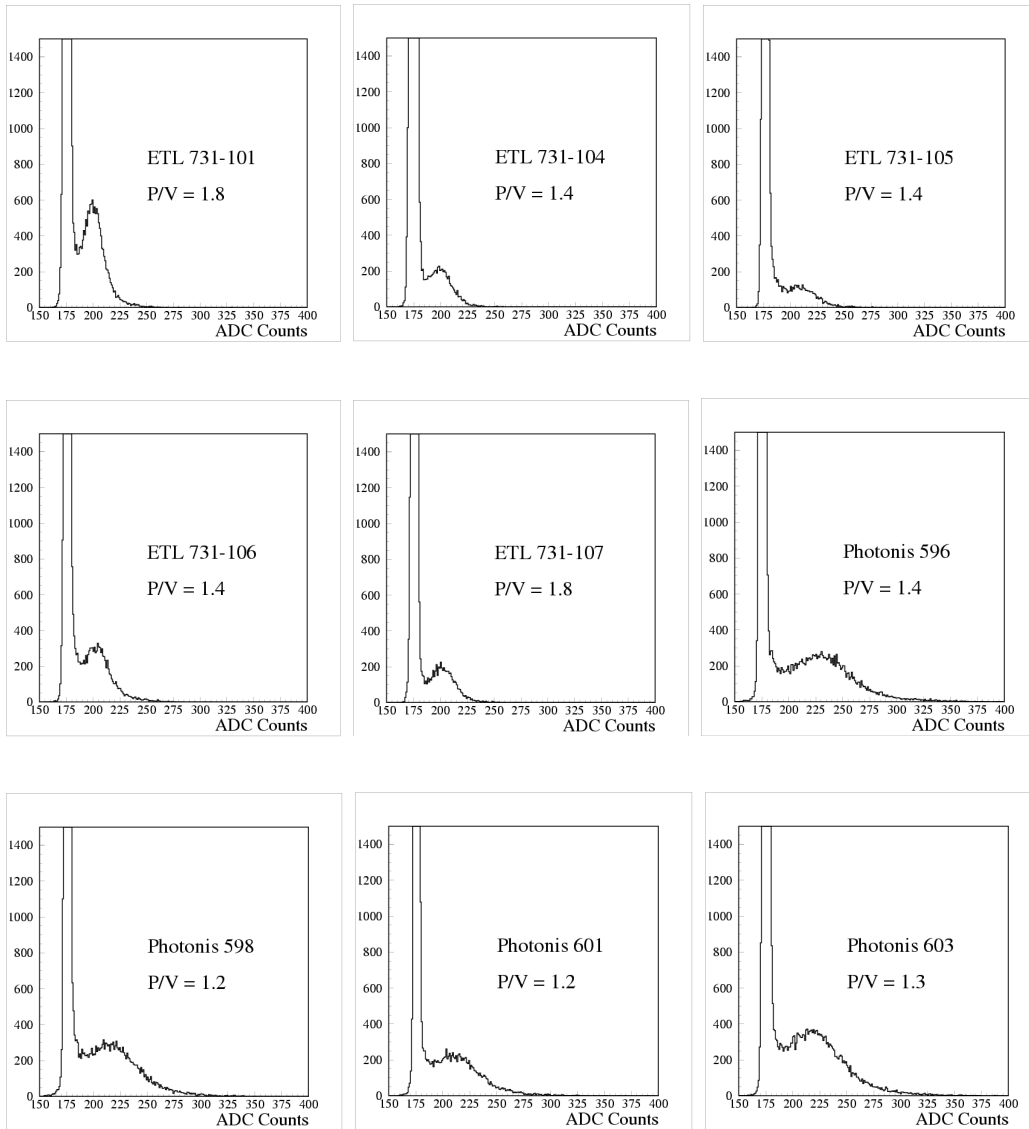


Figure 3.2.1 Single photoelectron spectra from ETL and Photonis PMTs.

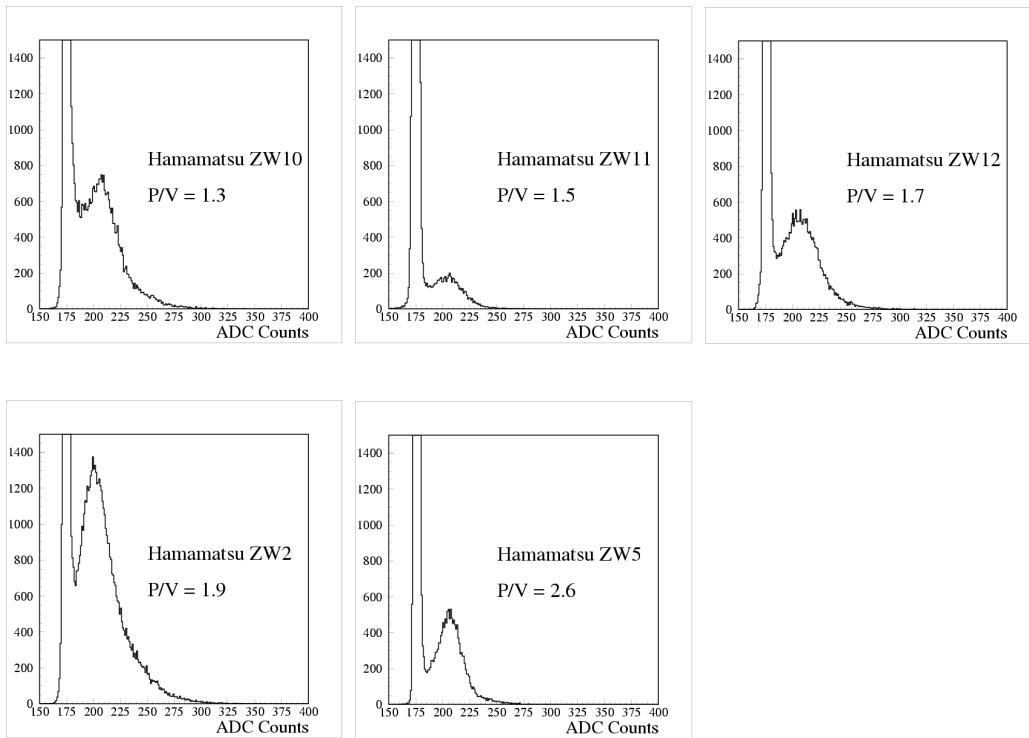


Figure 3.2.2 Single PE spectra for Hamamatsu PMTs.

3.3 Linearity

The method used to measure linearity of the PMTs is described in [1]. The measurements were done at four different gains: 10^5 , 2×10^5 , 5×10^5 and 10^6 . The results are displayed in Figures 3.3.1, 3.3.2, 3.3.3, 3.3.4 and 3.3.5.

It can be seen from these figures that all the PMTs satisfy our specification that the nonlinearity be less than 5% at 50 mA anode current at a gain of 2×10^5 .

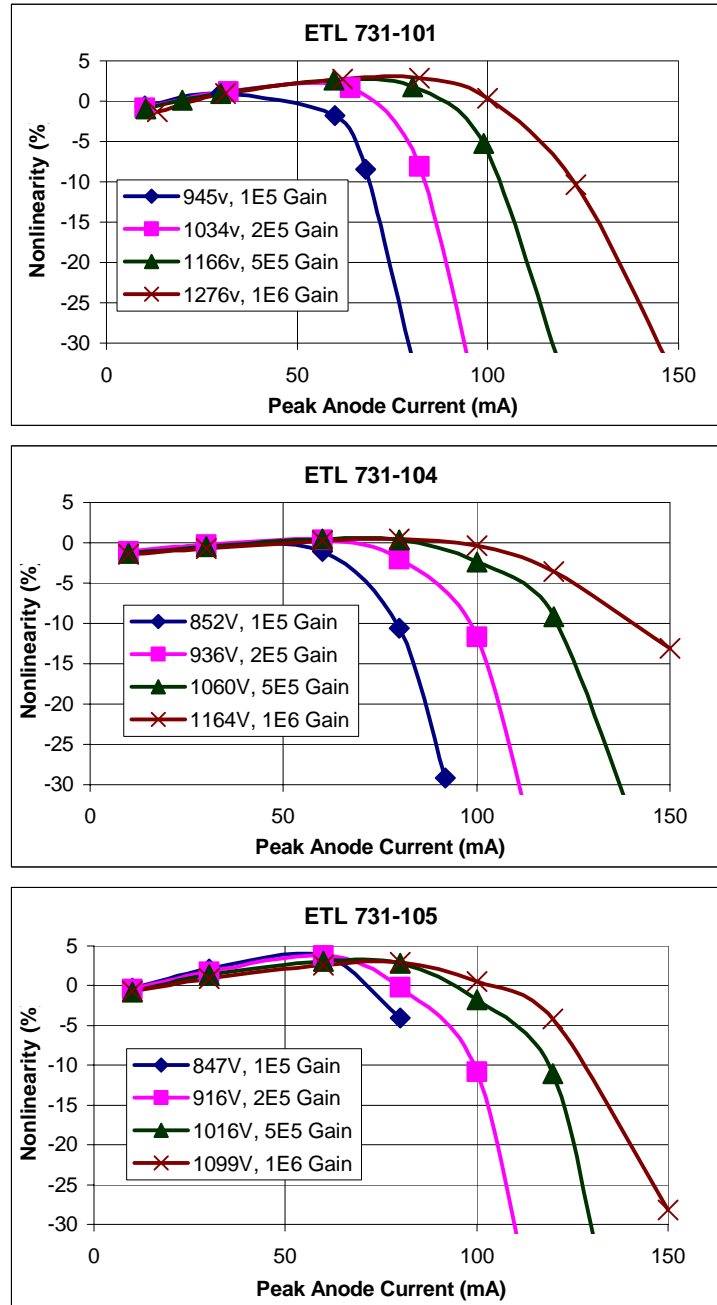


Figure 3.3.1 Linearity results for ETL-101, 104 and 105 PMTs.

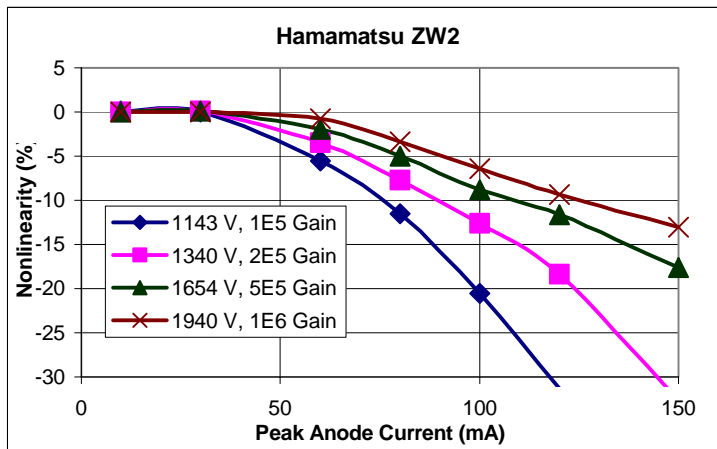
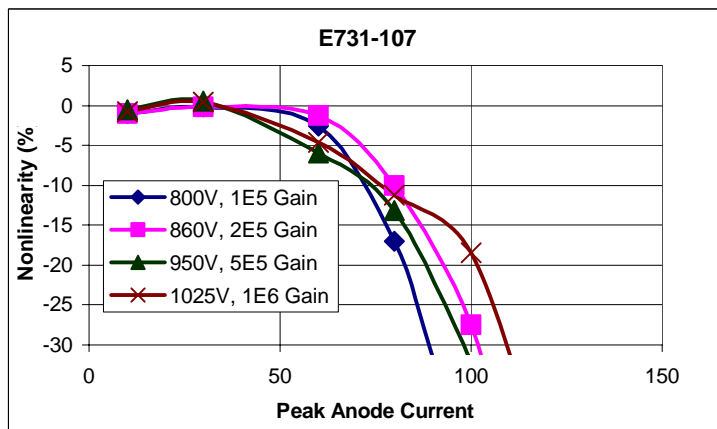
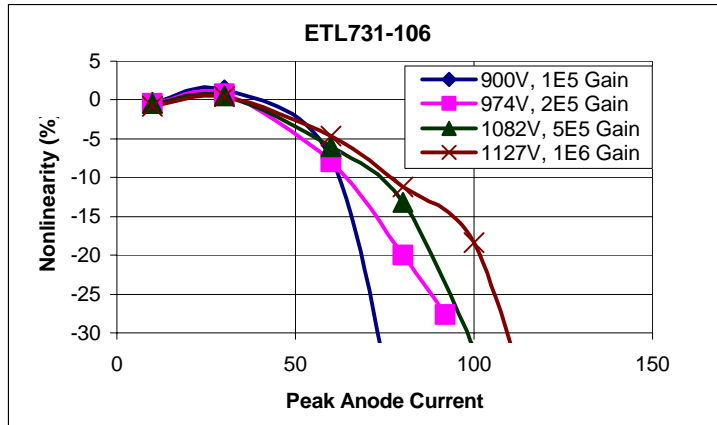


Figure 3.3.2 Linearity results for ETL-106, 107 and HamamatsuZW2 PMTs.

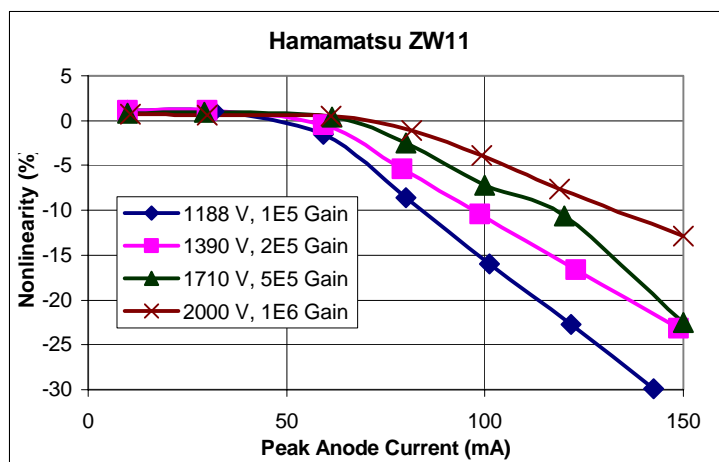
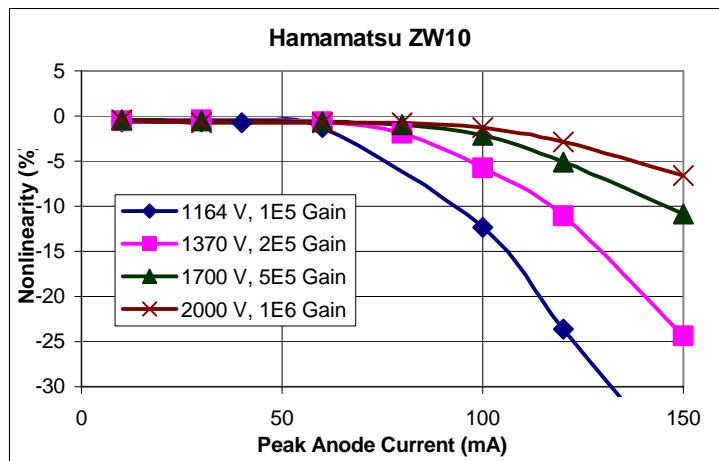
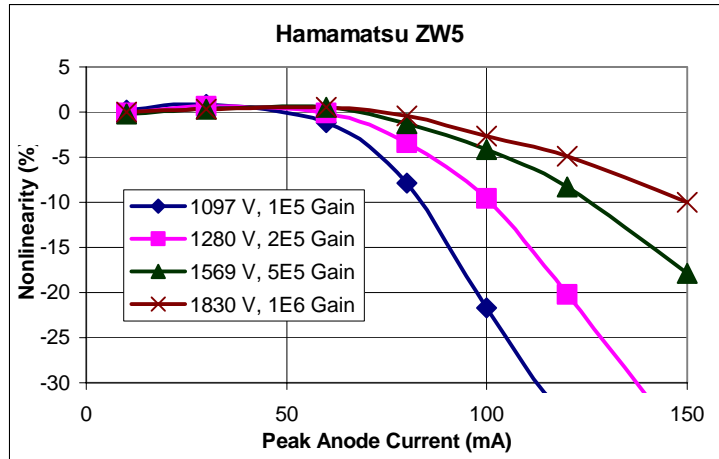


Figure 3.3.3 Linearity results for Hamamatsu ZW5, 10 and 11 PMTs.

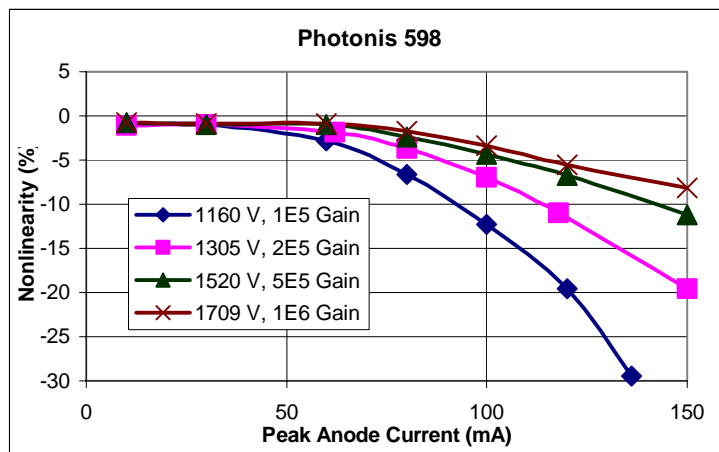
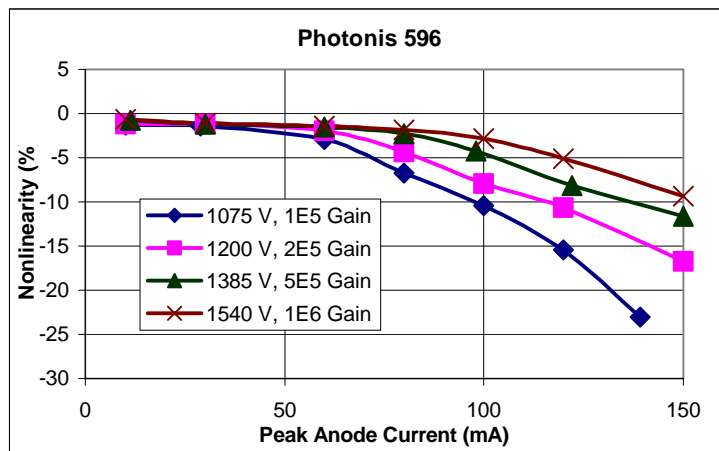
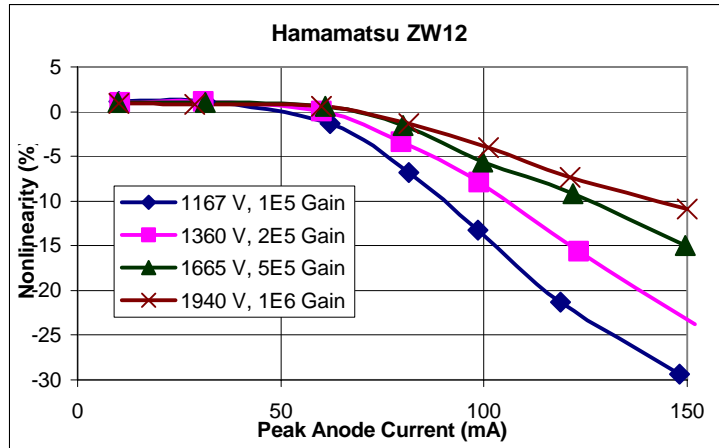


Figure 3.3.4 Linearity results for Hamamatsu ZW12, and Photonis 596 and 598 PMTs.

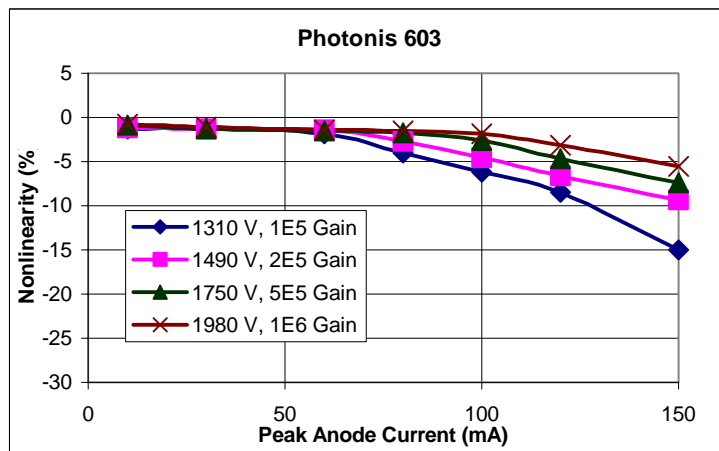
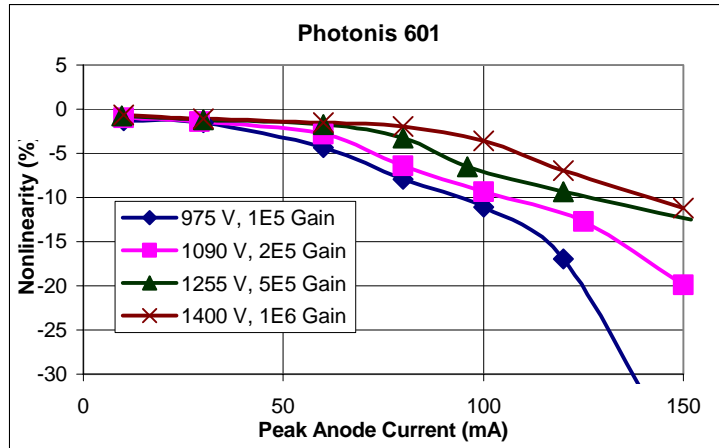


Figure 3.3.5 Linearity results for Photonis 601 and 603 PMTs.

3.4 Dark Pulse Rate

The dark pulse rates measurements were done after keeping the PMTs in dark for 2 hr. The results are shown in Table 3.4.1 for different thresholds.

PMT	Position of Valley In terms of PE	Dark Pulse Rate (KHz)			
		Threshold= Valley	Threshold= 0.25PE	Threshold= 0.3PE	Threshold= 0.4PE
ETL101	0.5	5.2 ± 1.4	10.9 ± 2.0	8.6 ± 1.8	6.7 ± 1.6
ETL104	0.4	16.1 ± 0.7	23.7 ± 0.8	18.6 ± 0.7	16.8 ± 0.7
ETL105	0.6	1.6 ± 0.2	3.1 ± 0.3	2.4 ± 0.2	2.0 ± 0.2
ETL106	0.5	7.9 ± 0.6	15.2 ± 0.9	12.6 ± 0.8	8.9 ± 0.7
ETL107	0.4	8.1 ± 0.7	11.8 ± 0.8	9.9 ± 0.7	8.3 ± 0.7
Hamamatsu ZW2	0.3	4.5 ± 0.3	4.5 ± 0.3	3.8 ± 0.3	3.2 ± 0.3
Hamamatsu ZW5	0.3	1.5 ± 0.2	2.1 ± 0.2	1.5 ± 0.2	1.3 ± 0.1
Hamamatsu ZW10	0.4	1.1 ± 0.2	1.6 ± 0.2	1.3 ± 0.2	1.0 ± 0.2
Hamamatsu ZW11	0.5	2.5 ± 0.2	7.3 ± 0.3	5.1 ± 0.3	2.7 ± 0.2
Hamamatsu ZW12	0.3	2.2 ± 0.2	4.2 ± 0.3	2.7 ± 0.2	1.9 ± 0.2
Photonis 596	0.5	12 ± 0.8	15.2 ± 0.9	14.1 ± 0.9	13.0 ± 0.8
Photonis 598	0.5	2.4 ± 0.3	4.7 ± 0.4	3.5 ± 0.3	2.6 ± 0.3
Photonis 601	0.4	2.1 ± 0.2	3.7 ± 0.3	3.2 ± 0.3	2.3 ± 0.2
Photonis 603	0.4	13.8 ± 0.9	17.1 ± 1.0	15.7 ± 0.9	14.0 ± 0.9

Table 3.4.1 Dark pulse rates for different PMTs at a gain of 10^6 for different thresholds.

As can be seen from Table 3.4.1, four of the ETL PMTs and two of the Photonis PMTs are still quite noisy after having been in dark for two hours. For these PMTs, the dark pulse rate was recorded as a function of time in dark for more extended periods, in order to determine the length of time before they settle down to dark pulse rates of less than 10 KHz.

The dark pulse rates as a function of time for different PMTs are shown in Figures 3.4.1 (ETL), 3.4.2 (Hamamatsu) and 3.4.3 (Photonis). A 0.25 PE threshold was used to make these graphs.

It can be seen from these graphs that even the noisy PMTs quiet down to dark pulse rates of less than 10 KHz in about 4 hrs. Also, these graphs show that Hamamatsu is generally the quietest PMT and ETL the most noisy.

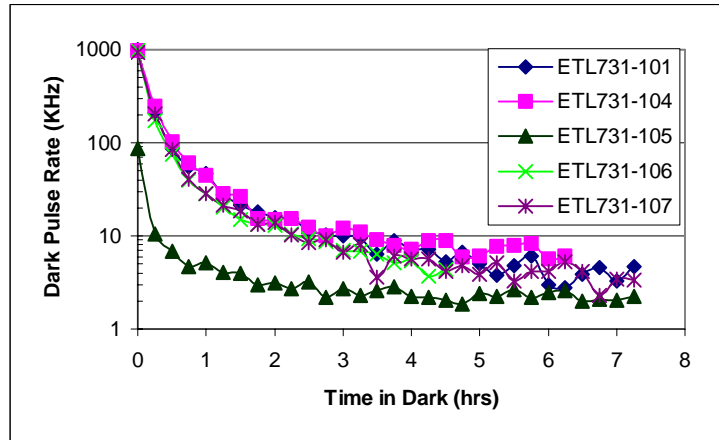


Figure 3.4.1 Dark pulse rate as a function of time in dark for ETL PMTs. A 0.25 PE threshold was used to count the dark pulses.

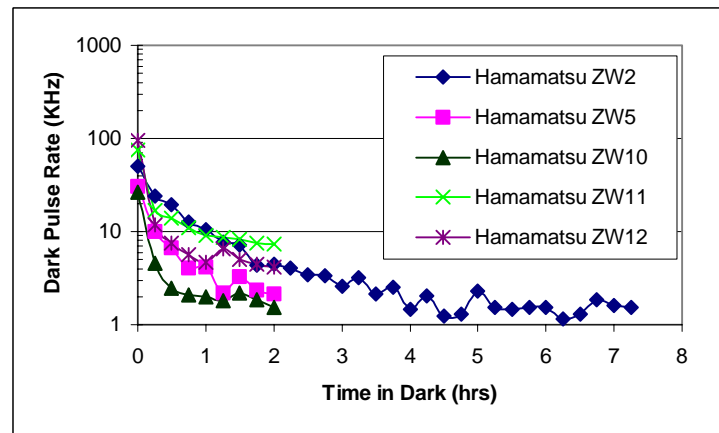


Figure 3.4.2 Dark pulse rate as a function of time in dark for Hamamatsu PMTs. A 0.25 PE threshold was used to count the dark pulses.

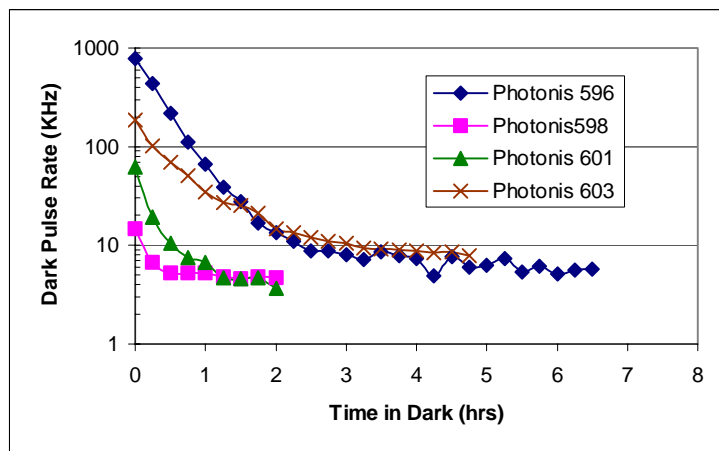


Figure 3.4.3 Dark pulse rate as a function of time in dark for Photonis PMTs. A 0.25 PE threshold was used to count the dark pulses.

3.5 Afterpulse ratio

After pulse ratios were measured for a gain of 1×10^6 . The afterpulse ratio is defined as the ratio of the charge in a 200ns-5000ns time window after the main pulse, to that of the main pulse. The results are shown in table 3.5.1.

All the PMTs satisfy the specification that the afterpulse ratio be less than 5%, when measured at a gain of 10^6 in the 200ns-5000ns time window after the main pulse.

PMT	Afterpulse ratio (200ns-5000ns) (%)
ETL731-101	3.9
ETL731-104	2.1
ETL731-105	3.0
ETL731-106	4.0
ETL731-107	2.8
Hamamatsu ZW2	1.2
Hamamatsu ZW5	1.4
Hamamatsu ZW10	2.6
Hamamatsu ZW11	3.4
Hamamatsu ZW12	2.8
Photonis 596	0.6
Photonis 598	1.3
Photonis 601	3.5
Photonis 603	2.1

Table 3.5.1 Afterpulse ratios for different PMTs.

3.6 Quantum Efficiency

The method used to measure the quantum efficiency (QE) is described in [1]. The QE curves for different PMTs are shown in Figures 3.6.1, 3.6.2 and 3.6.3.

All the PMTs have QE greater than 16% both at 350 nm and 420 nm, satisfying our specs.

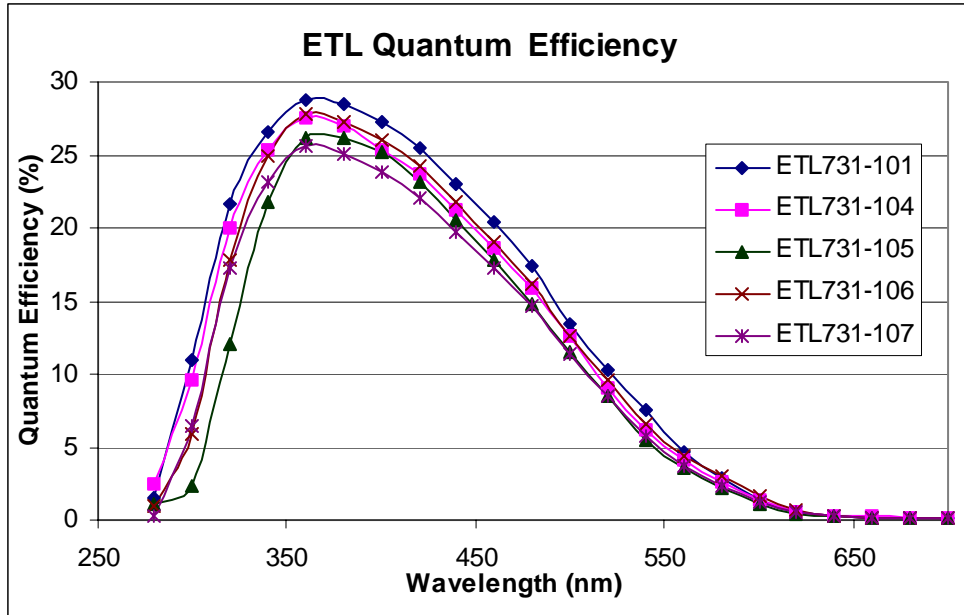


Figure 3.6.1 Quantum efficiency as a function of wavelength for ETL PMTs.

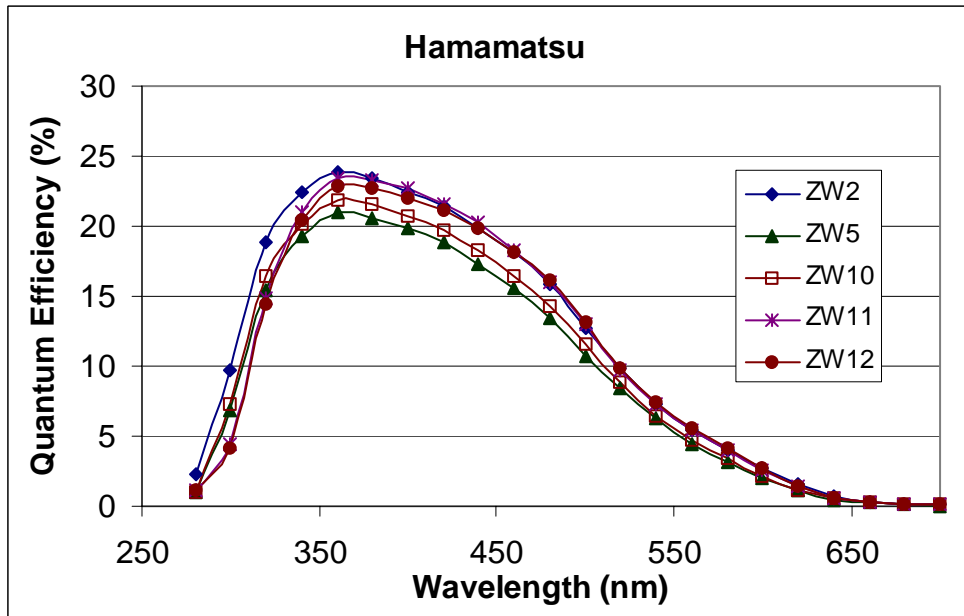


Figure 3.6.2 Quantum efficiency as a function of wavelength for Hamamatsu PMTs.

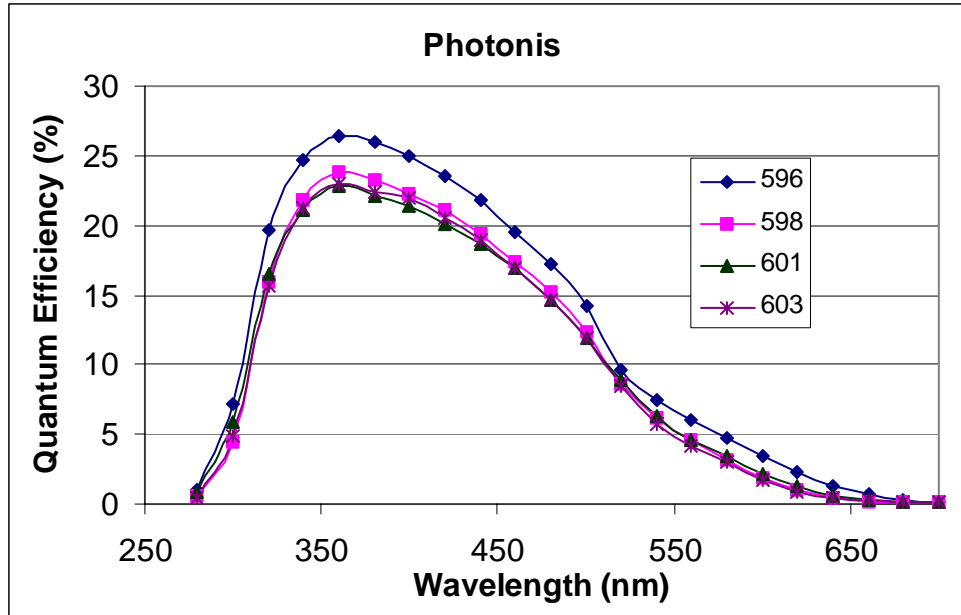


Figure 3.6.3 Quantum efficiency as a function of wavelength for Photonis PMTs.

4 Summary

The results of all the measurements are summarized in Table 4.1. One can draw the following general conclusions about the three different kinds of PMTs based upon these measurements:

Hamamatsu PMTs satisfy the specs on linearity, dark current, P/V ratio for single photoelectrons, dark pulse rate, afterpulse ratio and QE. However, the HV required for a gain of 10^6 for some of these PMTs is 2000 V, which is too high, because the power supply in Auger bases can only supply up to 2000 V.

ETL PMTs satisfy the specs on linearity, P/V ratio, afterpulse ratio and QE. The dark pulse rate and the dark current appears to be high for most of these PMTs, when measured after standard settling time in dark (30 min for dark current, 2hrs for dark pulse rate). However, these PMTs settle down to dark pulse rates of less than 10 KHz after about 4 hours in dark.

Photonis PMTs satisfy the specs on linearity, dark current, P/V ratio, afterpulse ratio, and QE. The dark pulse rate is higher than the specs for two of the PMTs (after 2hrs in dark), but it goes down to less than 10 KHz after about 4 hours in dark.

	HV for 2E5 Gain	HV for 1E6 Gain	I-Dark (G=1E6)	I-Dark (1E6) / I-Dark (2E5)	P/V Ratio	Non-linearity for 50 mA at 2E5 Gain	Peak Anode Current for -5% Non-linearity at 2E5 gain	Dark Pulse Rate (0.25 PE Thr.)	Dark Pulse Rate (0.4 PE Thr.)	Afterpulse Ratio (200ns-5000ns)	QE at 350 nm	QE at 420 nm	Remarks
Unit	V	V	nA			%	mA	KHz	KHz	%	%	%	
Spec		<2000	<20	<10	>1.2	<+5		<10		<5	>16	>16	
Hama-matsu													
ZW02	1340	1940	5	3.3	1.9	-2.5	65	4.5	3.2	1.2	23.1	21.4	
ZW05	1280	1830	3	2.5	2.6	0	85	2.1	1.3	1.4	20.1	18.8	
ZW10	1370	2000	4	2.6	1.3	-0.5	95	1.6	1	2.6	21	19.7	HV too high
ZW11	1390	2000	1.3	3.2	1.5	0.5	80	7.3	2.7	3.4	22.2	21.6	HV too high
ZW12	1360	1940	0.9	2.6	1.7	0.7	90	4.2	1.9	2.8	21.6	21.2	
ETL													
731-101	1034	1276	36.5	6.5	1.8	1.7	80	10.9	6.7	3.9	27.6	25.4	Dark high
731-104	936	1164	18.6	3.8	1.4	0	90	23.7	16.8	2.1	26.4	23.7	Dark high
731-105	916	1098	6	2.6	1.4	3.8	80	3.1	2	3	24	23.1	
731-106	974	1127	17.5	4.2	1.4	-4.5	50	15.2	8.9	4	26.3	24.2	Dark high
731-107	860	1025	5.2	3.2	1.8	0	70	11.8	8.3	2.8	24.4	22	Dark high
Photonis													
596	1200	1540	3	3.8	1.4	-1.2	85	15.2	13	0.6	25.5	23.5	Dark high
598	1316	1700	5.7	2.7	1.2	-1.2	90	4.7	2.6	1.3	22.8	21	
599													
601	1090	1405	2.4	2.4	1.2	-2	75	3.7	2.3	3.5	21.8	20.1	
603	1490	1993	11	3.6	1.3	-1.2	105	17.1	14	2.1	22.1	20.5	Dark high
Old PMTs							at 1E5 Gain	at 1E5 gain	0.3 PE Threshold		At ~10 ⁷ Gain		
Hama-matsu													
SA2097	818	1000	1.3	3.2	2.3	N/A		2.5		5.8	20	19.1	
SA2128	704	850	0.4	2	2.3	>30	13	2		3	22.3	22.1	
ETL													
706	807	950	1.5	1.9	1.6	N/A		1		2.3	24	22.3	
728	960	1120	3	3.7	1.6	-8	34	2.5		7.1	27.6	23.5	
Photonis													
544	880	1050	2.4	2	1.2	N/A		2.5		4.7	20.7	18.5	
558	855	1000	1.3	2.2	1.4	-7	46	2.5		3.7	23.8	20.9	

Table 4.1 Summary of the PMT test results.

5 References

1. A. Tripathi, C. DiPasquale, D. Barnhill, C. Jillings et. al; Testing of 8" PMTs at UCLA for Pierre-Auger Surface Detectors, Auger Technical Note **GAP 2000-040**.