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A systematic study of large PMTs for the Pierre Auger Observatory

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Abstract

In order to select the most suitable Photomultiplier Tubes (PMTs) for the surface detectors of the Pierre Auger Observatory, we have performed extensive tests on large PMTs from three different manufacturers: Electron Tubes Limited, Hamamatsu Photonics, and Photonis Imaging Sensors. The test and their results are described in this report.

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1. Introduction

The Pierre Auger Observatory is a large area hybrid detector designed to detect and study a high statistics sample of ultra high energy cosmic rays (UHECR), with energies greater than 10^{19} eV. This report focuses on the surface detector Photomultiplier Tubes (PMTs), but the complete detector details can be found elsewhere [1–5]. Briefly, each observatory consists of 1657 surface detectors (SD), and four fluorescence detectors (FD). Each surface detector is a cylindrical plastic tank of 3.6 m diameter, filled with purified water to a depth of 1.2 m. The interior of these tanks is lined with white diffuse tyvek sheet. The air shower particles reaching the ground are detected by the Cherenkov light they emit in the water by three PMTs, mounted symmetrically on top of each tank with the photocathode looking vertically downward. The surface detectors are arranged on a hexagonal grid, with a spacing of 1.5 km, covering a total area of approximately 3000 km^2. This array of surface detectors is viewed by four fluorescence detectors [3,4] located along the periphery of the array.

2. Relevant PMT properties for Auger surface detectors

The SD PMTs must have good quantum efficiency (QE) in the 350–450 nm range, where the Cherenkov spectrum peaks after transmission through water and reflection from tyvek. Low dark pulse rate and dark current are required in order to ensure the survival of the PMTs over the 20 year lifespan of the Auger experiment. Since the arrival time of the shower particles at ground can

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be spread over several microseconds, even late afterpulses can fake a signal. As a result, low level of afterpulsing is desirable. Because of the large intrinsic spread in the arrival times of the shower particles, and 1.5 km separation between the detectors, fast timing is not needed. All the criteria mentioned so far are easily satisfied by the large PMTs already available.

Linearity, however, is one crucial aspect where already available large PMTs do not meet Auger needs. The Auger SD PMTs must be operated at a low gain ($\sim 2 \times 10^5$) so that the digitizing electronics does not saturate at the highest expected signals. At the same time, the PMT must be linear over a large dynamic range of ~ 50 to $\sim 50\,000$ photoelectrons (PE) per 25 ns. The large PMTs already available in the market were designed to operate at very high gains ($> 10^7$) for neutrino experiments, where the expected range of signals is small: 1 PE to a few PE. These PMTs, when operated at low gain, become non-linear at the largest expected signals in Auger.

Mainly based on the this consideration for linearity over a large dynamic range at low gain, the Auger project requested three different vendors (ETL, Hamamatsu, and Photonis) to manufacture sample candidate PMTs designed to satisfy the specifications for the Auger surface detectors. The details of all the specifications can be found in Refs. [6,7]. These PMTs were required to be linear within $\pm 5\%$ up to an anode current of 50 mA at a gain of 2×10^5.

3. The candidate PMTs

During the spring of 2001, ETL, Hamamatsu, and Photonis manufactured the new sample PMTs according to the Auger specifications. The PMT model numbers and the dynode structure information for the PMTs tested are listed in Table 1. The main change in these PMTs compared to their previously available counterparts is the reduced number of dynode stages. As a result, these PMTs require higher voltages to operate at a given gain, giving rise to improved linearity. Pictures of sample PMTs are shown in Fig. 1.

Table 1
Dynode information for the three candidate PMTs optimized for Auger project

Manufacturer	PMT model	Bulb diameter (mm)	Dynode information
ETL	D731KB	200	Ten stages, linear focus
Hamamatsu	R5912MOD	200	Eight stages, linear focus
Photonis	XP1805/D1	230	Eight stages, linear focus foil first dynode

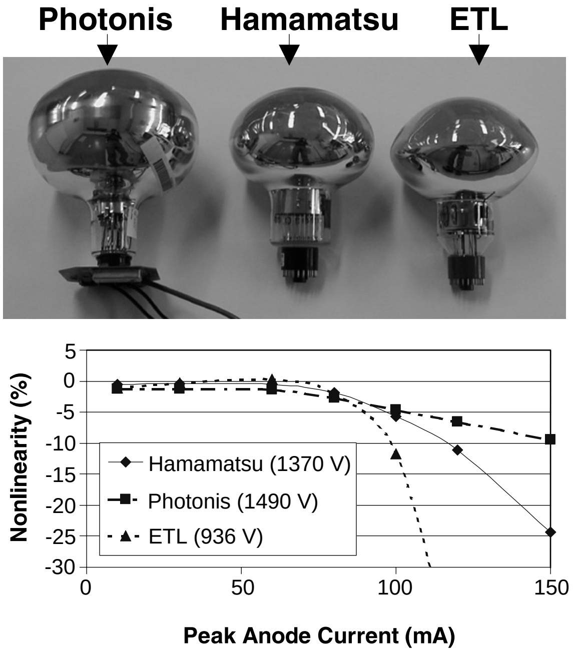
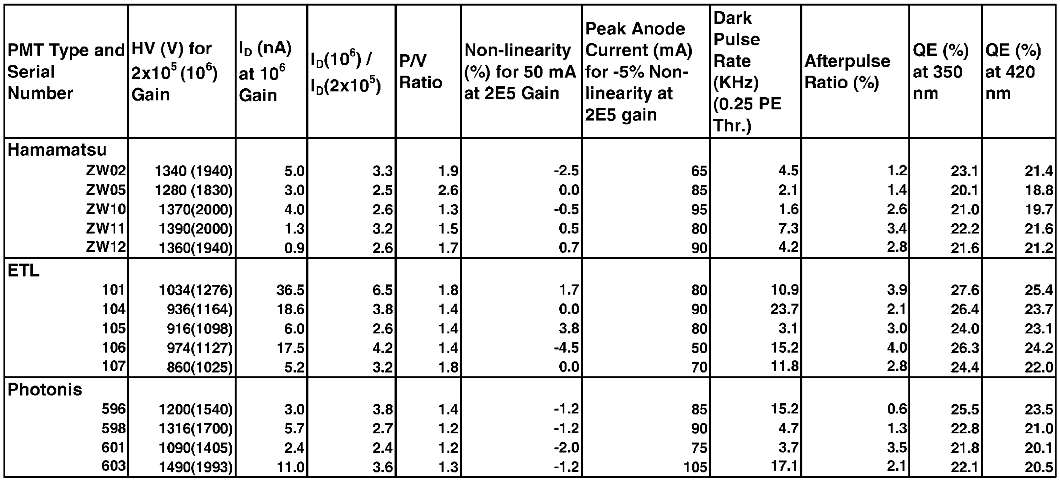


Fig. 1. Photographs (top) of the three kinds of PMTs and sample linearity curves (bottom) at 2×10^5 gain for each kind of PMT tested.

4. Measurements

After procuring the PMTs from the manufacturers, following tests were performed on five PMTs of each kind: (1) QE as a function of wavelength, (2) single photoelectron spectrum, (3) gain as a function of applied high voltage, (4) dark



PMT Type and Serial Number	HV (V) for 2x10^5 (10^6) Gain	I_D (nA) at 10^6 Gain	I_D(10^6) / I_D(2x10^5)	P/V Ratio	Non-linearity (%) for 50 mA at 2E5 Gain	Peak Anode Current (mA) for -5% Non-linearity at 2E5 gain	Dark Pulse Rate (KHz) (0.25 PE Thr.)	Afterpulse Ratio (%)	QE (%) at 350 nm	QE (%) at 420 nm
Hamamatsu										
ZW02	1340 (1940)	5.0	3.3	1.9	-2.5	65	4.5	1.2	23.1	21.4
ZW05	1280 (1830)	3.0	2.5	2.6	0.0	85	2.1	1.4	20.1	18.8
ZW10	1370(2000)	4.0	2.6	1.3	-0.5	95	1.6	2.6	21.0	19.7
ZW11	1390(2000)	1.3	3.2	1.5	0.5	80	7.3	3.4	22.2	21.6
ZW12	1360(1940)	0.9	2.6	1.7	0.7	90	4.2	2.8	21.6	21.2
ETL										
101	1034(1276)	36.5	6.5	1.8	1.7	80	10.9	3.9	27.6	25.4
104	936(1164)	18.6	3.8	1.4	0.0	90	23.7	2.1	26.4	23.7
105	916(1098)	6.0	2.6	1.4	3.8	80	3.1	3.0	24.0	23.1
106	974(1127)	17.5	4.2	1.4	-4.5	50	15.2	4.0	26.3	24.2
107	860(1025)	5.2	3.2	1.8	0.0	70	11.8	2.8	24.4	22.0
Photonis										
596	1200(1540)	3.0	3.8	1.4	-1.2	85	15.2	0.6	25.5	23.5
598	1316(1700)	5.7	2.7	1.2	-1.2	90	4.7	1.3	22.8	21.0
601	1090(1405)	2.4	2.4	1.2	-2.0	75	3.7	3.5	21.8	20.1
603	1490(1993)	11.0	3.6	1.3	-1.2	105	17.1	2.1	22.1	20.5

Fig. 2. Summary of all the PMT measurements. In the above figure, HV = applied high voltage in volts, I_D = dark current, P/V = peak to valley ratio. The afterpulse ratio is defined as the ratio of the charge in the afterpulse (integrated over 200–5000 ns following the main pulse) to that of the main pulse.

current as a function of high voltage, (5) dark pulse rate as a function of storage time in dark, (6) afterpulse ratio and (7) linearity as a function of peak anode current. The details of technique and instrumentation used in these measurements can be found elsewhere [6,7]. Fig. 1 shows sample linearity curves for the three different kinds of PMTs at 2×10^5 gain, since this is the most important PMT property for Auger. Fig. 2 summarizes the results of all the measurements. All the three PMTs now show good linearity up to 50 mA anode current at a low gain of 2×10^5, as well as satisfying all other Auger requirements.

5. Summary

We have performed extensive tests on large PMTs from ETL, Hamamatsu and Photonis. These PMTs were custom designed for Auger needs, in particular, to provide good linearity over a large dynamic range at low gains. The test results show that all three PMTs satisfy the linearity requirement as well as other Auger criteria. Photonis XP1805 was finally selected by the Auger collaboration for use in the surface detectors.

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