Production Test System and Results on Large PMTs for Pierre-Auger Surface Detectors

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Abstract

We have developed a fully automated test facility to evaluate 9 inch PMTs for Pierre-Auger Surface Detectors. The facility, now located at the Auger site in Malargüe, Argentina, is capable of testing 16 PMTs simultaneously. It automatically measures the following quantities: Gain (vs. High Voltage), Relative Quantum Efficiency, Single Photoelectron Distribution, Excess Noise Factor, Dynode/Anode Ratio, Dark Pulse Rate, After Pulse Ratio, and Pulse Linearity. Using this facility, 441 PMTs have already been tested and evaluated, of which 95% have passed our specifications. These PMTs are being deployed in water tanks successfully. We plan to continuously test the remaining 4500 PMTs during the production deployment for the next three years.

1. Introduction

To characterize and ensure the quality of 9 inch photomultiplier tubes to be used in the Pierre Auger surface detectors, UCLA and UTN Mendoza test each PMT. They are tested to see if they are within the specifications given to Photonis [1]. The specifications given to Photonis are designed to minimize systematic errors in data taking with the surface detectors and to maximize the lifetime of each PMT, and are designed around physics data taking. In regards to linearity, we specified that the tubes must be less than ± 5% non-linear with up to 50 mA of peak anode current. This spec was obtained after simulating a 10^{21} eV cosmic ray and computing the current in a phototube in a water tank located 500 m from the core. We also specified that after 2 hours in a dark room, the PMT must have less than 10 kHz of dark pulses at $\frac{1}{4}$ photoelectron threshold to maximize the lifetime of the PMTs. The PMT must be designed to operate optimally at a gain of 2×10^5, but be able to operate at a gain of 10^6 with less than 2000 volts. This was due to the fact that we are unable to apply more than 2000 V to the PMT with the base and water tank station electronics. We specified that the tube must have less than 5% after pulse ratio so that we won't overestimate

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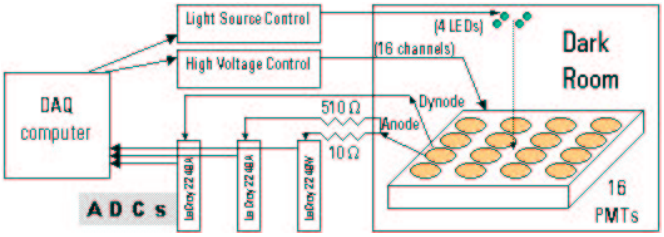

Fig. 1. PMT test system DAQ

the energy deposited in a water tank due to after pulsing of the PMT. There are specs provided in regards to quantum efficiency, at least 16% at 350 nm to be able to see the Cerenkov radiation in the water tank, and a peak to valley ratio of the single photoelectron distribution of greater than 1.2, for good low signal resolution.

Previously, PMTs for the Pierre Auger surface detectors were tested by the UCLA group in a test facility located at UCLA [2]. We tested 171 PMTs before constructing a duplicate test system in Malargüe, Argentina. In conjunction with UTN Mendoza, in this new testing facility we have tested 270 PMTs [3].

2. Method

The PMT test system is designed to test 16 PMTs at a time in a single run. The voltages to the PMTs are controlled by the DAQ computer as well as the intensity and frequency of the light source. There are 4 LEDs used in testing, 3 are 400 nm LEDs and 1 is 370 nm. The signals from the anode and amplified last dynode stage of the PMTs are measured using CAMAC LeCroy 2249A and 2249W ADCs, and then read into the DAQ computer and analyzed using Root, see Fig. 1.

To monitor the stability of the system, we have 4 permanent PMTs located at the corners of the test stand. These PMTs monitor the stability of the light source as well as the readout electronics and the performance of the system overall. Each test run lasts about 4 hours and is completely automated enabling us to test 24 PMTs per day.

3. Test Results

We have been able to test 441 PMTs in our test facilities. The tests we run are: single photoelectron (spe) distribution, gain vs. high voltage, dynode/anode ratio, dark pulse rate at $\frac{1}{4}$ pe threshold, after pulse ratio, pulse linearity, excess noise factor, and relative quantum efficiency.

We measure the single photoelectron spectrum to calculate the absolute gain of the phototube. To do this, we turn our light source intensity down until

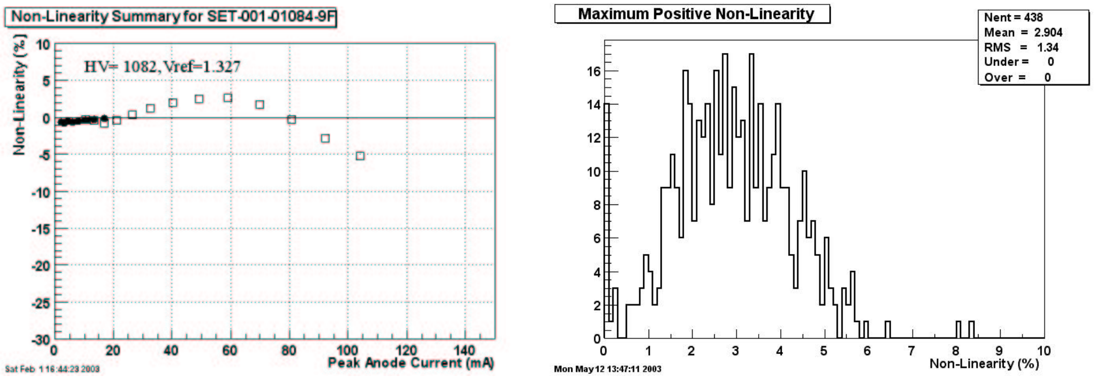

Fig. 2. Typical non-linearity curve (left) and distribution of maximum positive non-linearities for tested PMTs (right)

90% of the time it gives no light and (following Poisson statistics) 9% of the time it gives 1 photon. The average peak to valley ratio is 1.43 with an RMS of 0.20.

Using the data from the single photoelectron spectrum to calculate the absolute gain, we then take data at several different voltages to determine gain as a function of voltage. To take the SPE data we use the signal from the amplified last dynode stage, and to get our gain vs. voltage curve, we use the anode signal. To convert values obtained from one to the other, we must measure the dynode/anode ratio. Nominally, the amplifier on the last dynode stage has a value of 40, and the mean value of dynode/anode ratio is 32 with an RMS of 1.4.

Setting the PMT's voltage to get a gain of 2×10^6, we count the number of events per second above a threshold of $\frac{1}{4}$ photoelectron, this is the dark pulse rate. The mean dark pulse rate is 3.3 kHz with an RMS of 1.6 kHz.

After pulses are caused by gas contamination in the vacuum of the phototube. There is a slight systematic negative after pulse ratio probably due to the system used to measure the PMTs, but no after pulses due to gas contamination.

To measure pulse linearity, we flash LED A, then LED B, then LED (A+B) and compute any deviation from a linear response. The results of our pulse linearity testing shows consistently that the PMTs experience a positive non-linearity. The positive non-linearity is a result of the dynode chain design. They are designed to optimize collection of electrons assuming an infinite dynode chain. This causes a loss of electrons due to bad trajectories, not due to a space charge effect, the usual cause of non-linearity. With larger signals, the loss of electrons reduces resulting in a positive non-linearity, and at even larger signals space charge effects again reduce the collection of electrons at the last dynode stage resulting in a decrease in linearity, see Fig. 2.

When dealing with PMTs, one can not calculate the number of initial photoelectrons just knowing the spread in the measured values assuming Poisson statistics. The amplification process introduces a widening of the spread in the

Table 1. Out of Spec PMTs

Test	Number of Failed PMTs	Specification
Pulse Linearity	9	$< \pm$ 5% at 50 mA peak current
Dark Pulse Rate	8	$<$ 10 kHz after 2 hr cooldown
Gain Voltage	2	$<$ 2000 V to get 10^6 gain
General Failure	5	2 Base, 3 Undiagnosed

distribution. The "widening" factor is called the excess noise factor (ENF) and for the PMTs used in the Pierre Auger experiment, the mean value is 1.57 with an RMS of 0.13.

When measuring quantum efficiency (QE), what we are able to measure is actually a convolution of collection efficiency (CE) and QE since we are unable to measure cathode current with the bases used in the surface detectors. To deconvolve these values, we compare our results for gain vs. those provided by Photonis. Our definition of gain does not include CE while Photonis' definition does. Therefore, we are able to untangle CE from QE in our measurement. We compute the mean CE to be 75 ± 10% and the mean SKCB is 9.3 ± 1.3 μA/lmF.

After testing 441 PMTs, we have found 24 that have not passed specifications. The specific non-conformities are explained in table 1. Nine PMTs failed the linearity spec with 5 of these tubes having a positive non-linearity problem and 4 tubes that had extremely negative non-linearity. The other main source of rejected PMTs is dark pulse rate. Generally speaking, the PMTs are quiet with low dark pulse rates of around 2.5 kHz. The failed PMTs were all near 10 kHz with the exception of 2 PMTs who were extremely noisy. Two PMTs had very low gains, needing more than 2000 V to get a gain of 10^6. This makes them unusable in the surface detectors. Five PMTs we received failed all tests run on them. For 2 of them we were able to determine that they were base problems while for the other 3 we were unable to determine the source of the failures. These PMTs have been sent back to Photonis to further investigate the non-conformities.

4. Conclusion

The PMTs conform to our specs as expected with few exceptions. Currently there is about a 5% failure rate due to non-conformity to specifications (but that rate is decreasing), with an additional 1% failure rate due to mechanical problems incurred during shipping. We will be able to test the remaining 4500 PMTs to be deployed in the surface detectors.

5. References

1. Tripathi et al., 2001, GAP 2001-049
2. Jillings et al., 2002, GAP 2002-037
3. Barnhill et al., 2003, GAP 2003-037