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# Photomultiplier Qualification Tests for the Fluorescence Detectors of the Pierre Auger Observatory

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We present the results from acceptance qualification tests of the 11000 photomultipliers (XP-3062 by *Photonis*) for the fluorescence detectors of the Pierre Auger Observatory.

## 1. Introduction

Each of the 24 fluorescence telescopes [1] of the Pierre Auger Observatory [2] is equipped with a camera of 440 photomultipliers (PMT), XP-3062 produced by *Photonis* [3]. This is an eight-stage PMT with flying leads and a 40 mm edge-to-edge hexagonal shaped photocathode of bialcali type. Each PMT is soldered to small printed circuit boards, the Head Electronics unit (HE) [4]. The HE implements a voltage divider for the PMT and delivers the PMT signal, after low noise amplification, with twisted pair differential output. A total of 11000 PMTs, with mounted head electronics, has been tested and pre-calibrated in our home institutions at Rome and Wuppertal prior to the installation at the observatory.

## 2. The test facility

The main objectives of the measurements have been:

- Identification of dead and unstable PMTs (or HE).
- Calibration of the effective gain[1] as function of the applied high voltage and classification of PMTs of similar response into gain classes. Groups of 44 PMTs share the same channel of the HV supply. This classification prior to the mounting of the camera allows to select PMTs of similar response to share the same high voltage channel. This results in a more uniform response of all camera pixels.
- Test of the linearity of the PMT response as function of the applied light intensity.
- Test of the spectral response for UV wavelengths, which are relevant for the fluorescence detection *in situ*.

Two similar but independent test facilities have been built by the Universities of Rome and Wuppertal. Both designs were guided by the requirement to measure a large number of PMTs and thus allowed to measure several PMTs in parallel, in an automated procedure. Schematic sketches of the two test systems are shown in figure 1. Details are described in [5, 6]. The Roman test system is located in a long light tight rectangular box of about 2 m length. Different light sources can be mounted outside of the box. The light enters the box

[1] The effective gain should not be confused with the electronic gain, which is usually the charge with respect to the incident number of photo electrons. The objective here is to calibrate the response with respect to the number of incident photons per unit area and thus taking also into account different values of the quantum and collection efficiency and the sensitive photo-cathode area. The effective gain at which the PMTs are operated corresponds to an electronic gain of typically $10^4$ to $10^5$.

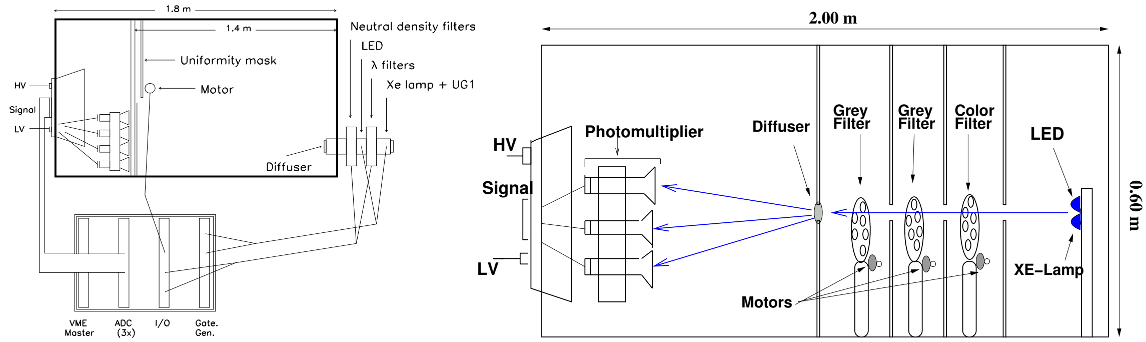


**Figure 1.** Sketches of the test setups in Rome (left) and Wuppertal (right)

through optical filters along a light-tight path before it is diffused. A total of 24 PMTs can be mounted on the opposite side of the box. The PMT response is digitized by conventional charge sensitive ADCs housed in a VME crate. The Wuppertal setup is very similar, except that all components are mounted on an optical bench inside a 2m long wooden box. Optical filters, located on motor driven wheels, can be inserted into the light path by the remote control software. A total of 37 PMTs can be mounted in parallel. A specialty of the setup here is the use of a more complex DAQ system in which the full PMT waveforms are digitized by FADCs; the system was adopted from [7]. The digitization with FADCs provided the opportunity to implement a highly automated online monitoring and analysis of the PMT's charge response, checking for saturation, and implementing dynamic integration gates and pedestal subtraction.

The measurements were done using a blue led with the exception of the spectral measurement, where a Xe-lamp was used. The width of the pulses was set to about 1-2 $\mu$s which corresponds to the expected duration of fluorescence signals in the experiment. With different neutral density attenuation filters we were able to change the light intensity by more than 3 orders of magnitude. Filters for $350\,\mathrm{nm}$ and $380\,\mathrm{nm}$ ($337\,\mathrm{nm}$ and $390\,\mathrm{nm}$) were used for the Rome (Wuppertal) setup, respectively, to select specific wavelength-intervals. For each measurement batch, PMTs of similar factory gain class were mounted together with 4 absolutely calibrated *reference* PMTs. The different measurements were then performed in a sequential order. According to the results of the data analysis the PMTs are then sorted and packed in portions optimized for the construction procedures in Argentina. The results of the data analysis are stored in a MySQL based database, which provides access to each individual result for the Pierre Auger Collaboration. The same reference PMTs were used throughout the entire measurement campaign to monitor changes of the setup; the test PMTs are calibrated with respect to these PMTs. Deviations in the homogeneity of the light at positions of the PMTs are of the order of a few%; this was frequently monitored and corrected for in the data analysis.

## 3. Measurement Results

### 3.1 Gain calibration

As explained above, the most important step is the calibration of the PMT gain as function of the applied high voltage (HV). A typical measurement is shown in figure 2. The collected charge is well described by a power-law $Q = K \cdot (\mathrm{HV})^{\alpha}$. The fit values for $\alpha$ are found to be Gaussian distributed with a mean of $\simeq 6.1$ and variance of $\simeq 0.1$. This is consistent with the typical expectation of $\alpha \approx 6$ for an 8-stage PMT. The values of the fit parameters $K$ and $\alpha$ are used to calculate the nominal high voltage, $\mathrm{HV}_0$, corresponding to a gain of $10^5$. The PMTs are then classified according to $\mathrm{HV}_0$ into 10 gain classes $A \rightarrow J$ where $\mathrm{HV}_0(A) = 782\,\mathrm{V}$

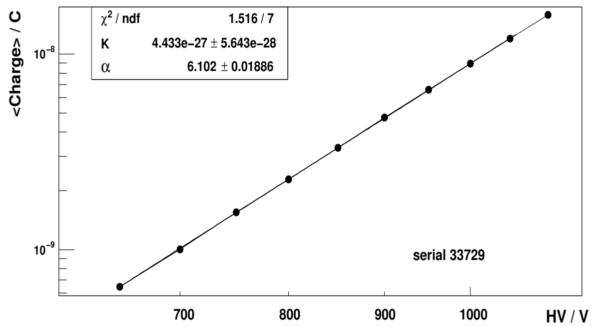


**Figure 2.** Typical result of the calibration of the gain as function of the applied high voltage.

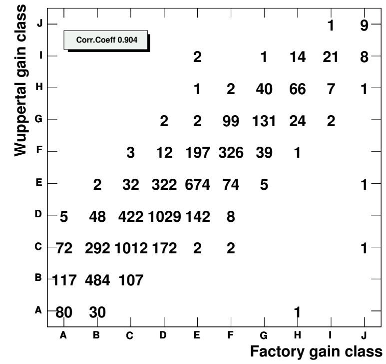


**Figure 3.** Distribution of the classified gain classes. The numbers correspond to the number of PMT in each bin.

and $\mathrm{HV}_0(J) = 1027\,\mathrm{V}$. The distribution of gain-classes can be seen in figure 3. Each entry in the scatter plot corresponds to a PMT with its gain class as classified by *Photonis* and by us, respectively. Apart from the generally good correlation, we have observed an apparent migration from the initial factory classification to our final value. It should be noted that our measurement includes the mounted head-electronic and conditions closer to the operation *in situ* than for the initial factory calibration. Using our estimate of the total error $\delta(HV_0) \approx 3.5\,\mathrm{V}$ and the natural spread of $HV_0$ within one gain class we expect gain variations within one high voltage channel of the FD camera to be $\simeq 5\%$. This can be corrected for in the front-end electronics of the camera.

## 3.2 Linearity

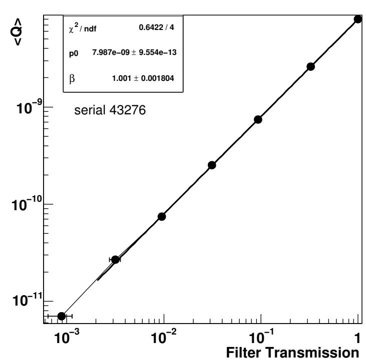


**Figure 4.** Typical result of the linearity measurement.

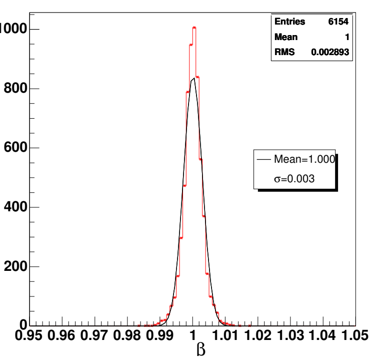


**Figure 5.** Distribution of the linearity power-index $\beta$ for the tested PMTs.

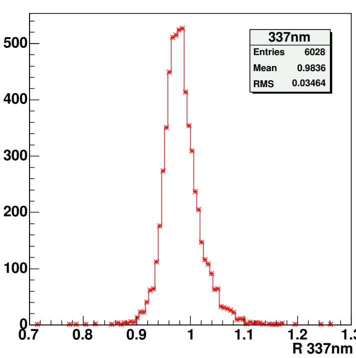


**Figure 6.** Distribution of the spectral response $R_{337}$ for the tested PMTs.

The linearity of the charge response of the PMT is measured at the nominal $\mathrm{HV}_0$ using a blue LED. The light intensity is varied by neutral density transmission filters and the corresponding response is fitted with a power-law $< Q >= p_0 \cdot T^\beta$ as function of the relative transmission $T$. Figure 4 shows the excellent linear behavior for a typical single measurement and figure 5 the distribution of the power-index $\beta$. The values are consistent with $\beta = 1$ and the fits have a reasonable distribution of $\chi^2$ values.

### 3.3 Spectral response

The relative sensitivity of the PMTs for different wavelengths is tested using a Xe light source and measuring the charge response with narrow band transmission filters and without filters ("*white*"). In order to account for fluctuations in the intensity of the Xe-lamp and its wavelength spectrum we investigate the response with respect to our reference PMTs and only inspect the double ratio $< R_\lambda > \equiv \frac{<Q_\lambda>/<Q_\lambda^{ref}>}{<Q_{white}>/<Q_{white}^{ref}>}$ , in which these effects are largely canceled out. As an example, figure 6 shows the result for $\lambda = 337$ nm. The deviations from unity have an RMS of only $\sim 3.5\,\%$ and the largest observed deviation is $28\,\%$.

## 4. Conclusions

We have designed, constructed and operated two independent test systems for the final acceptance tests of the 11000 PMTs which are installed in the AUGER fluorescence telescopes. The systems allowed for fast and highly automized testing procedures and were operated for about 1 year under stable conditions. They have obtained quantitatively similar results for the investigated PMT properties. The reproducibility was successfully demonstrated by repeatedly measuring the same PMTs.

In each of the setups about half of the PMTs were tested ( 6000 in Wuppertal and 5000 in Rome). This unusual large statistics is a good basis to study the quality of the PMT production and to understand its variances over the production time. In total 24 units failed the acceptance tests out of which more than half of the failures were related to the mounted head electronics. We can thus confirm a high quality of the PMT production by *Photonis*.

These final acceptance tests delivered a large statistics of initial calibration data for each used PMT and proved to be important for the optimum installation in Argentina because many PMTs needed to be re-classified with respect to their initial factory gain calibration. The linearity and spectral response was found to be satisfactory for all accepted PMTs. The detailed results of all measurements can be found in [6, 8, 9]

## 5. Acknowledgments

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