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Development of bases and qualification tests of Photomultiplier Tubes for the AugerPrime scintillation detectors

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We describe two test benches that were designed and constructed to perform a set of acceptance tests for about 1200 Photomultiplier Tube (PMT) units to be installed in the surface scintillation detectors of AugerPrime. Besides possessing robustness, long-term reliability, and low power consumption, each PMT-unit requires a dynamic range wide enough to cover signals ranging from a single to more than 20,000 minimum ionizing particles with not more than 5 % deviation from linear response. This posed a particular challenge which was met by combining a specially selected 1.5” PMT type with a custom made Cockcroft Walton type base. The characteristics of the PMT units and qualification results obtained for a large quantity of tested units will be presented and discussed. Besides measuring the gain and linearity for each PMT-unit for different supply voltages, in a sub-sample of about 10 %, we also measured the quantum-efficiency of the photocathode as a function of wavelength as well as its homogeneity across the full photocathode area with 1 mm spatial resolution. The latter is of importance because of the fiber-optical readout of the scintillation detectors.

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1. Introduction

The Pierre Auger Observatory [1] is currently being upgraded to what is called AugerPrime [2]. A key motivation for this upgrade is to improve the measurement of cosmic ray mass composition on a shower-by-shower basis with the surface detector array. As compared to the Pierre Auger fluorescence telescopes, operated only in clear moonless nights, this promises a much more rapid growth of statistics in measurements of the cosmic ray mass composition. The surface detector array comprises 1660 autonomously operated water Cherenkov detectors (WCD) distributed over an area of 3000 km^2. A key component of AugerPrime is to install a 3.8 m^2 large scintillation detector on top of each WCD. With the signal response of the surface scintillation detector (SSD) being dominated by the photons and electrons and the signal response of the WCD being dominated by the muons of an extensive air shower, the addition of the SSD will enhance the e/μ-discrimination, which is known to be a key observable for cosmic ray mass composition measurements by particle detector arrays.

The scintillators of the SSDs are subdivided into two modules, each covering an area of 1.9 m^2. Their scintillation light is read out by wavelength-shifting fibers guiding the light to a single photomultiplier tube (PMT). The peak wavelength at the PMT is observed at 500 nm. The signals of the PMT are recorded by custom made unified readout boards (UUB) which sample the signals at a rate of 120 MHz in two 12-bit analog-to-digital converters (ADCs). On the UUB, the signal of the PMT is split into two channels. One channel is amplified by a factor of 32 and the other one is attenuated by a factor of 4. Using these high- and low gain channels with 5 bits of overlap, an effective dynamic range of about 19 bits is reached. This is sufficient to both calibrate the detector on single minimum ionising particles (MIP) and to detect up to 20,000 MIPs which are expected for the most energetic air showers at distances of 250 m from the shower core.

2. The PMT and its active base

The physics requirements of the AugerPrime upgrade impose very high demands on the performance of the SSD detector and its PMT. Besides the high reliability needed for more than 15 years of operation, the most important criteria are (i) a linear response over a very large dynamic range, (ii) high sensitivity at a wavelength of 500 nm, (iii) low power consumption, (iv) low sensitivity on operation temperature, and (v) cost effectiveness. Evaluating the market of PMTs, a short list of candidates has been selected and was carefully evaluated in lab tests. Silicon photomultipliers (SiPMs) were also considered, but achieving the required dynamic range was found to be a challenging task.

The R9420 linear-focused 8-stage 1.5” PMT manufactured by Hamamatsu offers a high pulse linearity of 30 mA at less than 2 % deviation from linearity [3]. The PMT features a dynode structure that is optimized for large peak currents and its has been further optimized and specially selected by Hamamatsu for the demands of the Pierre Auger Observatory. This optimized R9420-022 PMT guarantees a pulse linearity with a maximum deviation of ±5 % up to peak currents of 150 mA at a gain of $g = 7 \cdot 10^5$. Also, it guarantees a quantum efficiency of > 18 % at $\lambda = 500$ nm.

To reach these peak currents with minimum deviation from linearity at a 50 ns pulse width and repetition rates up to 100 Hz, a classical voltage divider with optimized tapering and capacitive buffering of the last dynodes has been developed and extensively tested in the lab. For later operation in the field, it has been replaced by a custom made integrated HV supply developed in cooperation with the ISEG company [4].

Integrated HV bases using a Cockcroft-Walton HV-generation are widely used in particle and astroparticle experiments and they offer a number of advantages particularly relevant for the use in the surface detector array of the Pierre Auger Observatory. The key advantages are: (i) A reduced power consumption compared to an external HV supply driving a bleeder current in a classical PMT base which is particularly important because of solar power operation, (ii) elimination of a HV cable that would need to be operated in the open environment of a detector station, (iii) large thermal balance and high temperature stability, and (iv) significant overall cost and complexity reduction.

The Cockcroft-Walton developed for the R9420-022 PMT generates 250 V per pass and a classical voltage divider chain is employed for the first dynodes to resemble the tapered HV distribution optimized with the classical passive base. Stabilization of the last dynodes and anode is accomplished by capacitive buffering and additional stabilization circuitries. The supply voltage to the base is 12 V and the power consumption is at a level of 100 mW at nominal PMT operation voltage. Special care has been taken to minimize noise and ripple to allow reliable signal calibration on the MIP peak. For this purpose, the HV generator has been placed on a separate PCB with extra shielding. The HV generator PCB is then connected to the actual base PCB soldered to the flying leads of the PMT. For optimal use in the Auger Observatory, the integrated base has been designed to be compatible to the UUB slow-control, i.e. HV setting, read-back, and current monitoring is done via the UUB. Also, a temperature sensor is integrated on the PCB to monitor the PMT environment. The base is powered and controlled via a shielded $\sim$ 2 m long light plastic-sheathed cable which simplifies the installation in the field. A photograph of a PMT with its base soldered to the flying leads, with both slow control and signal cable connected to it is shown in Fig. 1.

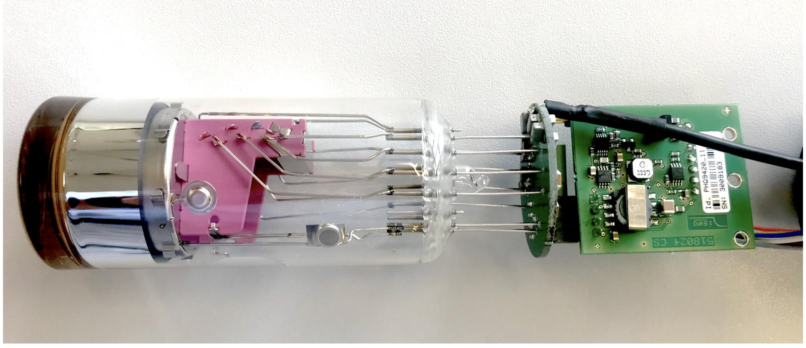

Figure 1: Hamamatsu R9420-022 PMT soldered to a custom made integrated ISEG base. The shielded upper black cable soldered to the base PCB transmits the PMT-signal. The slow control cable, which also provides the 12 V of operation power, is seen at the bottom soldered to the HV generator PCB.

3. Quantum efficiency and homogeneity of photocathode

The PMT specifications require a quantum efficiency larger than 18 % at a wavelength of 500 nm when integrated over the entire area of the photocathode. The variation of the quantum efficiency across the surface is required to be less than ±25 %. The former criteria is important for achieving a good light detection efficiency, while the latter is relevant as the bundle of 96 fibres from the scintillators is fed via a poly(methyl methacrylate) (PMMA) cylinder to the photocathode. Inhomogenities of the quantum efficiency across the photocathode area would thus result in a inhomogenous detector response across its 3.8 m^2 area.

Measurements of the quantum efficiency were done for a randomly selected sub-sample of 10 % of the 1600 PMTs. For these measurements, a dedicated test bench has been set up which otherwise consists, effectively, of a broad-band tungsten light source, and a monochromator with an optical system focusing the monochromatic light into a lightfibre which illuminates either a calibrated photodiode or the photocathode of the PMT, both of which are located in a dark box. The DC currents from both the photodiode and PMT are measured with a pico-Amperemeter and their ratio, corrected for the known quantum efficiency of the photodiode, yields the quantum efficiency of the PMT. For this measurement, a potential difference of 150 Volts is applied to the first dynode, at which the current from the photocathode was measured. The mean quantum efficiency of the PMT was then measured by diffusively illuminating the entire photocathode. For measuring the homogeneity of the quantum efficiency across the surface of the photocathode, the light fibre was positioned very close to the PMT so that only a circle of about 1 mm was illuminated. Using an automated x-y-scanner, the full area of the photocathode was scanned. Results of typical measurements are shown in Fig. 2. All tested PMTs have passed this acceptance test.

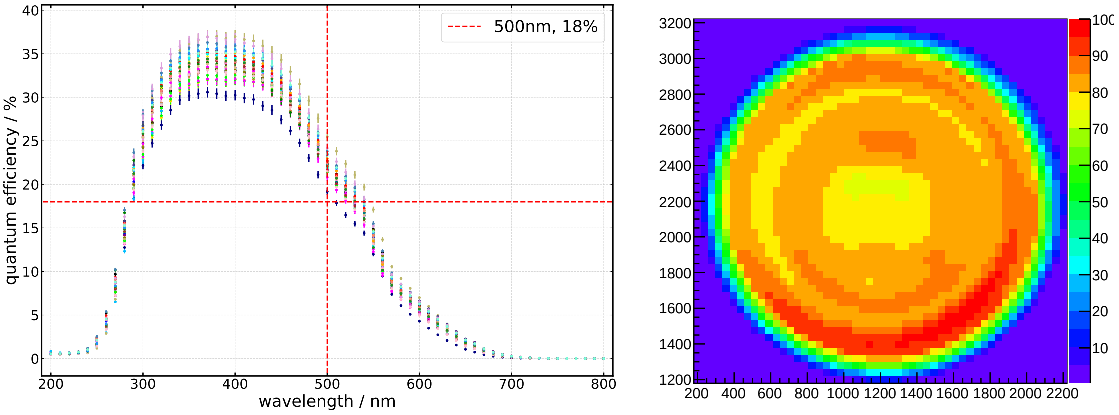

Figure 2: Left: Quantum efficiency as a function of wavelength for a sample of R9420-022 PMTs. The dashed horizontal line indicates the minimum 18 % required at a wavelength of 500 nm. Right: 2D-scan of the quantum efficiency measured across the surface of the photocathode. A variation of about ±10 % is found, well in line with the allowed ±25 %.

4. Gain calibration

A pre-calibration of each individual PMT was performed by Hamamatsu and the HV-settings were provided to us for adjusting the gain to $5 \cdot 10^4$ and $7 \cdot 10^5$, respectively. For operating the PMT in the SSD, the lower gain is used as this allows the measurement of up to 20,000 MIPs without exceeding a peak output voltage at the PMT of 7 V. A single MIP measured in the SSD yields about 30 photoelectrons at the first dynode of the PMT.

Measuring the PMT charge response to single photoelectrons (SPE) allows for the extraction of the absolute gain of the PMT. Such measurements have been performed again for only a sub-sample of PMTs, because the calibration in field will continuously monitored in units of MIPs. For the purpose of verifying the absolute calibration in the laboratory, the light from an ultra-fast Laser was fed via an optical fibre to the photocathode. For SPE counting the light was then dimmed to a level that on average only every tenth laserpulse resulted in a SPE detected by the PMT. The integrated signal charge of such a pulse then provides a direct measure of the PMT gain. To allow a clean separation from spurious noise pulses of the PMT, the readout of the signal trace is triggered externally by the Laser. An example of such a measurement is depicted in Fig. 3 where the distribution of the SPE amplitudes is shown at a load resistor of 50 Ω. These measurements confirmed the HV-settings provided by Hamamatsu when accounting for uncertainties in the high voltage which typically are at a level of 5-10 Volts.

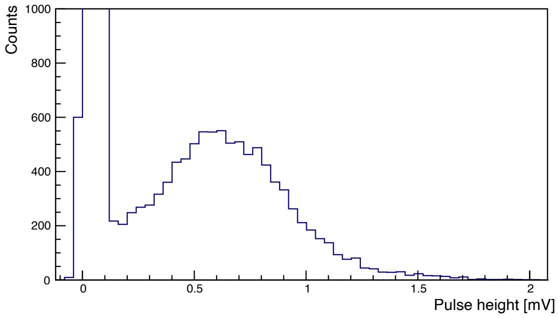

Figure 3: Typical distribution of signal amplitudes of a PMT when illuminated with single photons. The signals are measured at 50 Ω load for an operation voltage of 1200 V, corresponding to a gain of about $3 \cdot 10^5$.

5. The PMT test bench

The test bench developed for performing the serial acceptance tests for about 1200 PMTs is depicted in Fig. 4. To cope with the large number of PMTs to be tested in a short amount of time, it is designed to allow for the testing of 20 PMTs simultaneously. The test box described here is effectively a modified version of a test facility that has been used to qualify about 10,000 PMTs operated in the Fluorescence Detector of the Pierre Auger Observatory [5]. A most demanding requirement in the present case is to mimic the light expected for the up to about 25,000 MIPs detected by the SSD, corresponding to $7.5 \cdot 10^5$ photoelectrons released by the photocathode. Since this could not be accomplished by a single LED, an array of 7 LEDs mounted very close to each other and emitting light dominantly at 505 nm was assembled. The LED-array is driven by a pulse generator providing 100 ns wide pulses of 37 V amplitude at a repetition rate of 100 Hz.

For testing the linear response of a PMT, and respectively, deviations from it, the illumination of the photocathode is to be reduced in small well controlled steps so that the signal height can be studied as a function of it. The large dynamic range covering measurements from 1 to 20,000 MIPs combined with the need to measure the PMT linearity at two different gain settings, differing by a factor 14, imposes strong demands on changing the light intensity in a controlled way over a dynamic range of about $20,000 \times 14 \simeq 3 \cdot 10^5$. Moreover, scanning the linearity near the saturation point

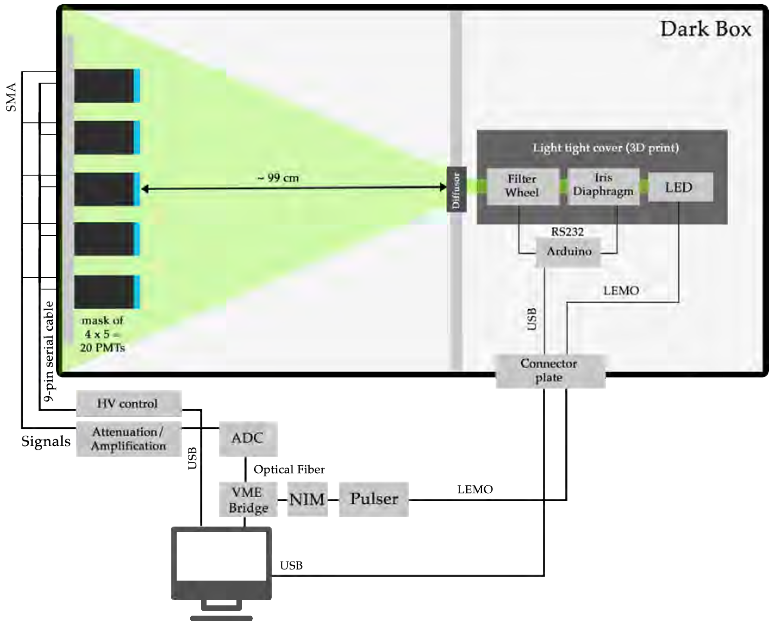

Figure 4: Sketch of the PMT test box with its main components used for the serial PMT tests.

requires being able to change the light intensity at relative levels of 10-20 %. This is accomplished by attenuating the LED light in two independent steps: first is a computer controlled filter wheel holding 11 pre-loaded calibrated absorptive neutral density filters allows to reduce the light intensity in well defined discrete steps down to a level of 0.006 % of the original. To allow scanning the signal pulses in finer steps than is possible by this discrete set of absorption filters, a second component is introduced into the light beam, which is a computer controlled iris diaphragm. It allows reducing the light intensity continuously to any value between 100 % and $\sim$ 1 %. With the combination of these two components, the fixed discrete comb of light attenuation steps realized by the absorption filters can be shifted to lower and higher light intensities by the iris diaphragm so that a fine scan in the region of the onset of non-linearities can be accomplished. It is important to note that the absolute light attenuation caused by the iris diaphragm does not need to be known at high precision, as the chosen iris setting only provides another starting point for the fixed attenuation comb structure of the calibrated attenuation filters with the filter settings always covering the linear and non-linear range of the PMT.

A light diffusor is the last component in the light beam and is installed to improve the homogeneity of the light intensity across the area of the 5×4 PMT matrix (c.f. Fig. 4). The light intensity is found to drop from the center to the corners of the of PMT matrix by about 25 %. This inhomogeneity does not cause any systematic effect to the non-linearity measurement, only that the central PMTs are generally driven more strongly into the saturation region than would be needed to extract the maximum current at which the signal deviates by more than 5 % from linearity.

Similarly as is done with the UUB readout cards in the field, the PMT signals in the test bench are digitized by commercial 12 bit ADCs operated at a sampling rate of 100 MHz. Again, the signals of the PMTs are split into a low- and high-gain channel, using custom made attenuator and amplifier boards to cope with the large dynamic range of the detected signals in the test bench.

Additional tests are performed including measuring the gain as a function of the high voltage, $\Delta g/\Delta HV$, and recording the dark current of each PMT. All these tests are fully automated and controlled by a PC and the results are recorded for offline analysis. A full test of 20 PMTs lasts about 2 hrs to which another 2 hrs are added to allow the PMTs to cool down at operation voltage in the dark box. Generally, 3 PMTs are kept in the setup and serve as reference PMTs to monitor the stability of the test bench and its extracted results. Still, up to 200 PMTs could be tested per week without major complications. In total, more than 1200 PMTs have been qualified and their key characteristics have been stored in a MySQL database. The remaining 400 PMTs will be tested by collaborators in Naples for which an independent test bench has been developed [6].

6. Linearity of the PMT-signal

The linearity measurement is performed to evaluate the percentage of deviation from linearity of the PMT output as a function of the peak-current. According to the specifications, the pulse height of the signal must be linear up to peak currents of 150 mA when operating the PMT at a gain of $7 \cdot 10^5$. The maximum linear range of a given PMT is known to depend on the gain, or more precisely on the electric field strength applied between the dynodes. At reduced electric field strength, i.e. reduced HV applied to the PMT, space charge effects already become important at lower electron densities accumulated at the last stages of the PMT, with the result that sagging of the signal starts to set in already at lower peak currents. However, due to the lower gain of the PMT, the lower peak current relates to a correspondingly higher number of MIPs recorded at the maximum current. Despite the fact that this improves the overall situation of measuring up to 20,000 MIPs in the linear range, it is of importance to measure the linear range of the PMTs also for the reduced operation voltage that will be applied in the field which is set to a gain of $g \simeq 5 \cdot 10^4$.

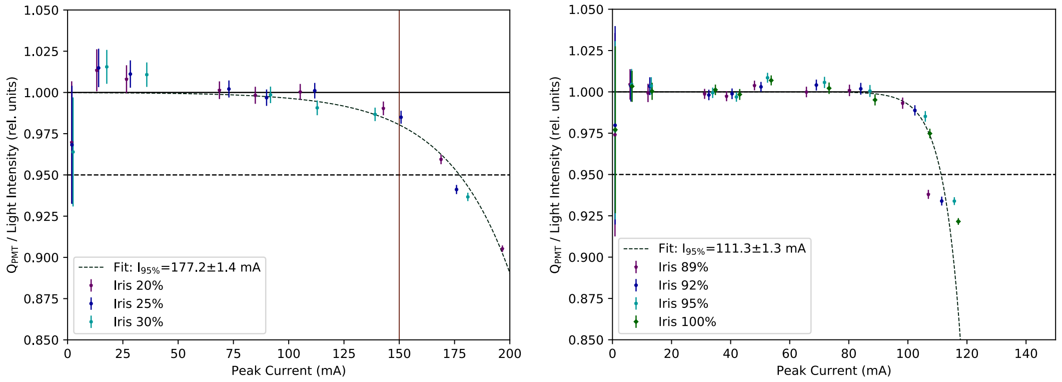

Figure 5: Linearity curves of a typical PMT operated at a gain of $7 \cdot 10^5$ (left) and $5 \cdot 10^4$ (right).

An exemplary result of a single PMT operated at the two gain values is presented in Fig. 5. The ordinate represents the ratio of the measured signal charge relative to the light intensity derived from the filter settings and anchored at low peak currents in the linear range. The abscissa represents the measured peak current at the PMT. Each of the 10 symbols of a given color represent a set of measurements performed with a fixed opening of the iris diaphragm and using 10 different absorption filters. In this case, the transmission values of the iris diaphragm were set to about 100, 95, 92, and 89 % for the low gain measurement and to about 30, 25, and 20 % for the high gain measurement. The horizontal lines at 95 % mark the maximum allowed deviation from linearity. The dashed curves represent fits to the data points using a function $Q_{\mathrm{rel}} = 1 - \exp\left(c \cdot (I - I_{95}) + \ln 0.05\right)$, where c represents the curvature and I_{95} the current at which the signal drops below 95 % w.r.t. to a linear response. The vertical line in the left figure illustrates the specification of 150 mA for the minimum linear peak current. As can be seen with $I_{95} = 177.2 \pm 1.4$ mA reached for this PMT, it meets the specs very well.

The r.h.s. of Fig. 5 shows the results when operating the PMT at reduced high voltage. As expected, deviations from a linear response already start at lower peak currents, here at 111 mA. Given the fact that particles in an air shower arrive over an extended period of time, on the order of $O(100)$ ns close to the shower core, saturation points found above ~ 80 mA are sufficient to meet the physics goals of AugerPrime.

Despite these extreme demands put on the dynamic range, no PMTs had to be rejected in a preliminary analysis.

7. Conclusions

Two test benches have been set up to qualify a large number of 1.5" PMTs to be operated in the surface scintillation detectors of the AugerPrime upgrade. One test bench is used to measure the quantum efficiency of the PMTs as a function of wavelength to verify a minimum value of 18 % at a wavelength of 500 nm. For a fixed wavelength of 505 nm, the quantum efficiency has been mapped across the area of the photocathode. Inomogeneities were found to be generally below ±15 % and even less across the cathode area used to readout the light from the wavelength shifting fibres transmitting the light from the 3.8 m^2 area of the scintillators. A particular challenge has been to measure the linearity of the PMT signals for two different gain settings over an extremely large dynamic range, ranging from a single MIP to beyond 20,000 MIPs. In total, about 1,200 PMTs have been tested with a rate up to 200 PMTs per week. A preliminary analysis did not show major problems in passing all quality criteria defined in the mutually agreed specification sheets. A full report for a large number of PMTs is currently being prepared.

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