Characterisation of PMTs for KM3NeT

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***Abstract*. Recent improvements in photocathode materials have led to Photomultiplier Tubes (PMTs) with increased quantum efficiencies. To assess these new devices, a testbench has been developed at ECAP (Erlangen Centre for Astroparticle Physics) allowing us to determine the quantum efficiency of a PMT across all wavelengths of its sensitivity window. This is achieved by measuring the photocurrent induced by illumination with a standard halogen lamp / monochromator combination, relative to the current induced by a calibrated photo-diode. These measurements go beyond the data provided by the manufacturers and in particular allow for individual calibration of PMTs, as required for the future KM3NeT neutrino telescope. The setup of the test bench and its measurement principle is described and results for different PMTs with different photocathodes are shown.**

***Keywords*: photomultiplier, quantum efficiency, KM3NeT**

I. Introduction

KM3NeT is a future neutrino telescope to be built in the Mediterranean Sea [1]. It is planned to encompass an instrumented volume of at least one cubic kilometre. Since the neutrinos are detected via Cherenkov light emitted by charged secondary particles from neutrino interactions, highly sensitive optical sensors are needed. Therefore, depending on the final detector layout, several 100,000 PMTs will be used in the project. For the best possible detector calibration, the full characteristics of each and every individual PMT need to be known. These characteristics include quantum efficiency, photocathode homogenity, angular acceptance for single PMTs and the complete optical modules, time resolution, gain, single photo electron response and dark rates. Several test benches have been developed at the ECAP to meet this demand. The test bench for quantum efficiency measurements will be presented in this paper.

II. Tested Photomultipliers

For low-level light detection applications one needs to select the photocathode that is best suited to the expected spectral distribution of the incoming photons. Fig. 1 shows the expected Cherenkov photon spectrum after absorption by sea water. Bialkali photocathodes (SbKCs, SbRbCs) have their maximum efficiency between 300 and 400 nm wavelength with a relatively wide plateau well matched to this spectrum and are widely used. While common bialkali cathodes reach a maximum quantum efficiency of around 25%, newer enhanced photocathodes are claimed to achieve up to 43% efficiency [3].

Four different PMT models were tested. These included three 10-inch hemispherical models from Hamamatsu (R7081, R7081-20, R7081_SEL) and 3-inch tubes from Hamamatsu (four units of type R6233) and Photonis (three samples of the XP53B20 series). One Hamamatsu 10-inch PMT, two of the Hamamatsu 3-inch PMTs and all Photonis 3-inch tubes had enhanced photocathodes. Thus it was possible to compare different photocathode materials in otherwise identical photomultipliers, as well as between different models and manufacturers.

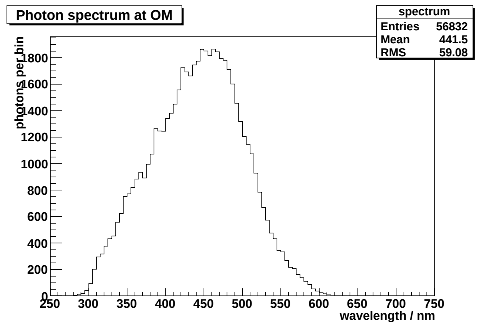

Fig. 1. Spectral distribution of Cherenkov photons after propagation through sea water (generated with Geant4, mean photon path length 30 m).

TABLE I
TESTED PMTs

Model	Size	Photocathode
Hamamatsu		
R7081	10”	Bialkali
R7081-20	10”	Bialkali
R7081 SEL	10”	SuperBialkali
R6233	3”	Bialkali
R6233-100	3”	SuperBialkali
Photonis		
XP1804	10”	Bialkali
XP53B20	3”	enhanced bialkali

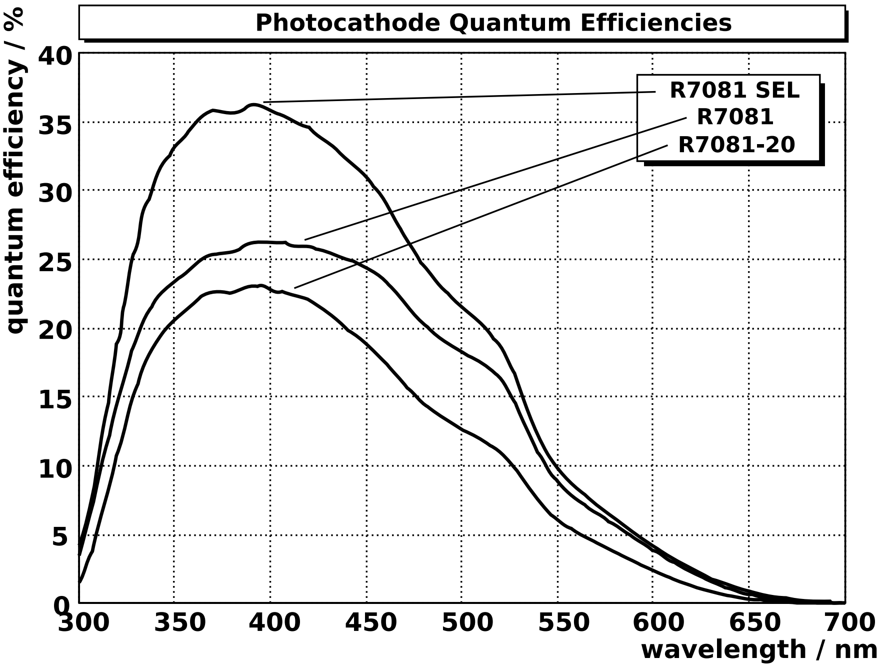

Fig. 2. Measured quantum efficiency for 10-inch PMTs. From top to bottom the results for R7081 SEL with a SuperBialkali photocathode and a maximum QE of 36%, the R7081 with a maximum of 26% and the R7081-20 with a maximum of 23% are shown.

III. Measurement Principle

To determine the quantum efficiency (QE) of the photocathode of a PMT, i.e. the fraction of incoming photons that generate a photo-electron, one needs to directly measure the photo-current induced in the cathode when illuminated by monochromatic light and compare that current to the absolute photo-current obtained from a calibrated sensor. By varying the wavelength of the light source one can scan the QE of the PMT across its sensitivity window.

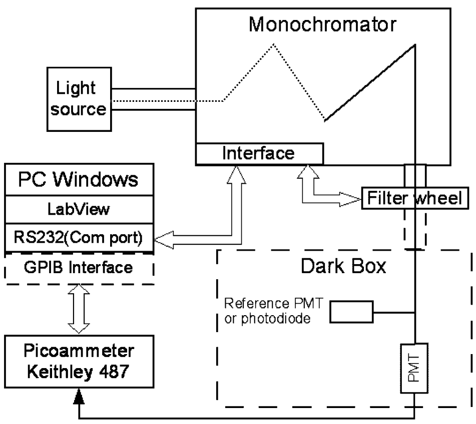

Fig. 3. Schematic of QE test setup

IV. Setup

The QE test bench consists of a light-tight black wooden crate containing supports for a PMT or the calibrated reference photo-diode[1], connected to the output side of a monochromator[2], and a halogen lamp[3] as a broad spectrum light source. The input and output ports of the monochromator have adjustable slits and a filter wheel containing neutral-density filters is fitted to the output. In the crate the spot size can be adjusted by an iris. By using a rather high intensity lamp a high signal-to-noise ratio is achieved at low wavelengths. Excessive photo-currents at longer wavelengths are avoided by using neutral-density filters. For current measurements a picoamperemeter[4] is used. Monochromator and amperemeter are controlled and read out using Python scripts.

In order to directly measure the photo-current induced in the cathode, one needs a specially tailored PMT base which provides a negative high voltage only to the cathode while connecting all other electrodes (focussing electrodes, dynodes, anode) to ground via the picoamperemeter.

The PMT is illuminated by a focussed light spot of typically several millimeters in diameter. Light impinges orthogonally on the surface of the tube to minimise reflection losses.

V. Measurement

To calculate the QE it is necessary to measure the light intensity with the reference photo-diode. Both

[1]Photo-diode: Hamamatsu S6337

[2]Monochromator: LOT Oriel MSH301 with filter wheel accessory

[3]Halogen lamp: LOT Oriel LSN111 using low voltage halogen bulb Osram 64623 HLX

[4]Picoamperemeter: Keithley 487

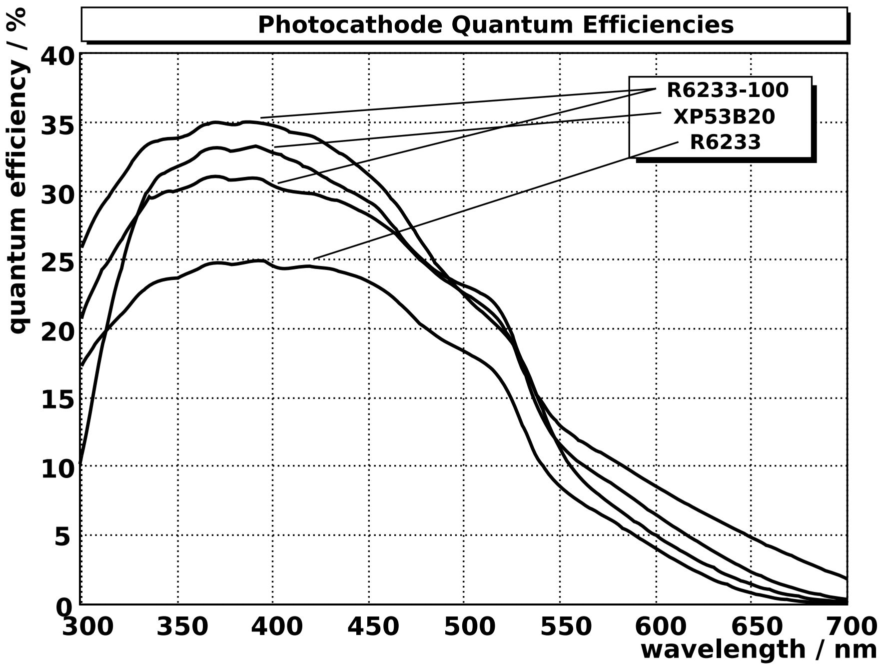

Fig. 4. Quantum efficiency for 3-inch PMTs. Maximum QEs vary between 31 and 35% for SuperBialkali / enhanced bialkali 3-inch PMTs. The lower curve denotes a standard bialkali-type R6233.

measurements are conducted as a scan over all relevant wavelengths. It turned out that it is not necessary to measure both at the same time, as the halogen lamp has a very stable output after a sufficiently long warm-up period (at least one hour). Therefore and also for practical reasons, the photo-diode measurement is conducted before and after PMT measurements.

For this purpose the reference photo-diode is mounted in place of a PMT. Special care is taken that the spot is centered on and does not extend beyond the active area of the diode.

A PMT that was exposed to high ambient light during handling exhibits an increased dark current. Therefore, after placing a PMT in the box, it is necessary to let it rest with high voltage applied to allow the dark current to return to its normal value.

Also, care must be taken not to exceed a maximum photocathode current that is unique to each PMT. It was found that if light levels were too high, the photo-current, which has its maximum typically between 500 and 520 nm, exhibits saturation. To avoid this, it is advisable to keep the photo-current below 15 nA.

Both current measurements need to be corrected by the dark current to calculate the QE.

VI. Quantum Efficiency Calculation

To calculate the QE one divides the photocathode current by the absolute photo-current measured with the calibrated sensor, having corrected for dark current. The measured photo-current is a product of the absolute light flux reaching the PMT envelope, the transmission coefficient of the glass shell and the collection efficiency, which in normal PMT operation is the probability that a produced photo-electron reaches the active area of the first dynode.

The collection efficiency is usually not exactly specified by manufacturers and depends on the voltage applied and the impact point and wavelength of the incoming light. The Photonis catalogue[2] shows a typical wavelength-dependent collection efficiency with values between 80% and 100%. In the measurements presented here, where light impinges centrally and orthogonally on the photocathode, and the whole metallic structure surrounding the first dynode is connected to it electrically, the collection efficiency is supposed to be 100%.

The transmission coefficient includes the transmissivity of the glass bulb as well as reflection on the medium boundary. The transmissivity is known for each tube material and greatly depends on the wavelength.

Reflection at a medium boundary is a function of angle and the respective refractive indices, therefore its influence will vary depending on the application. In deep-sea optical modules the PMTs are mounted within a glass shell and embedded in transparent gel with refractive indices similar to the sea water. This minimises reflection but increases losses due to absorption.

The quantum efficiency curves shown here have not been corrected for the transmission coefficient but are taken as is for a PMT in air.

VII. Results

The quantum efficiencies obtained for the 10-inch PMTs are presented in fig. 2 and for the 3-inch ones in fig. 4.
Independent of the PMT model one expects standard bialkali photocathodes to yield a quantum efficiency of about 25% at the maximum. The ”Super Bialkali” photocathodes are expected to be significantly better at up to 35% according to manufacturer claims. Photonis does not provide the maximum QE for their enhanced photocathodes.
The tested 10-inch PMT with SuperBialkali photocathode meets the expectations. The two standard bialkali PMTs show a visible difference in QE.
The 3-inch PMTs exhibit a variance of the SuperBialkali photocathodes. The Hamamatsu PMTs mark both the highest and lowest QE measured for this type of photocathode with a maximum of 31% and 35%, respectively. The three Photonis PMTs cover the space in between, so for clarity only one curve has been plotted. On average, the SuperBialkali photocathodes were measured at a peak QE of 33%.
A large number of measurements have been conducted to ascertain that the test setup yields self-consistent results. Due to the relatively high light intensity statistical variations of the obtained photo-currents are substantially less than 1%. The highest systematic uncertainty is in the calibration of the photo-diode, which yields an uncertainty of 1% QE at the maximum.

VIII. Conclusion

A number of 3-inch and 10-inch photomultiplier tubes both from Hamamatsu and Photonis have been tested to compare the quantum efficiency of standard bialkali photocathodes and enhanced ones. While mostly the manufacturers' claims have been met, variations in sensitivity due to the manufacturing process are clearly visible in the measurements presented. This result emphasises the need to characterise all PMTs that will be used for the construction of the detector.

IX. Acknowledgements

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