Status of the PMT development for KM3NeT

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Abstract

KM3NeT is a future large volume (multi km^3) neutrino telescope to be constructed at the bottom of the Mediterranean Sea. The detection volume will be instrumented using multi-PMT optical modules, consisting of an array of small photomultipliers housed in a spheric glass vessel. Three companies are presently developing three-inch PMTs as candidates for the construction of these modules. Main characteristics of the prototypes, such as quantum efficiency, single electron gain, dark current and transit time spread, are required to meet the specification established by the KM3NeT consortium.

We report on the current stage of PMT development and recent results of tests performed at the Erlangen Centre for Astroparticle Physics.

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1. Introduction

One of the main goals of neutrino astronomy is the exploration of the sources and acceleration mechanisms of high energy cosmic particles. Being uncharged and thus not deflected by magnetic fields neutrinos are natural messengers for this task. Neutrinos having energies between 10^{11} eV and 10^{16} eV can be detected indirectly via Cherenkov light emission of their secondary particles such as muons passing through water. To assure reasonable flux rates the volume equipped with photosensors has to be of the order of a few km^3.

The building of such a telescope in the Mediterranean Sea is the aim the KM3NeT project. The optical sensors will consist of an array of three inch photomultipliers (PMTs) housed in 17 inch glass spheres, the “multi-PMT” optical modules, which were found to have several advantages compared to the “conventional” single PMT optical module layout, including an increase of sensitive area per optical module and a larger angle of signal acceptance. Moreover, a multi-PMT equipped optical module can derive the amount of incoming photons from the number of hit PMTs, rather than from the signal waveform, leading to significantly improved ability of photon counting.

At present, eligible PMT prototypes are produced by ET Enterprises (D783FL) and Hamamatsu (R6233-01MOD). Another possible candidate is under development by a company named MELZ. A batch of 50 to 100 PMTs was ordered from each manufacturer. Their characteristics are being tested by NIKHEF and ECAP with respect to the requirements formulated in the KM3NeT Technical Design Report [1] (see table 1). Recent results of tests performed at NIKHEF can be found in this issue [4].

Table 1: Selected minimum quality standards of PMT properties required for KM3NeT multi-PMT optical modules [1].

quantum efficiency (at 470 nm)	$\geq 20\,\%$	supply voltage	< 1400 V
transit time spread	< 2 ns	dark rate	< 3 kHz
gain	$> 5 \cdot 10^6$	length	< 12 cm

In the following sections, we present the latest results from measurements of key PMT properties based on the examination of 50 R6233-01MOD PMT prototypes which was carried out at a specially developed test stand in Erlangen.

2. Quantum efficiency

Quantum efficiency was measured in DC photocurrent mode. Light provided by a Xenon lamp was guided through a monochromator to the photocathode of a PMT. In order to avoid saturation effects of the cathode material, neutral density filters were applied to adjust light intensity. In the wavelength interval between 280 nm and 340 nm white stray light was suppressed by colour filters. The produced photocurrent was recorded using a picoamperemeter in the wavelength range (280 nm $< \lambda <$ 700 nm) and calibrated using a photodiode of known quantum efficiency (S6337-01 by Hamamatsu) resulting in a characteristic quantum efficiency spectrum of the PMT. Aiming at the contribution of the photocathode only, all dynodes were tied to the same potential using a specially adapted base. A potential difference of 360 V was established between photocathode and the dynodes. According to earlier analyses

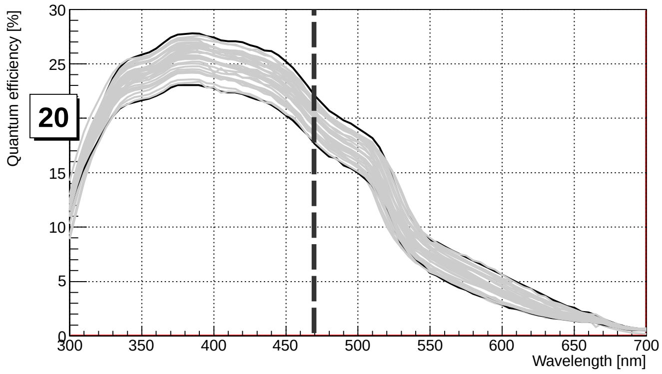

Figure 1: Quantum efficiency spectra for analysed PMTs. The spectral shape is characteristic for bialkali photocathodes. Photomultipliers having a quantum efficiency of 20 % or higher at a wavelength 470 nm (indicated by dashed line) are suited for use in mult-PMT optical modules.

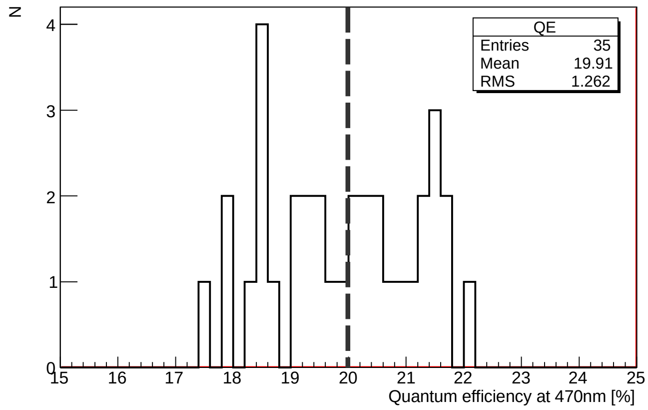

Figure 2: Distribution of quantum efficiency measured for PMT type R6233-01MOD. PMTs showing values higher than 20 % (to the right of the dashed line) fulfil the KM3NeT quality requirements for the use in multi-PMT optical modules.

this technique leads to typical measurement uncertainties in quantum efficiency of the order of 1 %. For detailed information concerning the test bench set-up and a discussion of precision achieved, see [2, 3] .

Quantum efficiency spectra for 35 presently analysed PMTs are shown in figure 1. Some 51 % of the analysed prototype sample were found to have a quantum efficiency of 20 % or higher at the wavelength of interest ($\lambda = 470$ nm), whereas $\sim$ 49 % showed a poorer performance (see figure 2). This result demonstrates that the design of R6233-01MOD is in principle capable of meeting the requirements of the Technical Design Report, however the quantum efficiency performance has to be improved.

3. Gain

To measure the signal amplification (gain) the PMT was illuminated homogeneously at the single photoelectron level using a sub-nanosecond pulsed LED (PLS 450) in combination with

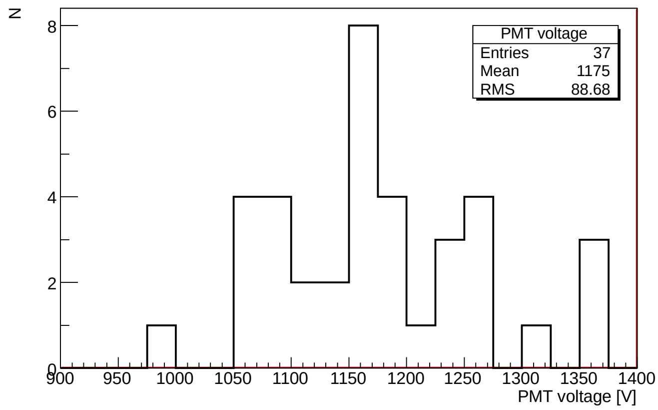

Figure 3: Distribution of PMT voltages needed to achieve a gain of $5 \cdot 10^6$. The values are shown for a sub-sample of the analysed PMT prototypes. To meet the requirements of the KM3NeT Consortium, the applied voltages have to be lower than 1400 V, which is true for all PMTs analysed yet.

a PicoQuant PDL 800 B picosecond pulsed LED driver. The pulses have a centroid wavelength of 460 ± 10 nm . The pulse width (FWHM) was typically between 800 ps and 900 ps, corresponding to the timing uncertainty. The output signal was amplified by factor 10. The PMT signal voltage waveform was recorded by means of a digital oscilloscope (LeCroy waveRunner 6100). The achieved timing precision made it possible to use the same waveforms for time resolution analyses (see section 4).

Data processing involved the estimation of signal pulse position and (base) width. For this purpose all recorded waveforms were added. The width was found to be in the range 50 ns to 60 ns. The voltage signals contained in this range were converted to current taking into account the load resistor of the oscilloscope ($R = 50\,\Omega$) and integrated to obtain a charge distribution of the output pulses. The resulting distribution was fitted using a convolution of several Gaussians (for details see [5]). The gain was determined by:

$$gain = \frac{Q_{1\text{phe}} - Q_{\text{ped}}}{A \cdot e} \tag{1}$$

where e is the electron charge and $A = 10$ the applied amplification factor. $Q_{1\text{phe}}$ and Q_{ped} are the positions of single photoelectron peak and the pedestal, respectively.

Gain values were typically determined for PMT voltages ranging from 1000 V to 1400 V. In this voltage range the gain was found to be of the order of several 10^6. Also none of the applied PMT voltages exceeded the permitted maximum of 1400 V. A summary of the obtained results can be found in figure 3. The displayed distribution features PMT supply voltages needed to achieve a gain of $5 \cdot 10^6$. The values were obtained interpolating an exponential fit of the measured gain as a function of utilised PMT voltage. As can be seen from the plot, the TDR specifications (gain higher than $5 \cdot 10^6$ at voltages lower than 1400 V) were met by all PMTs so far analysed.

4. Time resolution

A measure of the time resolution achieved by a PMT is given by the transit time spread (TTS) of the electrons. The term transit time, as used in this work, is defined as the time interval between the emission of an electron at the photocathode and and its detection at the anode (see also [3]). TTS measurement relied on the same raw data as the measurement of single photoelectron gain. The technique of data acquisition is described in section 3. The charge distribution derived from recorded signal waveforms was utilised to define a voltage amplitude threshold corresponding to a ~ 0.3 photoelectron input level. Application of the cut-off resulted in a distribution of signal arrival times. The FWHM values of the main peak of this distribution were used as TTS. The results of the measurements are summarised in figure 4.

The TTS criterion for PMTs was specified in order not to corrupt the overall timing precision of the muon reconstruction. Intrinsic uncertainties originate in the maximum achievable precision of positioning (approximately 20-40 cm , corresponding to 1-2 ns in timing) as well as the light dispersion in water for a typical light travelling distance of 50 m ($\sim$ 2 ns). As a result, the time resolution of PMTs must be $\sigma \leq 2$ ns or FWHM $\lesssim 4.6$ ns [1].

As can be seen in figure 4, only one of the tested PMTs actually fulfilled the standard imposed by the TDR. Yet, the achieved values are not much worse than the limit, making R6233-01MOD suitable for utilisation in prototypes of multi-PMT optical modules. Based on the fact that the tested model is only a simple modification of the high-TTS type R6233 there may still be capacities for improvements. A better performance appears realistic given further development of the design.

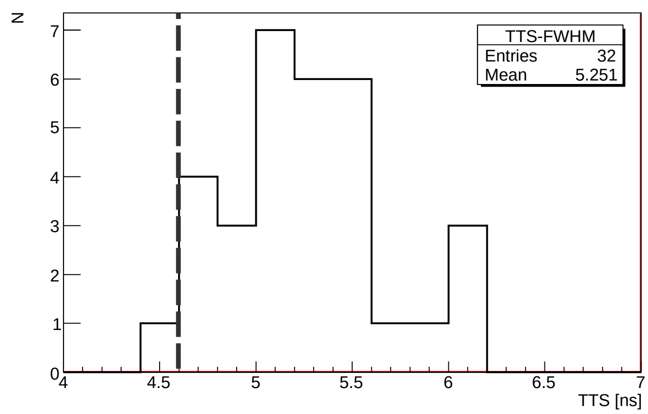

Figure 4: FWHM values of the signal arrival time distribution for Hamamatsu R6233-01MOD. The upper TTS limit of 2 ns demanded by the KM3NeT Technical Design Report corresponds to a FWHM of ≈ 4.6 ns, marked by a dashed line in the histogram.

5. Dark rate

The determination of the dark count and the after-pulsing behaviour was scheduled after the measurements of gain and time resolution. Consequently the PMTs were typically kept in a light-isolated environment for one to three days before being tested. A counting signal was generated by a discriminator whenever the resulting anode voltage exceeded a predefined threshold roughly corresponding to a ~ 0.3 photoelectron input level. As a first lower estimate, the dark current frequency was calculated from the number of triggered events per minute. A more realistic value can be derived from the analysis of the corresponding signal waveforms, recorded using a digital oscilloscope. The waveforms covered a time interval of 8 μs to detect potential after-pulses.The after-pulsing analysis will be performed later and published after completion. Applied PMT voltages corresponded to the ranges of the gain measurement (see section 3).

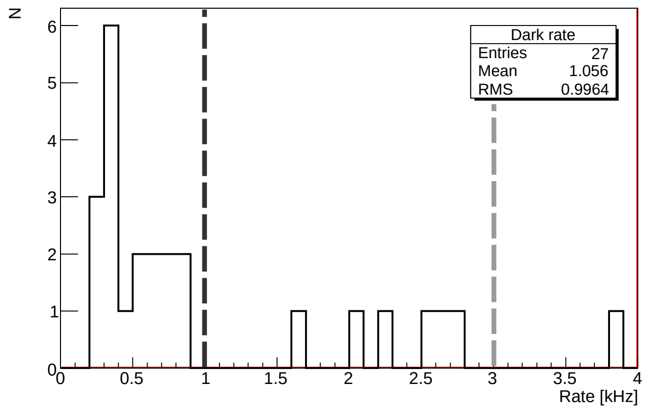

Figure 5: Distribution of dark rates obtained at PMT supply voltages corresponding to a gain value of $5 \cdot 10^6$. Rates below 3 kHz are in agreement with original TDR standards (light dashed line). Meanwhile, the dark rate requirements have developed towards a value of ~1 kHz, marked by the dark dashed line.

In first analyses for most PMTs the dark rate was determined to be lower than 1 kHz in the voltage range of interest, corresponding to a signal gain of $5 \cdot 10^6$ (see figure 5). These values are in very good agreement with the TDR requirements. Few PMTs featured higher rates. As these copies usually had earlier serial numbers, the problem might have been solved in the ongoing development process. As all measurements were performed at room temperature, the operation at more realistic temperatures ($\sim 14°$C) will lead to a slight decrease of the dark count rate.

6. Outlook

The tests carried out at the Erlangen Centre for Astroparticle Physics have shown R6233-01MOD to be a good, but not yet perfect candidate for the construction of multi-PMT optical modules.

In the current configuration the prototypes properly fulfil the quality requirements concerning the signal gain and the maximum supply voltage, as well as the tolerable maximum dark rate. The data recorded to determine the latter will be further analysed for the after-pulsing behaviour. The publication of the results is in preparation.

Quantum efficiencies of the tested PMTs showed a distribution around the required value with slightly more than one half meeting the KM3NeT TDR specification. This allows us to feel optimistic that the R6233-01MOD PMT could meet these elements of the KM3NeT specification with further improvement. In spite of the unfavourable behaviour of the basic R6233 model, the transit time spread was found to be of the order of few nanoseconds. Nevertheless the limit of FWHM $\lesssim$ 4.6 ns was not met by any PMT from the analysed sample.

In the near future this problem may however be solved by a new 80 mm diameter PMT by Hamamatsu (R12199), presently in the final stages of development. One of the major changes is the modification of the box and linear-focused dynode structure, as used in the currently tested type, promising improved time resolution.

In the meantime three first prototypes of the new PMT model were delivered. The test program commenced in January 2012. Results of the testing will be published elsewhere as soon as available.

Aknowledgements

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