Study on 3-inch Hamamatsu photomultipliers

Valentina Giordano[a], Sebastiano Aiello, and Emanuele Leonora on behalf of the KM3NeT Collaboration

INFN Sezione di Catania, via Santa Sofia 64, 95125 Catania, Italy

Abstract. Several kinds of photomultipliers are widely used in astroparticle physics detectors to measure Cherenkov light in media like water or ice. In neutrino telescopes the key element of the detector is the optical module, which consists of one or more photodetectors inside a transparent pressure-resistant glass sphere. It serves as mechanical protection while ensuring good light transmission. The KM3NeT collaboration has developed an innovative design of an optical module composed by 31 photomultipliers (PMTs) of 3-inch diameter housed in a 17-inch glass shpere. The performance of the telescope is largely dependent on the presence on noise pulses present on the anode of the photomultipliers. A study was conducted of noise pulses of Hamamatsu 3-inch diameter photomultipliers measuring time and charge distributions of dark pulses, pre-pulses, delayed pulses and after-pulses, focusing in particular on analysis on multiple afterpulses. Effects of the Earth's magnetic field on 3-inch PMTs were also studied.

1. Introduction

The KM3NeT Observatory [1] is a large scale neutrino telescope to be built in the deep waters of the Mediterranean Sea. With several cubic kilometres instrumented with thousands of optical sensors, KM3NeT will be the largest and most sensitive high energy neutrino detector. In neutrino telescopes the key element of the detector is the optical module (OM), which consists of one or more photomultipliers (PMTs) stored inside a transparent pressure-resistant glass sphere that serves as mechanical protection while ensuring good light transmission. The final configuration of KM3NeT neutrino telescope in Italian site of Capopassero will be hybrid, with 8 towers instrumented with large area PMTs of 10-inch diameter and 24 strings instrumented with 3-inch diameter PMTs. Concerning the strings; the KM3NeT collaboration has developed an innovative design of an optical module composed by 31 PMTs of 3-inch diameter and the readout electronics housed together in a 17-inch glass sphere looking downwards and upwards. This is called Digital Optical Module (DOM). After the successful experience of the NEMO project, in November 2014 the first KM3NeT tower with large area PMTs has been deployed in the test-site at 3500 m depth offshore the coast of Portopalo di Capopassero in Sicily (Italy) and this is now in taking data. The performance of the telescope is largely dependent on the main properties of the PMTs and on the presence of noise pulses on their anode. In order to investigate the DOM performance, a complete study was conducted on noise pulses of 3-inch diameter 10-stages R12199-02 bialkali photocathode PMTs produced by Hamamatsu. We have measured time and charge distributions of dark pulses, pre-pulses, delayed pulses and afterpulses, focusing also on the analysis of multiple afterpulses. For all projects where the orientation of the PMTs is critical, the variations in

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[a] e-mail: `valentina.giordano@ct.infn.it`

their performance due to Earth's magnetic field must be investigated. Indeed the performance of a PMT could be subject to significant variation due to magnetic fields. Detection efficiency, Transit time spread (TTS) and gain were measured simultaneously while varying the PMT's orientations with respect to the Earth's magnetic field, both with and without a mu-metal cage as magnetic shielding.

2. Noise and spurious pulses measurements

Noise pulses can be defined as anode output pulses that are not the response of the photomultiplier to a light event detected by the photocathode. They often disturb accurate measurements of low-level signals, degrade energy measurements and causes errors in pulse counting applications. We will distinguish dark pulses from spurious pulses. Dark pulses are random pulses that can be measured at the anode of a photomultiplier even in total darkness.

Spurious pulses are instead noise pulses time-correlated with the main PMT response to detected light events, because they can be early or delayed by a characteristic time with respect to the electron transit time through the PMT. Spurious pulses are the pre-pulses (a pulses in time that ranges between 80 ns and 10 ns before the main temporal position), the delayed pulses (pulses delayed in time from 10 ns to 80 ns after the main temporal position) and the afterpulses (noise pulses that appear following the main PMT response to a detected light event). Pre-pulses and delayed are present in place of the main pulse while afterpulses follow it.

The PMT under test was located in a light-tight dark box in order to shield it from the environmental light. This box was made in opaque black plexiglass, to avoid internal reflection of the light coming from the calibrated light source. This was a pulsed laser with a laser head of 410 nm and a width of 60 ps, attenuated to a single photoelectron (spe) condition, 3 photoelectron (pe) condition and 5 pe condition. The laser source was located outside the box, and the light pulses were guided inside the box by means of a multimode optical fiber coupled to the laser head. All measurements were carried out at room temperature and atmospheric pressure, with the PMT powered by a passive base made by the ECAP-Erlangen team of KM3NeT collaboration. In order to set the signals and acquire the data, NIM electronics, time to amplitude converters and analog charge amplitude converter were used. A digital oscilloscope was also used to digitize the PMT signals during multiple after pulses measurements. The dark count rate was measured using a NIM counter, with a threshold set to 1/3 of the spe amplitude. The first batch of 20 PMTs under study shows the following characteristics. Without laser, the dark rate counts found was about 1 kHz after 12 hours in the dark. In Fig. 1(a) the typical charge spectrum distribution for a 3-inch PMT in spe condition at a gain of $5 \cdot 10^6$ is shown. The first peak is the pedestal due to electronic noise without signal, while the second one is the spe peak. The peak to valley ratio P/V was measured as the ratio of the number of events of the spe peak and the number of events of the region of the valley in each spe charge spectrum and has a mean value of about 3 for the first batch of PMTs tested. The time distributions show a median value of 4 ns (full width half maximum FWHM) in TTS in spe (blue line on Fig. 1(b)) and typical fractions on spurious pulses of 0.1% for pre-pulses, 5% for delayed and 6% of afterpulses. Increasing the laser intensity in order to change the PMT response condition from 1 pe to 3 pe and 5 pe the TTS decreased from 4 ns to 3 ns and 2.8 ns as seen in Fig. 1(b). Moreover fractions of pre-pulses and delayed pulses became lower as shown on Fig. 1(b): indeed pre-pulses vary from 0.3% to 0.01% until 0.002% going from 1 pe condition to 3 pe and 5 pe condition. The delayed pulses vary from 6.40% to 1.14% until 0.47% going from 1 pe condition to 3 pe and 5 pe condition. Concerning afterpulses (AP), we have to distinguish the first type of
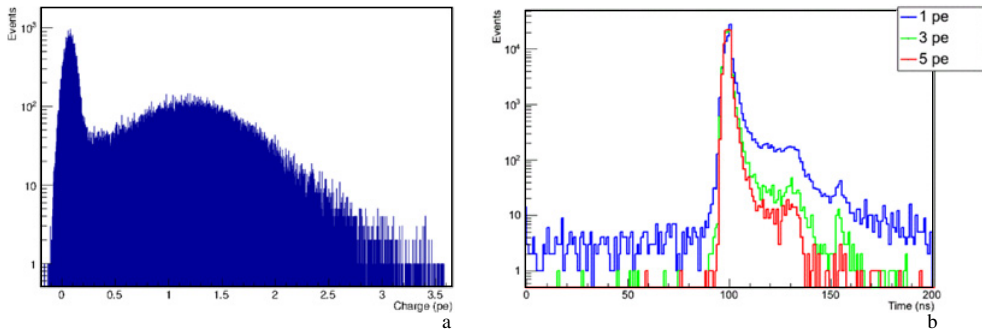
Figure 1. (a) Charge spectrum of a 3-inch PMT at a gain of $5 \cdot 10^6$. (b) Transit Time Distribution at different PMT response condition: blue line for spe, green line for 3 pe and red line for 5 pe. Main pulse is at about 100 ns; pre-pulses ranges from 20 ns until 90 ns a nd delayed from 110 ns to 190 ns.
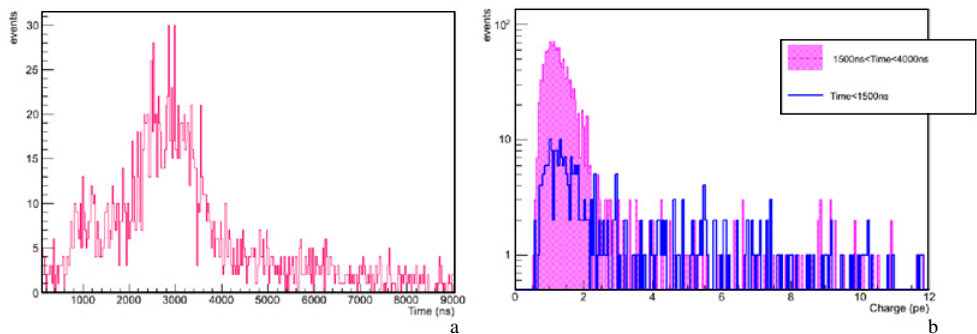

Figure 2. (a) Typical time distribution of type 2 after pulses. (b) Charge distribution of after pulses for two different time ranges. In magenta area there is CH_4 (arrival time lower than $1.5 \mu s$) while in blue there is Cs (with arrival time between $1.5 \mu s$ and $4 \mu s$).

afterpulses (AP1) that ranges from 10 to 80 ns after the main pulses and the afterpulses type 2 (AP2) that ranges from 80 ns until $5 \mu s$ after the main pulse. For the first batch of PMTs, we measured a mean value of 0.1% of AP1 and 4% of AP2. AP1 are mainly of spe in the charge spectrum. AP2 can consist of several pulses. The majority of AP2 events consist of single pulse with a fraction of 3.81% and a mean charge per pulse of 1.2 pe. We measured 2 AP2 with a percentage of 0.25%, 3 AP2 with 0.07% and 4 AP2 with 0.02%. For multiple AP2 the mean charge per pulse is about 1.2 pe. The mean charge per AP2 is lower than that found for large area 10-inch PMTs used for KM3NeT tower construction [2]. The AP2 are due mainly to residual gases during the construction of the PMT. Looking at the time distribution in Fig. 2(a) we can see that there are two major components that are associated to CH_4^+ ions (at $1 \mu s$) and Cs^+ ions (at $3 \mu s$). In 10-inch PMTs we pointed out that the CH_4^+ peak had more charge per AP2 in confront of the Cs^+ peak [2]. For 3-inch PMTs this effect is present, even if less highlighted, as shown on bidimensional plot on Fig. 2(b) where Cs peak is mainly of spe instead of CH_4 peak that has an higher charge component.

3. Influence of the Earth's magnetic field

Laboratory tests have shown that an ambient magnetic field with a value of 44 μTesla (the Mediterranean Sea zone) could degrade significantly timing and charge characteristics on

Table 1. Gain Measurements.

Gain	$\Phi = 90°$		$\Phi = -50°$		$\Phi = 50°$	
	naked	shielded	naked	shielded	naked	shielded
Minimum Value [10^6]	4.59	4.75	4.67	4.77	4.63	4.77
Maximum Value [10^6]	4.72	4.83	4.91	4.86	4.80	4.90
Average Value [10^6]	4.67	4.78	4.83	4.81	4.72	4.82
Maximum Variation [%]	2.98	1.62	5.10	1.79	4.10	2.83

Table 2. Relative Detection Efficiency Measurements.

Rel. Detection Eff.	$\Phi = 90°$		$\Phi = -50°$		$\Phi = 50°$	
	naked	shielded	naked	shielded	naked	shielded
Minimum Value [10^{-3}]	11.86	12.34	12.34	12.34	12.34	11.90
Maximum Value [10^{-3}]	13.28	13.17	15.22	13.17	13.11	13.20
Average Value [10^{-3}]	12.58	12.36	14.17	12.67	12.35	12.48
Maximum Variation [%]	11.93	6.76	23.30	6.75	11.90	11.10

Table 3. Transit Time Spread Measurements.

TTS FWHM (ns)	$\Phi = 90°$		$\Phi = -50°$		$\Phi = 50°$	
	naked	shielded	naked	shielded	naked	shielded
Minimum Value (ns)	3.638	3.550	3.632	3.525	3.578	3.492
Maximum Value (ns)	3.785	3.610	3.753	3.577	3.866	3.667
Average Value (ns)	3.725	3.576	3.713	3.550	3.708	3.591
Maximum Variation [%]	4.04	1.69	3.30	1.49	8.10	5.01

large area PMTs [3]. Magnetic shielding is thus largely used to reduce magnetic effects and make the response of the PMT sufficiently orientation independent. Since PMTs are installed into an underwater neutrino telescope, they can change their orientation because of the movements of the detector structure due to sea currents so the influence of Earth's magnetic field should be investigated. We tested two 3-inch PMTs R12199-02. In order to characterize the PMT response to an injected light source while varying its orientation relative to the Earth's magnetic field, a light-tight dark box able to rotate with respect to vertical axes (step of 1°) and to change its inclination (step of 10°) was constructed.It is possible to shield a 3-inch PMTs against the magnetic field using a passive magnetic shield. The shield studied in this work was a wire cage, made of 1 mm diameter wire of mu-metal, a nickel-iron alloy with very high magnetic permeability 10^5. The used cage was composed of two parts. A hemispherical part which surrounds the entire PMT and a flat part. The pitch of the grid was $(68 \cdot 68)$ mm, giving a shadow effect on the photocathode less than 1%. The reduction factor of the magnetic field inside the cage is about 4. In order to compare results obtained in the different photomultipliers, each PMT started its rotation from the same position with respect to the box and to the Earth's magnetic field.

Both PMTs were measured in three inclinations of the box: horizontally oriented ($\Phi = 90°$), 50° downwards and 50° upwards. For each inclination, the PMT under test was rotated of 360° in step of 45°. All measurements were made first with the PMTs un-shielded and then repeated with the mu-metal magnetic shield. The Tables 1, 2 and 3 summarize the main measurements. For all sets of measured parameters the minimum, maximum, average values and maximum variation (($max.value - minvalue)/min.value$) are given for the unshielded and shielded condition of the PMT. Gain and TTS measurements in Tables 1 and 3 don't show high variations in the two PMTs while the detection efficiency (defined as the ratio between the number of detected pulses and those emitted by the laser) in Table 2 seems to be a parameter with higher variation between shielded and un-shielded condition.

The same measurements were performed on 10-inch PMTs used for KM3NeT tower and the larger nvariations from un-shielded to shielded condition, required to use the mu-metal cage in the optical module construction [3]. For the DOM this constraint does not seem to be so crucial since the magnetic effects are lower.

4. Conclusion

A large study was conducted on 3-inch bialkali photocathode R12209-02 PMTs produced by Hamamatsu in order to measure time and charge distributions of noise pulses and the variations of the PMTs performances with the Eart's magnetic field. In the study of spurious pulses the laser was regulated at different response of the PMT: spe, 3 pe and 5 pe. Concerning dark pulses, they correspond mainly to single photoelectron pulses with typical rates of 1 kHz. Pre-pulses have a random distribution before the main pulses, in a range of 10–80 ns, and they have an average charge per pulse lower than that of the main PMT response. Their fraction is usually very small, less than 1% in spe and this fraction decreases when the number of photoelectrons per light pulse increases. The average charge per pulse measured corresponds mainly to single photoelectrons in 1 pe condition and about 2 pe and 4 pe in 3 pe and 5 pe PMT conditions. Their typical fraction is about 6%, and this fraction decreases when the number of photoelectrons per light pulse increases. The measurements of afterpulses show fractions of about 0.11% for type 1 after pulses and of 4% for type 2. The time distribution of type 2 after pulses shows a peak at around 1 μs presumably produced by CH_4 ions and another peak around 3 μs presumably produced by Cs ions. The last measurements done on 3-inch PMTs deal with the influences of the Earth's magnetic field. The maximum variations are not so high for TTS (8.1%) and gain (4.1%) changing from shielded to un-shielded measurements, but cause an higher effect on detection efficiency it causes an higher effect. Given the moderate size of performance variation, KM3NeT has chosen to not use the mu-metal shielding.

References

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