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Multi-PMT optical module for the KM3NeT neutrino telescope

O. Kavatsyuk*, Q. Dorosti-Hasankiadeh, H. Löhner

KVI, University of Groningen, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands

on behalf of the KM3NeT Consortium

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ABSTRACT

The future cubic kilometre scale neutrino telescope KM3NeT will employ a novel type of a Digital Optical Module (DOM), developed during the recent FP6 Design Study. A pressure-resistant glass sphere hosts 31 photomultiplier tubes (PMTs) of 3-in. diameter, together with all the electronics for high-voltage generation and signal readout. The optical module forms a complete stand-alone detector that is connected to the outside world via a single optical fibre and two copper conductors providing electrical power. The advantages of using multiple small PMTs in the same DOM are the higher quantum efficiency ($>30\%$ expected), smaller transit time spread, better two-photon separation capability and directional sensitivity. Moreover, a longer operating lifetime is expected than for large PMTs due to the accumulation of less charge on the anode. In addition, small PMTs are insensitive to the Earth's magnetic field and do not require μ-metal shielding. In order to maximise the detector sensitivity, each PMT will be surrounded by an expansion cone collecting photons that would normally miss the photocathode. Such an expansion cone consists of an aluminium ring filled with silicone gel. An increase in the overall sensitivity, integrated over all angles of incidence, was estimated to be about 27%. Monte-Carlo simulations have shown that a detector configuration with multi-PMT DOMs requires three times less OMs to achieve the same performance as conventional OMs hosting 10-in. PMTs. Prototype DOMs are currently being built by the KM3NeT consortium.

1. Introduction

KM3NeT is a future European research facility in the Mediterranean Sea that will house a neutrino telescope of cubic kilometre scale. Cherenkov light from neutrino-induced secondary particles will be detected by an array of Digital Optical Modules (DOMs). The DOM is a high-pressure resistant glass sphere containing an array of photomultiplier tubes (PMTs). KM3NeT aims at an angular resolution better than 0.3° for neutrino energies above a few TeV necessary to identify possible discrete neutrino sources. Therefore, accurate measurements of the light arrival times and amplitudes are required. These, together with a precise knowledge in real time of the positions and orientations of the photo-sensors, are mandatory to reconstruct direction and energy of the high-energy cosmic neutrinos. To realise the instrumentation of a volume of sea water of several cubic kilometres the KM3NeT consortium has undertaken a design study [1] financially supported by the FP6 framework of the EU. In the framework of the KM3NeT design study different options for the optical modules were considered.

* Corresponding author. Tel.: +31 503633617; fax: +31 503634003.
E-mail address: o.kavatsyuk@rug.nl (O. Kavatsyuk).

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2. Advantages of the multi-PMT DOM

A novel multi-PMT DOM containing 31 3-in. PMTs, as an alternative to the conventional approach using one single 10-in. PMT, was chosen due to several advantages. First, the total photocathode area that can be fitted in a standard 17-in. diameter glass pressure sphere is significantly larger when using small PMTs. The segmentation of the detection area in the DOM will aid in distinguishing single-photon from multi-photon hits. Moreover, two-photon hits can be unambiguously recognised if the two photons are registered in separate tubes. For a homogeneous distribution of photon pairs arriving at the DOM from a particular direction this occurs with 85% probability. Small PMTs can offer a quantum efficiency above 30%, provide a small transit time spread, and do not require shielding from the Earth's magnetic field. Another advantage is that the loss of a single photomultiplier will only minimally degrade the performance of the DOM. Failure rates of small PMTs have been determined to be of the order of 10^{-4} per year [2]. The PMTs run at a gain of 10^6 and their individual photocathode area is small, therefore the integrated anode charge is small. The multi-PMT DOM is designed to reduce the number of connectors in the detector as much as possible. The objective of the multi-PMT DOM is to measure photons at the single-photon level.

3. Technical solution

The housing of the multi-PMT DOM is a transparent 17-in. glass sphere (VITROVEX glass, wall thickness 14 mm) built to withstand the ambient hydrostatic pressure in the range of 250–400 bar. The sphere is separated into two identical hemispheres and contains the PMTs, front-end and readout electronics. The PMTs are suspended in a foam support structure: 19 in the lower hemisphere and 12 in the upper hemisphere (Fig. 1).

The centre of the front face of the PMT is placed 4 mm from the inner surface of the glass sphere. Optical gel fills the cavity between the foam support and the glass in order to assure optical contact. The foam support and the gel are sufficiently flexible to allow for the deformation of the glass sphere under the hydrostatic pressure.

Each PMT has its own adjustable high-voltage supply [4], and electronic circuit providing an extra amplification of the PMT signal. Each hemisphere has a signal-collection (printed circuit) board that collects signals from the PMTs to transfer to the DOM-logic board [5]. The DOM-logic board converts the electronic signals from the PMTs to time, amplitude and identification information. It also contains electronic and photonic components for an optical serial link to the shore.

A mushroom-shaped aluminium structure transfers the heat generated by the DOM electronics via the glass sphere to the seawater. The power consumption of the module is kept within 7 W. The outer connector is a dry mateable bulkhead connector that penetrates the glass sphere and allows for two power conductors and one fibre to be connected to the high-pressure oil-filled inter-storey cable. In Fig. 1a photograph of the mechanical reference model of the multi-PMT DOM is shown together with a cross-section drawing (Fig. 1, right).

Currently a few major PMT producers are developing a dedicated PMT type to meet the KM3NeT requirements. Among those is an overall length limitation set by the space available in the glass sphere and the curvature of the photocathode area. The concave inner surface of the photocathode area is required to achieve appropriate timing, whereas the outer convex surface must match the curvature of the inner surface of the glass sphere. A PMT chosen for the DOM should have a diameter of 76 mm, a length of less than 122 mm incorporating a 10-stage dynode structure with a minimum gain of 10^6.

The performance specifications for the PMT are summarised in Table 1. Recently, first batches of new PMT types were received by the consortium (detailed results of the tests are the subject of a contribution [6] to this conference).

The geometrical layout of the PMTs in the optical module is shown in Fig. 1. Table 2 gives the directions in which the axes of the PMTs point.

For accurate muon reconstruction, it is necessary to know PMT positions with an accuracy of the order of 10 cm, and for this a position calibration system is required. The multi-PMT DOM contains three calibration devices. They are

- The compass-tiltmeter incorporated on the storey logic board (to measure the orientation of each storey).
- The acoustic piezo sensor glued to the inner surface of the glass sphere and its electronics incorporated on an extension board.

Table 1
Specifications for PMTs for the multi-PMT DOM.

Cathode (CsK) quantum efficiency	$>32\%$ at 404 nm
	$>20\%$ at 470 nm
Inhomogeneity of cathode response	$<10\%$
Supply voltage	<1400 V
Dark count rate[a]	<3 kHz at 15 °C
Transit time spread	<2 ns (σ)
Peak-to-valley ratio	>3
Operation temperature	10–25 °C

[a] For a threshold of 0.3 SPE.

Table 2
Orientation of the PMTs within the multi-PMT DOM. The positive z-axis points upward [2].

θ	ϕ					
50	30	90	150	210	270	330
65	0	60	120	180	240	300
115	30	90	150	210	270	330
130	0	60	120	180	240	300
147	30	90	150	210	270	330
180	0					

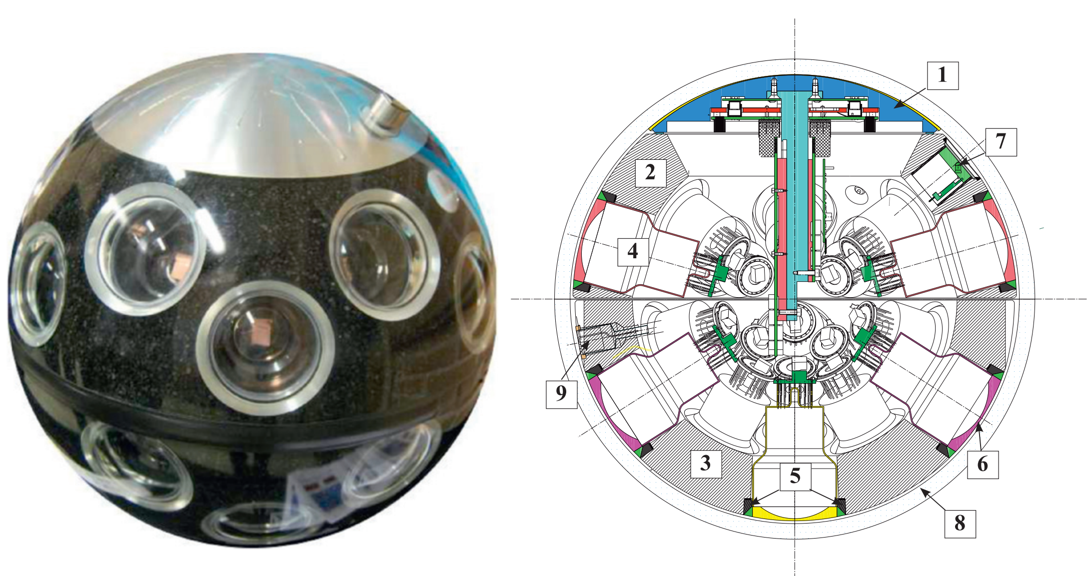

Fig. 1. *Left*: a mechanical reference model of a multi-PMT DOM. Prototype of the MultiPMT optical module. *Right*: cross-section of a multi-PMT DOM [3]. Numbers refer to: (1) heat conductor, (2,3) foam cores, (4) PMT with PMT base, (5) expansion cone, (6) optical coupler, (7) nanobeacon, (8) glass sphere, (9) piezo element.

- The nanobeacon, a compact low-cost nanosecond light flasher, incorporated on an extension board. A multimode fibre runs from the LED to the glass and is oriented so as to illuminate the optical module vertically above.

The DOM positions are extracted by measuring the acoustic travel time between the transceiver signals from the long base-line reference array (anchored on the seabed) and the receivers on the DOMs.

4. Expansion cone to increase photo sensitivity

The dense packing constrains the space available for power supply and readout in the centre of the DOM. However, due to the tube design, extra space is available on the inner surface of the sphere, surrounding the cathode entrance window (Fig. 1). To exploit this extra space for light collection, a reflector (expansion cone) may be employed to guide additional light to the photocathode. For the Photonis XP53B20 PMT, that passed specification requirements of KM3NeT, the convex-shaped glass window has a thickness of about 9 mm at the circumference, leaving this height available for the entrance of light from the side. An expansion cone is made of silicon gel (Wacker 612) which is shaped and kept in place by an aluminium structure serving as reflector, shown in Figs. 2 and 3. The reflection of the 45-degree tilted surface was improved by silver evaporation.

The main idea behind such an expansion cone is demonstrated in Fig. 4. Each PMT in the DOM will be surrounded by an expansion cone designed to collect photons that would normally miss the photocathode, thus increasing the effective photocathode area.

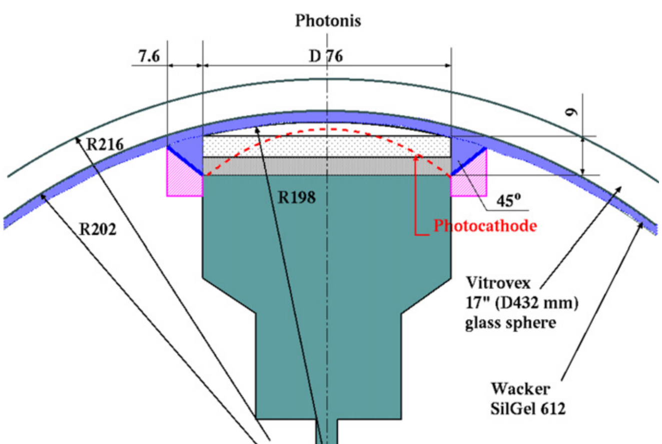

Fig. 2. Sketch of a PMT in the 17-in. glass sphere.

Fig. 3. Expansion cone mounted on a PMT.

In order to demonstrate potential benefit of using the expansion cone, measurements in air with a single PMT with an expansion cone mounted have been performed inside a light-tight box (DarkBox). As a light source a laser with wavelength $\lambda = 405$ nm and time jitter < 70 ps between trigger and pulse was used. Additionally, a variable neutral density filter was used to reach intensities of single photoelectrons (SPE) per pulse. The light from the laser was guided with a light-fibre inside the DarkBox and shone onto the entrance window.

A remote-controlled 2D scanning system allowed for precise measurements of the expansion cone performance with respect to position and angle of incidence. For every chosen angle of incidence, a horizontal scan of the collection efficiency was performed. To this end, a set of 32 points was measured on the line running horizontally across the photocathode through the centre of the PMT. For every measured combination of angle of incidence and position a charge spectrum was generated. In order to determine the relative collection efficiency, the number of events with a charge above 0.3 SPE out of a total number of laser shots was obtained for various points on the photocathode and angles of incidence. Measurements of reflectivity under various angles of incidence have been performed,

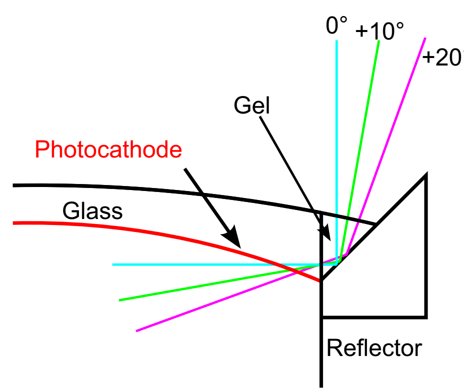

Fig. 4. The idea of light collection by an expansion cone. Positive angles of incidence are defined as indicated.

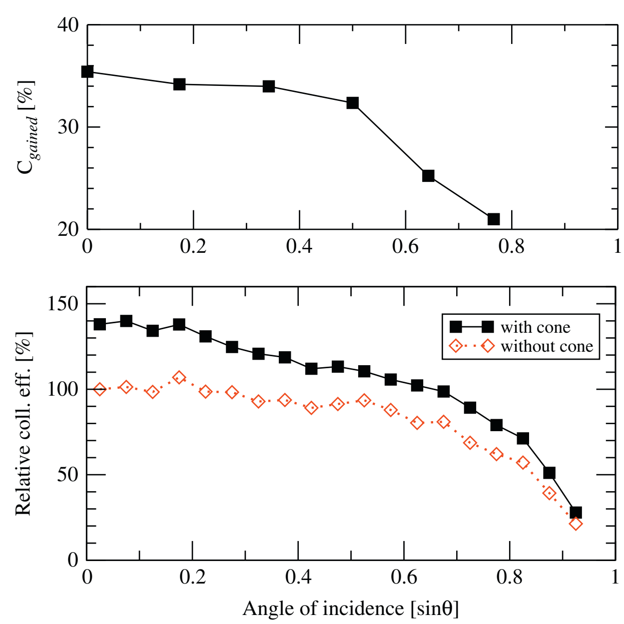

Fig. 5. Results of the measurements of collection efficiency under various angles of incidence (upper panel) compared to photon-propagation simulations (lower panel). Curves in the lower panel show the collection efficiency as a function of the angle of incidence for a single PMT with (filled squares) and without expansion cone (open diamonds), respectively. More details in text.

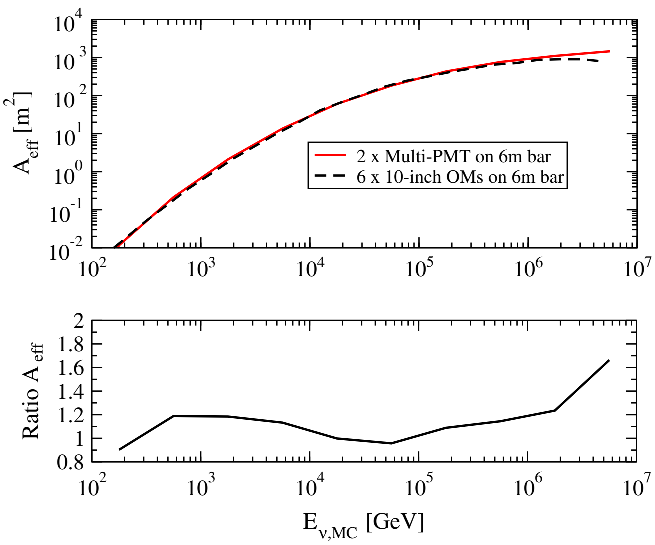

Fig. 6. Monte-Carlo generated effective area for neutrino detection as a function of the neutrino energy after full reconstruction for the KM3NeT design option with multi-PMT DOMs (solid curve) and with conventional OMs hosting 10-in. PMTs (dashed curve). The ratio of the curves in the upper panel is shown in the lower panel.

demonstrating an increase in collection efficiency by 30% on average for angles of incidence from -50° to $+45^\circ$, with a maximum of 35% for perpendicular incidence.

In order to estimate the benefit of the expansion cone, the gained collection efficiency C_{gained} was calculated as a ratio

$$C_{gained} = \frac{C_{PMT+Cone} - C_{PMT}}{C_{PMT}} \times 100\% \quad (1)$$

where $C_{PMT+Cone}$ and C_{PMT} are the collection efficiency of the system PMT+Cone and PMT, respectively. Results for various angles of incidence are presented in Fig. 5 (upper panel).

5. Simulation results and discussion

Ray-tracing calculations were performed by using SLitrani [7], a general purpose Monte-Carlo program simulating light propagation. Results for collection efficiency as a function of incident angle are shown in Fig. 5. These estimated the increase in overall sensitivity, integrated over all angles of incidence, of 27%.

Monte-Carlo simulations have shown that a detector configuration with multi-PMT DOMs requires three times less OMs to achieve the same performance as conventional OMs hosting 10-in. PMTs [8]. In Fig. 6 the improvement in effective area is presented compared to the design option with 10-in. PMTs obtained after a full reconstruction applying cuts for the maximum neutrino point-source sensitivity for a neutrino flux with an energy spectrum decreasing E_ν^{-2} with the neutrino energy E_ν. To enable a fair comparison, a so called reference detector was simulated with the same structure in both cases: 154 detection units (towers), 20 floors with 40 m spacing, and the same detector footprint. Each floor consists of a 6 m bar with two multi-PMT DOMs or six 10-in. PMTs. The distance between towers was set to 180 m. Moreover, the results of the ^{40}K background simulations indicate the possibility to reduce the trigger rate by about a factor five by exploiting coincidences between single PMTs in the same DOM [9]. All above mentioned advantages of the multi-PMT DOM make it an optimal solution not only for the KM3NeT neutrino telescope but also for other experiments based on single-photon registration. In the currently running Preparatory Phase prototypes and Pre-Production Models are being built.

Acknowledgements

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References

[1] KM3NeT Design Study for a Deep Sea Facility in the Mediterranean for Neutrino Astronomy and Associated Sciences, FP6 contract number 011937.
[2] KM3NeT Technical Design Report, ISBN 978-90-6488-033-9; 〈http://km3net.org/KM3NeT-TDR〉.
[3] Technical description of the PPM of the KM3NeT detection unit, 〈http://www.km3net.org/PPM/KM3NeT_FL_REP_PPM-description.pdf〉.
[4] P. Timmer, et al., Journal of Instrumentation 5 (2010) C12049. doi:10.1088/1748-0221/5/12/C12049.
[5] D. Gajanana, et al., Journal of Instrumentation 5 (2010) C12040. doi:10.1088/1748-0221/5/12/C12040.
[6] O. Kalekin, Photomultipliers for the KM3NeT optical modules, contribution to this conference.
[7] F.X. Gentit, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 486 (2002) 35. 〈http://gentitfx.fr/SLitrani〉.
[8] C. Kopper, private communication.
[9] B. Herold, private communication.