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Photomultipliers for the KM3NeT optical modules

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ABSTRACT

The KM3NeT project aims to construct a multi-cubic-kilometre scale neutrino telescope in the Mediterranean Sea. The telescope's detection units, deployed in the deep sea, will be instrumented with optical modules, each housing 31 three-in. photomultiplier tubes (PMTs). Three companies are developing new types of 3 in. PMTs for the KM3NeT project. The first PMT samples of type R6233mod have been delivered from Hamamatsu and tested at the Erlangen Centre for Astroparticle Physics and at Nikhef. The results of these tests are presented. Many of the parameters of the existing versions of these PMTs already meet the KM3NeT requirements and production versions will be used to build the first developmental optical modules. Hamamatsu have started the development of new versions of PMTs of current interest, with better timing parameters and a slightly larger photocathode. The first two examples of a new PMT from ET Enterprises are under tests at Nikhef. The delivery of first 82 mm diameter PMTs from MELZ is also expected in October 2011. To increase photodetection efficiency in the multi-PMT optical module, PMTs will be surrounded by reflective light gathering rings ('expansion cones'). Test results of such an assembly are also presented.

1. Introduction

A detailed description of the KM3NeT neutrino telescope is given in the KM3NeT Technical Design Report (TDR) [1]. It contained two main options for telescope optical modules (OM). One was a "classical" OM with a large 8 in. or 10 in. photomultiplier tube (PMT) in a 17 in. glass pressure sphere similar to OMs in the NEMO and NESTOR pilot projects and in the ANTARES deep sea neutrino telescope. The main alternative was a multi-PMT OM with 31 three-in. photomultipliers, which was chosen in January 2010 as the baseline for the final telescope design. One can find the technical specification of the multi-PMT OM in the KM3NeT TDR and in a contribution [4] to this conference.

2. PMTs

A few years ago, Photonis had designed a 3 in. XP53B20 PMT, which generally met the present KM3NeT specification:

- Quantum efficiency (QE) at 470 nm $>20\%$
- Inhomogeneity of photocathode response $<10\%$
- Effective photocatode size ≥ 76 mm diameter
- Supply voltage <1400 V
- Gain $>2\times 10^6$
- Dark count rate at 15 °C <3 kHz
- Transit time spread (TTS) <2 ns (sigma)
- Peak to valley ratio >3
- Length <12 cm
- Convex input window 198 mm radius

In 2009, Photonis terminated all PMT production. A subsequent review of the remaining 3 in. range of PMT types on the market showed that none fully met the KM3NeT specification. PMTs were not satisfactory either through geometrical size (ET Enterprises, 9822B – too long) or through inferior time resolution (Hamamatsu, R6233 and MELZ, FEU184TD – 6–8 ns TTS). All three companies agreed to develop new 3 in. PMTs to meet the requirements of KM3NeT. The main features of the new PMTs are high speed coupled with a compact dynode structure, and an input window adapted to the curvature of a 17 in. pressure sphere. Other improvements were to reduce center-to-edge-difference (CED) in transit times of photoelectrons from the concave photocathode to the first dynode.

The first three samples of the new R6233mod PMT (Fig. 1) were delivered from Hamamatsu in January 2011. Measurements of various parameters of these PMTs were performed at the Erlangen Centre for Astroparticle Physics and at Nikhef. The results are presented in the following section. The first two new

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Fig. 1. The new Hamamatsu R6233mod PMT.

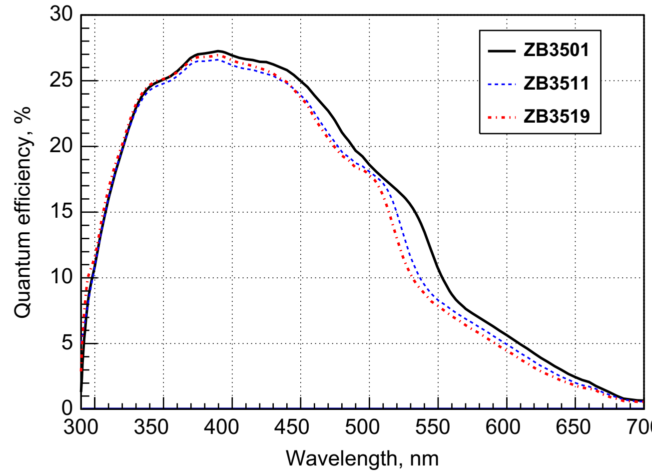

Fig. 2. Photocathode quantum efficiency of three examples of the new Hamamatsu R6233mod PMT.

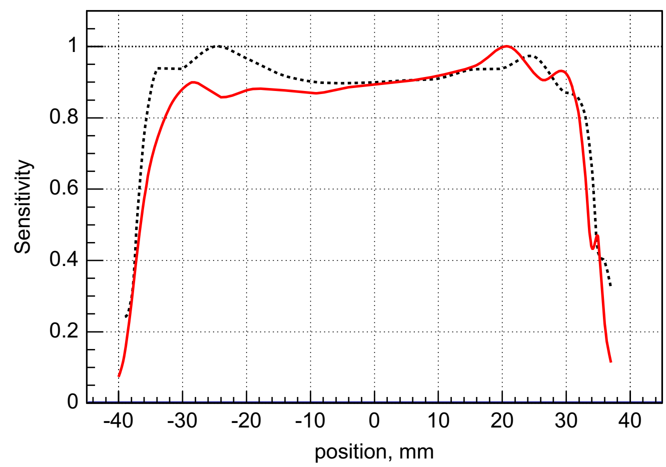

Fig. 3. Relative sensitivity of a Hamamatsu R6233mod PMT measured across the photocathode center in two perpendicular directions.

D783KFLA PMTs from ET Enterprises were delivered in June 2011. They are under tests at Nikhef. Results will be presented elsewhere. Delivery of new PMT prototypes from MELZ is expected in October 2011.

3. R6233mod: test results

3.1. Quantum efficiency

The method of QE measurement is described in detail in Refs. [2,3]. QE is measured in a DC mode. A nonpulsed Xenon lamp is used as a light source. Light from the lamp is focused on the input slit of the monochromator. A monochromator can extract a monochromatic light in a wavelength range of interest of 300–700 nm. Monochromatic light is guided to a black box, where the PMT to be tested is installed. The Dynode-to-Anode structure is shunted (all set to the same potential) and the typical recommended photocathode-to-first-dynode voltage increment is applied between the photocathode and the combined structure. A calibrated photodiode S6337-01 from Hamamatsu is used as a reference photodetector to provide an absolute calibration of PMTs by a comparison of detected photo-currents. Results of QE measurements for the Hamamatsu PR6233mod PMT are presented in Fig. 2. As expected, the quantum efficiency achieves 26–27% at maximum, typical for a standard bi-alkali photocathode. Hamamatsu is able to mass-produce only this type of photocathode in the quantities of 3 in. PMTs needed for KM3NeT. However, measured QE is relatively high ($\geq 20\%$) at 470 nm wavelength, at which water is the most transparent.

3.2. Photocathode inhomogeneity and effective size

To estimate the inhomogeneity of the photocathode deposition and the photocathode's effective area, the PMT surface was scanned with a pulsed light source. The results of such scans of the R6233mod PMT are presented in Fig. 3. Both scans were taken for the same PMT in two directions perpendicular to each other. For one scan total variation of sensitivity is $\sim 10\%$, for the other scan, it is $\sim 15\%$. The strong asymmetry of the solid curve (scan parallel to the dynode structure symmetry plane) and the symmetry of the curve for the perpendicular scan lead us to conclude that the variations are mainly due to different collection efficiency of photoelectrons on the first dynode from different positions on the photocathode.

Defining the effective photocathode radius as the radial position on the photocathode where the photodetection efficiency drops to 50% of its central or peak value, the effective diameter is ~ 71 mm for the scanned R6233mod PMT. This value is less than the 76 mm diameter specified by KM3NeT. An increase of the photocathode's effective area would be possible with the increase of PMT diameter to 3.5 in., proposed by KM3NeT, which would not exceed geometrical limitations of placement of the 31 PMTs in the 17-in. sphere.

3.3. Transit time spread

Hamamatsu specifies TTS of PMTs in terms of full width at half maximum (FWHM) of a signal's transit time distribution. According to Hamamatsu specification, this parameter is in a range of 5.8–6.8 ns for delivered PMTs, which corresponds to TTS $=$ 2.5–3.0 ns sigma, which is outside the required TTS of < 2.0 ns. Our measurements of this parameter shown in Fig. 4 confirmed these numbers. The main peak of the distribution characterizes the single photoelectron transit time jitter. In the presented measurement, it has a double-peak structure caused by electronics noise from the laser driver. This modulation does not change