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Design and Assembly of the Optical Modules for Phase-2 of the NEMO Project

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Abstract

The NEMO collaboration team has undertaken a Phase-2 project, which aims at the realization and installation of a new infrastructure at the Capo Passero (Italy) deep-sea site at a depth of 3500 m. With this objective in mind, a fully equipped tower with 8-storey hosting two optical modules at each end is under construction. Following a well established procedure, 32 optical modules have been assembled. The optical module consists of a large area photomultiplier tube enclosed in a pressure resistant glass sphere with a diameter of 13 inch. The photomultiplier is a R7081 type, produced by Hamamatsu, with a photocathode area with a diameter of 10 inch and 10 dynodes. Mechanical and optical contacts between the front of the photomultiplier tube and the glass surface is ensured by an optical bi-component silicone gel. A mu-metal cage is used to shield the photomultiplier against the influence of the Earth’s magnetic field.

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1. Introduction

At the end of Phase-1 of the NEMO project [1], which provided an important test of the technologies proposed for the construction and installation of an under-water neutrino detector, a Phase-2 project started, which aims at the development of a new infrastructure at the Capo Passero deep-sea site [1].

It consists of a shore station located in the harbour of Portopalo, near Capo Passero, a 100 km long electro-optical cable, linking the 3500 m deep-sea site to the shore, and the underwater infrastructures needed to connect the prototypes of the detection units of the detector. For deployment on this site, a fully equipped tower with 8-storey hosting two Optical Modules (OMs) at each end (4 OMs per storey) is under construction. The design and assembly of the optical modules, which are key elements for the detector, have been finalized

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following an intense R&D phase. They are described in this paper.

2. Underwater Neutrino Detector

The major scientific objective of a high-energy neutrino telescope is the study of the Universe by means of neutrino detection [2]. The most widely-used technique for detecting neutrinos in the energy range of about $10^{11} – 10^{16}$ eV is to detect in large volumes of water the Cherenkov light emitted by the muons and hadrons produced when neutrinos interact with the matter inside and around the detector. This light can be detected by a three-dimensional array of optical sensors called Optical Modules (OMs). The measurement of the arrival time of the Cherenkov light at each OM with the information of its position allows for the reconstruction of the muon direction; the amount of light collected can be used to estimate the muon energy.

3. Optical Module

The scientific goals of the NEMO project have led to some global requirements for the design of an Optical Module [3]. The detection of the Cherenkov light has to be optimized. Hence sensors with a large photon detection area must be used. The optical coupling between the water and the photocathode has to be good and the influence of the Earth’s magnetic field on the performance of the photomultiplier must be minimized. A high pressure resistant vessel must protect the photon detector and its associated electronics against the pressure of the surrounding deep sea-water and ensure good light transmission. With a foreseen operation time of 10 years, the reliability of all the components must be high. The Optical Module designed for the NEMO phase-2 project (Fig. 1) has a large area photomultiplier (PMT) glued inside a pressure resistant glass sphere by means of optical gel. A cage of mu-metal wire is used to shield the PMT against the Earth’s magnetic field. Inside the OM there are also the voltage supply circuit soldered to the PMT, the front-end module (FEM) [4] and an optical system for timing calibration (Tim-Cal) [5].

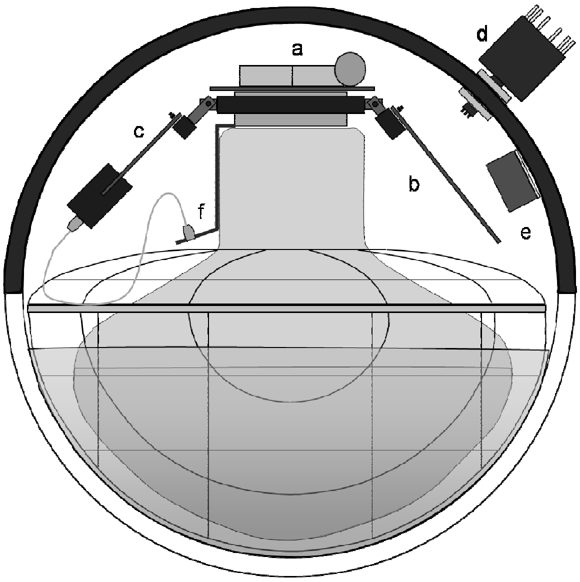

Figure 1 Sketch of an Optical Module: a)ISEG base; b)FEM; c)Tim-Cal; d)connector; e)pressure-gauge; f)optical fibre

The Transparent High-pressure Container

The requirements for the high pressure glass sphere have been identified as: the ability to resist high hydrostatic pressure, up to 35 MPa, transparency to photons in the range of 400-600 nm and a refractive index close to that of the sea-water and of the window of the PMT. Some of the main characteristics are summarized in table 1.

Refractive index (>350nm)	1.48
Transmission (>350 nm)	> 95%
Density at 20°C (g cm^{-3})	2.23
Overall diameter (mm)	330
Wall thickness (mm)	11
Mass (Kg)	7.89
Depth rating (m)	10000
Diameter shrinkage per 1000 m (mm)	0.30

Table 1 Main properties of the glass sphere

The chosen glass sphere is a standard 13 inch. deep-sea instrumentation vessel in borosilicate glass, produced by Vitrovex. Each sphere is made of two hemispherical parts. The lower, transparent part contains the PMT and the mu-metal cage, glued by means of the gel. The upper part is painted black, to conserve the information regarding the direction of the detected photons, and contains electronics, a pressure gauge glued onto the inner surface, and a 12-pin SEACON connector which provides electrical connections (see Fig. 1).

The Photomultiplier

Different types of photomultipliers from various manufacturers have been evaluated. The PMT selected was a Hamamatsu PMT type R7081 [6], with 10 dynode stages and a 10 inch. bialkali photocathode with a quantum efficiency of about 25% at 400nm. Measurements of a batch of 72 PMTs [7] showed good charge characteristics, good time resolution and a low dark count rate. In Table 2 the results are summarized. Also the measured fractions of spurious pulses [7] are shown. Measurements are performed using a pulsed laser set in single photo-electron condition, and using the voltage supply circuit described later.

	mean value	values range
Voltage at Gain 5E7 [V]	1655	1595÷1775
Dark Count rate [Hz] (1/3 spe)	1388*	674÷3000*
P/V ratio	3.5	2.6÷4.3
Charge resolution σ [%]	31.6	23.5÷ 41.4
TTS FWHM [ns]	2.8	2.5÷3.3
Pre-Pulse [%]	0.02	0.001÷ 0.11
Late Pulse [%]	5.5	3.8÷6.6
Type 1 after pulse [%]	1.1	0.8÷1.9
Type 2 after pulse [%]	4.4**	2.2÷7.3 **

Table 2 Measurements from 72 R7081 PMTs

* Excluding one PMT which has a DC rate of 4093 Hz

** Excluding one PMT with type 2 after pulse fraction of 10.4%.

The Voltage Supply Circuit

The high voltage system provides all the intermediate voltages necessary for the correct operation of the PMT. An active base (PHQ7081-i-2m) developed by ISEG and modified to meet the NEMO requirements was chosen. The main features are a low voltage supply (5 Volt) individually-controllable, focusing voltage between photo-cathode and first-dynode, maximum anode current of 100 mA and a power consumption of 150 mW at 2000V. Damping resistors were added at the output to minimize the ringing effect on the anode signal. Tests have shown that signal saturation starts at around 100-120 pe, at about 1 nC for laser pulsed (width of 60 ps).

The Magnetic Shield

Laboratory tests [3][8] have shown that the performance of a large area photomultiplier is subject to significant variations due to its orientation with respect to the Earth’s magnetic fields. Similarly to other experiments [7], in the NEMO OMs a passive magnetic shield was used: a wire cage made of 1 mm diameter mu-metal wire, a nickel-iron alloy with high magnetic permeability ($\approx 10^5$) (ITEP, Moscow, [9]). The cage used had two parts. A hemispherical part (30 cm diameter, 14 cm height) which surrounds the entire photocathode area, and a flat part (30 cm diameter) which consists of a disk with a hole in its centre through which the PMT neck fits. The wire cage shielding provides a good compromise between field reduction and shadowing effects on the photocathode. The pitch of the grid was 68x68 mm, giving a shadow effect on the photocathode of less than 4%. The magnetic reduction factor (RF) inside the volume of the cage was measured. An average RF of 4 was found. Measurements made on the overall response of the 10 inch. R7081 PMT while varying its orientation relative to the Earth’s magnetic field, showed that without the magnetic shielding most of the main parameters of the PMT varied widely [8]. The mu-metal cage described above greatly reduced the variations and even improved performance. For the detection efficiency the largest variation measured with a PMT without shielding was up to 40%, a value that was reduced to less than 6% by using the magnetic shield. The variation in gain was reduced from 29% on the “naked” PMT to less than 7% for the shielded PMT. Even variations for charge and timing resolution were minimized significantly by using the magnetic shield.

The Optical Gel

The main purpose of the optical gel inside the OM is twofold: it creates the optical coupling between the PMT photocathode and the glass sphere and ensures the mechanical contact of the PMT with the glass sphere and the mu-metal cage. With these objectives in mind , the main requirements for the gel were high transparency, a refractive index close to that of the glass sphere and PMT glass window and sufficient mechanical stiffness to suspend the OM components, with sufficiently elastic properties to absorb shocks and prevent the deformation of the glass under pressure. The properties must be stable for the long operational period of about 10 years. The material chosen was a two-component (A and B) silicon gel, Wacker SilGel 612. Four mixtures with different combinations of the two components were produced and their optical and mechanical properties were tested. Table 3 shows the optical measurements of transmittance, absorption length and refraction index.

Gel Composition	**40B / 100A**	**50B / 100A**	**60B / 100A**	**70B / 100A**
Tansmittance [%] (@ 400 nm)	85	93.8	94.3	94.7
Absorbtion length [cm] (@ 400 nm)	12	30	33	35
Refraction index (@ 400 nm)	1.43	1.50	1.47	1.38

Table 3 Optical properties measured for 4 gel compositions

For mechanical tests of the gel a scale prototype of the PMT and glass sphere system was made, and the load and torque resistance of the gel was measured. For the optical and mechanical tests, the 50B/100A mixture was selected as the combination with properties closest to the project requirements.

The Optical Module Assembly Procedure

Finally, the procedure to assemble the optical module using the different components was defined. For the acceleration of the outgassing of the optical gel and for the closure of the two hemispheres of the optical module, two plexiglass vacuum boxes were constructed (1m x1m x1 m), in which the pressure can be decrease to 300 mbar in less than 2 minutes.

The main phases of the assembly procedure were:

- soldering of the supply voltage circuit on the leads of the PMT
- cleaning of each element by using optical paper and methyl alcohol, with particular care on the inner surface of the hemi-spheres and the mu-metal cage
- positioning of the mu-metal cage in the glass hemisphere
- 1 cycle of out-gassing in the vacuum box at 250 mbar (3 min.), followed by a phase of air reentry.
- mixture gel preparation : 1.5 litre x OM, with 1 l A and 0.5 l B, mixed at 120 turns/min.
- pouring the gel into the glass hemisphere
- 3 cycles of out-gassing, to remove residual air-bubbles from the gel
- positioning the PMT in the hemisphere by means of a centering tool
- 3 cycles of out-gassing
- polimerization of the gel at atmospheric pressure and room temperature for over 12 h

After these steps, the front end module and the timing calibration system were mounted on the neck of the PMT (see Fig.1), and were cabled and connected electrically to the twisted pairs of the inner part of the connector. A mechanical support for an optical-fibre connected to the optical-pulser of the Tim-Cal was glued on the neck of the PMT (Fig.1). Finally, the hemispheres were aligned and joint to close the OM at a vacuum of 250 mbar. An external adhesive and tape were applied to the joint between the two hemispheres. The watertight and mechanical resistance of each assembled OM was tested in the hyperbaric chamber at the NEMO test site (Catania harbour) up to 350 atm.

4. Conclusions

A 13” optical module with single large 10” PMT was designed as part of Phase-2 of the NEMO project. Each component was chosen after an intense testing phase which included PMTs, base of voltage supply, composition of the optical gel and the magnetic shield. Following a well established assembly procedure, 32 OMs were assembled, tested in a hyperbaric chamber. In 2012 they will be deployed with the Phase 2 NEMO tower.

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