Journal logo

# A Large Spherical HPD for a Novel Deep Sea Neutrino Experiment

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**Elsevier use only:** Received date here; revised date here; accepted date here

**Abstract**

An underwater neutrino experiment has been proposed which provides precise measurements of the neutrino mixing parameters $\theta_{23}$ and $\Delta m^2_{23}$ and permits an increase of sensitivity for the small angle $\theta_{13}$ by more than one order of magnitude. A Cherenkov detector of about 1.5 Mt active mass, deployed in the Gulf of Taranto, utilizes the CNGS beam in off-axis configuration which represents an essentially mono-energetic source of muon neutrinos. A unique feature of the experiment is the possibility to move the detector and therefore exploit different baselines around 1200 km where the oscillation pattern is fully developed. The conceptual detector design consists of $\mathcal{O}$(30,000) large area and acceptance photosensors arranged in a matrix of ~300 × 300 $m^2$ size. Hybrid Photon Detectors are considered as promising candidates as they provide clean signal characteristics and uniform collection efficiency. We discuss the design and expected performance of a large spherical HPD with 380 mm diameter, which is housed in a high-pressure glass container. A scaled prototype HPD of 208 mm diameter is currently under development using the existing CERN HPD facility.



Keywords  Neutrino; Hybrid Photon Detector; HPD;

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## 1. Introduction

We have studied the concept, implementation and performance of a novel deep sea neutrino experiment [1] which has the main goal to measure the mixing angle $\theta_{13}$ with high precision. The CNGS [2] neutrino beam, which is currently under construction, could be converted with modest effort (no civil engineering) to a quasi-monoenergetic off-axis neutrino beam, delivering $\nu_\mu$ of $E_\nu \approx 0.8$ GeV from CERN to the Gulf of Taranto (C2GT) (radial distance from CNGS Beam axis: 44 km). The experimental concept of C2GT consists of a planar Cherenkov underwater detector, operated at a depth of ~1000m, and at baselines around 1200 km. A 600 km long deep see trench with minimal depth of 1000 m allows to displace the detector in order to assess baselines from 1100 – 1700 km.

Under certain assumptions, neutrino oscillations at large (planetary) distances can be described by only 3 parameters: $\theta_{23}$, $\Delta m^2_{23} \approx \Delta m^2_{13}$, $\theta_{13}$

In a first phase the experiment measures $\nu_\mu \leftrightarrow \nu_\tau$ oscillations at 3 different baselines $L$ and determines $\sin^2\theta_{23}$ and $\Delta m^2_{23}$ from

$$P(\nu_\mu \leftrightarrow \nu_\tau) \cong \cos^4\theta_{13}\sin^2 2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{23}L}{E_\nu}\right)$$

As the neutrino energy is below the $\tau$ production threshold, a $\nu_\mu$ disappearance experiment is performed. At a certain baseline $L^*$, depending on the precise value of $\Delta m^2_{23}$, the term $\sin^2\left(1.27\Delta m^2_{23}L^*/E_\nu\right)$ will have the value one and the experiment will provide maximum sensitivity for the measurement of $\nu_\mu \leftrightarrow \nu_e$ oscillations, which allow to extract $\sin^2\theta_{13}$ from

$$P(\nu_\mu \leftrightarrow \nu_e) \cong \sin^2\theta_{23}\sin^2\theta_{13}\sin^2\left(\frac{1.27\Delta m^2_{23}L^*}{E_\nu}\right)$$

After running for 1+1+5 years (at baselines $L_1$, $L_2$, $L^*$) the expected precision on $\sin^2\theta_{23}$ and $\Delta m^2_{23}$ are 8% and 1%, respectively. The experiment would allow to improve the current upper limit of $\sin^2\theta_{13}$ of 0.05 by a factor 30 or could establish a non-zero value of $\sin^2\theta_{13}$ down to 0.0039.

The detector consists of a grid of ~ 300 × 300 $m^2$ size, subdivided in mechanical modules of 10 × 10 $m^2$ (see Figure 1), on which about 32'000 optical modules are mounted with a pitch of about 1.5 m. The size of the photodetector needs to be chosen such that the detectors cover about 8% of the total surface.

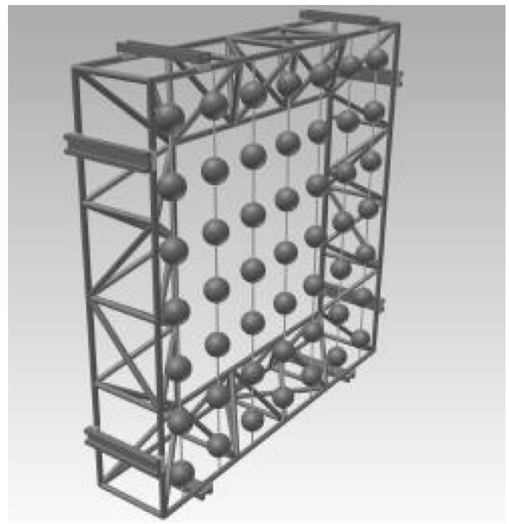


Figure 1: Representation of a mechanical module of 10 × 10 $m^2$ size with 49 Optical Modules.

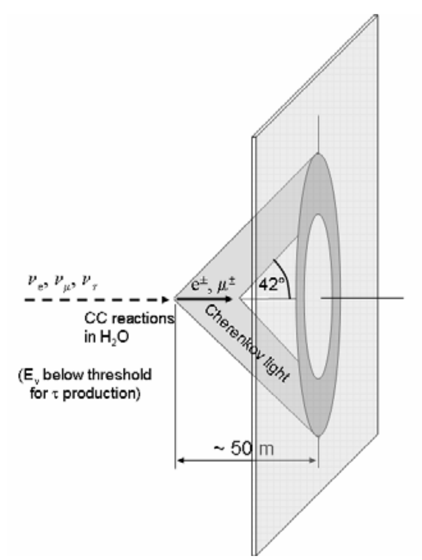



Figure 2: Detection principle of electron and muon neutrinos with a planar water Cherenkov detector (not to scale).

As illustrated in Figure 1, this photosensitive wall intercepts the Cherenkov light cone produced by the charged leptons produced in CC reactions of $\nu_\mu$ and $\nu_e$. Muon and electron events can be unambiguously distinguished by analyzing the hit distribution on the grid, exploiting characteristic differences of electron and muon interactions in water (shower formation, multiple scattering). The typical Cherenkov ring width is about 3 m, driven by the length of the electron shower and the muon absorption length in water. The light transmission of sea water is limited to the wavelength range $300 < \lambda < 600$ nm with a peak absorption length $\lambda_{abs} \approx 55$ m around $\lambda = 450$ nm. The mean value $<\lambda_{abs}>$ in this wavelength range is about 20 m, which defines together with the grid's extension a fiducial active detector mass of about 1.5 Mt.

## 2. Photodetector requirements

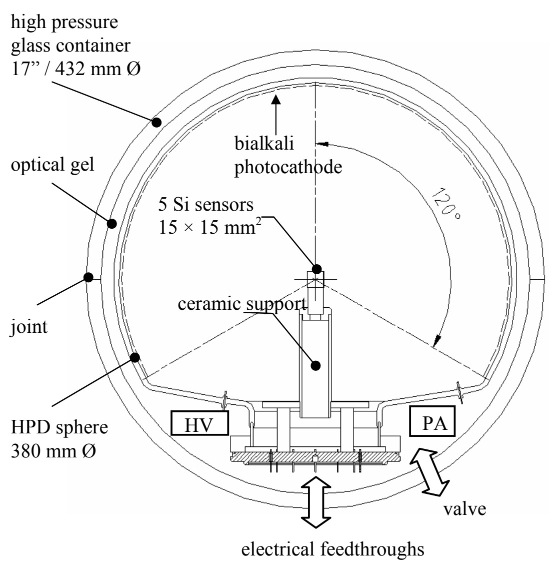
The design of the Optical Module is driven by the experimental requirements and the special environmental conditions:

- efficient light detection in the wavelength range 300 - 550 nm;
- maximal surface and angular acceptance;
- sensitivity to single photoelectrons;
- timing resolution ~ 2 ns (TTS + electronics);
- dark count rate per module < 1 MHz ;
- operation in sea water at a depth of > 1000 m.

Driven by these specifications, but also by considerations of cost, we embarked on a concept of an Optical Module which consists of a large, almost spherical, Hybrid Photon Detector (HPD), inserted in a spherical glass container which withstands high pressure. The pressure sphere houses the supplies for the HV and LV power and the front-end electronics. The detector must provide amplitude information; spatial resolution is not required though. We have chosen the HPD technology [3] rather than a conventional photomultiplier tube because it provides very clean signal characteristics and uniform collection efficiency for even large angles of photon incidence.

## 3. Concept of a large spherical HPD

Our HPD design is schematically shown in Figure 3. It is based on a spherical envelope of borosilicate glass of 380 mm outer diameter (wall thickness about 5 mm). The bottom part of the glass envelope is sealed by a metallic baseplate, which supports the silicon sensor (see below) and is equipped with electrical feedthroughs. A semi-transparent bialkali photocathode (quantum efficiency ~25% at 400 nm) is best suited for the near-UV and visible wavelength range. It covers the inner glass surface down to the




contact electrode which is evaporated on the glass surface. The photoelectrons are accelerated in the radial electric field between the cathode and the silicon anode ($E \sim 1/r^2$).

Figure 3: Schematic view of an optical module based on a spherical HPD

Electrostatic simulations[2] predict a uniform angular acceptance of up to 120º with a transit time spread (TTS) below 1 ns. The strongly increasing field leads to a focusing effect towards the anode, which reduces the point spread originating from the angular spread

[2] SIMION 3D™. www.simion.com

of the electrons at the photocathode. The photocathode is maintained at negative high voltage ($U_C$ = -20 kV), while the Si sensor is grounded. The charge gain of the detector is given by the number of electron-hole pairs, which are produced when a photoelectron is stopped in the Si sensor: $G = e \cdot U_C$ / 3.6 eV ≈ 5000. The dissipative nature of this gain mechanism leads to a well defined signal with fluctuations generally below the pedestal noise of the readout electronics (see below) and allows for photoelectron counting up to at least five photoelectrons. The large angular coverage is achieved by arranging the anode as five individual silicon sensors of 15 × 15 $mm^2$ size, mounted edge-to-edge on a ceramic support cube. The bottom face of the cube sits on an insulated cylinder which is mounted on the baseplate. The cube is surrounded by a round field cage of about 30 mm diameter, which is largely transparent to the photoelectrons. Its rôle is to reduce the electric field gradient in the vicinity of the silicon sensor to values which exclude electric discharges from the silicon surfaces. In the simulation the effect of the earth magnetic field (0.5 Gauss) on the electron optics is found to be negligible, a behaviour which was experimentally demonstrated for the conceptionally similar Quasar tubes used in the Lake Baikal experiment [4].

**The high-pressure container**

The HPD is housed in a standardized high-pressure glass container as used by the fishing industry. The 380 mm HPD fits in a 17-inch container with a gap of 1 cm. The lower part of the container provides sufficient space for a compact HV supply, readout and calibration electronics. Industrial pressure and sea-water proof feedthroughs permit electrical supply, control and readout of the Optical Module. The optical and mechanical contact between the HPD and the container is ensured by an optical gel with matched refractive index (the gel also diminishes the vacuum volume, thus reducing the shock wave in water generated by an imploding Optical Module).

**The readout electronics**

The relatively small signal amplitude (5000 $e^-$ ≈ 1 fC) and the required timing precision (~ 2 ns) call for a custom designed low noise front-end, possibly followed by a pulse shape digitization unit. We aim for a signal-to-noise ratio of at least 10 for single photoelectrons, i.e. the pedestal noise must not exceed 500 $e^-$ (RMS) and the shaping time of the filter/shaper circuit should be of the order 20 ns. A front-end with 20 ns shaping time is able to achieve noise levels of the order 60-70 $e^-$/pF. The above-mentioned silicon sensors of 15 × 15 $mm^2$ (80 pF) are therefore segmented in 9 cells such that the capacity per cell drops well below 10 pF each. All cells are read out by a single chip. Waveform digitization is performed at a rate of about 300 MHz.

An alternative approach is to equip the HPD with an avalanche silicon diode, commonly used as avalanche photodiode (APD). This leads to a conveniently large signal amplitude (~ $10^5$ $e^-$), as the HPD `bombardment' gain is augmented by the avalanche gain. However, the specific detector capacitance of avalanche diodes (300-1500 $pF/cm^2$) and the non-availability of large diodes (> 5 × 5 $mm^2$) pose limitations, which may be incompatible with a large size and acceptance HPD.

## 4. Fabrication of a large spherical HPD

The large quantity of photodetectors required for a neutrino experiment calls for an optimized cost efficient industrial production. The standard method to produce large hemispherical photomultiplier tubes is internal photocathode processing. The phototube is pumped through a small glass pumping stud, while the tube is vacuum baked, and the photocathode is processed by heating the small sources (e.g. Sb, K, Cs) which remain inside the tube. The tube is sealed after processing by a hot glass seal. An internal processing method leads to short turn-around cycles as only the tube volume needs to be pumped and baked. The tube with all its internal structures is exposed to the vapor of the alkali metals, which in contrast to Sb spread out over the whole tube volume. In a HPD with its characteristic high electric fields, the presence of the alkali metals, particularly Cs which is known to lower the work function of metals, can seriously compromise the capability of a tube to achieve the design high voltage. Sparking and sustained discharges well below this voltage may be a consequence. HPDs are therefore produced in a so-called external or transfer process. The entrance window or the base plate are kept separate from the tube while all components are baked in a vacuum tank The tube is sealed in-situ only after photocathode processing, usually by means of a cold or warm Indium sealing technique. This method minimizes the 'pollution' of the tube and its internal components with alkali vapors. The use of local heating elements reduces the thermal load of delicate HPD components like Silicon sensors, ceramic printed circuit boards and readout ASICs. The turn-around time is significantly longer than that of an internal process, and the set-up is more complex and expensive. While the half-scale prototype discussed below will be fabricated in our existing transfer chamber [5] by an external process, we intend to develop a simple and fast semi-external process for the processing of the large HPD. The process, illustrated in Figure 4, combines elements of the internal and external processes described above. The spherical glass body is connected to a vacuum system and evacuated through the bottom hole. The glass sphere is surrounded by an external oven (at ambient pressure). The evaporation sources are mounted on a movable support which allows to place them in the sphere centre. After cathode processing the sources are removed and the sphere is indium-sealed by the baseplate which carries the silicon

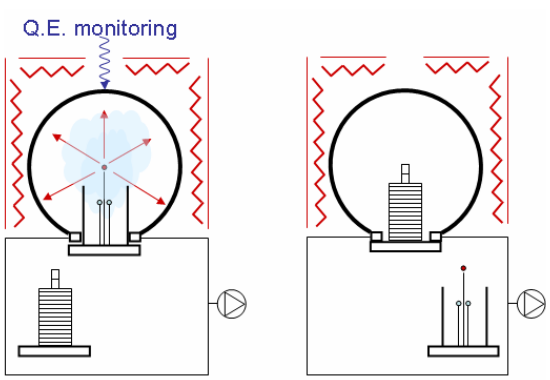



Figure 4: Schematic representation of the semi-external process. Left: Configuration during photocathode processing. Right: Configuration for tube sealing.

sensor arrangement. This process allows to reduce the size of the vacuum tank (short pump down times, little maintenance) and efficiently protects the high field region from alkali vapor. The bottom flange of the glass sphere is a challenging component, currently still under design. It needs to provide a connection to the vacuum system and allow an in-situ sealing with the base-plate.

## 5. Development of a half-scale prototype

Considerable experience exists at CERN in the design and construction of HPDs up to 10 inch diameter and with highly pixelized silicon anodes. The photocathode evaporation and tube encapsulation plant at CERN allows building a prototype HPD of the above type with an outer diameter of about 208 mm (see Figure 5). A large part of the equipment is available from previous developments and can be adapted with modest effort. The reduced-scale prototype allows to verify most of the HPD's characteristics, including sensitivity, electrostatics and signal properties. A spherical glass envelope, which can be sealed with an existing base plate of the 5-inch Pad HPD [6], is under development at SVT[3]. The anode is formed by 5 non-segmented silicon

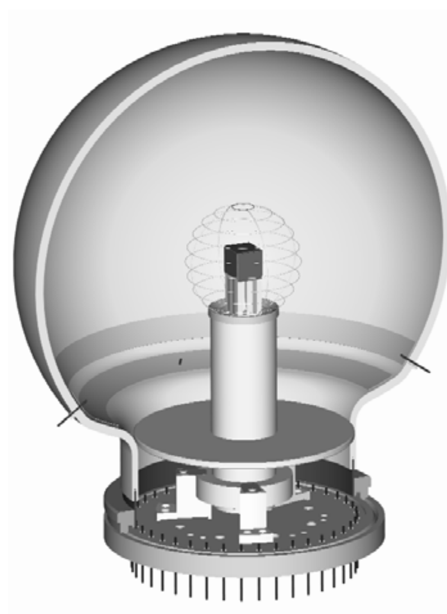


Figure 5: Artistic view of the half-scale prototype tube. The outer diameter of the glass sphere is 208 mm.

[3] SVT-Vacuum Technology, 91170 Viry-Chatillon, France.

sensors of 10 × 10 $mm^2$ active size, read out by external electronics. A set of measurements proved that the required wire length of about 20 cm between the sensor and the external amplifier does not lead to a sizable degradation of the noise performance. It is however clear, that the large capacitance of the non-segmented Si sensor (36 pF) used in this first prototype tube will not allow to achieve the design timing resolution of 2 ns.

## Acknowledgments

The authors would like to thank Alan Rudge, Michael Moll and Peter Weilhammer at CERN for clarifying discussions and test measurements on Silicon sensors.

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