Development of HPDs for Applications in Physics and Medical Imaging

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We discuss the design, construction and first results of two Hybrid Photon Detectors under development for applications in neutrino physics and Positron Emission Tomography. The concept of a large almost spherical HPD is being developed as instrumentation for a next generation underwater Cherenkov detector array. Its main advantages compared to a conventional hemispherical PMT are the considerably increased viewing angle, minimum transit time spread, high gain stability and immunity to the earth's magnetic field, intrinsic to the design. A proximity focused ceramic HPD with a flat sapphire entrance window has been developed in the framework of a conceptual design study of a novel 3D Axial PET scanner. The PET-HPD is equipped with custom designed fast front-end electronics, allowing sequential and sparse mode readout of its 208 pads. Prototypes of both HPDs are being built in a dedicated vacuum deposition facility at CERN.

Keywords: Photodetector; Hybrid Photodetector; HPD; Photocathode; Positron Emission Tomography; PET;

1. Introduction

The principle of a Hybrid Photodetector (HPD) has been demonstrated more than 40 years ago: Light quanta are converted in a usually semi-transparent photocathode to photoelectrons, which are then accelerated in an electric field and finally detected in a solid state sensor, where the kinetic energy of the photoelectrons gives rise to the creation of electron-hole pairs, i.e. to an electronic charge pulse. The concept is attractive as it combines the sensitivity of a classical photomultiplier tube (PMT) with the superb energy and spatial resolution of a (segmented) solid state device. The charge gain of a HPD is relatively small ($\approx$ 5000 e/h pairs, i.e. 0.8 fC, per photoelectron for a voltage of 20 kV between cathode and anode), however thanks to the single-step dissipative gain mechanism the signal is not compromised by avalanche fluctuations as in a PMT. The charge resolution is usually determined by the pedestal noise spread of the readout electronics. The silicon anode can be segmented over a wide range of granularity, from pixels as small as 50μm to pads in the multi mm range. Generally there is no inactive gap between the cells.

Developments over the last decade, in close collaboration with industrial partners, have led to two large scale applications of HPDs in high energy physics experiments: the readout of the CMS hadron calorimeter with proximity focused HPDs [1] and the readout of the two LHCb RICH with cross-focused HPDs [2]. Since 1997 our team has worked on prototype developments of various large and very large HPDs (5-inch and 10-inch [3,4]), which are produced in a dedicated facility at CERN. In this article we report about the status of ongoing developments of application specific HPDs for applications in neutrino physics and medical imaging.

2. Development of a spherical HPD for the C2GT study

A novel neutrino oscillation experiment, which is the subject of a conceptual study [5], proposes to send a quasi-mono-energetic neutrino beam

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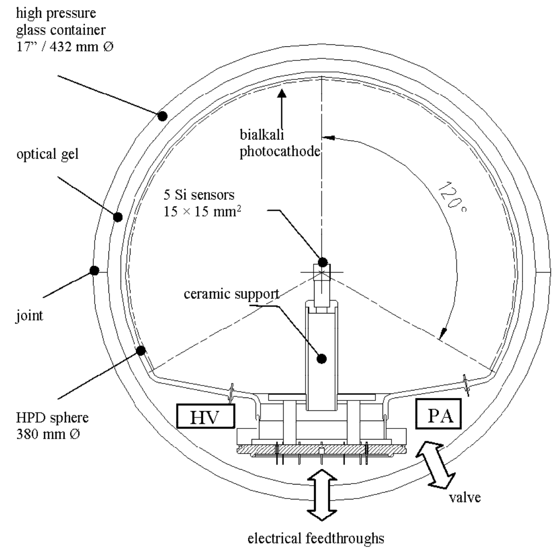

Figure 1. Schematic view of the optical module based on a spherical HPD.

Figure 2. Photograph of the 'dry' assembly of the half scale prototype HPD.

from CERN to the Gulf of Taranto (C2GT). The experimental concept of C2GT consists of a planar Cherenkov underwater detector, operated at a depth of $\approx$1000 m, and at baselines around 1200 km. A 600 km long deep sea trench with minimal depth of 1000 m allows to displace the detector in order to assess baselines from 1100 to 1700 km. The detector consists of a grid of $\approx 300 \times 300$ m^2 size, subdivided into mechanical modules of 10×10 m^2, on which about 32000 optical modules are mounted with a pitch of about 1.5 m.

The optical module has to combine maximal surface (>300 mm diameter) and angular acceptance ($\pm 120^o$) with high timing resolution (<2 ns). We propose an almost spherical HPD of 380 mm diameter inserted in a commercial glass pressure vessel (see Fig. 1). The envelope (borosilicate glass) is sealed by a metallic baseplate, which supports the silicon anode and is equipped with electrical feedthroughs. The HPD features a semi-transparent bialkali photocathode which is well suited for the near-UV and visible wavelength range transmitted by sea water. The anode consists of a cubic arrangement of five 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 photoelectrons are accelerated in the radial electric field between the cathode and the silicon anode ($E \sim 1/r^2$). Electron-optical simulations with SIMION[4] predict a transit time spread in the sub-ns range and immunity to the earth's magnetic field. A drawback is the geometry-inherent high electric field (up to 10 kV/cm) close to the anode. A grounded and largely transparent spherical grid of 30 mm diameter, around the anode, is expected to reduce the field by a factor of 5.

A half-scale prototype HPD of 208 mm diameter is currently being built. Its size is compatible with our existing production facility at CERN [7]

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[4] SIMION 3D^{TM}. www.simion.com

and required only minor adaptations. First tests will be performed with tubes with a metallic anode of cubic shape replacing the silicon sensors. The goal is to optimize the evaporation process parameters, study the uniformity of the quantum efficiency over the sphere surface and assess the high voltage stability. The developments are done in partnership with the company Photonis-DEP[5]. Fig 2 shows a photograph of a 'dry' assembly of a 208 mm prototype tube. The first sealed tube is planned to be fabriated in Autumn 2005.

3. An HPD for a novel 3D axial brain PET scanner concept

A concept for a Positron Emission Tomography (PET) detector module [8] has been proposed, which provides full 3D gamma reconstruction with high resolution over the total detector volume, free of parallax errors[6]. The key components of a camera module are a matrix of long axially oriented scintillator crystals and proximity focused HPDs with matched segmentation and integrated readout electronics.

The proximity focused HPD developed at CERN, hereafter called PET-HPD, is a round photodetector with a bi-alkali photocathode deposited on a thin (1.8 mm) flat sapphire entrance window of 105 mm diameter (see drawing and photograph in Figs. 3 and 4). The total length of the PET-HPD is 67 mm.

The proximity focusing electron optics of the HPD produces a 1:1 image of the scintillator array onto the Silicon sensor, which is segmented into 208 (13×16) diode pads of 4×4 mm^2 size, precisely matching the pattern of the crystal array. The sensor is mounted on a 4-layer ceramic PCB which receives the two front-end chips (type VATA-Gp5 [7]). The HPDs are operated at a moderate cathode potential of about 12 kV, sufficient for a signal of about 3000 electron-hole pairs in the Silicon sensor for every detected photoelectron. The point spread function, which describes the Gaussian width of the charge distribution on the silicon sensor for a point like light source is of the order of 0.3 mm.

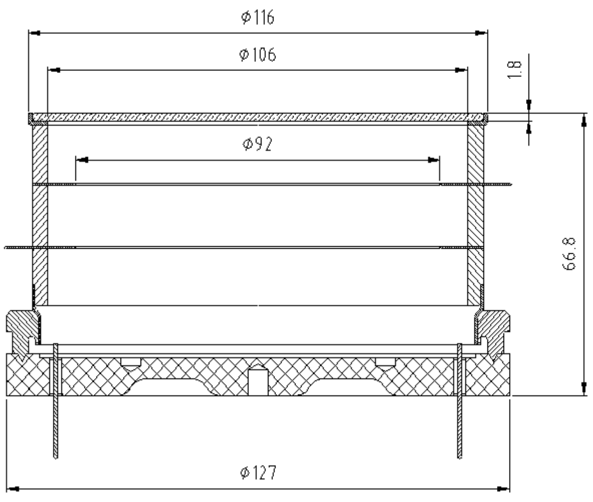

Figure 3. Cross-section of the proximity focused PET HPD tube.

3.1. The VATA-Gp5 front-end chip

The VATA-Gp5 chip is a custom-designed analog ASIC with 128 channels, produced in 0.6 μm CMOS technology. Self triggering capability is a must for medical applications. The incoming signal is therefore fed into an analog chain with 150 ns peaking time and in parallel to a fast shaper (25 ns peaking time) with subsequent discriminator. This branch generates a fast OR (FOR) of all hit pads. Coincident FOR signals of the two HPDs connected to one crystal matrix produce the Sample and Hold (S/H) signal for the readout of the analog chain. The chip provides serial and sparse readout options. The VATA-Gp5 has been tested together with the above mentioned Si sensor and ceramic PCB in a pumped HPD-like set-up where the photoelectrons originate from a CsI photocathode illuminated with pulsed UV light. This set-up allowed to characterize the full functionality of the circuit: serial and sparse readout, linearity over the full dynamic range up to 2 pC, and time walk

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[5] Photonis-DEP, Brive-La-Gaillarde, France. www.photonis-dep.com

[6] For the concept a patent has been filed by CERN under the publication number WO2004008177

[7] IDE AS, Fornebu, Norway, www.ideas.no

Figure 4. Photograph of a PET HPD.

compensation within ±5 ns in the charge range of interest.

3.2. Sealed PET-HPD tubes

Three sealed PET-HPD tubes have been fabricated. The first with a round Si sensor of 50 mm diameter, segmented in 2048 pads and read out by 16 VA-prime front-end chips used previously [3]. Two tubes were sealed with the above described VATA-GP5 chip set and the rectangular Si sensor described above. Unfortunately none of the tubes worked to our full satisfaction. Two problems were identified and are currently being solved. The high voltage could not be set to the design value of 12 kV. Above 8 kV we observed HV instabilities which were traced back to surface discharges on the ceramic rings of the tube body. A surface treatment of the ceramic surface, which leads to a reduced and controlled surface resistivity, is expected to solve this first problem. The sealed tube with the 16-VA-prime chips was fully operational from the read-out point of view. It allowed to verify the linear proximity focusing characteristics of the tube with maximum deviations of $\pm 200 \mu$m. The second problem was observed for the two tubes equiped with the VATA-GP5 chips. The solder paste chosen to mount the passive compnents on the ceramic PCB was not compatible with the vacuum bakeout, during which the PCB is heated to 160^oC. This led to interrupts in the supply lines of the chips and paralyzed the readout. Unless the PCB can be fixed by a vacuum and high temperature compatible conductive epoxy glue, the ceramic PCB has to be remade with the correct solder paste. We are confident that both problems can be solved on a timescale of a few months.

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REFERENCES

1. P. Cushman et al., Nucl. Instr. Meth. A504 (2003) 62-69.
2. T. Gys et al., these proceedings.
3. A. Braem et al., Nucl. Instr. Meth. A497 (2003) 202-205.
4. A. Braem et al. Nucl. Instr. Meth. A518 (2004) 574-578.
5. A. Ball et al., C2GT, Memorandum, CERN-SPSC-2004-025, SPSC-M-723.
6. A. Ball et al., proceedings of the RICH2004 conference, accepted for publication in Nucl. Instr. Meth. A.
7. A. Braem et al., Nucl. Instr. Meth. A502 (2003) 205-210.
8. Novel Geometrical Concept of a High Performance Brain PET Scanner - Principle, Design and Performance Estimates, Pre-print CERN PH EP/2004 050, submitted for publication in Nucl. Instr. Meth. A.