The X-HPD – A modern Implementation of a SMART Concept

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Abstract

The concept of hybrid photodetectors which combine a large area photocathode with a crystal scintillator anode in the centre of a hemispherical vacuum tube was demonstrated first with the Philips SMART tubes and, more recently, with the QUASAR tubes of the Lake Baikal experiment. Photoelectrons from the cathode are accelerated by a potential difference of 20-30 kV and deposit their kinetic energy in the scintillator (or Phosphor). The generated scintillation light is detected by a small and low cost photodetector, e.g. a conventional PMT. The X-HPD study is a variation of this concept aiming at improved performance and maximum simplicity. The glass envelope is essentially spherical and a spatial scintillator crystal is mounted in its centre. The spherical symmetry leads to a uniform collection efficiency and very small intrinsic time spread over the full viewing angle of 120° (3 π solid angle). We report about test results of a the first X-HPD prototypes of 208 mm diameter with cylindrical and conical LYSO crystal anodes.

1. Introduction

Initiated by the C2GT design study [1] we developed the concept of a large (e.g. 15-inch diameter) almost spherical Hybrid Photodetector (HPD) with centrally placed anode. While the anode was originally foreseen to consist of Silicon sensors, mounted on a ceramic cube of 15 mm side length, we chose instead a simpler and only slightly less performant alternative, namely to replace the Si-anode by a spatial scintillator crystal which is read out through a window by an external small PMT. This concept, which we gave the name *X-HPD*, is a modern implementation and extension of the *Dumand Smart PMT* [2] and *Lake Baikal Quasar* [3] approach to large area photon detectors. The readout of the scintillator can obviously be accomplished by other photodetectors, e.g. by Geiger mode APDs, as proposed in [4].

2. The X-HPD concept

An X-HPD consists of a glass sphere with a round opening which is sealed by a base plate. A scintillator crystal is mounted in the centre of the sphere, mechanically supported from the base plate, and serves as anode. A semi-transparent photocathode covers a large part ($\approx 3/4$) of the sphere. The electrical field between cathode and anode is radial ($E \sim 1/r^2$), apart from distortions in the vicinity of the anode support. A ring electrode, parallel to the edge of the photocathode area allows correcting for these distortions. The potential difference between cathode and anode is of the order 20-30 kV. Photoelectrons bombard the scintillator and create scintillation light, which is coupled to a small photodetector. For practical reasons, mainly for incompatibility with the vacuum bakeout process, the photodetector is mounted outside the vacuum sphere. The price to pay are light losses at the various interfaces crystal/window/light guide/photodetector. Particularly critical is the interface from crystal to window which involves a small vacuum gap. The scintillation photons have to pass an interface with high refractive index ratio ($\approx 1.8/1$) which unavoidably leads to substantial light losses. The scintillator is coated with a reflective, metallic coating, which has the function to define an equipotential surface and to avoid scintillation light leaking out of the crystal. The symmetry of the E-field allows in principle for imaging, i.e. it can be of interest for certain applications to segment the scintillator and also the photodetector. The scintillator crystal needs to have a minimum size to ensure a high hit probability for electrons from all regions of the photocathode. Its shape, e.g. cylindrical, hemi-spherical or conical has an impact on the optical characteristics of the anode (photon path lengths, number of reflections) and hence the final light yield.

The main advantages of the X-HPD concept are:

- Very large viewing angle. In practice the angle is limited by the geometry of the mechanical support of the crystal and the associated E-field distortions. Values of ±120° are easily possible, corresponding to an active solid angle of 3π.

- Sensitivity increase due to a 'double cathode' effect. Light which traverses the semitransparent cathode unconverted has a second chance to be detected on the opposite side, then in reflective mode.
- Low transit time spread. The central position of the anode implies that the trajectories of all photoelectrons have in first approximation the same length. The flight time differences are in the sub-ns range.

In addition, there are a number of features, which the X-HPD shares with its predecessors, the Smart and Quasar tubes:

- The scintillation mechanism leads to a first stage gain of the order of 20-60, depending on the applied HV, choice of crystal and quality of light coupling. This results in a well defined signal, also for single photons, and a modest photon counting capability.
- The radial field geometry leads to immunity to the earth magnetic field and makes shielding obsolete.
- The tube is conceptionally simple and consists of very few components which should lead to competitive fabrication costs.

These features make the X-HPD concept a promising option for future large volume water based Cherenkov detectors as studies e.g. by the KM3NeT collaboration [5].

3. Experimental studies

3.1. *Preparatory work*

We fabricated in the CERN photocathode facility [6] a first X-HPD prototype tube of 208 mm external diameter with a cubic metal anode of 1 cm^3 volume [7]. With this prototype, we measured the QE of the bi-alkali photocathode and its variation over the full angular acceptance of ±120°. For side illumination, where the light has a double chance to be converted, a QE of 50% was found at $\lambda = 350$ nm. In parallel, a number of scintillation crystals (YAP, LSO and LYSO) of $\sim$cm^3 volume were characterized in an evacuated HPD-like set-up with mono-energetic electrons of up to 29 keV energy [8], yielding up to 35 photoelectrons per electron.

An anode assembly, based on a cylindrical LYSO crystal of 12 mm diameter and 18 mm length was prepared and tested in the same set-up with electrons up to 27.5 keV and characterized in terms of photoelectric yield, backscattering and time resolution [8]. A light guide, made of an Al-coated truncated plexiglass cone ensures the optical contact between the window and the PMT tube of 25 mm diameter [2]. As a consequence of the additional optical interfaces the photoelectric yield was about 30% lower than for the above measurements where the crystals were directly coupled to the PMT.

Fig. 1. Photo of the X-HPD with conical LYSO crystal anode.

3.2. *Fabrication and test of full X-HPD tubes*

The first X-HPD (internal number PC119) was processed in the CERN facility [6] with a standard bi-alkali photocathode. The sealed tube was mounted in a test chamber and exposed to short light pulses from a self triggering H_2 flash lamp. Metal filters allowed to vary the light intensity from single to multiple photons. The signal from the PMT reading out the crystal was sampled by a charge sensitive ADC in a VME based readout system, triggered by a pick-up signal from the H_2 lamp. The photocathode and the corrector electrode were connected to negative HV, while the anode was kept on ground potential. The HV applicable to the cathode was limited to about -14 kV. The measured light yield confirmed the expectations from the previous work [8]. Above this limit, micro discharges led to substantial background which made the further characterization impossible. The micro discharges were believed to arise from charge build-up on the bare glass surfaces of the X-HPD envelope in the area between the base flange and the photocathode. Similarly, the glass cylinder which houses the PMT was suspected to contribute to the problem.

A second X-HPD (PC120, see Fig. 1)) was produced where these surfaces were coated with a special UHV and high temperature compatible resistive coating [3]. A second modification concerned the LYSO crystal. Its shape was modified in the upper part to a cone (60°) with a central flat of 3 mm diameter. The design of the crystal anode is shown in Fig. 2.

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[2] Photonis XP3102, Gain $6 \cdot 10^6$ at 1000 V, peak-to-valley ratio = 2.7

[3] Details of the product and its processing fall under a non-disclosure agreement with the company Photonis SAS.

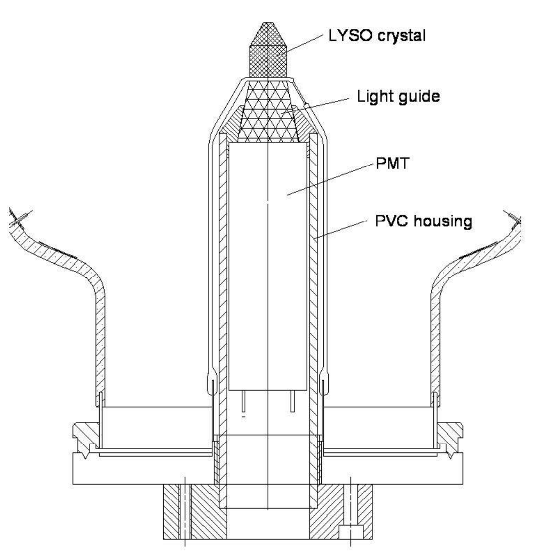

Fig. 2. Drawing of the X-HPD crystal anode assembly.

3.3. *Light yield modelling with Geant4*

In order to obtain a qualitative understanding of the light yield for the different crystal geometries, the generation of scintillation light and its propagation in the crystal was modelled with Geant4 [9]. Geant4 is a multi–purpose Monte Carlo tool for the simulation of passage of particles through matter in a wide energy range. The Geant4 electromagnetic physics package manages the electromagnetic interactions of leptons, photons, hadrons and ions, and provides specific code for optical photon transport. Optical photons can undergo in-flight absorption, elastic scattering (Rayleigh) and medium boundary interactions. The properties of media and surfaces relevant for the optical photon tracking can be assigned to a specific material, volume or interface between volumes, and modeled as a function of the wavelength. In this study, electrons of 20 keV energy interact in the crystal by depositing either their full or partial energy, according to the backscattering coefficient. A first series of simulation runs indicate that the conical crystal leads to a significantly higher light output than the cylinder, however only in the upper conical part (see Fig. 3). Common to both geometries is the substantial variety of different paths the photons can take before they escape from the crystal. This gives rise to pulse height fluctucation well above the Poisson statistical limits.

3.4. *Results*

We report here about a first series of measurements. Detailed tests will be described in a forthcoming article. The new X-HPD (PC120) was tested in the above mentioned chamber with negative HV applied to the cathode and the first electrode, while the anode was grounded. The chamber was filled with normal air. The tube could be operated with a cathode voltage of up to -24 kV which is a substantial improvement compared to the previous tube (PC119). Fig. 4 shows the pulse height spectrum at $U_C = -20$kV. The light intensity was chosen such that primarily single photoelectrons are hitting the crystal. The shoulder between the single photoelectron peak and the (subtracted) pedestal is due to backscattered electrons with only partical energy deposition. The calibration of the PMT allowed to convert the charge signal (ADC counts) to the number of photoelectrons at the photocathode of the PMT. The position of the single photoelectron peak varied in first approximation linearly with the applied HV. A small non-linearity is due to the relative light output LYSO [4] [10,11] which for energies below 30 keV deviates significanlty from 100%. A threshold of about -7 kV was found. At $U_C = -24\ kV$ we detected $N_e = 44$ photoelectrons for illumination of the X-HPD from the top. For this configuration, where the electrons hit primarily the top of the conical LYSO crystal, the expected light yield increase compared to the previously measured cylindrical shape ($N_e = 18$) [8] is confirmed. The width of the single photoelectron distribution is significantly wider than the value expected from the Poisson fluctuations $\sqrt{N_e}$ and consequently the capability to identify multi-photon peaks is limited. We attribute this mainly to the above mentioned fluctuations of the photon trajectories (pathlength and number of reflections). This phenomen spoils also the achievable time resolution.

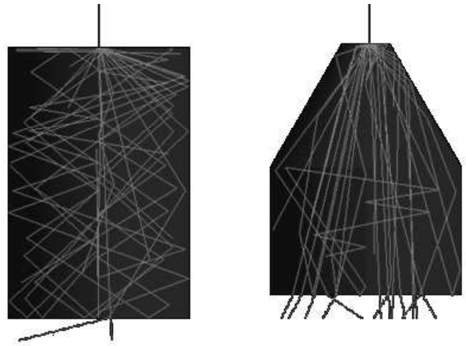

Fig. 3. Simulated photon trajectories in a cylindrical and conical crystal. The number of generated photons was scaled down for better clarity.

While the resistive coating has significantly improved the HV capability of the tube, the onset of micro discharges prevented the setting of the steering electrode to their nominal value ($U_C - 1\ kV$). We suspect these discharges to occur between the electrode and the base flange, possibly on the tube outer surface. We plan to operate the tube with the anode at positive HV and the cathode at ground which should eliminate this effect.

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[4] Relative light output data for LYSO is not available. We assume it to be very similar to the one of LSO.

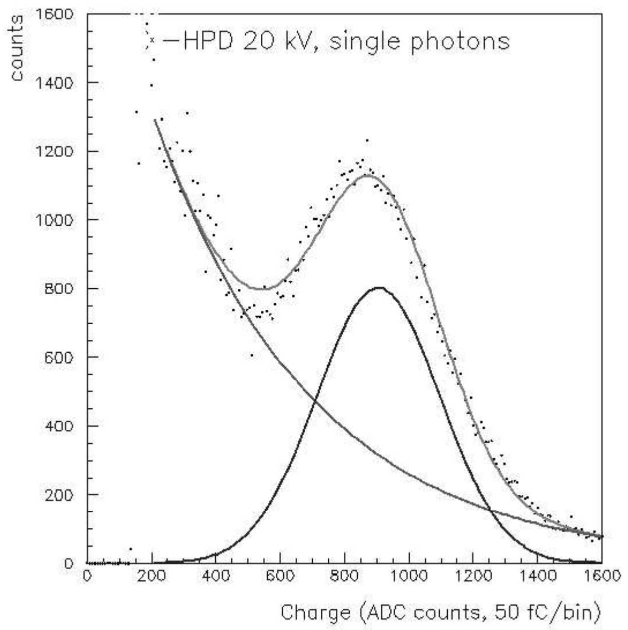

Fig. 4. Charge spectrum for single photons at $U_{cath} = -20$ kV. The dark noise spectrum, which is not shown in the plot, has been subtracted. A small contribution of the second photoelectron is visible.

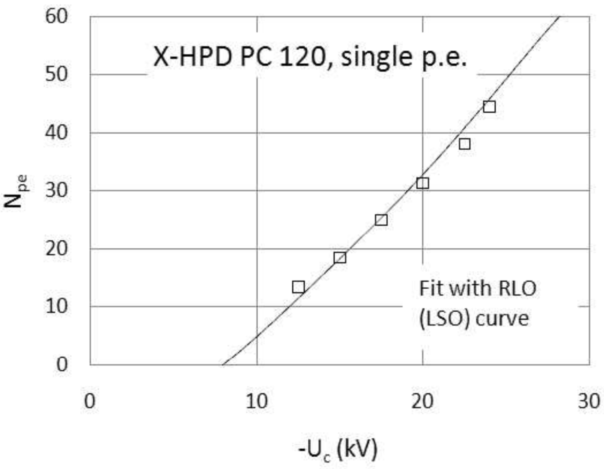

Fig. 5. Photoelectric yield vs. U_{cath}. The shape of the fit is based on the relative light output of an LSO crystal.

4. Summary and outlook

Two first X-HPD tubes were recently fabricated in the CERN facility and an initial characterization was performed. We could demonstrate several of the attractive features of the X-HPD concept. The second tube with the resisitve coating could be operated up to $U_C = -24$kV. The conically-shaped LYSO crystal led to a higher light output than the cylindrical one. Fluctations of the photon trajectories in the scintillation crystal affect the resolution of pulse height and timing. A better understanding of these effects is the aim of a planned systematic Monte-Carlo study with Geant4. Our current anode configuration is based on a straight forward design. We see the potential for improving the shape and the light transfer from the crystal to the photodetector with the aim to reduce the path fluctuations consequently further improve timing and pulse resolution. An alternative design based on a special phosphor anode is also under study.

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