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

A. Braem +, C. Joram +, J. Séguinot +, A-G. Dehaine * and P. Solevi #

+ CERN, Geneva (CH)  * Photonis SAS, Brive (F)  # ETH Zürich (CH)

- The X-HPD concept and design
- Geant4 studies of light transport in anode
- Fabrication of the X-HPD
- Proto 2 (PC120): The first operational X-HPD with LYSO crystal
- Summary and outlook
Neutrino detection by Cherenkov effect in **C2GT (CERN To Gulf of Taranto)**


- $\nu_e$, $\nu_\mu$, $\nu_\tau$
- CC reactions in H$_2$O
- (E$_\nu$ below threshold for $\tau$ production)
- ~50 m
- segmented photosensitive ‘wall’ about 250 × 250 m$^2$
- Fiducial detector mass ~ 1.5 Mt

The wall is made of ~600 mechanical modules (10 x 10 m$^2$), each carrying 49 optical modules.

Initiative was stopped in 2006 ...
… but **photodetector development** had in the meantime stimulated enough interest (e.g. at Photonis, KM3NeT community) to be continued.

$\rightarrow$ Partnership agreement CERN / Photonis.
X-HPD concept = spherical tube with central spacial luminescent anode

- Radial electric field
  - negligible transit time spread
  - ~100% collection efficiency
  - no magnetic shielding required

- Large viewing angle (dΩ ~ 3π)

- Possibility of anode segmentation
  - imaging capability (limited!)

- Sensitivity gain through ‘Double-cathode effect’

- Philips made ~30 tubes (1980s-1992)
- Both tubes used thin disks of P47 phosphor (YSO:Ce powder)

\[ g_{\text{primary}} \sim 35, \sigma_t \sim 2.5 \text{ ns} / \sqrt{N_{pe}} \]
SMART and Quasar tubes were the first X-HPDs

- however the use of a disk shaped scintillator didn’t allow to exploit full potential.
- need to use fast scintillator, e.g. cube or cylinder.
- Require
  - high light yield $\Rightarrow$ high gain
  - short decay time
  - Low Z preferable $\Rightarrow$ low back scattering coefficient
  - Emission around $\lambda = 400$ nm

<table>
<thead>
<tr>
<th></th>
<th>LY ($\gamma /$ keV)</th>
<th>$\tau$ (ns)</th>
<th>$Z_{eff}$</th>
<th>$\varepsilon_{BS}$</th>
<th>$\lambda_{emission}$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>YAP:Ce</td>
<td>18</td>
<td>27</td>
<td>32</td>
<td>$\sim$0.35</td>
<td>370</td>
</tr>
<tr>
<td>LYSO:Ce</td>
<td>25</td>
<td>$\sim$40</td>
<td>64</td>
<td>$\sim$0.45</td>
<td>420</td>
</tr>
<tr>
<td>LaBr$_3$:Ce</td>
<td>63</td>
<td>30</td>
<td>47</td>
<td>$\sim$0.4</td>
<td>360</td>
</tr>
</tbody>
</table>

LaBr$_3$ is quite hygroscopic

- side and top require conductive and reflective coating $\Rightarrow$ define el. potential, avoid light leaking out.
- Problem: crystals have high refr. index ($\sim$1.8) $\Rightarrow$ large fraction of light is trapped inside crystal due to total internal reflection.
X-HPD ½ scale prototype (208 mm Ø) with conical LYSO crystal (PC120)
Electrostatics (SIMION 3D)

Expected performance
- Viewing angle ±120°
- X-tal hit probability ~ 100%
- flight time spread ~0.4 ns (RMS)

Can be further improved by optimizing bulb geometry.
First build a HPD with metal-cube anode (1 cm³) …

‘Proto 0’

Built in CERN plant.

A. Braem et al., NIM A 570 (2007) 467-474
... then prepare and characterize components for real X-HPD
Anode consists of **cylindrical / conical** LYSO crystal : $12 \text{ mm } \varnothing \times 18 \text{ mm}$

Readout by conventional PMT Photonis XP3102 (25 mm $\varnothing$)
PMT XP3102 has very good signal properties.

Calibration: 1 p.e. = $0.0514 \times 10^9$ Vs

Photonis XP3102
1000 V, single photons

Gain = $6.4 \times 10^6$

P/V ~ 2.75
Gain, single photon resolution and timing resolution depend on
- how many photons are produced in the anode?
- which fraction is extracted from the anode and detected in the photodetector?
- how large are the fluctuations of these numbers (light paths, e\textsuperscript{-} back scattering)?

→ Geant4 studies of light transport

3 simulated geometries (not to scale)
Geant4 Results:

Detectable photons vs. incidence angle

$e^{-}$ back scattering ‘switched off’. Error bars correspond to RMS fluctuations in $N_{\text{photons}}$. 
Effect of e\(^{-}\) back scattering

In LYSO, \(\sim\)45\% of 20 keV electrons are back-scattered from X-tal. \(\rightarrow\) partial energy deposition \(\rightarrow\) reduced light yield.

Single (20 keV) photoelectron detection efficiency, averaged over all incidence angles.

\(E_{\text{det}} \geq 90\%\).
X-HPD processing in CERN transfer plant

Evaporation head (Sb, K, Cs)

Light beam for QE online monitoring

Base plate with LYSO anode
Cylindrical crystal (PC119)
X-HPD (PC120)
Testing the tube with short light pulses (H₂ flash lamp), readout of PMT via VME ADC.

→ Tube can be operated up to +/- 24 kV.

Response to (primarily) single photons

Less light for positive HV? Caused by use of C₆F₁₄ as dielectric liquid. Details not yet understood.
Multi photon spectrum

Path fluctuations lead to poor pulse height resolution → Modest photon counting.

C. Joram, NDIP08, Aix-les-Bains, 15-20 June 2008
Simple timing study with single photons from pulsed LED.

- use of digital scope
- measure LED jitter: 0.95 ns
- measure X-HPD resolution
- subtract LED jitter (quadratically)

\[ \Delta t(\text{FWHM}) \approx 2.6 \text{ ns} \]

X-HPD at +20 kV
Dark noise at $U_{acc} = +/- 20$ kV

Tube operates better with +HV at anode.
Polar scan with blue LED (DC mode)

90°

LED (420 nm)
θ +/- 10°

0°

Double cathode effect visible, but less clear than for proto-0 (metal anode).
Polar scan with blue LED (pulse mode, single photons)

Measured spectra at +20 kV

Comparison data / M.C.
Summary...

X-HPD

- is an attractive concept for large area photon detection (e.g. future large volume neutrino telescopes)
- promises higher performance than classical PMT (QE, collection efficiency, TTS)
- First operational X-HPD with LYSO crystal produced and tested.
- Tube works very stable up to +/- 24 kV
- Very good noise performance
- Double cathode effect clearly visible
- Light yield (gain) depends on polar angle, good agreement with Geant4 model.

Outlook...

- Room for improvement of anode geometry → better pulse height resolution and timing
- Demonstration of industrial fabrication.

Thanks to our technicians at CERN, in particular Claude David and Miranda v. Stenis
Back-up Transparencies
CERN photocathode ‘transfer’ plant
Dark noise rate at very low cut values

X-HPD PC 120, dark noise rate

- Cut at 0.5 p.e. PMT = 0.03 - 0.13 p.e. X-HPD

- Negative $U_{\text{acc}}$

- Positive $U_{\text{acc}}$

rate / area (kHz/cm²) vs. $|U_{\text{acc}}|$ (kV)