Development of HPDs for applications in physics and medical imaging

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Outline

- Why Hybrid Photo Detectors?
- Some Developments for physics experiments
  - 5-inch → 10-inch
  - A spherical HPD for neutrino detection
- A flat HPD for 3D-Axial PET scanner

www.cern.ch/ssd/HPD

Great support by our technical staff: F. Cossey, C. David, I. Mcgill, M. v. Stenis, …
Hybrid Photon Detectors (HPD)

Combination of sensitivity of PMT with excellent spatial and energy resolution of silicon sensor

Gain: \[ G \approx \frac{e \cdot U_c}{3.6 \text{ eV}} \]

\[ U_c = 20 \text{ kV} \rightarrow G \approx 5000 \]

Gain is achieved in a single dissipative step!

\[ \sigma_G \approx \sqrt{F \cdot G} \]

small compared to \( \sigma_{\text{electronics}} \)
Classical HPD designs

- Proximity focused
- 1:1 imaging
- Operates in axial magnetic fields.

- ‘Fountain’ focused
- Demagnification D
- No real focusing → ballistic point spread
- Intolerant to magnetic fields

- ‘Cross’ focused
- Demagnification D
- Focusing leads to small point spread
- Intolerant to magnetic fields
Main advantages of HPD technology

- Excellent signal definition
- Allows for photon counting
- Free choice of segmentation (50 µm - 10 mm)
- Uniform sensitivity and gain
- No dead zones between pixels

Drawbacks

- Rel. low gain (3000 - 8000) → low noise electronics required
- Expressed sensitivity to magnetic fields

Viking VA3 chip
(τ_{peak} = 1.3 µs, 300 e- ENC)
U_C = -26 kV

Pad HPD
Single pad
S/N up to 20

• e- backscattering from Si surface
  → continuous ‘background’
  → \( \varepsilon_{det} \) (p.e.) ~ 85-95 %
Some prototype developments for physics experiments
developed and built at CERN

5-inch

127 mm Ø, D ~ 2.5,
2048 channels 1mm²
bialkali photocathode

NIM A 442 (2000) 128-135
NIM A 478 (2002) 400-403
www.cern.ch/ssd/HPD

10-inch

254 mm Ø, D ~ 4,
2048 channels 1mm²
bialkali photocathode

NIM A 504 (2003) 19
NIM A 518 (2004) 574-578
Principle of neutrino detection in C2GT (CERN To Gulf of Taranto)

- $\nu_e$, $\nu_\mu$, $\nu_\tau$ CC reactions in $\text{H}_2\text{O}$
- Fiducial detector volume ~ 1.5 Mt
- Segmented photosensitive ‘wall’ about $250 \times 250 \text{ m}^2$
- $E_\nu$ below threshold for $\tau$ production

Cherenkov light

~ 50 m

10 m

A. Ball et al., C2GT, Memorandum, CERN-SPSC-2004-025, SPSC-M-723

A. Ball et al., Proc. of the RICH2004 conference, subm. to NIM A

The wall is made of ~600 mechanical modules (10 x 10 m²), each carrying 49 optical modules.
The ideal photodetector for C2GT

- large size (>10")
- spherical shape, must fit in a pressure sphere
- ± 120° angle of acceptance
- optimized QE for 300 < λ < 600 nm
- single photon sensitive
- timing resolution 1-2 ns
- no spatial resolution required
- electronics included
- cost-effective (need ~32,000 !)
- adapted to industrial fabrication
C2GT Optical Module

- benthos sphere (432 / 404)
- joint
- optical gel (refr. index matching + insulation)
- standard base plate of HPD 10" (prel. version)
- electrical feed-throughs
- valve

Si sensor

Ceramic support
Electrostatics

Simulations with SIMION 3D

- Potential and field distribution similar to a point charge.
- Low field at photocathode (~100 V/cm),
- Very high field close to Si sensor (~10,000 V/cm). Try to reduce by a grounded field cage around Si sensor.
Transit Time

\[ 0 < \phi < 120^\circ \]
A ‘half-scale’ prototype

208 mm (~8-inch)

Al coating
2 rings

Development in collaboration with Photonis-DEP, C. Fontaine et al.
Current status: All main components ready → ‘dry assembly’

First tests will be done with a metal cube rather than Si sensors
Development for HPDs for medical imaging

→ The 3D axial PET camera

Axial arrangement of camera modules based on matrices of long crystals read out on both sides by HPDs


§ Patent filed. No. WO2004008177 §
Technical realization

- 208 crystals (YAP)
  - $3.2 \times 3.2 \times 100 \text{ mm}^3$
  - gap between crystals 0.8 mm

- HPD
  - proximity focused
  - ceramic body
  - sapphire window
  - bialkali PC

- 2 VATA-GP5 ASIC

Si sensor
- 2 x 104 pads
- (4 x 4 mm$^2$)

Ceramic PCB
- (4 layers)
VATA-GP5

(CERN – IDE AS co-development, www.ideas.no)

- VATA-GP5, 128 ch./chip
- Auto-triggering analog front-end
- Serial and sparse readout
- Time walk compensation
- 0.6 µm CMOS
VATA-GP5 ASIC + ceramic PCB + Si-sensor operational

Si Sensor Depletion
($U_{PC}$ = -15 kV)

- UC (kV)

- $V_{bias}$ (volt)

- signal (ADC counts)

- Qin (fC)

- signal (ADC bin)

Cut-off at 6 kV
(too thick n+ layer)

Serial readout
Sparse readout

DAQ

CsI

CaF$_2$

UV light source

Photo-electrons

Development of HPDs for applications in physics and medical imaging
2 sealed prototype tubes produced so far ... both were not perfect

**PC109**
- 50 mm Ø Si-sensor
- VA-prime electronics
- bialkali cathode (22%)
- HV problem

**PC113**
- PET Si-sensor
- VATA-GP5 electronics
- bialkali cathode
- electronics suffered due to accident during processing
Summary and Outlook

Our team is developing …

- a flat HPD with auto-triggering electronics, aimed at medical imaging applications, in particular PET with single crystal readout.
  
  Sealed fully operational prototype imminent (days!)

- a spherical HPD for underwater Cherenkov detector for neutrino physics.
  
  Sealed prototype later this year.

After finally having entered HEP at large scale (CMS, LHCb), HPDs may also have a bright future in some advanced applications(niches?) in other fields.
BACK-UP slides
Effect of angular spread and magnetic field

- $E_{\text{kin}}(t_0) = 2$ eV (conservative)
- $-40^{\circ} \leq \theta_{\text{em}} \leq 40^{\circ}$ (rel. to surface)

$E \sim 1/r^2$ produces a focusing effect

Effect of earth magnetic field seems to be marginal

- 0.45 Gauss
Is E-field around Si sensor too high?

A grounded grid could help

Grid at ‘natural’ potential: -11 kV

Gradients up to 2000 V/mm at edges of Si sensor

Gradients at Si sensor reduced to ~500 V/mm. High field around grid, f(diam.).
Fabrication

Large number of tubes needed → industrial fabrication
→ internal process (as for large PMTs).

However, this would lead to a ‘pollution’ of Si-sensor and high field region with Cs/K/Sb.
👍 protect by mask (difficult!)
👍 use ‘hybrid’ process?

Q.E. monitoring
Processing in the existing set-up at CERN, used for 5” and 10” HPDs

Only minor mechanical adaptations required.
The graph shows the relationship between input charge (fC) and time walk (ns) for two gains: Gain 0 and Gain 1. The time walk is indicated as +/- 5 ns for both gains. The curves demonstrate a decrease in time walk as the input charge increases.
Experimental set-up for VATA-GP5 tests with photo-electrons

CsI photocathode (300 nm)
Deposited on a grid
(Au, 80% transparency)

UV H₂ flash lamp
(self triggering)

UV H₂ flash lamp
(self triggering)

MgF₂

collimator

MgF₂

CaF₂

photo-electrons

Si sensor (300 µm)
208 pads (4×4 mm²)

mask (at ground)

-vpc = 15-20 kV

vacuum pump (turbo)
P < 10⁻⁵ mbar

DAQ Readout card

VME