Novel Photon Detectors

J. Va’vra, SLAC
Pedro Cabral’s ships - discovery of Brazil at around 1500

When one tries something new, one often does know what to do initially

To succeed, one has to try many possibilities
Status of photon detectors at around 2006:

- MCP-PMT
- MaPMT
- HPD
- HPD+APD
- Drift SiPMT
- Mesh PMT
- SiPMT
- Multi-GEM
- Micromegas+MCP
- Multi-GEM+MHSP
- ReFerenc
- PMT+G-APD

When one tries something new, one often does not know what to do initially. To succeed, one has to try many possibilities.

J. Va'vra, Photon Detectors, Coimbra, Portugal
Content

• **Basic properties of materials used in the photon detectors:**
  (Photocathodes, Transmission of materials, refraction index, etc.)

• **Vacuum-based photon detectors:**
  (MCP-PMT, MaPMT, mesh PMTs, new versions of classical PMTs)

• **Silicone photon detectors:**
  (APD, Geiger mode APD = G-APD = SiPMT)

• **Hybrid photon detectors - vacuum+Si:**
  (HPD, ReFerenc, APD, HPD with APD, etc.)

• **Gaseous-based photon detectors:**
  (Multi-GEM, Micromegas+MCP, etc.)
What is important for the photon detector choice these days?

• Photocathode QE wavelength response
• Large photoelectron detection efficiency (Detected QE)
• Gain characteristics
• Timing characteristics ($\sigma_{TTS}$)
• Pixilization
• Cross-talk
• Operation in magnetic field
• Aging and reliability
• Affordability
Photocathode QE
In the past 20 years, there was a steady push to develop photocathodes operating in the visible wavelength range. The main reasons: (a) The radiators are very chromatic in the UV region, (b) Materials are less transparent, expensive, (c) Mirrors are difficult to make, expensive, (d) The far UV region is difficult to work in (cleanliness, outgasing pollution, etc).

- **Benzene** was used by HRS, **TMAE** by DELPHI, SLD, OMEGA, CERES, JETSET and CAPRICE; **TEA** by CLEO, **CsI** by ALICE, COMPASS, HADES; **Bialkali** by HERA-B, DIRC, HERMES, Belle, CELEX, **Multi-alkali** by LHC-b, and **GaAsP, GaAs or Si** will be pushed by new detectors.

- **QE** in TMAE, TEA and Benzene measured in the gas.
QE depends on the manufacturer

Different manufacturers have different QE response.
Not all photocathodes are available commercially!
QE in the gas is smaller than in the vacuum

To compete with the vacuum-based devices in QE, the gaseous detector needs a high electric field to reduce the photoelectron backscattering to the photocathode.

Choice of gas is important!!

QE boost with a Lacquer (anti-reflection coating) & Wavelength Shifter (WLS)

R. Mirzoyan, M. Hayashida, E. Lorenz, M. Teshima, Max-Planck-Institute for Physics, Munich, Germany

1) Lacquer:

2) WLS:
   - Butyl-PBD (260-340 to 360-460 nm)
   - POPOP (300-400 to 400-500 nm)
   - Paraloid B72 (n = 1.4) in Toluene
New trends in timing

- Here I mean a resolution of 5-20 ps, not 50-100 ps!
- Do we have a “know how”, detectors and electronics to do it?
Timing is a new direction in the photon detector physics

- A timing resolution of a few ps would be a revolution in the PID techniques!! There are no books to follow...
- **Progress driven by:**
  a) Use of the Cherenkov radiator rather than scintillators, b) use of new detectors with small transit time spread $\sigma_{TTS}$, c) progress in the ASIC-based electronics, d) paying attention to every detail (light travels $\sim300\mu$m/ps), e) new laser-based testing methods.
## Transit Time Spread $\sigma_{TTS}$ of photon detectors

($\sigma_{TTS}$ refers to the single electron Transition Time Spread)

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Name</th>
<th>Type/Feature</th>
<th>$\sigma_{TTS}$ [ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photonis</td>
<td>Quantacon</td>
<td>XP2020/UR</td>
<td>~ 150</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>HAPD</td>
<td>HPD+Multi-cell APD</td>
<td>~ 90</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>Flat-panel</td>
<td>H-8500</td>
<td>~ 140*</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>Multi-mesh</td>
<td>R-6135</td>
<td>~ 80</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>MCP-PMT</td>
<td>6µm hole dia.</td>
<td>~ 30</td>
</tr>
<tr>
<td>Burle/Photonis</td>
<td>MCP-PMT</td>
<td>10µm hole dia.</td>
<td>~ 32*</td>
</tr>
<tr>
<td>Sopko/Prague</td>
<td>G-APD</td>
<td>Single-cell APD</td>
<td>~ 38*</td>
</tr>
<tr>
<td>Dolgoshein</td>
<td>G-APD/SiPMT</td>
<td>Multi-cell APD</td>
<td>~ 60</td>
</tr>
</tbody>
</table>

* measured by author
Chromatic broadening of a light impulse

\[ v_{\text{group}} = \frac{c_0}{n_{\text{group}}} = \frac{c_0}{[n_{\text{phase}} - \lambda \frac{dn_{\text{phase}}}{d\lambda}]} \]

\[ t = \frac{L}{v_{\text{group}}} = L \frac{[n_{\text{phase}} - \lambda \frac{dn_{\text{phase}}}{d\lambda}]}{c_0} \]

\[ dt = \frac{L \lambda d\lambda}{c_0} - \frac{d^2n}{d\lambda^2} \]

- Chromaticity can easily dominate the timing resolution.

Red gets ahead of blue

\[ n_{\text{phase}}(\text{red}) < n_{\text{phase}}(\text{blue}) \Rightarrow v_{\text{group}}(\text{red}) > v_{\text{group}}(\text{blue}) \]
New laser-based testing methods

J. Va'vra, log book

PiLas laser head:

Control unit
Laser diode
Lens + collimator
Start
1.5-meter long cable

5m-long fiber

Lens + collimator

Detector

Calibration of a fast detector:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SLAC tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser diode source</td>
<td>PiLas</td>
</tr>
<tr>
<td>Wavelength</td>
<td>635 nm</td>
</tr>
<tr>
<td>TTS light spread (FWHM)</td>
<td>~ 35 ps</td>
</tr>
<tr>
<td>Fiber size</td>
<td>62.5 µm</td>
</tr>
</tbody>
</table>

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J. Va'vra, Photon Detectors, Coimbra, Portugal
Vacuum-based photon detectors

1. Micro-channel PMTs (MCP-PMT)
2. Multi-anode PMTs (MaPMT)
3. Mesh PMTs
4. HPD with APDs (HAPD)
5. PMTs with Geiger mode APDs (G-APD)
6. ReFerenc detector
### Burle/Photonis MCP-PMT

#### Burle data sheets

![Faceplate and Dual MCP Diagram]

#### A real device:

![Real Device Image]

#### Open area tube:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photocathode</td>
<td>Bialkali or Multi-alkali</td>
</tr>
<tr>
<td>Number of MCPs</td>
<td>2</td>
</tr>
<tr>
<td>Total average gain @ -2.4kV &amp; B = 0 kG</td>
<td>~5 x 10^5</td>
</tr>
<tr>
<td>Geometrical collection efficiency of the 1-st MCP</td>
<td>60 - 70%</td>
</tr>
<tr>
<td>Geometrical packing efficiency (plus QE edge effects)</td>
<td>50 - 85%</td>
</tr>
<tr>
<td>Fraction of late photoelectrons arrivals</td>
<td>20 - 30%</td>
</tr>
<tr>
<td>Total fraction of “in time” photoelectrons detected</td>
<td>25 - 50%</td>
</tr>
<tr>
<td>$\sigma_{TTS} = 10 \mu m &amp; 25 \mu m$ MCP hole dia. &amp; B = 0 kG</td>
<td>30-32 &amp; 50-60 ps</td>
</tr>
<tr>
<td>Matrix of pixels</td>
<td>2x2 or 8x8 or 32x32</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>4 or 64 or 1024</td>
</tr>
<tr>
<td>Pixel size (8x8 &amp; 32x32 matrix)</td>
<td>5.94 x 5.94 or ~1 x 1 [mm^2]</td>
</tr>
</tbody>
</table>
MCP-PMT: transit time & gain
Burle/Photonis information

**Cathode – MCP Transit Time:**

Increased voltage or decreased gap can reduce the transit time.

**MCP Transit Time:**

Smaller pore size smaller the transit time.

**MCP Gain:**

- Typical secondary yield is 2.
- L:D = 40:1 seems to be optimum design; for this ratio there are typically 10 strikes, i.e., Gain ~ $2^{10} \sim 10^3$ per single MCP plate; $G \sim e^{(A/L/D)}$
- For 10 $\mu$m dia. MCP hole, a ratio of 40:1 cannot be achieved for a 50x50 mm$^2$ size MCP (too fragile); therefore, a ratio of 60:1 is used. As a result, such MCP has slightly worse transit time.
**Tails & edge effects in MCP-PMT timing**


25 µm hole dia. (L = 6mm):

- **Burle/Photonis MCP-PMT, 85011-501 Nominal design, B = 0 kG.**
- A long tail is due to recoiled electrons from top MCP surface. To reduce the tail one wants to decrease L.
- Measure typically σ = 70-80ps in the central pad region, and 20-30% worse near the boundary.
- Worse timing resolution around edges is due to the charge sharing, causing a lower pulse height.
- Use the Constant-Fraction-Discriminator; TDC with 25ps/count TDC
- Measurements done with PiLas laser diode (635nm) in the single photo-electron mode. The laser beam aims at one spot of less than 1 mm in dia.

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MCP-to-cathode distance


MCP-to-Cathode distance = 6 mm
85011-501 Nominal design:

MCP-to-Cathode distance ~0.85 mm
85011 430 Drop Faceplate:

Penalty of this design: the efficiency drops to zero half way through all edge pads.

J. Va'vra, Photon Detectors, Coimbra, Portugal
Limit of the Single-photon timing resolution

J. Va’vra et al., The 10th Pisa meeting on Advanced detectors, a Biodola, Italy, 2006

Burle MCP-PMT 85012-501 (open area = Small margin around the boundary)

- 10 µm MCP hole diameter
- B = 0 kG
- 64 pixel devices, pad size: 6 mm x 6 mm.
- Phillips CFD
- PiLas red laser diode operating in single photoelectron mode (635 nm).

Hamamatsu C5594-44
1.5 GHz BW, 63x gain

Ortec VT120A
~0.4 GHz BW, 200x gain + 6dB

Fit: g + g

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Timing resolution = \( f(N_{\text{photoelectrons}}) \)

J. Va’vra et al., The 10th Pisa meeting on Advanced detectors, a Biodola, Italy, 2006

- **MCP-PMT with no amplifier:** \( \sigma \sim 10-11 \text{ ps for } N_{\text{pe}} \sim 140 \).
- **MCP-PMT with amplifier:** \( \sigma \sim 12 \text{ ps for } N_{\text{pe}} > 30 \) (with Hamamatsu C5594-44; similar results with Ortec 9306 amp, and somewhat worse result with slower Ortec VT120A).

- **Electronics:** \( \sigma_{\text{electronics}} \sim 10 \text{ ps} \) => **Electronics resolution dominates the result!**

- **In the “<10ps timing resolution domain,” the amplifier speed & noise performance** are both crucial: the resolution is \( \sigma_t \sim \sigma_A/(ds_0/dt)_{t=0} \), where \( \sigma_A \) is the noise, and \( (ds_0/dt)_{t=0} \) is the slope at the zero-crossing point of CFD.
The best timing resolution achieved with an MCP-PMT
K. Inami et al., Nagoya Univ., Japan - SNIC conference, SLAC, April 2006

MCP-PMT:
R3809U-50-11X
Window: 11 mm
MCP hole: 6 mm

TDC:

Electronics resolution:

Use two identical TOF detectors in the beam (Start & Stop):

Single photon resolution
= \sigma_{TTS} (N_{pe} \sim 1):

Beam resolution with Qtz. Radiator (N_{pe} \sim 180):

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MCP gain reduction in a magnetic field

Russian MCP-PMT:
Barnyakov et al., Novosibirsk, Russia, The 10th Pisa meeting, La Biodola, Italy, 2006

Burle MCP-PMT:
M.Akatsu et al., Nagoya, Japan

• **Gain in MCP:** \( G \sim e^{(A \times \text{MCP thickness}/\text{MCP dia})} \) - drops in a magnetic field.

• **The 25µm dia. holes are too large. One needs to reduce their size to ~6-10µm dia., to operate at 15kG.**

9/10/06  J. Va'vra, Photon Detectors, Coimbra, Portugal
Single photon timing resolution at $B = 15 \text{ kG}$

J. Va’vra et al., The 10th Pisa meeting on Advanced detectors, a Biodola, Italy, 2006

### Reduction of pulse height in a large magnetic field leads to the degradation of the timing resolution.

- 10µm hole 4-pad Burle/Photonis MCP-PMT with Ortec VT-120A amplifier.
Aging rate of MCP-PMT

I. Adachi, et al., Nagoya University, SuperB workshop at SLAC

Protective $\text{Al}_2\text{O}_3$ film:

- The protective $\text{Al}_2\text{O}_3$ layer blocks the positive ions backflow to cathode.
- Nagoya group predicts ~13 years of lifetime at Super B-factory.
- However, there is a price: a 40% reduction of the photoelectron transmission.
- Japanese group concluded that the Russian protective film does not work as well.
- Russian results indicate that the blockage of positive ions with 3 MCPs seems to be as effective as with a protective $\text{Al}_2\text{O}_3$ layer, up to a rate of $\sim 10^8 \text{ pe/sec}$. They do not show an equivalent integrated charge dose as the Nagoya people show.
- It is hopeful, but more studies are needed.

A. Barnyakov et al., Novosibirsk, Russia

The 10th Pisa meeting, La Bioldola, Italy, 2006

Three MCP solution:
Possible applications of the MCP-PMT detectors

Super B-factory RICH detectors:

TOP counter (Nagoya Univ.):

![Linear-array type photon detector](image)

Focusing DIRC prototype (SLAC):

![Focusing DIRC prototype](image)

PID based on TOF with a ps resolution:

(Chicago Univ., Argonne lab, SLAC collaboration)

Aim: To find limits of intrinsic timing resolution of a MCP-PMT - \( \sigma < 10 \) ps

ATLAS p-p diffractive collisions

A. Brandt et al., FP420 collaboration

1) Cherenkov quartz detector:

![Cherenkov quartz detector](image)

2) Cherenkov gas detector:

![Cherenkov gas detector](image)

Goal: \( \sigma \sim 10-20 \) ps
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Photocathode</strong></td>
<td>Bialkali only at present</td>
</tr>
<tr>
<td>Number of dynodes</td>
<td>12</td>
</tr>
<tr>
<td>Total average gain @ -1kV</td>
<td>~10^6</td>
</tr>
<tr>
<td>Geometrical collection efficiency of the 1-st dynode</td>
<td>70 - 80%</td>
</tr>
<tr>
<td>Geometrical packing efficiency (plus QE edge effects !!)</td>
<td>97%</td>
</tr>
<tr>
<td>Fraction of late photoelectrons arrivals</td>
<td>~5%</td>
</tr>
<tr>
<td>Total fraction of “in time” photoelectrons detected</td>
<td>65 - 75%</td>
</tr>
<tr>
<td>$\sigma_{\text{TTS}}$ (SLAC measurement) - H8500</td>
<td>~ 140-150 ps</td>
</tr>
<tr>
<td>Matrix of pixels (H8500 &amp; H9500)</td>
<td>8 x 8 &amp; 16 x 16</td>
</tr>
<tr>
<td>Number of pixels (H8500 &amp; H9500)</td>
<td>64 &amp; 256</td>
</tr>
<tr>
<td>Pixel size (H8500 &amp; H9500)</td>
<td>5.8 x 5.8 &amp; 2.9 x 2.9 [mm^2]</td>
</tr>
</tbody>
</table>
Hamamatsu MaPMT

C. Field, T. Hadig, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, J. Schwiening, J. Uher, and J. Va’vra,

Flat Panel H8500 PMT:

430nm:

- MaPMT has much smaller tail compared to MCP-PMTs.
- The Hamamatsu MaPMT uniformity is ~1:2.5, compared to Burle’s MCP-PMT uniformity of ~1:1.5.
- Hamamatsu Flat Panel MaPMT relative efficiency is 50-70% of the Photonis XP 2262B PMT at 430nm. The efficiency drops to 30-50% around the edges.
- Clearly see the details of the dynode electrode structure. Spatial resolution of the system is less than 150 µm, for a step size of 25µm.

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Mesh PMTs
Hamamatsu Multi-anode Fine-mesh PMT
R-6135-L24 $\alpha$, $\beta$, $\gamma$

M. Hirose et al., NIM A460(2001)326, Hamamatsu&Nagoya R&D

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photocathode</td>
<td>Bi-alkali</td>
</tr>
<tr>
<td>Maximum magnetic field</td>
<td>1.5 Tesla</td>
</tr>
<tr>
<td>Geometrical packing efficiency</td>
<td>$\sim90%$</td>
</tr>
<tr>
<td>Collection efficiency of the dynode structure</td>
<td>$52% (\alpha) &amp; 63% (\beta) &amp; 85% (\gamma)$</td>
</tr>
<tr>
<td>Cathode-the 1-st dynode distance = L</td>
<td>2.5-3 ($\alpha$) and 1 ($\beta,\gamma$) mm</td>
</tr>
<tr>
<td>Mesh design (lines/inch)</td>
<td>2000 ($\alpha,\beta$) 2500 ($\gamma$) lines/inch</td>
</tr>
<tr>
<td>Mesh design (pitch)</td>
<td>9 ($\gamma$) $&amp;$ 12.5 ($\beta$) $\mu$m</td>
</tr>
<tr>
<td>Operating voltage (B=1.5 Tesla)</td>
<td>-3.4 kV ($\gamma$)</td>
</tr>
<tr>
<td>Pixel size</td>
<td>26.5 mm x 0.8 mm</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>24</td>
</tr>
<tr>
<td>Gain in 1.5 Tesla</td>
<td>$\sim5\times10^6 @ -3.4$ kV ($\gamma$)</td>
</tr>
<tr>
<td>Number of stages</td>
<td>24 ($\alpha$) 19 ($\beta,\gamma$)</td>
</tr>
<tr>
<td>Resistor chain (K - D1 - D2 - -&gt; A)</td>
<td>1-1-......-1 ($\alpha$) $&amp;$ 2-1-......-1 ($\beta,\gamma$)</td>
</tr>
<tr>
<td>PMT rise-time</td>
<td>$\sim1.0$ ns</td>
</tr>
<tr>
<td>Timing resolution for Npe =1 @ B &lt; 1Tesla</td>
<td>$\sigma_{TTS} \sim100$ ps</td>
</tr>
<tr>
<td>Timing resolution for Npe =1 @ B = 1.5 Tesla</td>
<td>$\sigma_{TTS} \sim150$ ps</td>
</tr>
</tbody>
</table>

- A good single photon pulse height distribution.
- A good transit time spread.
- It can operate at 1.5 Tesla magnetic field.
HPD

1. HPD with cross-focusing optics
2. HPD with fountain-focusing optics
3. HPD with proximity-focusing optics

- Motivation: to provide a single photoelectron detection with excellent spatial resolution by employing highly pixilated PIN diode array
HPD equivalent circuit

- **Gain** \( \sim (V_{\text{high voltage}} - V_{\text{threshold}}) \frac{q_e}{3.62 \text{ eV}} \)
  
  where \( V_{\text{threshold}} \sim -2.1 \text{ kV} \) typically, is energy loss in the Al contact layer, \( q_e \) is the electron charge.

- **HPD rise time** is a convolution of:
  
  \[ \text{Amp}_\text{rise time} \otimes \text{Electron } \sigma_{\text{TTS}} \otimes \text{Hole } \sigma_{\text{TTS}} \]
  
  \( \sim 2\text{-}3 \text{ ns} \otimes \sim 100\text{ps} \otimes 3\text{-}4\text{ns} \).

- **Electron \( \sigma_{\text{TTS}} \)** is controlled by the electrostatics
  

- **Hole \( \sigma_{\text{TTS}} \)** is controlled by PIN diode parameters current \( I(t) \) and its width, which is controlled by variables such as the depletion depth, bias voltage, depletion voltage, and Si resistivity.
  
  (P.B. Cushman & A. Heering, IEEE, San Diego, CA, 2001)

- **Photoelectron back-scattering from Si at 20kV:**
  
  - \( \sim 20\% \) electrons deposit lower energy to Si ! \( \Rightarrow \) detection eff. is \(< 100\% \).
  
  - for higher light levels develop background between peaks.
  
  - backscattered electrons will hit another pixel, which results in cross-talk
    
HPD with cross-focusing optics
Thierry Gys et al., LHC-b development

DEP tube:

Cross-focussing optics:

- Sensitive to magnetic field
- Low gain operation (~5000 x)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Photocathode</strong></td>
<td>Multi-alkali (S-20)</td>
</tr>
<tr>
<td><strong>Accelerating medium</strong></td>
<td>vacuum</td>
</tr>
<tr>
<td><strong>Operating voltage</strong></td>
<td>-20 kV</td>
</tr>
<tr>
<td><strong>Geometrical packing efficiency</strong></td>
<td>~81%</td>
</tr>
<tr>
<td><strong>Detector</strong></td>
<td>Canberra PIN diode</td>
</tr>
<tr>
<td><strong>Photoelectron detection efficiency</strong></td>
<td>70 - 80%</td>
</tr>
<tr>
<td><strong>Electron optics &amp; demagnification size</strong></td>
<td>Cross-focused &amp; 5</td>
</tr>
<tr>
<td><strong>Si PIN diode pixel size</strong></td>
<td>500 µm &amp; 500 µm</td>
</tr>
<tr>
<td><strong>Pixel size (at the photo-cathode)</strong></td>
<td>2.5 mm x 2.5 mm</td>
</tr>
<tr>
<td><strong>Pixel Matrix &amp; Number of pixels</strong></td>
<td>32 x 32 &amp; 1024</td>
</tr>
<tr>
<td><strong>PIN diode silicon volume resistivity</strong></td>
<td>~5 kΩ.cm</td>
</tr>
<tr>
<td><strong>Ion feedback rate</strong></td>
<td>&lt; 10⁻³</td>
</tr>
<tr>
<td><strong>Gain ~ (V-V_th)q/3.62 eV, V_th ~2.1kV</strong></td>
<td>~5000 @ -20kV</td>
</tr>
<tr>
<td><strong>Pixel capacitance</strong></td>
<td>~4 pF</td>
</tr>
<tr>
<td><strong>Electronics noise</strong></td>
<td>~160 electrons</td>
</tr>
<tr>
<td><strong>Dark count noise rate</strong></td>
<td>0.03 - 3 kHz/cm²</td>
</tr>
<tr>
<td><strong>Encapsulated amplifier’s shaping time</strong></td>
<td>~25 ns</td>
</tr>
</tbody>
</table>

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HPD with fountain-focusing optics
J. Sequinot, C. Joram, A. Bream, P. Wielhammer, E. Chesi, T. Ypsilantis, CERN development

CERN 5 inch dia. tube:

Fountain-focusing optics:

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</tr>
<tr>
<td>Accelerating medium</td>
<td>vacuum</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>-20 kV</td>
</tr>
<tr>
<td>Detector</td>
<td>Pixel Silicon PIN diode</td>
</tr>
<tr>
<td>Electron optics &amp; demagnification</td>
<td>Fountain focusing &amp; 4</td>
</tr>
<tr>
<td>Si PIN diode Pixel size</td>
<td>250( \mu )m x 250( \mu )m</td>
</tr>
<tr>
<td>Pixel size (at the photo-cathode)</td>
<td>1 mm x 1 mm</td>
</tr>
<tr>
<td>Matrix &amp; Number of pixels</td>
<td>16 x 128 &amp; 2048</td>
</tr>
<tr>
<td>Gain ( \sim (V-V_{th}) \frac{q_e}{3.62 \text{ eV}} ), ( V_{th} \sim 2.1 \text{ kV} )</td>
<td>( \sim 5000 @ -20 \text{ kV} )</td>
</tr>
<tr>
<td>Measured electronics noise</td>
<td>( \sim 400 ) electrons</td>
</tr>
<tr>
<td>Random noise per pad at 20 kV</td>
<td>( 5.6 \times 10^{-4} )</td>
</tr>
<tr>
<td>Type of amplifier</td>
<td>Viking VA3</td>
</tr>
<tr>
<td>Shaping time</td>
<td>1.3 ( \mu ) s</td>
</tr>
</tbody>
</table>

- **Sensitive to magnetic field**
- **Low gain operation (~5000x)**

9/10/06  J. Va'vra, Photon Detectors, Coimbra, Portugal
Pulse height spectrum of HPD

**DEP tube** (Thierry Gys et al., LHC-b):

- Superb pulse height spectrum
- Allows the photon counting

**CERN tube** (C. Joram, J. Seginot, T. Ypsilantis):

- Viking VA3 chip ($\tau_{\text{peak}} = 1.3$ μs, 300 e$^-$ ENC)
  - $U_C = -26$ kV
- Pad HPD
  - Single pad S/N up to 20
**HPD with proximity-focusing optics**

**DEP tube for CMS HCAL readout:**

<table>
<thead>
<tr>
<th>Photocathode</th>
<th>Multi-alkali (S-20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerating medium</td>
<td>vacuum</td>
</tr>
<tr>
<td><strong>Operating voltage</strong></td>
<td>-12 kV</td>
</tr>
<tr>
<td><strong>Geometrical packing efficiency</strong></td>
<td>~63%</td>
</tr>
<tr>
<td>Detector</td>
<td>Canberra PIN diode</td>
</tr>
<tr>
<td>Overall uniformity</td>
<td>~98%</td>
</tr>
<tr>
<td>Cross-talk from pixel-to-pixel</td>
<td>&lt;2%</td>
</tr>
<tr>
<td>Pixel capacitance</td>
<td>~5pF</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>19 or 73</td>
</tr>
<tr>
<td>PIN diode bias voltage</td>
<td>60-100 Volts</td>
</tr>
<tr>
<td>Pixel size at the photo-cathode</td>
<td><strong>2.5 mm flat-to-flat</strong></td>
</tr>
<tr>
<td>Electron optics &amp; demagnification</td>
<td>Proximity focused &amp; 1</td>
</tr>
<tr>
<td>PIN diode silicon volume resistivity</td>
<td>~5 kΩ.cm</td>
</tr>
<tr>
<td><strong>Gain</strong> ((V-V_{th})q_e/3.62 \text{ eV}, V_{th} \sim 2.1kV)</td>
<td>~2500 @ ~12kV</td>
</tr>
<tr>
<td><strong>Required electronics noise</strong></td>
<td>~400-600 electrons</td>
</tr>
<tr>
<td>Type of amplifier</td>
<td>Charge integrating</td>
</tr>
</tbody>
</table>

**Uniformity of the CMS HCAL19-pixel HPD:**

- Very uniform response; no dead zones.
- Can operate in a 4 Tesla magnetic field


9/10/06 J. Va'vra, Photon Detectors, Coimbra, Portugal
Timing resolution of HPD: $\sigma = f(N_{pe})$

R. DeSalvo:

- **For Si detectors**, followed by charge sensitive amplifier, the timing resolution is typically determined by a ratio of the amplifier noise and the slope of the pulse at the threshold $V_{th}$:

$$\sigma_t = \frac{\sigma_{AMP}}{(dV/dt) \mid_{at \ threshold \ V_{th}}} \sim \sigma_{AMP} \times Tr/V_{peak}$$

where $\sigma_{AMP}$ [mV] is amplifier noise, $Tr$ is the pulse rise time and $V_{peak}$ [mV] is the peak amplitude of the HPD signal.

- $V_{peak}$ should be large (high HPD gain, or add APD).
- $\sigma_{AMP}$ should be small.
- $Tr$ should be small

$\Rightarrow$ small capacitance/pixel, large PIN diode bias voltage, use APDs, drift electrons instead of holes in Si, etc.

- Want to trigger where pulses $dV/dt$ is max.

A.H. Heering:
(DEP internal memo)

- The formula works to ~10%
- For $N_{pe} = 1$, the best we can do $\sigma_{TTS} \sim 400$ ps
HPD + APD

1. HPD+APD with single APD
2. HPD with Multi-pixel APD

- Motivation: to improve a S/N ratio & timing resolution of HPD
The first HPD + APD = HAPD
R&D development in 1995 by INTERVAC Co., USA, E. Lorenz, private communcation

<table>
<thead>
<tr>
<th>Photocathode</th>
<th>GaAsP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerating medium</td>
<td>vacuum</td>
</tr>
<tr>
<td>Max. recommended value of $V_{\text{photocathode}}$</td>
<td>$&lt; 10 \text{ kV}$</td>
</tr>
<tr>
<td>Pixel capacitance</td>
<td>$\sim 40 \text{ pF}$</td>
</tr>
</tbody>
</table>
Hamamatsu HAPD R7110U-07
(derivative from an old INTERVAC tube)
S. Matsui et al., NIM A463(2001)220, Belle Detector R&D in Nagoya

HAPD:

<table>
<thead>
<tr>
<th></th>
<th>Multi-alkali</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photocathode</td>
<td></td>
</tr>
<tr>
<td>Accelerating medium</td>
<td>vacuum</td>
</tr>
<tr>
<td>Max. recommended value of $V_{\text{photocathode}}$</td>
<td>-8.5 kV</td>
</tr>
<tr>
<td>APD diode bias voltage $V_{\text{APD}}$</td>
<td>~155 Volts</td>
</tr>
<tr>
<td>Avalanche Photodiode Detector diameter</td>
<td>3mm dia.</td>
</tr>
<tr>
<td>Sensitive area</td>
<td>8 mm dia.</td>
</tr>
<tr>
<td>Pixel capacitance</td>
<td>120 pF</td>
</tr>
<tr>
<td>Geometrical packing efficiency</td>
<td>16 %</td>
</tr>
<tr>
<td>Gain @ $V_{\text{photocathode}} = -9$ kV and $V_{\text{APD}} \sim 160$ V</td>
<td>$\sim 1.5 \times 10^5$</td>
</tr>
<tr>
<td>Type of amplifier</td>
<td>MITEQ, 60dB, 300MHz BW</td>
</tr>
<tr>
<td>Rise time, fall time, width</td>
<td>~1.1 ns, ~14.8 ns, ~4.9 ns</td>
</tr>
<tr>
<td>Timing resolution per single photon</td>
<td>$\sigma_{\text{TTS}} \sim 150$ ps</td>
</tr>
<tr>
<td>Planned operating magnetic field</td>
<td>1.5 Tesla</td>
</tr>
</tbody>
</table>

Pulse height spectrum:

9/10/06  J. Va'vra, Photon Detectors, Coimbra, Portugal
Hamamatsu HAPD for MAGIC experiment

Based on the initial development of R7110U-01MOD tube - initiated by E. Lorenz,
MPI/Hamamatsu joint development for MAGIC experiment

HAPD:

The MAGIC telescope:

Pulse height spectrum:

Photocathode | GaAsP
---|---
Bandwidth [nm] | 250 < λ < 700
Max. value of $V_{\text{photocathode}}$ | -8 kV
APD diode bias voltage $V_{\text{APD}}$ | ~400 Volts
Sensitive area | 18 mm dia.
Pixel capacitance | 24 pF
Total HPD gain @ -8kV | ~1600
Total APD gain @ 400 V | ~50
Total gain (APD gain alone is ~30x) | ~8 x $10^4$
Rise time | ~0.8 ns
Fall time | ~1.9 ns
Pulse width | ~2.1 ns

Aging of GaAsP photocathode

Very fast pulses thanks to small capacitance:

9/10/06

J. Va'vra, Photon Detectors, Coimbra, Portugal
**HPD with Multi-pixel Avalanche Diode**


**HAPD with 8x8 APD array:**

<table>
<thead>
<tr>
<th>Photocathode</th>
<th>Multi-alkali</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. value of $V_{\text{photocathode}}$</td>
<td>$\sim 9$ kV</td>
</tr>
<tr>
<td>Max. APD diode bias voltage $V_{\text{APD}}$</td>
<td>$\sim 400$ Volts</td>
</tr>
<tr>
<td>Sensitive area</td>
<td>18 mm dia.</td>
</tr>
<tr>
<td>APD pixel matrix</td>
<td>8 x 8</td>
</tr>
<tr>
<td>Area per pixel</td>
<td>2 x 2 mm$^2$</td>
</tr>
<tr>
<td>Sensitive area</td>
<td>16 x 16 mm$^2$</td>
</tr>
<tr>
<td>Total HPD gain @ -8kV</td>
<td>$\sim 2000$</td>
</tr>
<tr>
<td>Total APD gain @ 400 V</td>
<td>$\sim 50$</td>
</tr>
<tr>
<td>Total Gain (design)</td>
<td>$\sim 5 \times 10^4$</td>
</tr>
<tr>
<td>Transit time spread $\sigma_{\text{TTS}}$</td>
<td>$\sim 90$ ps</td>
</tr>
<tr>
<td>Pixel uniformity</td>
<td>$\sim 8%$</td>
</tr>
<tr>
<td>Low gain region between pixels</td>
<td>$\sim 0.12$ mm</td>
</tr>
</tbody>
</table>

- **Proximity focusing design**
  - $\Rightarrow$ can work in magnetic field
- **Back-illuminated APD array** $\Rightarrow$ more uniformity

**Back-illuminated 8x8 APD array:**
HPD with Multi-pixel Avalanche Diode


Timing resolution:

Pulse height spectrum:

QE:

Present status:

- So far, in the experimental test setup, they reached rather low gain of ~10^4, poor S/N ratio, and somewhat lower QE.
- Activation changes properties of APD
- More R&D needed.
ReFerence Photosensor = HPD + Winston cone
D. Ferenz, IEEE, 2001 & Beaune 2005, and private communication

Concept:

Hermetic coverage with hexagonal cells:

- Could be used for large area applications with low cost, if one could “parasit” on the technology of the flat TVs’.
- R&D is in progress

9/10/06

J. Va'vra, Photon Detectors, Coimbra, Portugal
Silicone photon detectors

1. Single-cell Geiger mode APD (G-APD)
2. Multi-cell Geiger mode APD (G-APD or SiPMT)
3. Geiger mode APD with a drift
Single-cell Geiger mode operating APD = G-APD


G-APD:

Single photoelectron timing resolution:

J.Va’vra, log book

- Slightly worse timing resolution result than the MCP-PMT with 10 µm holes.
- 100 µm dia. GaP G-APD operating in a Geiger mode with active quenching. These devices are 15-20 years old !!!
- Timing tests with the PiLas laser diode
Multi-cell Geiger mode operating APD = G-APD = SiPMT

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photocathode</td>
<td>Silicon</td>
</tr>
<tr>
<td>Accelerating medium</td>
<td>Si</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>24-25V</td>
</tr>
<tr>
<td>Geometrical packing efficiency</td>
<td>~44%</td>
</tr>
<tr>
<td>Pixel size</td>
<td>42 µm x 42 µm</td>
</tr>
<tr>
<td>Pixel capacitance</td>
<td>~100 fF</td>
</tr>
<tr>
<td>Protecting resistor on each pixel</td>
<td>~100-200 kΩ</td>
</tr>
<tr>
<td>$V_{bias} - V_{breakdown}$ (Geiger condition: $V_{bias} &gt; V_{breakdown}$)</td>
<td>A few Volts</td>
</tr>
<tr>
<td>Number of pixels (possible limit ~4000/mm²)</td>
<td>~576 / mm²</td>
</tr>
<tr>
<td>Electric field in the silicon</td>
<td>(3-5) x 10⁵ V/cm</td>
</tr>
<tr>
<td>Dark noise rate (at room temperature)</td>
<td>A few MHz/mm²</td>
</tr>
<tr>
<td>Gain</td>
<td>1.5x10⁶ @ 24.5V</td>
</tr>
<tr>
<td>Gain uniformity</td>
<td>~10%</td>
</tr>
<tr>
<td>Typical rise time</td>
<td>~1ns</td>
</tr>
<tr>
<td>Typical fall time ($\tau \sim C_{pixel} R_{pixel} \sim 30$ns)</td>
<td>~100ns</td>
</tr>
<tr>
<td>Timing resolution per single photon</td>
<td>$\sigma_{TTS} \sim 60$ps</td>
</tr>
</tbody>
</table>

Each pixel = binary device  SiPM = analogue detector

9/10/06
J. Va'vra, Photon Detectors, Coimbra, Portugal 48
Dark count rate of SiPM = f(Threshold)

Pulse height spectrum
B. Dolgoshein, Erice, 2003:

Dark Count Rate
V. Saveliev, IEEE2005, 2005, Puerto-Rico:

- The single photoelectron detection threshold has an excessively large dark noise rate (>10^7 Hz). This limits application for the RICH detectors, at present, even though that the pulse height spectra are superbly good.
Limitations of SiPMTs at present

V. Saveliev & R. Mirzoyan presentations:

- Optical cross-talk: probability to fire the neighbor cell is >50% in the Geiger mode regime.
- To reduce the optical cross-talk build trenches around each cell.
- Because of the dead space around each cell, the active area ~25 - 80%.
- Photon detection efficiency (PDE):
  
  Highest reported value ≈ 30%

(Beatne-2005 http://beaune.in2p3.fr/)
The answer to SiPMT geometrical acceptance problems: The Avalanche Drift Diode - backilluminated SiPMT


- Combine “Si drift detector & G-APD” & “Backillumination” => uniform response.
- Advantages: (a) 100% fill factor, (b) high (>80%) detection efficiency for 300 < λ < 600nm, (b) small capacitance (c) short integration & dead time, (d) ~1 ns timing resolution, (e) high gain (>10^5), large pixel size (1cm^2 desired).
- Status: Simulation, design a production done. Available in 2007 after extensive testing.
A new readout of large area Smart Photomultiplier by Geiger-mode APDs

E. Lorenz and D. Ferenc

“Smart PMT” for deep water detector (original design by Phillips):

In this study use Geiger mode APD (G-APD) from Micron Co. for the secondary detector

Area: 3x3mm²
Pixel density: 10⁴/mm²

• Motivation: Future neutrino detectors require large detector volumes and this requires large number of PMTs. This in turn requires to develop large area PMTs, require simplicity, high QE, high photoelectron collection, reliability, low power consumption
Gaseous photon detectors

1. Multi-GEM detector with CsI photocathode
2. Permanently sealed Multi-GEM detector with Bialkali
3. Electrostatic tricks to reduce the ion backflow
4. Micromegas with MCP

- For more detailed review of the gaseous photon detectors see: A. Breskin, Beaune 2005
Triple-GEM with CsI coating on upper side of 1-st GEM
F. Sauli, RICH2004, Cancun, Mexico

Hexaboard readout:
Single electron accuracy ~50µm
Double point resolution ~300µm (using ADC)

Collimator-attenuator
Quartz window (inverted) drift field grid
GEM1 CsI-coated
GEM2
GEM3
Anode strip readout

The ALTRO Processing Chain

9/10/06
J. Va'vra, Photon Detectors, Coimbra, Portugal
Quadruple-GEM with Bialkali photocathode
A. Breskin et al., RICH2004, Cancun, Mexico

Permanently sealed, Bialkali photocathode, 95/5 Ar/CH₄:

Max. gain in DC mode (Bialkali): 10²-10³

Max. gain in ion-gating mode (Bialkali): >10⁵
(Ion backflow limit reached: 10⁻⁴)

A breakthrough!

The paper argued for the 1-st time to adopt a 4-GEM solution for the RICH photon Detector application.

J. Va’vra and A. Sharma, NIM, A478(2002)235
CsI photocathode, 95/5 Ar/CH₄ gas:

- The idea: divert some fraction of the ion backflow to local cathodes
- High gain of ~10⁷ reached.
- Ion back flow: ~2x10⁻²
- 3-D simulations made by O. Bouianov
The concept works well in the single electron mode at SLAC. The magnitude of the ion backflow with the inclined holes is zero, consistent with a pico-ammeter noise.

However, so far, Hamamatsu did not succeed to make this detector even with the straight holes. Apparently, during the Bialkali evaporation process, the MCP holes are contaminated and one cannot achieve the single electron gain. Still trying though.

Hamamatsu tube (95/5 Ar/CH$_4$):

One can reduce the ion backflow by aligning the MCP holes with the electron’s Lorenz angle.

Hamamatsu tube (95/5 Ar/CH$_4$): Ion backflow: tiny, not measurable

9/10/06 J. Va’vra, Photon Detectors, Coimbra, Portugal
Conclusions

• There is a new trend trying to push the TOF technique to a new resolution limit at a ps level. Can it be done? Stay tuned!!
• There is a plenty of photon detector ideas out there. However, there is no a clear winner yet, which would work at 15-20kG, with a single-photon detection sensitivity, with a high timing resolution, low noise, and no aging. Is the MCP-PMT a good direction to choose, or is it better to wait for a SiPMT design?
• In the area of the photon gaseous detectors, the sky is the limit for the imagination. Will they remain competitive with silicon or vacuum-based detectors? I think they will.
• Clearly, not all solutions work, as Pedro Cabral already knew very well at around 1500….