High-resolution timing in photon detection – a new frontier in physics?

J. Va’vra, SLAC

Light travels 300µm in one ps
Some photon detectors in the past 10-20 years:

- MCP-PMT
- Mesh PMT
- G-APD (SiPMT)
- MCP-PMT
- ReFerenc
- PMT+G-APD

Other detectors:

- College de France
- Cornell RICH
- DELPHI
- CERES
- SLD CRID
- OMEGA
- JETSET
- G-APDs
- HPD
- GEM+MHSP
- HAPD
- Multi-GEM
- Micromegas+MCP
- MCP-PMT
- MaPMT
- G-APD (SiPMT)
Content

• **Aim of the talk is to explore high resolution timing**
• **Basic properties of the photon detectors:**
  (TTS, Photocathodes, PDE = photon detection efficiency, timing tails, etc.)
• **Timing strategies:**
  - double-threshold timing, time-over-threshold timing, waveform sampling, CFD.
• **Compare timing results for these detector:**
  - Vacuum-based photon detectors with micro-channel plates (MCP-PMT)
  - Silicone photon detectors (APD) operating in a Geiger mode (G-APD)
  - Hybrid photon detectors, combining vacuum and APD detector (HAPD)
• **Examples of applications:**
  - CMS and Atlas TOF detector for FP420 experiments at LHC: goal is $\sigma \sim 10\text{-}15$ ps
  - TOF for Super B Forward PID: goal is $\sigma \sim 15\text{-}20$ ps
  - Focusing DIRC for Super B to tag Cherenkov photon color: goal is $\sigma \sim 150$ ps
  - TOP DIRC at Super B at KEK to measure photon coordinate: goal is $\sigma \sim 50$ ps
  - Add a TOF capability to the PET machines in medicine: goal is $\sigma \sim 30\text{-}50$ ps.
  - The astrophysics detectors such as MAGIC: goal is $\sigma \sim 100\text{-}200$ ps (or even less ???)
• **Institution interested in a high resolution timing at present:**
  - Nagoya U., KEK, Saclay, U. of Chicago, Argonne lab, Fermi lab, Arlington U., SLAC, etc.
A bit of history of a high resolution timing

- **~35 years ago:**
  Helmuth Spieler of LBL (private communication):
  Built, as a part of his Ph.D. thesis work, a TOF system using MCPs for an experiment detecting heavy ions. He routinely achieved a timing resolution of $\sigma \sim 20\text{-}30 \text{ ps}$.

- **~27 years ago:**
  Bill Attwood of SLAC (lecture on the TOF technique at SLAC in 1980):
  The lecture series did not even mention MCP-PMTs. The technology clearly existed at that time, but was either not affordable or obtainable or simply ignored for large scale applications.

- **~10 years ago:**
  Crispin Williams of CERN proposes a TOF detector for ALICE based on multi-gap glass-based RPC chambers; test beam results indicate resolution of $\sigma \sim 40\text{-}50 \text{ ps/track}$.

- **~4 years ago:**
  Henry Frisch of Univ. of Chicago (the 1-st proposal for a 1 ps timing with a MCP-PMTs coupled to a Cherenkov radiator):

- **~2 years ago:**
  Takayoshi Ohshima’s group in University of Nagoya (reached a $\sigma \sim 6.2 \text{ ps}$ in the test beam)
What are the reasons to push the TOF technique towards the new limits?

• Fast Cherenkov light rather than a scintillation

• New detectors with a small transit time spread (TTS)

• Fast electronics is easily available even from catalogues (amplifiers, splitters, cables, etc., in 1-19 GHz BW range)

• New optics available for testing (fast laser diodes, fiber optics, light splitters, etc.)
Issues important for fast photon detectors?

- Photon Detection Efficiency (PDE).
- Transit time spread ($\sigma_{TTS}$).
- Detector design.
- Current best experimental timing results.
- Degradation of performance in magnetic field.
- Bad effects (aging, rate effects, cross-talk, bad ground return, etc.).
- Systematic effects (start time error, tracking, drifts, etc.).
- Pixilization and its effect on timing.
- Electronics.
- Reliability and affordability.

Will concentrate on these issues in this talk.
Photon Detection Efficiency

\[ \text{PDE} = \text{QE} \times \varepsilon_{\text{pe collection}} \times \varepsilon_{\text{detection}} \times \varepsilon_{\text{packing geometry}} \]

Watch out for after pulsing. Do not include them in PDE!

Examples of typical PDE values at present:

1. PMT: > 20%
2. Multi-pixel G-APD: ≥ 40%
3. MaPMT such as H-8500: < 20%
4. MCP-PMT: < 20%
Photocathode QE
Typical photocathodes

- Typically, PMT companies measure QE in a DC current mode. Pulses are used rarely. Therefore QE could include after pulsing, which would enhance QE.
- The photocathode sensitivity $S$ is usually not given as QE but instead in mA of photocurrent per Watts of incident power at a given wavelength.
- QE uniformity is important issue for timing performance.
- Photocathodes, such as GaAs or GaAsP, are slower than Bialkali (worse TTS).

$$QE = S \frac{(hc)}{(e\lambda)} = \left(\frac{S}{\lambda}\right) 1.24 \times 10^6 \text{ Wm/A}$$
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.
We will see that moving towards the red wavelength range reduces the time spread of the photoelectrons at the photocathode. However, the Cherenkov light yield is smaller for red wavelengths.

For example, Photonis Multi-alkali photocathode, which I am not allowed to show, would yield half of photoelectrons from the quartz radiator compared to Burle Bialkali on MCP-PMT, all else equal.
Factors influencing PDE: **tail and dead space**


**MCP-to-Cathode distance ~ 6 mm**
Burle 85011-501 Nominal design:

Penalty of this design: the efficiency drops to zero near edges.

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

L should be small:

$$x \leq 2L$$
Timing strategy

(this is the hardest part of the problem)
Timing resolution = \( f(\text{Rise time, noise}) \)

- **What speed of amplifier does one need?**
  
  => It needs to be fast enough to follow MCP (this means 1-2 GHz BW for 10\(\mu\)m MCP)
  
  => **A deciding factor is a rise-time & noise:**

- **For good timing one needs:**
  
  - fast photon detector (200-300ps rise time)
  
  - correspondingly fast amplifier with a low noise.
Timing strategies

1) High gain operation, non-linear operation:
   - **Single photoelectron sensitivity. This actually would work, however:**
     - amplifier saturates for larger number of pe, say, for Npe >25 => waveform bad for a while
     - one would expect worse aging effects
     - MCP-PMT does not like the large current overloads

2) Low gain, linear operation:
   - **Constant-fraction-discriminator (CFD).**
     - time-walk as number of photoelectrons changes even over 10-20%
     - therefore it needs an ADC correction.
   - **Waveform sampling (a’la Gary Varner’s design from U. of Hawaii).**
     - needs to be tested and be proven for 10-20ps resolution regime
     - needs large number of corrections, probably
   - **Double-threshold timing on both leading and trailing edges.**
     - probably most accurate to get time & amplitude
   - **Time-over-threshold timing (a single threshold on both pulse edges).**
     - the most simple
     - needs to be proven that it works over some amplitude variation
At a level of 5-10 ps, the time-walk needs to be corrected with ADC - for all methods, including CFD method! So, why to use a CFD discriminator at all?

Ortec 9327 Amp/CFD time-walk is the smallest, but still significant!
Double threshold timing?

- Burle/Photonis MCP-PMTs with 10 µm MCP holes operating at 2.80kV; no amplifier; red laser (635 nm).
- Tektronix TDS 5104 scope with 1 GHz BW; trigger: PiLas trigger; thresholds 5 & 20 mV; scope: 200ps/div & 10 mV/div.

- A double-threshold method does not lead to a single intersect point, probably due to a nonlinearity in the amplification process, if one accepts a large variation in Npe! It may work only over a small range of variation in Npe => need uniformity.
- Important point: (a) one should be linear, (b) Npe should not vary much.
Some basic principles for detector candidates for high resolution timing
Various detector designs

Conventional PMT:

G ~ 10^7

Microchannel PMT:

G ~ 5x10^5

HAPD:

G ~ 2x10^5

Geiger mode APD = G-APD:

G ~ 2x10^6

Also called SPAD
(single photon Avalanche Diode)

- A crucial characteristics is the single photoelectron Transit Time Spread (TTS), which should be small to get a small rise time, which is crucial for a good timing resolution.
- For X-ray detection or for the laser monitoring there are many photoelectrons available. And therefore it is sufficient to use fast Si PIN or APD diodes (a typical rise time of a fast Si diode is ~150 ps, fastest is ~ 11ps). These devices cannot detect single pe^-, and TTS quantity is not defined for them.
Relative comparison of pulses

- MCP-PMT has lower gain, very narrow pulses, needs a fast amplifier, and needs a fast ADC to know its charge.
- One consequence of the MCP speed is that one needs to have fast components (cables, splitters, terminatores, etc.), and many “usual” practices are not allowed.
**MCP-PMT: Gain**

- **Typical secondary yield is 2 for each strike on the wall.**
- **L:D = 40:1 seems to be optimum design;** for this ratio there are typically 10 strikes, i.e., \( \text{Gain} \approx 2^{10} \approx 10^3 \) per single MCP plate.
- **For 10 \( \mu \text{m} \) 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 longer transit time.
- Holes are arranged at angle of 5-12° to limit a backflow of ions towards the photocathode. The ions are created by electrons striking a residual gas.
- MCP hole dia. is a crucial variable for the magnetic field operation and timing.

**Smallest MCP hole ever:**

- 2\( \mu \text{m} \) hole dia.

**R3809U-50:**

- Hamamatsu tube (~11 mm dia)
- has 6 or 10 \( \mu \text{m} \) dia. holes:

**85013-501:**

- Burle/Photonis tube (~50mmx50mm)
- comes with 10 or 25 \( \mu \text{m} \) dia. holes:
Single electron transit time spread - TTS

Standard PMT:
- Emission at the photocathode = f(\lambda).
- Cathode-to-dynode transit (or 1-st MCP)
- Multiplication process.
- Emission at MCP exit towards anode.
- Light source jitter
  (usually one is trying to subtract this)
- Timing jitter of subsequent electronics
  (usually one is trying to subtract this)

\[ \sigma_{\text{TTS (best)}} \approx 150 \, \text{ps} \]

MCP-PMT:
- Emission at MCP exit towards anode.
- Light source jitter
  (usually one is trying to subtract this)

\[ \sigma_{\text{TTS (best)}} \approx 10-11 \, \text{ps} \]

G-APD (=SPAD):
- Different depth of photon conversion = f(\lambda).
- Multiplication process.
- Sensitivity to passive quenching circuit.
- Light source jitter
  (usually one is trying to subtract this)
- Timing jitter of subsequent electronics
  (usually one is trying to subtract this)

\[ \sigma_{\text{TTS (best)}} \approx 17 \, \text{ps} \]
Example of a TTS measurement

J. Va’vra, log book

PiLas laser head:

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>~ 30 ps</td>
</tr>
<tr>
<td>Fiber size</td>
<td>62.5 µm</td>
</tr>
</tbody>
</table>

Ultra-fast Si Detector:
(can use also a Streak camera)
Burle/Photonis MCP-PMT TTS measurement

J. Va’vra, log book

MCP-PMT 85012-501:

- 10 µm MCP hole diameter
- $B = 0$ kG
- 64 pixel devices, pad size: 6 mm x 6 mm. (ground all pads except one)
- PiLas red laser diode operating in the single photoelectron mode (635 nm):
  \[
  \sigma_{\text{TTS}} < \sqrt{(32^2 - 13^2 - 11^2)} = 27 \text{ ps}
  \]

Hamamatsu C5594-44 amplifier
1.5 GHz BW, 63x gain

Ortec VT120A amplifier
~0.4 GHz BW, 200x gain + 6dB
Hamamatsu MCP-PMT TTS measurement

Hamamatsu data sheets

MCP-PMT R3809U-50:

- 6 µm MCP hole diameter
- Useful photocathode dia.: 11 mm
- Rise time: ~150 ps.
- Single pixel device.
- MCP-to-anode capacitance: ~3pF
- \( \sigma_{TTS} = 10-11 \) ps
- Light source jitter: ~5 ps (FWHM)

(see next page for the setup to measure TTS)

Hamamatsu C5594-44 amplifier

1.5 GHz BW, 63x gain

This is one of the fastest photon detector available
Setup to measure a very small TTS of R3809U-50 tube
(Hamamatsu Co.)

- Nd-YAG laser jitter: $\sigma \sim 2.1 \text{ ps}$
- Red wavelength: $\lambda = 596 \text{ nm}$
Variables controlling the MCP rise time
Rise time = f(MCP pore size)

(Photek Ltd. & Burle/Photonis information)

Transit time in a MCP hole (from Burle):

Smaller pore size, smaller the transit time.

Rise time = f(pore size) in MCP (Photek):

Smaller MCP pore size, faster rise time.

Note:
Cost to buy of ~20 GHz scope: ~$140k.
Cost to rent: ~$5k/month.
Rise time $= f(E_{MCP-to-anode})$

(Photek Ltd. information)

This gap

MCP-to-anode electric field (Photek data):

Typical nominal operation of Burle tube

- Rise time is influenced by the electron exit velocity variation from MCP towards anode. Larger variation of the velocity, larger TTS, and larger rise time. The rise time can be reduced by increasing the electric field between MCP & anode.
Rise time \(= f(E_{\text{Cathode-to-MCP}})\)  
(Photek Ltd. & Burle/Photonis information)

\[
\frac{dt}{du} = \frac{1}{\alpha} \left[ \frac{u}{\sqrt{u^2 + 2ad}} - 1 \right]
\]

**This gap**

**Cathode-to-MCP voltage (Photek):**

18 GHz scope

**Cathode – MCP Transit Time (from Burle):**

Increased voltage or decreased gap can reduce the transit time.

- Electron exit velocity variation from the cathode towards MCP affects the rise time also. However, it is a small effect for red wavelengths & Bialkali because:
  
  \[635 \text{ nm } \approx 2 \text{ eV} \Rightarrow \frac{dt}{du}_{\text{max}} \approx \frac{(2-\phi)}{200 \text{ eV}} \times 1000\text{ps} \approx 0,\] for 200 Volts and Bialkali photocathode’s work fctn. \(\phi \approx 1.5-2 \text{ eV}\). **May be more significant for } \lambda < 300 \text{ nm} !!**
An example of the detector possible choice for the TOF application

- Our effort
- Nagoya U. effort
**Burle/Photonis MCP-PMT**

Burle/Photonis data

A real device:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photocathode: Bi-alkali QE at 420nm</td>
<td>28 - 32%</td>
</tr>
<tr>
<td>Number of MCPs/PMT</td>
<td>2</td>
</tr>
<tr>
<td>Total average gain @ -2.4kV &amp; B = 0 kG</td>
<td>$\sim 5 \times 10^5$</td>
</tr>
<tr>
<td>Geometrical collection efficiency of the 1-st MCP</td>
<td>70 - 80% *</td>
</tr>
<tr>
<td>Geometrical packing efficiency</td>
<td>85 - 90% *</td>
</tr>
<tr>
<td>PDE = Total fraction of “in time” photoelectrons detected (for Bi-alkali QE)</td>
<td>17 - 23% *</td>
</tr>
<tr>
<td>Maximum average total anode current</td>
<td>3 µA</td>
</tr>
<tr>
<td>$\sigma_{TTS}$ - single electron transit time spread (for 10 µm dia. pores)</td>
<td>27 ps</td>
</tr>
<tr>
<td>Matrix of pixels</td>
<td>2x2, 8x8, 16x16 or 32x32</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>4, 64, 256 or 1024</td>
</tr>
<tr>
<td>Pixel size (8x8 &amp; 32x32 matrix)</td>
<td>5.94 x 5.94 or $\sim 1 \times 1$ [mm$^2$]</td>
</tr>
</tbody>
</table>

*Higher number is for a future improvement*

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A TOF counter prototype

- **Burle/Photonis MCP-PMTs (85013-501)** with 10 μm MCP holes.
- **Short together 4 pads to get a signal; all the rest of pads grounded.**
- **A 10mm-long, 10mm dia, quartz radiator, Al-coating on cylinder sides.**
- **Ortec 1GHz BW 9327Amp/CFD & TAC566 & 14 bit ADC114.**
  - Calculation: 10mm long quartz radiator & a window should give Npe ~ 50 pe/track.
  - Laser diode light can be easily adjusted to provide Npe ~ 1-200 pe.
  - The laser spot size: ~1mm dia.; beam spot size typically σ ~1-2mm
What resolution do we expect to get?

- A calculation indicates \( N_{\text{pe}} \sim 50 \) for 1 cm-long Fused Silica radiator & Burle/Photonis Bialkali photocathode:

- **Expected resolution (a simple approach):**
  
  **a) Beam** (Radiator length = 10 mm + window):
  \[
  \sigma \sim \sqrt{\left[ \sigma^2_{\text{MCP-PMT}} + \sigma^2_{\text{Radiator}} + \sigma^2_{\text{Pad broadening}} + \sigma^2_{\text{Electronics}} + \ldots \right]} = \\
  = \sqrt{\left[ (\sigma_{\text{TTS}}/\sqrt{N_{\text{pe}}})^2 + ((12000\, \mu\text{m}/\cos\Theta_C)/(300\, \mu\text{m}/\text{ps})/n_{\text{group}})/\sqrt{12N_{\text{pe}}})^2 + \right. \\
  + \left. ((6000\, \mu\text{m}/300\, \mu\text{m}/\text{ps})/\sqrt{12N_{\text{pe}}})^2 + (3.42\, \text{ps})^2 \right]} \sim \\
  \sim \sqrt{\left[ 3.8^2 + 3.3^2 + 0.75^2 + 3.42^2 \right]} \sim 6.1 \text{ ps}
  \]

  **b) Laser** (\( N_{\text{pe}} \sim 50 \, \text{pe}^{-}\)):
  \[
  \sigma \sim \sqrt{\left[ \sigma^2_{\text{MCP-PMT}} + \sigma^2_{\text{Laser}} + \sigma^2_{\text{Electronics}} + \ldots \right]} = \\
  = \sqrt{\left[ \sigma_{\text{TTS}}/\sqrt{N_{\text{pe}}} \right] + \sqrt{(\text{FWHM}/2.35)/\sqrt{N_{\text{pe}}})^2 + (3.42\, \text{ps})^2 \right]} \sim \\
  \sim \sqrt{\left[ 3.8^2 + 1.8^2 + 3.42^2 \right]} \sim 5.4 \text{ ps}
  \]

  **SLAC test:** \( \sigma_{\text{TTS}} \) (Burle MCP-PMT, 10\( \mu\text{m} \)) = 27 ps
  
  **Nagoya test:** \( \sigma_{\text{TTS}} \) (HPC R3809U-50, 6\( \mu\text{m} \)) = 10-11 ps

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SLAC
Setup with two MCP-PMTs and a fiber splitter

Control unit
PiLas
635 nm

Laser diode

Fiber splitter

MCP_start

MCP_stop

Ortec 9327
Amp/CFD

Ortec 9327
Amp/CFD

TAC 566
START
STOP

ADC 114

Npe ~ 50
2.33 kV
400 ps/div
10 mV/div

σ MCP-PMT

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Calibration of the electronics

\[ \sigma = \sqrt{2 \sigma_{\text{MCP-PMT}}^2 + (\sigma_{\text{Pulser+TAC_ADC+Amp/CFD}}^2 - \sigma_{\text{Pulser}}^2)} \]

\[ + \text{ Systematic effects (much smaller when the PiLas source eliminated)} \]

\[ \sigma_{\text{Pulser+TAC_ADC+Amp/CFD}} \approx 3.42 \text{ ps} \]

\[ \sigma_{\text{MCP-PMT}} \]

- The best electronics performance to my knowledge.

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A final result with two TOF counters in tandem

Two detector resolution (Npe ~50 pe):

\[ \sigma_{\text{single detector}} \sim \frac{1}{\sqrt{2}} \sigma_{\text{double detector}} \sim 7.2 \text{ ps} \]

Each detector has Npe ~ 50 pe:

\[ \sigma \sim 10.2 \text{ ps} \]

Running conditions:
1) Low MCP gain operation (<10^5)
2) Linear operation
3) CFD discriminator
4) No additional ADC correction

- Two Burle/Photonis MCP-PMTs with 10 µm MCP holes operating at 2.27 & 1.88 kV.
- Ortec 9327Amp/CFD (two) with a -10mV threshold and a walk threshold of +5mV & TAC566 & 14 bit ADC114

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A single MCP resolution = $f(N_{pe})_{\text{threshold}}$

- The data does not agree very much at small $N_{pe}$. Does the CFD timing walk as pulse heights fluctuates at small $N_{pe}$? No fast ADC available in this measurement to correct the CFD timing.

- Two Burle/Photonis MCP-PMTs with 10 µm MCP holes operating at 2.27 & 1.88 kV.
- Ortec 9327Amp/CFD (two) with a walk threshold of +5mV & TAC566 & 14 bit ADC114

CFD threshold:
- 10 mV $\leftrightarrow$ 2-3 pe
- 20 mV $\leftrightarrow$ 3-6 pe
- 100 mV $\leftrightarrow$ 15-20 pe
Can we improve it further?
Rise time = \( f(\text{pore size}, E_{\text{MCP-to-anode}}, E_{\text{Cathode-to-MCP}}) \)

(Photek Ltd. information)

MCP-to-anode electric field:

\[
\frac{dt}{du} = \frac{1}{a} \left( \frac{u}{\sqrt{u^2 + 2ad}} \right)^{-1}
\]

\( t \) - time spread
\( u \) - init. velocity
\( a \) - acceleration

- As we discussed earlier, rise time can be reduced by reducing the velocity variation of photoelectrons escaping from MCP towards the anode. Larger MCP-to-Anode electric field, faster rise time.
- So, modify the resistor chain to increase the \( E_{\text{MCP-to-anode}} \).
A single MCP resolution = $f(N_{pe})_{MCP-to-anode field}$

Comparison of two resistor chains:

- Two Burle/Photonis MCP-PMTs with 10 µm MCP holes operating at 2.27 & 1.88 kV.
- Ortec 9327Amp/CFD (two) with a -10mV threshold and a walk threshold of +5mV & TAC566 & 14 bit ADC114

- Only a small improvement seen doubling the MCP-to-anode field.
- Not worth the risks of a possible damage.
The best result with two TOF counters in tandem

Two detector resolution (resistor chain #2):

\[ \sigma \approx 7.0 \text{ ps} \]

Each detector has \( \text{Npe} \approx 115-120 \text{ pe}^- \):

\[ \sigma_{\text{single detector}} \approx \left(\frac{1}{\sqrt{2}}\right) \sigma_{\text{double detector}} \approx 5.0 \text{ ps} \]

Running conditions:
1) Low MCP gain operation (<10^5)
2) Linear operation
3) CFD discriminator
4) No additional ADC correction

Contribution of the MCP-PMT itself to the above single detector resolution:

\[ \sigma_{\text{MCP-PMT}} < \sqrt{\frac{1}{2} \left\{ \sigma^2 - \left[ \sigma^2_{\text{Pulser}} + \text{TAC_ADC} + \text{Amp/CFD} - \sigma^2_{\text{Pulser}} \right] \right\} } < 4.5 \text{ ps} \]

Running conditions:

- Two Burle/Photonis MCP-PMTs with 10 µm MCP holes operating at 2.85 & 2.43 kV.
- Ortec 9327Amp/CFD (two) with a walk th. of +5mV & TAC566 & 14 bit ADC11

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Super-B Belle: Status of Japanese competition
K. Inami et al., Nagoya Univ., Japan - SNIC conference, SLAC, April 2006

MCP-PMT:

Amp/CFD/TDC:

Electronics resolution:

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

Test beam resolution with ~3 mm quartz radiator (N_{pe}~20):

Test beam resolution with ~13 mm quartz radiator (N_{pe}~50):

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Other competing fast detectors
Silicone photon detectors: G-APD

- **Single-pixel Geiger mode APD’s** were developed long time ago !!!! They were called SPAD. (for example: \textit{R.Haitz et al, J.Appl.Phys. (1963-1965)}).
- **Multi-pixel Geiger mode APD’s** were first made 5-10 years ago by Dolgoshein et al. (he called them SiPMT).
- **Explosion of names**: SPAD, SiPM, MGPD, MRS-APD, PSiPs, SPM, MPPC, G-APD… I prefer to call them simply either “single pixel” or “multi-pixel” G-APD.
Example of a commercial G-APD

Fiber coupling:

TTS:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photocathode</td>
<td>Si</td>
</tr>
<tr>
<td>( \sigma_{TTS} )</td>
<td>(~ 17 , \text{ps} )</td>
</tr>
<tr>
<td>Low noise</td>
<td>&lt; 20 Hz</td>
</tr>
<tr>
<td>Spectral range</td>
<td>350-900 nm</td>
</tr>
<tr>
<td>After pulsing probability</td>
<td>&lt; 3 %</td>
</tr>
<tr>
<td>Dead time</td>
<td>(~ 50 , \text{ns} )</td>
</tr>
<tr>
<td>Maximum rate</td>
<td>(~ 20 , \text{MHz} )</td>
</tr>
<tr>
<td>Active area</td>
<td>(~ 50 , \mu m )</td>
</tr>
</tbody>
</table>

- A device **id-100** is made by "id Quantique SA", Switzerland

12/27/07  J. Va'vra, Photon Detectors, AIS SLAC
Single-cell Geiger mode operating APD = G-APD

Measurements by J. Va’vra, G-APD from Sopko, Active quenching from Prochazka, CVUT Prague

G-APD:

Single photoelectron timing resolution:

- G-APD operating in a Geiger mode with active quenching and temperature control.
- With a PiLas red ($\lambda = 635$ nm) laser diode operating in the single pe mode, I obtained:

$$\sigma_{TTS} < \sqrt{(38^2 - 13^2 - 11^2)} \approx 35 \text{ ps}$$
The 1-st multi-cell Geiger mode operating APD = G-APD

B. Dolgoshein et al., Nucl. Instr. & Meth., A442(2000)18 - he called them SiPMTs

<table>
<thead>
<tr>
<th>Photocathode</th>
<th>Silicon</th>
</tr>
</thead>
<tbody>
<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_{\text{bias}} - V_{\text{breakdown}}) (Geiger condition: (V_{\text{bias}} \geq V_{\text{breakdown}}))</td>
<td>A few Volts</td>
</tr>
<tr>
<td>Number of pixels (possible limit (~4000/\text{mm}^2))</td>
<td>~576 / mm²</td>
</tr>
<tr>
<td>Electric field in the silicon</td>
<td>(3-5) \times 10^5 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>1.5 \times 10^6 @ 24.5V</td>
</tr>
<tr>
<td>Gain uniformity</td>
<td>~10%</td>
</tr>
<tr>
<td>Typical rise time</td>
<td>~1 ns</td>
</tr>
<tr>
<td>Typical fall time (\tau \sim C_{\text{pixel}} \times R_{\text{pixel}} \sim 30\text{ns})</td>
<td>~100 ns</td>
</tr>
<tr>
<td>(\sigma_{\text{TTS}}) Timing resolution per single photon</td>
<td>(\sigma_{\text{TTS}} \sim 60\text{ps})</td>
</tr>
</tbody>
</table>

Each pixel = binary device  SiPM = analogue detector

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J. Va'vra, Photon Detectors, AIS
SLAC
How does a multi-pixel G-APD compare to MCP-PMT for a TOF application?

A simple calculation, assuming $\sigma_{\text{TTS}}$(G-APD)$\sim 80$ ps:

- MCP-PMTs are winners for timing, although a resolution of $\sigma_{\text{G-APD}} \sim 12$ps for 1 cm thick quartz radiator ($\sim 50$ pe) is not bad.
HAPD

A combination of vacuum tube and APD
The first HAPD
R&D development in 1995 by INTERVAC Co., USA

<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 single-channel HAPD
A.Fukusawa et al., KEK & Hamamatsu, IEEE San Diego, 2006

HAPD:

Waveform:

Resolution: Bialkali vs GaArP

Pulse height spectrum:

<table>
<thead>
<tr>
<th>Photocathode</th>
<th>Bialkali or GaArP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain @ $V_{\text{photocathode}} = -8 \text{kV}$ and $V_{\text{APD}} \approx 405 \text{ V}$</td>
<td>$\sim 1.8 \times 10^5$</td>
</tr>
<tr>
<td>Raw pulse height</td>
<td>$\sim 2 \text{ mV}$</td>
</tr>
<tr>
<td>Rise time &amp; fall time ($1.5 \text{ GHz BW scope}$)</td>
<td>$\sim 360 \text{ ps}$ &amp; $\sim 340 \text{ ps}$</td>
</tr>
<tr>
<td>$\sigma_{\text{TTS}}$ (Bialkali &amp; light illumination over $\phi 8 \text{ mm}$)</td>
<td>$\sim 28 \text{ ps}$</td>
</tr>
<tr>
<td>$\sigma_{\text{TTS}}$ (Bialkali &amp; restrict light illumination over $\phi 1 \text{ mm}$)</td>
<td>$\sim 9 \text{ ps}$</td>
</tr>
<tr>
<td>$\sigma_{\text{TTS}}$ (GaArP &amp; restrict light illumination over $\phi 1 \text{ mm}$)</td>
<td>$\sim 28 \text{ ps}$</td>
</tr>
<tr>
<td>$\sigma_{\text{TTS}}$ (GaArP &amp; restrict light illumination over $\phi 3 \text{ mm}$)</td>
<td>$\sim 38 \text{ ps}$</td>
</tr>
</tbody>
</table>
HPD with Multi-pixel Avalanche Diode


HAPD with 8x8 APD array:

- Proximity focusing design => can work in magnetic field
- Relatively small gain so far.

### Table: Photocathode vs Multi-alkali

<table>
<thead>
<tr>
<th>Photocathode</th>
<th>Multi-alkali</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. value of $V_{\text{photocathode}}$</td>
<td>$\sim 9, \text{kV}$</td>
</tr>
<tr>
<td>Max. APD diode bias voltage $V_{\text{APD}}$</td>
<td>$\sim 400, \text{Volts}$</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 $\sigma_{TTS}$</td>
<td>$\sim 90, \text{ps}$</td>
</tr>
<tr>
<td>Low gain region between pixels</td>
<td>$\sim 0.12, \text{mm}$</td>
</tr>
</tbody>
</table>

**Back-illuminated APD array => more uniformity**

---

12/27/07 J. Va'vra, Photon Detectors, AIS SLAC 53
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:**

<table>
<thead>
<tr>
<th>Photocathode</th>
<th>GaAsP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth [nm]</td>
<td>$250 &lt; \lambda &lt; 700$</td>
</tr>
<tr>
<td>Max. value of $V_{photocathode}$</td>
<td>-8 kV</td>
</tr>
<tr>
<td>APD diode bias voltage $V_{APD}$</td>
<td>~400 Volts</td>
</tr>
<tr>
<td>Sensitive area</td>
<td>18 mm dia.</td>
</tr>
<tr>
<td>Pixel capacitance</td>
<td>24 pF</td>
</tr>
<tr>
<td>Total HPD gain @ -8kV</td>
<td>~ 1600</td>
</tr>
<tr>
<td>Total APD gain @ 400 V</td>
<td>~ 50</td>
</tr>
<tr>
<td>Total gain (APD gain alone is ~30x)</td>
<td>$\sim 8 \times 10^4$</td>
</tr>
<tr>
<td>Rise time</td>
<td>~0.8 ns</td>
</tr>
<tr>
<td>Fall time</td>
<td>~1.9 ns</td>
</tr>
<tr>
<td>Pulse width</td>
<td>~2.1 ns</td>
</tr>
</tbody>
</table>

Very fast pulses thanks to small capacitance:

12/27/07

J. Va'vra, Photon Detectors, AIS

SLAC
Summary of best results

Best timing results in the field of photon detectors:

a) Laser:
- **MCP-PMT R3809U-50** (6µm holes): $\sigma_{TTS} \sim 10-11$ ps for $Npe \sim 1$
  (Hamamatsu measurement).
- **HAPD (restrict light to 1 mm dia.)**: $\sigma_{TTS} \sim 9$ ps for $Npe \sim 1$
  (KEK group with Hamamatsu tube).
- **MCP-PMT 85013-501** (10µm holes): $\sigma_{single\,MCP} \sim 5.0$ ps for $Npe \sim 50$,
  (my measurements with Burle/Photonis tube).

b) Particle beam:
- **MCP-PMT R3809U-50-11X** (6µm holes): $\sigma_{TTS} \sim 6.2$ ps for $Npe \sim 50$
  (Nagoya Univ. group with Hamamatsu tube).

c) Best electronics bench performance:
- **Electronics contribution**: $\sigma_{Total\,electronics} \sim 3.4$ ps
  (my measurement with Ortec 1 GHz BW Amp/CFD 9327, TAC566, 14 bit
  ADC114, and a fast pulser).
### 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>Single-cell</td>
<td>~ 29</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>R3809U-50 (6 µm)</td>
<td>10 -11</td>
</tr>
<tr>
<td>Burle/Photonis</td>
<td>MCP-PMT**</td>
<td>85013-501 (10 µm)</td>
<td>~ 27*</td>
</tr>
<tr>
<td>id Quantique</td>
<td>G-APD</td>
<td>id100 - single-cell</td>
<td>~ 17</td>
</tr>
<tr>
<td>Dolgoshein</td>
<td>G-APD</td>
<td>Multi-cell (SiPMT')</td>
<td>~ 60</td>
</tr>
</tbody>
</table>

* ~ 12 mm dia, small single pixel detector  
** ~ 2” x 2”, 64 pads detector, all pads grounded except one  
* measured by speaker
Towards a final TOF detector design
Towards a better MCP-PMT design for timing

- Starting parameters, which Burle/Photonis is willing to try next:
  - 5 mm quartz window & radiator => ~ 25 pe
  - 0.07” (~1.8mm) cathode-to-MCP distance (allows a placement of a getter).
  - 0.02” (~0.5mm) MCP-to-anode distance.
  - 64 pads, 6x6 mm initially, combine 4 into one just like we did so far. This would create 16 macro-pixels.
- Electronics:
  - One threshold on leading edge and one on the trailing edge of a pulse.
This is end

Let’s hope that we will not have wait another ~35 years before a high resolution timing will become reality
Backup slides
Bad effects
Cross-talk and coherent oscillations in Burle/Photonis MCP-PMTs

A.Brandt’s MCP-PMT with his cable harness (tests related to the LHC FP420 experiment):

When a large number of pe arrives at MCP, cross-talk adds coherently (FDIRC prototype):

All pixels shows this

- MCP avalanche is a very fast phenomenon. It can excite a resonance in a cable harness or cause reflections. One needs to do a coupling to the anode with a care. Preferably electronics should be on the tube, and one has to work closely with the company to fix this.
- For comparison, MaPMT H-8500 does not have this problem.
Systematic effects
Systematic errors when doing timing at a level of $\sigma \sim 10-20$ps

- Laser diode start up instability
- Laser diode temperature stability
- Noise
- TDC linearity stability
- “Sleep-wake up” ADC effect
- Non-uniform MCP gain response
- Deflection of MCP front window
- Cross-talk, ringing
- Vertexing, tracking to get a precise track length
- START time accuracy
- Aging issues.
- Magnetic field effects.
- QE non-uniformity.
- On-line calibration to keep track of drifts.
- Etc.
Magnetic field effects
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:** \( G \sim e^{(A \cdot \text{MCP thickness}/\text{MCP dia})} \) - drops in a magnetic field.
- **25\(\mu\)m dia. holes are too large. One needs to reduce their size to \(~6-10\mu\)m dia., to operate at 15kG.
Aging issues
The protective $\text{Al}_2\text{O}_3$ layer blocks the positive ions backflow to cathode.

Nagoya group predicts $\sim 13$ 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.
Applications for fast timing
Possible applications of the MCP-PMT detectors

Super B-factory RICH detectors:

TOP counter with MCP-PMTs (Nagoya Univ.):

Goal: \( \sigma \sim 30-50 \text{ ps} \)

Focusing DIRC with H-8500 MaPMTs:

Goal: \( \sigma \sim 150 \text{ ps} \)

CMS/ATLAS p-p diffractive collisions (FP420 collaborations)

1) Cherenkov quartz detector:

Goal: \( \sigma \sim 30-50 \text{ ps} \)

2) Cherenkov gas detector:

Goal: \( \sigma \sim 10-15 \text{ ps} \)
PID systems in Super-B

- Four possible PID systems:
  - Barrel DIRC & Backward TOF & Forward TOF or Forward Aerogel
Timing at a level of $\sigma \sim 15\text{ps}$ can start competing with the RICH techniques.

Example of various Super-B factory PID designs:

- The PID performance of a forward TOF system with $\sigma \sim 15-20\text{ps}$ is equivalent to the PID performance of BaBar DIRC.
Tagging of photon color in the Focusing DIRC prototype for Super B application

- We have demonstrated that we can correct the chromatic error of $\theta_c$ by color tagging photon by timing. The required resolution to do that is $\sigma \sim 100-200$ ps/photon. This is the first RICH detector which has been able to do this.

Cherenkov angle production controlled by $n_{\text{phase}}$ ($\cos \theta_c = 1/(n_{\text{phase}} \beta)$): $\theta_c (\text{red}) < \theta_c (\text{blue})$

Propagation of photons is controlled by $n_{\text{group}}$ ($v_{\text{group}} = c_0/n_{\text{group}} = c_0/(n_{\text{phase}} - \lambda \cdot dn_{\text{phase}}/d\lambda)$): $v_{\text{group}} (\text{red}) > v_{\text{group}} (\text{blue})$
Cherenkov light: tagging color of photon by time

Principle of chromatic correction by timing:

\[ \text{TOP} = \text{time of propagation of photon in the bar} \]

\[ \frac{\text{TOP}}{\text{Lpath}} = \frac{1}{v_{\text{group}}(\lambda)} \]

Data:

\[ \text{Correlation in data, 10m photon path} \]

Cherenkov angle production controlled by \( n_{\text{phase}} \) (\( \cos \theta_c = 1/(n_{\text{phase}}\beta) \)):

\[ \theta_c (\text{red}) < \theta_c (\text{blue}) \]

Propagation of photons is controlled by \( n_{\text{group}} \) (\( v_{\text{group}} = c_0/n_{\text{group}} = c_0/[n_{\text{phase}} - \lambda \cdot dn_{\text{phase}}/d\lambda] \)):

\[ v_{\text{group}}(\text{red}) > v_{\text{group}}(\text{blue}) \]
\( \theta_C \) resolution and Chromatic correction

- All pixels:
  - Correction off: \( \sigma \approx 11 \) mrad
  - Correction on: \( \sigma \approx 9.1 \) mrad

- 3mm pixels only:
  - Correction off: \( \sigma \approx 7.6 \) mrad
  - Correction on: \( \sigma \approx 5.6 \) mrad

- The chromatic correction starts working for Lpath > 2-3 meters due to a limited timing resolution of the present photon detectors.
- Holes in the uncorrected distributions are caused by the coarse pixilization, which also tends to worsen the resolution. In the corrected distributions this effect is removed because of the time correction.
- Smaller pixel size (3mm) helps to improve the Cherenkov angle resolution.
### Hamamatsu H-8500 & H9500 Flat panel MaPMTs

**Hamamatsu Co. data sheet**

#### Parameter

<table>
<thead>
<tr>
<th><strong>Parameter</strong></th>
<th><strong>Value</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Photocathode: Bi-alkali QE at 420nm</td>
<td>20 - 24% *</td>
</tr>
<tr>
<td>Number of dynodes</td>
<td>12</td>
</tr>
<tr>
<td>Total average gain @ -1kV</td>
<td>~10⁶</td>
</tr>
<tr>
<td>Geometrical collection efficiency of the 1-st dynode</td>
<td>75%</td>
</tr>
<tr>
<td>Geometrical packing efficiency (plus QE edge effects !!)</td>
<td>97%</td>
</tr>
<tr>
<td>PDE = Total fraction of “in time” photoelectrons detected (includes QE)</td>
<td>15 - 17% *</td>
</tr>
<tr>
<td>Fraction of photoelectrons arriving “in time”</td>
<td>~95%</td>
</tr>
<tr>
<td>( \sigma_{TTS} ) - single electron transit time spread</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 [mm²]</td>
</tr>
</tbody>
</table>

* Higher number is a future improvement
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:

- 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.

430nm:

Micro-structure of the dynode electrodes:

12/27/07

J. Va'vra, Photon Detectors, AIS
SLAC