A high resolution TOF counter
- a way to compete with a RICH detector?

J. Va’vra, SLAC
Content of this talk

• A bit of history
• TOF detector for Super-B Forward PID
• Timing strategy
• Laser diode measurements
• Lessons from the test beam
• Systematic errors
• Summary
A bit of history as I know it

• **~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 $\sigma \sim 20$-30 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 HEP applications. Instead, Pestov spark counters were mentioned as a way to progress towards a resolution of $\sigma \sim 30$-50 ps for large areas.

• **~4 years ago:**
  Henry Frisch of Univ. of Chicago (the 1-st proposal for a 1 ps timing with a MCPs and the Cherenkov radiator):

• **~2-3 years ago:**
  Takayoshi Ohshima of University of Nagoya (reached a $\sigma \sim 6.2$ 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 small transit time spread $\sigma_{TTS} < 30\text{ps}$

• Fast electronics

• New fast laser diodes for testing
Forward PID with TOF detector at Super B
(in Italy)
PID systems in Super-B

- Two PID systems: **Barrel DIRC & Forward TOF**
Timing at a level of $\sigma < 15\text{ps}$ can start competing with the RICH techniques.

Example of various Super-B factory PID designs:

Calculation done for a flight path length: 2m
Detector choice for the TOF application
### 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>~5 x 10⁵</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>Fraction of photoelectrons arriving “in time”</td>
<td>70 - 80%</td>
</tr>
<tr>
<td>σ&lt;sub&gt;TTS&lt;/sub&gt; - single electron transit time spread (for 10 µm dia. pores)</td>
<td>27 ps</td>
</tr>
<tr>
<td>Matrix of pixels</td>
<td>2x2, 8 x 8, 16x16 or 32 x 32</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 ~1 x 1 [mm²]</td>
</tr>
</tbody>
</table>

*Higher number is a future improvement*
Timing strategy
(this is the hardest part of the problem)
Timing strategy

• **Work with the detector & amplifier gain sensitive to single photoelectrons:**
  => a better resolution at lower Npe
  => can use thinner radiator
  => **however, worse aging effects**

• **Reduce the gain and amplification to be sensitive to higher threshold:**
  => worse resolution at lower Npe limit,
  => **more linear operation**
  => may need thicker radiator

• **What speed of amplifier does one need?**
  => It needs to be fast enough to follow MCP
  => A deciding factor is a rise-time & noise:

• **CFD, or time-over-threshold timing with ADC correction, or waveform sampling?**
  => **After going through a full circle, I am leaning towards the third option, if one can do it.**
Measurements with a laser diode
New laser-based testing methods

PiLas laser head:

Calibration of a fast detector:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</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>

Manufacturer: Ultra-fast Si Detector or a streak camera:

10/2/07 J. Va'vra, TOF vs. RICH, Chicago
Single-photon timing resolution - $\sigma_{TTS}$

Burle/Photonis MCP-PMT 85012-501 (64 pixels, ground all pads except one)

- 10 $\mu$m MCP hole diameter
- Phillip CFD
- PiLas red laser diode (635 nm):

$$\sigma_{TTS} < \sqrt{\left(32^2 - 13^2 - 11^2\right)} \sim 27 \text{ ps}$$

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

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

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Two laser diode setups

- **Single MCP-PMT providing a TDC stop, and the laser diode PiLas electronics provides a TDC start:**

- **Two MCP-PMTs providing a TDC start & stop. The light is split by a fiber splitter:**
Single MCP-PMT measurements
Timing resolution with PiLas laser diode

$$\sigma = \sqrt{\sigma^2_{MCP-PMT} + \sigma^2_{Fiber} + \sigma^2_{Amp/CFD} + \sigma^2_{Delay} + \sigma^2_{PiLas} + \sigma^2_{Pulser+TAC_ADC} + \sigma^2_{PiLas\_trigger}}$$

+ Systematic effects: laser & temperature drifts, ground loops, etc.

- $\sigma_{PiLas} \approx 13 \text{ ps}/\sqrt{N_{pe}}$
- $\sigma_{Fiber} \approx 7 \text{ ps}$
- $\sigma_{Amp\_CFD} \approx 6-7 \text{ ps}$
- $\sigma_{Pulser+TAC\_ADC} \approx 3.2 \text{ ps}$

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$\sigma = f(N_{pe})$ - with amplifier, timing with a CFD

- The 1-st pe$^{-}$ timing mode can reach a $\sigma \sim 12$ ps resolution even for $N_{pe} \sim 25$.
- 1cm-thick Quartz radiator + window & with Burle Bialkali QE: $N_{pe} \sim 50$
\( \sigma_{\text{RMS}} = f(\text{Npe}) \) - no amplifier, timing with a 1GHz BW scope

- No amplifier \( \Rightarrow \) MCP voltage rather high to see small Npe.
- Threshold: 15-20 pe
- The scope-based timing resolution are worse - is it due to a scope triggering noise?
Time-walk = f(Npe)

Zoom into a more likely range of variation in Npe:

- Time-walk **needs** to be corrected by ADC - **for all methods**!
- Ortec 9327 time-walk is the smallest, but still significant!
- **So, why to use a CFD discriminator at all?**
Time-walk in a double threshold method using a 1GHz BW scope

- 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.

- Even the double-threshold method does not project into a single point!
- Would it work for more reasonable range of variation in Npe?
- One may need to digitize the pulses with more sampling points!
Double MCP-PMT measurements
A TOF counter prototype

- Burle/Photonis MCP-PMTs with 10 µm MCP holes.
- A 10mm-long quartz radiator, coated with Al-coating on cylinder sides.
- Calculation: 10mm long quartz radiator & a window should give Npe ~ 50 pe/track.
- Ortec 9327Amp/CFD & TAC566 & 14 bit ADC114.
- Laser diode light adjusted to provide typically Npe ~ 50 pe.
- The laser spot size: ~1mm dia.
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

- Parameters:
  - Npe ~ 50
  - 2.33 kV
  - 400 ps/div
  - 10 mV/div

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Calibration of the electronics

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

+ Systematic effects (much smaller when the PiLas source eliminated)

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

\[ \sigma_{\text{MCP-PMT}} \approx 3.42 \text{ ps} \]

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A final result with two TOF counters in tandem

Two detector resolution:

Each detector has Npe ~ 50 pe−:

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

Running conditions:
1) Low MCP gain operation
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
A single MCP resolution = $f(N_{pe})_{\text{threshold}}$

- 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

- Can we aim for a 5mm thick radiator ($N_{pe} \sim 25$ pe⁻)?
Let’s change the voltage divider

(Can we improve the resolution further?)
MCP-PMT: transit time

Burle/Photonis information

Increased voltage or decreased gap can reduce the transit time.

Smaller pore size and smaller L/D leads to smaller transit time.
Rise time = \( f(\text{pore size, } E_{\text{MCP-to-anode}}, E_{\text{Cathode-to-MCP}}) \)

(Photek Ltd. information)

Pore size:

- Rise time is determined by:
  - Transit time variation in MCP pores
    - Smaller MCP pore size, faster rise time
  - Exit velocity variation from MCP towards anode
    - Larger MCP-to-Anode electric field, faster rise time
  - Exit velocity variation from cathode towards MCP
    - Small effect for red wavelengths & Bialkali
      [635 nm \(\leftrightarrow\) \(~2\) eV \(\Rightarrow\) \(dt/du\)\(_\text{max}\) \(~((2-\phi)/200)\)*1000ps], \(\phi\) \(~1.5\)~2 eV. **Could be a problem for \(\lambda<300\) nm!!**

MCP-to-anode electric field:

Cathode-to-MCP voltage:

6\(\mu\)m MCP pore
5\(^o\) hole angle

18 GHz scope

1-st HV divider
2-nd HV divider

- Time spread
- Init. velocity
- Acceleration

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Modify resistor chain

Resistor chain #1:

Resistor chain #2:

- A substantial increase in the total voltage is necessary to get the same gain (more than I predicted; is $R_{MCP} = f(E_{MCP})$?)

<table>
<thead>
<tr>
<th>Detector</th>
<th>$V_{cathode}$</th>
<th>$E_{MCP-to-Anode}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOF 1</td>
<td>2.27 kV</td>
<td>444 V/cm</td>
</tr>
<tr>
<td>TOF 2</td>
<td>1.88 kV</td>
<td>367 V/cm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Detector</th>
<th>$V_{cathode}$</th>
<th>$E_{MCP-to-Anode}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOF 1</td>
<td>2.85 kV</td>
<td>1014 V/cm</td>
</tr>
<tr>
<td>TOF 2</td>
<td>2.43 kV</td>
<td>865 V/cm</td>
</tr>
</tbody>
</table>
A single MCP resolution = $f(N_{pe})_{MCP\text{-to-anode field}}$

Resistor chain #2:

- 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

- Not much improvement by running high MCP-to-anode field
- Not worth the risks of a possible damage and reduction of the operating range for the magnetic field application.
The best result with two TOF counters in tandem

Two detector resolution (resistor chain #2):

- 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

σ ~ 7.0 ps

Each detector has Npe ~ 115-120 pe-:

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

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

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

Running conditions:
1) Low MCP gain operation (<10⁵)
2) Linear operation
3) CFD discriminator
4) No additional ADC correction

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Lessons from the test beam
Beam test - problem with the radiators

To make these pictures possible, send monitor signals over a long delay cable => rise time is affected:

- A poor reflectivity of radiator’s Al coating created a non-uniform number of photoelectrons. The 2-nd radiator’s yield is worse than the 1-st one.
- One could still correct it if we would have a fast ADC!! (Ortec 9327 Amp/CFD provides a fast bipolar monitor of the amplifier. However, an ordinary ADC, such as LeCroy, would integrate it to a fixed constant. We did not have a better ADC available, which could be used to correct for the pulse height variation. If we would have it, we would get a better result.)
- \[ \sigma_{\text{single detector}} \approx 22.6 \text{ ps} \]

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

Amp/CFD/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 ($N_{pe} \sim 50$):

TOF1
TOF2
500mV/div
500ps/Div

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Systematic errors

(They will ultimately decide what will be a final performance)
Systematic errors when doing timing at a level of σ~10-20ps

- 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, track length
- START time

Manufacturer’s claim:

**Drift in the PiLas time offset:**
~10ps/hour after ~20 min., < 3ps/hour after ~1 hour
Systematic errors when doing timing at a level of $\sigma \sim 10-20$ps

- Laser diode start up instability
- Laser diode & its electronics stability
- Noise
- TDC linearity stability
- “Sleep-wake up” ADC effect
- Non-uniform MCP gain response
- Deflection of MCP front window
- Cross-talk, ringing
- Vertexing, track length
- START time

On shorter time scale, say $\sim 10$ minutes, one can see occasionally:

Observe temperature-driven drifts as large as 50-100 ps/day
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, track length
- START time

Observing departure from linearity at a level of $0.02$ps/count

Daily variations in linearity:

Phillips 7186

Time [day]

Jeff’s pulser:
(Use stop to trigger PiLas)

25ps/count nominally
Systematic errors when doing timing at a level of $\sigma \approx 10-20\text{ps}$

- 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, track length
- START time

“Sleep-wake up” ADC effect can be $\approx 250\text{ps}$ effect in the first $\approx 1000\text{ events}$
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, track length
- START time

A gain drop as large as $\sim 30\%$ near the MCP edges
Systematic errors when doing timing at a level of $\sigma \sim 10\text{ps}$

- 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, track length
- START time

Assume: 50 $\mu$m deflection of MCP window

A 50 $\mu$m deflection could create ~8 ps time spread
Systematic errors when doing timing at a level of $\sigma \sim 10\text{-}20\text{ps}$

- 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, track length
- START time

A. Brandt’s 10 $\mu$m MCP & coaxial cable harness (plus still using the Burle inductive connector):

This effect is known for 2 years now, but not yet solved by Burle

=> We should get rid of the Burle connector
Towards a final design

My initial thoughts:

- Starting parameters, which Burle/Photonis is willing to try:
  - 5 mm quartz window & radiator $\Rightarrow \sim 25$ pe$^-$
  - 0.07” cathode-to-MCP distance (this still allows a placement of the getter)
  - 0.02” MCP-to-anode distance
  - 64 pads, 6x6 mm initially $\Rightarrow \sigma_{\text{pad size}} \sim 6$ ps (later 256 pads, $\sim 3$ ps)

U. of Chicago solution:
Equal-time trace PC board & ground layout:
Conclusions

• **Our present best laser diode results:**
  - $\sigma_{\text{single MCP}} \sim 7.2$ ps for $N_{\text{pe}} \sim 50$, expected from a 1cm thick radiator.
  - $\sigma_{\text{TTS}} \sim 27$ ps for $N_{\text{pe}} \sim 1$.
  - **Electronics contribution** (Amp, CFD, TAC, ADC): $\sigma_{\text{Total_electronics}} \sim 3.4$ ps.
  - **Upper limit on the MCP-PMT resolution:** $\sigma_{\text{MCP-PMT}} \sim 4.5$ ps.

• **Our present best test beam results:**
  - $\sigma_{\text{single MCP}} \sim 22.5$ ps (believed to be due to a poor radiator Al-coating).
Backup slides
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.

Photon detectors were a combination of Hamamatsu MaPMTs and Burle/Photonis MCP-PMTs.
Focusing DIRC prototype photon detectors

Focusing DIRC prototype photon detectors

Nucl.Inst.&Meth., A 553 (2005) 96

1) Burle 85011-501 MCP-PMT (25µm pores, 64 pixels, 6x6mm pad, $\sigma_{TTS} \sim 50-70$ps)

2) Hamamatsu H-8500 MaPMT (64 pixels, 6x6mm pad, $\sigma_{TTS} \sim 140$ps)

3) Hamamatsu H-9500 Flat Panel MaPMT (256 pixels, 3x12mm pad, $\sigma_{TTS} \sim 220$ps)

- Timing resolutions were obtained using a fast laser diode in bench tests with single photons on pad center.