MCP photon detectors studies for the TORCH detector

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On behalf of the TORCH Collaboration (CERN, Bristol and Oxford Universities)

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Introduction to TORCH

Photon detector characterization:
- Commercial MCP devices performance with single-channel and custom multi-channel front-end electronics
- Custom MCP devices performance with single-channel electronics

Simulation and optical studies

Beam test preparation

Conclusions and perspectives
**TORCH detector**

- **Time Of internally Reflected Cherenkov light (TORCH)**
  - a proposed precision Time-of-Flight (TOF) detector for particle identification (PID) at low momentum  
    [R. Forty, 2014 JINST 9 C04024]
  - Motivation for TORCH development is LHCb upgrade  
    [CERN-LHCC-2011-001]
  - Measure the TOF of charged-particle tracks with 12.5ps precision/track
  - Path length reconstruction $\rightarrow$ ~1mrad precision required for $(\theta_x, \theta_z)$
  - Photon propagation time in quartz $\rightarrow$ crossing time

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[Image of quartz plate with track, detected photon, and Focusing block mirror]

- Path length reconstruction: $L = \frac{h}{\cos \theta_z}$
- Photon propagation time in quartz: crossing time
- Track dimensions: 6m × 5m
- Total internal reflection of photons
- Quartz plate thickness: ~1cm
Photon detectors requirements

- Single photon sensitivity \(\rightarrow\) MCPs best for fast timing of single photons

- Development of photon detectors with **finely segmented anode** (8x128 channels)
  - Propagation angle projected on the quartz plate \((\theta_x)\) \(\rightarrow\) coarse segmentation (~6mm) sufficient
  - Propagation angle \((\theta_z)\) \(\rightarrow\) fine segmentation (~0.4mm) \(\rightarrow\) 50ps smearing of photon propagation time due to pixellization

- **Arrival time precision of \(\leq 50\text{ps}\)** for single photon signal at a gain of \(\sim 5 \times 10^5\)

\[
\sqrt{\sigma_{\text{pixellization}}^2 + \sigma_{\text{timing}}^2} \sim 70\text{ps} / \text{detected photon}
\]

- **Lifetime aspects:**
  - detected photon rate: 1-10MHz/cm²
  - Integrated anode charge per year: 1-10C/cm²
TORCH R&D project

- 4 year TORCH R&D project awarded by ERC, started 2 years ago (collaboration between CERN, Bristol and Oxford Universities)


  - Proof-of-principle with a prototype TORCH module

- Development of suitable MCP photon detectors with industrial partner: Photek (UK)

  - 1st phase: Circular MCP with extended lifetime (~5C/cm²)
    - Atomic layer deposition (ALD) coating
  
  - 2nd phase: Circular MCP with fine granularity
    - Modelling studies to achieve the required granularity

  - 3rd phase: Final square MCP with extended lifetime and fine granularity
    - High active area (>80%)
Commercial MCP devices (Photonis)

- Initial tests with commercial devices
  - Poster @NDIP11 showed tests with single-channel electronics → TTS ≤ 40ps in single photon regime and MCP gain $5 \times 10^5$ [L. Castillo García, Nucl. Instr. Meth. A 695 (2012) 398]
  - Custom multi-channel electronics → beam and laboratory tests (see later)

- Photon detectors from Photonis:
  - 8x8 array Planacon MCP (test tube)
  - Single-channel MCP (as time reference)

- Using custom multi-channel front-end electronics: [R. Gao et al., 2014 JINST 9 C02025]
  - fast amplifier and Time-Over-Threshold (TOT) discriminator (NINO8 ASIC) [F. Anghinolfi et al., Nucl. Instr. and Meth. A 533 (2004) 183]
MCP 8x8array Planacon

- Single photon regime: 0.5 photoelectrons on average per pulse
- Modest Planacon gain ($6 \times 10^5$) → for lifetime aspects
- Planacon large input gap → long back-scattering tail

**Single-channel electronics**

START signal: time reference from laser sync. signal
STOP signal: Planacon pad

\[ \sigma_{\text{single-channel electronics}} \approx 38 \text{ps} \]

**Custom front-end electronics (NINO8+HPTDC)**

START signal: time reference from single-channel MCP
(<20ps) coupled to CFD and injected on a test channel of the NINO8+HPTDC electronics
STOP signal: Planacon

\[ \sigma_{\text{NINO+HPTDC}} \approx 77 \text{ps} \]

[Experimental data, Data fit, 1st Gaussian, 2nd Gaussian]

LOG scale!

Counts

Laser effect

Back-scattering effect

\[ (t_{b-s})_{\text{MAX}} \approx 1.5 \text{ns} \]

Without time walk correction and INL calibration of HPTDC chip 83% efficiency → NINO8 threshold not optimal

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Custom MCP devices (Photek) - 1st phase

- 5 single-channel MCP-PMT225 with extended lifetime have been manufactured
  - Using ALD process coating on MCP
- Some devices have already been successfully characterized through accelerated ageing tests

- Initial MCP gain set to $10^6$
- Total accumulated anode charge: $5.16\text{C/cm}^2$
- 30% reduction in MCP gain
- No reduction in QE $\rightarrow$ no photocathode degradation

![Graph showing ALD coated MCP-PMT Life Test with Uncoated Control]
Custom MCPs characterization

- PMT225/SN G1130510
- Dark count rate: 3.3kHz
- Modest gain $3 \times 10^5$ @-2200V
- PHS $\rightarrow \mu \sim 0.35$ photoelectrons
- TTS $\rightarrow \sigma \sim 23ps$


- Excellent timing performance $\rightarrow$ single-channel MCP
- Other 4 tubes show similar performance
QE and ageing tests at CERN

- **QE experimental setup**

  ![Experimental setup](image)

  - Light-tight box (MCP and reference photodiode)
  - Monochromator + filter wheel
  - Xe lamp
  - Picoampmeter /voltage source
  - Optical power meter

- **One custom MCP tube is currently under ageing test**
  - High dark count rate tube
  - Regularly monitoring of QE, gain and other parameters
  - After 0.5C/cm² no visible QE degradation, gain drop of 20% → in agreement with Photek tests

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**QE curves before ageing**

**QE curves after 0.5C/cm²**
Custom MCP devices (Photek) – 2\textsuperscript{nd} phase

- Modelling studies on-going to achieve required granularity
- 8x64 sufficient if charge-sharing between pads is used → Improve resolution and reduce number of channels
- Simulated spatial resolution in the fine direction using charge-sharing (NINO+HPTDC electronics) as function of MCP gain and NINO threshold
  
  \[\text{[J.S. Milnes et al., NIM A (2014), http://dx.doi.org/10.1016/j.nima.2014.05.035]}\]

- Strong dependence on MCP gain and NINO threshold
- Resolution degradation at higher thresholds
- Operate at $10^6$ MCP gain to achieve the required resolution
Simulation

- **Geant4 software framework**

- **Idealised TORCH detector**
  - All photons arriving at the photo-detector plane are registered

- **Photon loss factors:**
  - Rough surface
  - Rayleigh scattering
  - Quartz spectral cut off
  - EPO-TEK glue spectral cut off
  - Mirror in focusing block
  - Quantum efficiency
  - Collection efficiency

Event display for a single 10 GeV K+ crossing

Relative impacts

Photon generation

EPO-TEK 305

QE

EPO-TEK 301-2 (BaBar)
Optical studies

- Aim: measure and optimize transmission in UV region for radiator/optics coupled with UV epoxy glue
- Transmission curves for Quartz windows:
Beam test preparation

- Beam test periods:
  - SPS at CERN in October-November 2014 (high momentum beam: $p_{max} = 400 GeV/c$)
  - PS at CERN in December 2014 (low momentum beam)

- TORCH prototype:
  - Radiator plate (10x120x350mm³) and focusing prism → Fused Silica
  - 2 photon detectors on focal plane → various MCPs to be used
  - Radiator glued to optics
  - Air gap between optics-photon detectors
  - Optics ordered → final design ready, under manufacturing

- New electronics development on-going
  - design new board NINO32+HPTDC
  - improve channel density
  - possible integration of INL calibration and time walk correction
Conclusions and perspectives

- TORCH is an innovative detector proposed to achieve $\pi - K$ separation in the momentum range below $10\, GeV/c$

- Development of suitable photon detectors over a 3-phases R&D programme
  - 1st phase $\rightarrow$ COMPLETED
  - 2nd phase $\rightarrow$ ON-GOING
  - 3rd phase $\rightarrow$ next year
  - Finally, demonstration of TORCH concept with a prototype module

- Simulation studies on-going

- Development of next-generation custom front-end electronics (NINO32) on-going

- Beam tests foreseen end of 2014

- Further information $\rightarrow$ http://torch.physics.ox.ac.uk
TORCH detector

- It combines TOF and Ring Imaging Cherenkov (RICH) detection techniques

\[ \Delta TOF (\pi - K) = 37.5 \text{ ps at 10 GeV/c over a distance of } \sim 10 \text{m} \]

- PID system to achieve positive \( \pi/K \) separation at a 3\( \sigma \) level in the momentum range below 10\( GeV/c \)

- 30 detected photons/track \( \rightarrow \) Overall resolution per detected photon: \( \sim 70 \text{ps} \)

- Cherenkov light production is prompt \( \rightarrow \) use quartz as source of fast signal

- Single photon sensitivity
How to determine the TOF?

- Why do we measure $\theta_C$?
  \[ \cos \theta_C = 1/n\beta \]

\[
TOF = t_{TORCH} - t_{PV} = \frac{|x_{TORCH} - x_{PV}|}{\beta c} \quad t_{TORCH} = t_{photon\ arrival} - TOP
\]

- Correct for the chromatic dispersion of quartz: $n(\lambda)$
  - Cherenkov angle $\rightarrow$ phase velocity: \[ \cos \theta_C = 1/\beta n_{phase} \]
  - Time of Propagation (TOP) $\rightarrow$ group velocity: \[ TOP = path\ length \frac{n_{group}}{c} \]

- $\theta_C \rightarrow n_{phase} \rightarrow \lambda \rightarrow n_{group} \rightarrow TOP \rightarrow t_{TORCH}$ (crossing time)

- To obtain the TOF, we need the start time $t_{PV}$
  - Use other tracks from PV, most of them are pions $\rightarrow t_{PV}$: average time assuming they are all pions
TORCH detector

- Unrealistic to cover with a single quartz plate → evolve to modular layout

- For LHCb, surface to be instrumented is ~5x6m² at z=10m

- 18 identical modules, each 250×66×1cm³ → ~300 litres of quartz in total

- Reflective lower edge → photon detectors only needed on upper edge

  18 × 11 = 198 units, each with 1024 pads → 200k channels in total
Application: LHCb experiment

- Motivation for TORCH development is LHCb upgrade
  - Luminosity: $2 \cdot 10^{33} \text{cm}^{-2}\text{s}^{-1}$
  - Event read out rate increased to $40\text{MHz}$

- Currently, PID provided by two RICH detectors with three radiators (Silica aerogel, $C_4F_{10}$, $CF_4$) covering a momentum range from $\sim 2\text{GeV}/c$ up to $100\text{GeV}/c$

- PID Upgrade:
  - Silica aerogel will not give a good performance (low photon yield <10 detected photons/saturated track) → To be removed and possibly replaced later by TORCH

[CERN-LHCC-2011-001]

![Diagram of LHCb experiment](image)
Photon detector:
- 8x8 channels MCP-PMTs (Burle/Photonis)

XP85012/A1 specifications:
- MCP-PMT planacon
- 8x8 array, 5.9/6.5 mm size/pitch
- 25 μm pore diameter, chevron configuration (2), 55% open-area ratio
- MCP gain up to $10^6$
- Large gaps:
  - PC-MCPin: ~ 4.5mm
  - MCPout-anode: ~ 3.5mm
- 53 mm x 53 mm active area, 59 mm x 59 mm total area $\rightarrow$ 80% coverage ratio
- Total input active surface ratio $\leq$ 44%
- Bialkali photocathode
- Rise time 600 ps, pulse width 1.8 ns
- HV applied 2.6 kV (1.75 kV across the MCP)
Single-channel MCP tube (Photonis)

- Photon detector:
  - single channel MCP-PMT (Photonis NL)

- PP0365G specifications:
  - MCP-PMT tube
  - single channel (SMA connector)
  - 6µm pore diameter, chevron type (2), ~55% open-area ratio
  - low MCP gain typ. <10⁵
  - Small gaps:
    - PC-MCPin: 120µm
    - MCPout-anode: 1mm
  - S20 photocathode on quartz
  - 18mm active diameter
  - 6pF anode capacitance
  - Rise time 20-80% >700ps
  - HV applied 2.93kV (1.95 kV across the MCP) filter and bleeder chain 1+(1-10-3)
Custom MCP device (Photek)

- Photon detector:
  - single channel MCP-PMT225 (Photek Ltd)

- PMT225 SN-G specifications:
  - MCP-PMT tube
  - single channel (SMA connector)
  - 10µm pore diameter, chevron type (2), ALD coated
  - MCP gain typ. $10^6$
  - Small gaps:
    - PC-MCPin: 200µm
  - S20 photocathode on quartz
  - 25mm active diameter
  - Rise time 360 ps
  - HV applied 2.25 kV (1.2 kV across the MCP)
### MCP photon detectors tests - Summary

<table>
<thead>
<tr>
<th></th>
<th>8x8array Planacon MCP (Photonis)</th>
<th>Single-channel MCP (Photonis)</th>
<th>Single-channel MCP (Photek)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pore diameter [μm]</td>
<td>25</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>PC-MCP/MCP-anode gaps</td>
<td>large</td>
<td>small</td>
<td>small</td>
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<tr>
<td>Photocathode</td>
<td>Bialkali on borosilicate</td>
<td>S20 on quartz</td>
<td>S20 on quartz</td>
</tr>
<tr>
<td>Typical MCP gain</td>
<td>$10^6$</td>
<td>$10^5$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>Time resolution [ps]</td>
<td>Single-channel electronics: &lt;40</td>
<td>&lt;40</td>
<td>&lt;30</td>
</tr>
<tr>
<td></td>
<td>Multi-channel electronics: &lt;80</td>
<td></td>
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</tr>
</tbody>
</table>
**Experimental setup**

- Pulsed blue (405nm) laser diode @1KHz (20ps FWHM, sync<3ps)
- Monomode fibers
- ND filters: *single photon regime*
- Single-channel ORTEC electronics

**Light calibration setup:**
- Pulse height spectra (PHS)
- Standard Poisson distribution to fit data
- Average number of photoelectrons per pulse ($\mu$) inferred from $P(0)$

\[
N: \text{number of photoelectrons per pulse}
\]

\[
P_\mu(N) = \frac{\mu^N}{N!} e^{-\mu} = \frac{A_N \sigma_N \sqrt{2\pi}}{\text{total surface}}
\]

N-photoelectron peak width scales as:

\[
\sigma_{N\text{phe}} = \sqrt{N} \sigma_{1\text{phe}}
\]

where $\sigma_{1\text{phe}}$ is the 1-photoelectron peak width
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Timing setup:
- Time jitter distribution
- Exponentially-modified Gaussian distribution to fit prompt peak → time resolution (σ)
Discriminator behaviour

- For a given discriminator threshold:
  - The noise induces a **jitter** → signal is detected earlier or later in time
  - The signal height variation induces a **walk**:
    - Large signals are detected earlier
    - Small signals are detected later

- **Constant Fraction discriminator:**
  - Based on zero-crossing techniques
    - Large amplitudes:
      + walk → earlier / -walk → later
    - Smaller amplitudes:
      + walk → later / -walk → earlier
  - Produce accurate timing information from analog signals of varying heights but the same rise time
  - Principle: splitting the input signal, attenuating half of it and delaying the other half, then feeding the two halves into a fast comparator with the delayed input inverted
  - Effect: to trigger a timing signal at a constant fraction of the input amplitude, usually around 20%
Contributions to MCP timing response

- **Laser effect:**
  - Second relaxation pulse clearly seen after \((150 \pm 50)\) ps on laser timing profile \(\rightarrow\) visible on MCPs time response resulting in a shoulder after the main peak.

- **Back-scattered photoelectrons:**
  - Maximum back-scattered time (elastically at 90° with MCP input surface):
    \[
    (t_{\text{back-scattered}})_{\text{MAX}} = 2 \times t_{\text{transit}}
    \]
  - Maximum back-scattered spatial range (elastically at 45° with MCP input surface):
    \[
    (d_{\text{back-scattered}})_{\text{MAX}} = 2 \times \text{MCP input gap}
    \]

[Diagram showing PiLas test ticket with data indicating 60% (FWHM ~ 21 ps) optimal.]
Single-channel timing fitting model

- Single-channel MCP investigated at several light intensities and laser tune setting [L. Castillo García, LHcb-INT-2013-042]
- Main peak of timing distributions represents the MCP intrinsic time response \( \rightarrow \) fitted with an exponentially-modified Gaussian distribution [I. G. McWilliam, H. C. Bolton, Analytical Chemistry, Vol. 41, No. 13, November (1969) 1755-1762]

\[
f(t, A, t_c, \sigma_g, \tau) = \frac{A}{\tau} \exp \left( \frac{1}{2} \left( \frac{\sigma_g}{\tau} \right)^2 - \frac{t - t_c}{\tau} \right) \left( \frac{1}{2} + \frac{1}{2} \text{erf} \left( \frac{t - t_c}{\sigma_g \sqrt{2}} \right) \right)
\]

\( t \): time, \( A \): amplitude, \( t_c \): centroid at maximum height of the unmodified Gaussian, \( \sigma_g \): standard deviation of the unmodified Gaussian, \( \tau \): time constant of exponential decay used to modify the Gaussian and \( \text{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} dt \).

- Model chosen given the **asymmetry in the MCP time response** for large values of \( \mu \).
- **Time jitter** value defined as the standard deviation \( \sigma_g \) of the Gaussian.
- Use to extract the timing resolution for Planacon MCP