Beam tests of a large-scale TORCH demonstrator

Thomas H. Hancock,
on behalf of the TORCH collaboration

20th February 2019
Outline

• What is TORCH?

• The Beam Test Campaign

• Photon Timing Resolution

• Photon Counting Efficiency

• Simulated PID Performance

• Conclusions
The TORCH Detector

• Time of Flight (ToF) detector proposed for the future LHCb upgrade*
  ➢ Aims to provide PID in the 2 – 10 GeV/c momentum region

* Expected to install in Long Shutdown 3 (~2024)
TORCH Micro-Channel Plate (MCP) PMTs

• Employ custom designed MCP PMTs
  ➢ 8×128 effective granularity

• Anisotropic Conductive Film (ACF) used to interface detector and readout

Developed by PHOTEK

Active area of a TORCH tube

Front and back of a TORCH tube

MCP Window
Photocathode
Micro-channel Plate
Micro-channel Plate
Anode

Photons
10 μm pores
Charge Avalanche
TORCH Readout Electronics

- Readout based on the ALICE ToF system
- Employs NINO and HPTDC chipsets

- Backplane provides mechanical support and distributes power

![Readout Electronics in Lab Setup](image)
The TORCH Detector in LHCb

• At 10 GeV/c, $\Delta_{TOF}(K - \pi) = 35$ ps
  ➢ Aim for 15 ps per track
  ➢ Requires 70 ps individual photon time resolution with 30 detected photons per track

Introduction

Beam Test Campaign

Timing Resolution

Photon Counting

PID Performance

Conclusions
The Proto-TORCH module

- Proto-TORCH is a half-height, full-width TORCH module
- Instrumented with a pair of 8×64 TORCH MCPs
CERN East Area T9 facility

Proto-TORCH
Full-width, half-height

Timing Stations

Cherenkov Counters

Proto-TORCH

Full-width, half-height

Beam

~11 m

T2
Proto-TORCH
Telescope

T1
C2
C1
Initial look at Proto-TORCH data

October Proto-TORCH Hitmap

Difference in efficiency is due to Quantum Efficiency difference between tubes

Missing pixels are attributed to wire bonding

Blacked out channels on row 32 are time reference channels

Introduction

Beam Test Campaign

Timing Resolution

Photon Counting

PID Performance

Conclusions
Time Resolution Analysis

Goal:
To measure the single photon timing resolution of TORCH
Visualising Time Spread
Visualising Time Spread

Focus analysis on more efficient MCP
Visualising Time Spread
Visualising Time Spread

Project hitmap y-axis in time

Y coordinate (Pixels)
Separating Reflections

Example Time Projection Plot

Hit Time – Time Reference (ns)

Vertical Position (Pixels)

Photon Hit

TORCH Radiator Plate

Particle Hit
Residual Distribution Widths

- \( T_{measured} - T_{predicted} \) gives residual distribution

- Fit with **Crystal Ball** function
  - Gaussian spliced with an exponential tail
  - Width of Gaussian component gives timing resolution, almost...
Disentangling TORCH Time Resolution

\[ \sigma_{\text{TORCH}}^2 = \sigma_{\text{measured}}^2 - \sigma_{\text{beam}}^2 - \sigma_{\text{timeref}}^2 \]

- \( \sigma_{\text{beam}} \) is the time spread due to the beam profile
  - Measured using beam profile measurement and TORCH simulation
  - Varies between \( \sim 12 \) ps and \( \sim 32 \) ps depending on beam position

- \( \sigma_{\text{timeref}} \) is the resolution of the time reference station
  - Independently measured to be \( 42 \pm 3 \) ps
Preliminary Time Resolution Results

• Measure for each pixel column
  ➢ Best achieved is $88.8 \pm 1.3 \text{ ps}$

• Average individual column resolutions for beam positions down the plate

• Results still missing calibration of MCP charge per pixel
Photon Counting Analysis

Goal:
To determine the photon counting efficiency of TORCH
Photon Counting Method

- Compare number of photons seen in data with simulation

  - Optical processes modelled by Geant4
  - MCP/Readout modelled using custom TORCH libraries

- Development of the MCP/readout simulation is ongoing

<table>
<thead>
<tr>
<th>Simulated Effect</th>
<th>Loss Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Roughness</td>
<td>~10%</td>
</tr>
<tr>
<td>Rayleigh Scattering</td>
<td>Negligible</td>
</tr>
<tr>
<td>Glue Transmissivity</td>
<td>Negligible</td>
</tr>
<tr>
<td>Mirror Reflectivity</td>
<td>~10%</td>
</tr>
<tr>
<td>Geometric Efficiency</td>
<td>~12%</td>
</tr>
<tr>
<td>Quantum Efficiency</td>
<td>~85%</td>
</tr>
<tr>
<td>Collection Efficiency</td>
<td>41%</td>
</tr>
<tr>
<td>Readout Thresholds</td>
<td>~12%</td>
</tr>
</tbody>
</table>
Preliminary Photon Counting Results

<table>
<thead>
<tr>
<th>Position</th>
<th>Data Mean</th>
<th>Sim Mean</th>
<th>$\frac{\mu_{data}}{\mu_{sim}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.81</td>
<td>3.78</td>
<td>1.01</td>
</tr>
<tr>
<td>2</td>
<td>2.32</td>
<td>3.39</td>
<td>0.69</td>
</tr>
<tr>
<td>3</td>
<td>1.76</td>
<td>2.75</td>
<td>0.64</td>
</tr>
<tr>
<td>4</td>
<td>1.80</td>
<td>2.98</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Note: MCPs only cover 2/11 of the total active area!

⇒ counts for a fully instrumented module would be higher

Work ongoing to understand the effect of multiple edge reflections to account for photon losses
Simulating PID Performance in LHCb

• Measured using stand-alone Geant4 simulation of a full module
  ➢ Use full LHCb simulation as input to model TORCH in LHCb

• Pattern recognition algorithm based on delta log likelihood approach
Preliminary PID Performance

Inclusive B Events, $\mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$
Conclusions

• TORCH has taken big step towards a full scale demonstrator

• Time resolution is approaching the desired 70 ps
  ➢ Current results indicate the need for further calibrations (in progress)

• Trend seen in photon counting suggests loss factors involving photon propagation are underestimated
  ➢ Current working on understanding the effect of edge reflections on photon yield

• Simulation studies show strong PID performance in LHCb
  ➢ Work ongoing to implement TORCH in the full LHCb simulation framework
Back-up
Extracting the TORCH Resolution

\[ \sigma_{\text{meas}}^2 = \sigma_{\text{ideal}}^2 + \sigma_{\text{readout}}^2 + \sigma_{\text{beam}}^2 + \sigma_{\text{timeref}}^2 \]

Resolution measured from residual distribution of testbeam data:

- Spread from TORCH optics and detector granularity only
- Spread due to beam profile
- Spread from detector resolution & readout electronics
- Spread from time reference resolution

Measured to be 42 ± 3 ps
Spread from beam

• Measure spread from beam using simulation
➢ Compare width of residual distribution with and without beam spread

• Red fit is a single gaussian
• Each blue peak is two convolved gaussians, one with its width fixed from the red fit
Explaining the double peak

• Optics design results in a discontinuity in the photon path

• In data this cannot be resolved, but becomes apparent in simulation
The Testbeam Setup – Timing Stations

Scintillators

Borosilicate “Timing Finger”

MCP-PMT
The Testbeam Setup – Beam Telescope

Pixel (MIMOSA) Planes

Timing Plane

Pixel (MIMOSA) Planes

Beam
Time walk Correction

• Hits in TORCH are grouped into clusters
  ➢ 1 cluster = 1 incident photon

• Hits in a cluster should be simultaneous
  ➢ Time walk correction adjusts the relative time of all hits in a cluster to make this true

• Data driven approach utilises correlation between hit width ($w_x$) and leading edge time ($T_x$) to perform the correction

$$T_{Ch0} - T_{Ch1} = \Delta T(w_{Ch0}, w_{Ch1})$$