Status of the TORCH time-of-flight project

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Outline

- The TORCH concept
- Development of Microchannel Plate PMTs
- Test beam results
- Future R&D
- TORCH at LHCb
- Summary
I. The TORCH R&D project

- The TORCH (Time Of internally Reflected CHerenkov light) R&D project – to develop a large-area time-of-flight system eg. for the LHCb Upgrade II.

- TORCH combines timing information with DIRC-style reconstruction (BaBar DIRC, Belle II TOP detector, SuperB).

- $\sigma_{\text{TOF}} (\pi-K) = 35 \text{ ps}$ over a $\sim 10 \text{ m}$ flight path. To achieve positive identification of kaons up to $p \sim 10 \text{ GeV}/c$, need to aim for $\sim 10-15 \text{ ps}$ resolution per track.

- The $\sigma_{\text{TOF}}$ requirement dictates timing single photons to a precision of 70 ps for $\sim 30$ detected photons.
The TORCH detector

- Cherenkov light production is prompt → use a plane in a modular structure of 1 cm thick quartz as a source of fast signal

- Cherenkov photons travel to the periphery of the detector by total internal reflection and focused → time their arrival by Micro-Channel Plate PMTs (MCPs)

- Measure Cherenkov angle $\theta_c$ and path length $L$ in the quartz, plus the time of arrival. Then correct for the chromatic dispersion in the quartz.

- From simulation, $\sim 1$ mrad precision is required on measurement of the angles in both planes to achieve the required intrinsic timing resolution.
2. MCP development

• Need a photon detector with coarse granularity (in the non-focussing direction) and fine granularity (in the focussing direction) to achieve the 1 mrad angular precision.

• Micro-channel plate (MCP-PMT) photon detectors fulfil this requirement. They are well known for fast timing of single photon signals (~30 ps). Tube lifetime has been an issue in the past.

• Choose an anode pixel size: $128 \times 8$ pixels with a ~53 mm active area on a 60 mm pitch. The MCP-PMT pixel structure can in principle be adjusted according to resolution required as long as charge footprint is small enough.
A major TORCH focus is on MCP R&D with our industrial partner: Photek (UK).

**Three phases of R&D defined:**

- **Phase 1:** MCP single channel focuses on extended lifetime (up to 5 C/cm²) and ~35ps timing resolution. **COMPLETED** [JINST 10 (2015) C05003]

- **Phase 2:** Circular MCP with customised granularity (1/4 size active area). Beam tests 2015/16 **COMPLETED** [arXiv:1805.04889] [https://doi.org/10.1016/j.nima.2018.07.023]

- **Phase 3:** Square tubes with high active area (>80%) and with required lifetime, granularity and time resolution. **UNDER TEST**
New lifetime measurements (Phase 1 tube)

- Lifetime requirement 5 C/cm$^2$ : implement ALD coating.
  - Illumination up to 6.16 Ccm$^{-2}$
  - Gain drop observed, recovered by increase of HV
  - Marginal loss in quantum efficiency (at 3 C/cm$^2$) : a factor ~2 loss at 5 Ccm$^{-2}$. Hope is Phase 3 tubes will improve on this.

Phase 3 photon detectors

- 10 x Phase 3 MCP-PMTs delivered from Photek and are under test
- The MCP-PMT has a square $53 \times 53 \text{ mm}^2$ active area, 64 x 64 pixels. Resolution of $128 \times 8$ pixels by exploiting charge sharing.
- Readout connectors mounted on a PCB which gangs 64 pixels into 8 (or 4) and connected to anode via ACF (Anisotropic Conductive Film).
- Two types of readout PCB:
  - Readout connectors mounted on PCB, 64 x 4 pixels per tube (for use with previous version of NINO electronics – test-beam Nov 2017)
  - Readout connectors mounted on PCB, 64 x 8 pixels per tube (for use with new NINO electronics – test-beam June 2018)

L. Castillo García et al, JINST 11 C05022 (2016)
3. Demonstrator TORCH module

- Several test-beam campaigns between 2015 & 2018 at CERN PS / T9 (~5 GeV/c p/π beam)

- Quartz radiator (12×35×1 cm$^3$) with matching focusing block (from Schott Germany)

- NINO and HPTDC electronics

  R. Gao et al., JINST 10 C02028 (2015)

- Report here results from Nov 2017, read out with single Phase 3 MCP-PMT with 4×64 pixels
TORCH beam test infrastructure in PS/T9

Timing station (T1)

Timing station (T2)

TORCH prototype

Beam (mixed $\pi^+$ + $\rho$, 5 GeV/c)

CO$_2$ Cherenkov counter

Cherenkov counter

time reference

TORCH prototype

silicon pixel telescope (https://telescopes.desy.de/AZALEA)

F2/T2

F1/T1

scintillator pair
Pattern folding

- Cherenkov cone results in hyperbola-like patterns at MCP plane
- Reflections off module sides result in folding of this pattern
- Chromatic dispersion spreads line into band
- Pattern shown above for full TORCH module, however this pattern is only sampled in testbeam.
- Nominal test-beam configuration chosen to give cleanly resolved patterns.
Hit maps in MCP-PMT

- Proton-pion particle selection from ToF over ~1 m distance using beam-line borosilicate counters
- Clustering applied to get MCP centroid hit position
- Correct for non-linearity and time-walk in the TORCH electronics.

Proton – pion difference cleanly resolved
Hit maps in MCP-PMT

- Proton-pion particle selection from ToF over ~11 m distance using beamline borosilicate counters.
- Clustering applied to get MCP centroid hit position.
- Correct for non-linearity and time-walk in the TORCH electronics.

Proton – pion difference cleanly resolved.

Timing station ToF T1-T2 5 GeV/c

TORCH Preliminary 5 GeV/c protons
Time resolution

- For each column of pixels, plot time measured for each cluster relative to station T2 vs. vertical y-position
- Compare patterns relative to simulation
- Core distributions $\sigma \approx 100 - 125$ ps (energy and column dependent)
- Subtract contribution from timing reference, measure $\sim 85 - 100$ ps, approaching the target resolution of 70 ps per photon
- Tails due to imperfect calibration, backscattering
- Improvements are possible:
  - Pulse-height to width calibration
  - Limit of 100 ps binning in HPTDC
Photon energy dependence

**2 - 3 eV**
\[ \sigma = 110.6 \pm 2.0 \text{ ps} \]

**3 - 4 eV**
\[ \sigma = 105.1 \pm 1.7 \text{ ps} \]

**4 - 5 eV**
\[ \sigma = 117.0 \pm 2.2 \text{ ps} \]

**5 - 6 eV**
\[ \sigma = 148.0 \pm 3.0 \text{ ps} \]
4. Full-scale prototype

- Large prototype of a half-sized TORCH module is under construction
  Full width, half height: $125 \times 66 \times 1 \text{ cm}^3$
  Will be equipped with 10 MCP-PMTs 5000 channels

- Optical components from Nikon (radiator plate, focusing block)
June 2018 beam tests

- As an incremental step, single 64 x 8 pixel MCP-PMT and upgraded electronics have already been demonstrated in the small-scale TORCH in a beam test in June this year.
- Results are being analysed: calibrations and timing measurements in progress

- The full-scale module is planned for test-beam October/November 2018
5. TORCH for the LHCb Upgrade II

- The RICH system provides particle ID in LHCb
- But currently no positive kaon or proton ID below ~10 GeV/c
- Proposal to install TORCH in front of RICH2, possibly already in LS3 (2024)

CERN-LHCC-2017-003

- TORCH area 5 x 6 m²
- 18 module system
- 11 MCPs per module
TORCH performance studies at LHCb

- Simulated PID performance for charged particles produced in pp collisions and in heavy flavour decays (at $\mathcal{L} = 2 \times 10^{33}$ cm$^{-2}$s$^{-1}$).
- Good separation between $\pi$/$K$/$p$ in the 2 -10 GeV/c range and beyond.
- Physics studies started on key physics channels and tagging performance.
Summary

- Performance of a prototype detector in beam tests is very encouraging: 85-100 ps timing resolutions per photon achieved. With improvements hope to approach the desired 70 ps.

- TORCH future:
  - New optics half-sized module under construction
  - Final phase-3 MCP-PMTs are under test
  - New generation of electronics being commissioned
  - Physics studies underway for Technical Proposal for the Upgrade-II of the LHCb experiment
The TORCH project has been funded by an ERC Advanced Grant under the Seventh Framework Programme (FP7), code ERC-2011-ADG proposal 299175.
Spare slides from here on
Time of flight and time of propagation

\[ \Delta t \text{ ToF+ToP combined} \]
\[ d=2.0\text{m} \]  \ photon Time–of–Propagation

\[ \varphi_0 := 822\text{mrad} \]
\[ \text{normal incidence} \]

- ToF+ToP
- ToF
- \[ L=9.5\text{m} \]

\[ t(k) - t(\pi) \]
[ ps ]

- \[ \log_{10}(t(k) - t(\pi)) \]

- \[ \log_{10}(p) \]
[ GeV/c ]

- \[ \log_{10}(p) \]
[ GeV/c ]

- \[ t(k) - t(\pi) \] vs. \[ p \]
**Principle of ToF reconstruction**

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

- Time of propagation (ToP) in quartz:
  \[ t = \frac{L}{v_{\text{group}}} = \frac{n_{\text{group}} L}{c} \]

- Measure Cherenkov angle \( \theta_c \) and path length \( L \) in the quartz. Need to correct for the chromatic dispersion of the quartz.

- Can associate \( n_{\text{phase}} \) for K, \( \pi \), p hypotheses from \( \cos \theta_c \) to get photon wavelength → use dispersion relation for \( n_{\text{group}} \)

- \( L = (t - t_0) c / n_{\text{group}} \), measure arrival time at the top of a radiator bar → then assign most likely K, \( \pi \), p hypothesis from ToP and ToF

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**Motivation**

- \( L \approx 10 \text{ m} \) particle flight path

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IP
TORCH angular measurement ($\theta_x$)

- Need to measure angles of photons: their path length can then be reconstructed.
- In $\theta_x$ typical lever arm $\sim 2$ m
  - Angular resolution $\approx 1 \text{ mrad} \times 2000 \text{ mm} / \sqrt{12}$
  - Coarse segmentation ($\sim 6$ mm) sufficient for the transverse direction ($\theta_x$)
  - $\sim 8$ pixels of a “Planacon-sized” MCP of 53x53 mm$^2$ active dimension
TORCH angular measurement ($\theta_z$)

- Measurement of the angle in the longitudinal direction ($\theta_z$) requires a quartz (or equivalent) focusing block to convert angle of photon into position on photon detector.

- Cherenkov angular range = 0.4 rad
- Angular resolution $\sim$ 1 mrad: need $\approx 400/ (1 \times \sqrt{12}) \sim 128$ pixels
- Fine segmentation needed along this direction.

Representative photon paths: $0.55 < \theta_z < 0.95$ rad
Phase 1 Photek tubes: excellent timing resolution obtained in laboratory tests with fast laser and with commercial electronics

\[ \sigma_{\text{pmt}} = 23 \text{ps} \]
TORCH readout electronics


- TORCH is using 32 channel NINOs, with 64 channels per board (128 ch. board for the next phase)

- NINO-32 provides time-over-threshold information which is used to correct time walk & charge to width measurement - together with HPTDC time digitization (100 ps bins) non-linearities

- The calibration has proved challenging

R. Gao et al., JINST 10 C02028 (2015)
Position resolution

- Phase 2 tubes: tests of charge sharing between pixels: requires pulse charge to width calibration
- Point-spread function of MCP-PMT adjusted to share charge over 2-3 pixels
- TORCH requirement is $\sim 0.41\text{mm}/\sqrt{12} = 0.12\text{ mm}$. Improvement with charge division between adjacent channels $\rightarrow$ measure $\times 4$ better than that required in optimal scenario

![Anode segmentation of Phase-2 tube](image)

$L. Castillo García et al, JINST 11 C05022 (2016)$

$$y_c = \frac{\sum_i y_i \cdot q_i}{\sum_i q_i}$$
TORCH Prototype module
Beam telescope profiles

Silhouette of T2 Scintillator coincidence

Silhouette of F2 finger
Photon counting with Planecon

- Numbers of photon clusters measured in testbeam
- Mean number of photons expected from simulation: $4.89 \pm 0.02$
- Mean number of photons measured in data: $3.23 \pm 0.01$
- Around 33% fewer photons observed as expected
LHCb particle identification

- K-π separation (1–100 GeV) is crucial for the hadronic physics of LHCb. Currently achieved with two RICH radiators: C$_4$F$_{10}$ and CF$_4$.

Currently no positive kaon ID below ~10 GeV/c nor any proton ID. The plan is to achieve this via a ToF measurement with TORCH:
  - Area of 5 x 6 m$^2$ at z = 10 m
  - 18 module system (66 x 250 cm$^2$)
  - 198 MCPs (~100k readout channels)
Measuring start-time at LHCb

- To determine the time-of-flight, also need a start time \( t_0 \)
- This might be achieved using timing information from the accelerator, but bunches are long (~ 20 cm) → must correct for vertex position
- Alternatively use other tracks in the event, from the primary vertex
- Most of them are pions, so the reconstruction logic can be reversed, and the start time is determined from their average assuming they are all \( \pi \) (outliers from other particles removed)
- Can achieve few ps resolution on \( t_0 \)
TORCH for timing photons

- An idea for application of TORCH in LHCb:
  - TORCH would be placed in front of LHCb calorimeter
  - Use lead plate in front ($1X_0 \approx 6$mm) for conversion of high energy photons
  - Time tagging high energy photons can associate event vertex
  - Limited by spatial resolution of calorimeter (replaces tracking)

- Assessed with simulation
  - Time resolution is sufficient to be of great help in resolving pile-up
  - However, the PID capability will degrade due to MCS
Possible use of BaBar DIRC bars

- Possibility of re-use of BaBar DIRC quartz bars. Assigned bar still at SLAC and on hold for now.

K. Fohl et al., NIM A876 (2017) 202
TORCH possible re-use of BaBar quartz bars

- Bar length (at $z = 950$ cm) and total area $\sim 30 \text{ m}^2$ matches TORCH needs. Adapting the bars requires focusing in both projections.

- Effect of wedge (glued to bars) is to give two separate beams: depending on whether photons reflected or not: made up of 12 planar “bar-boxes” each containing 12 quartz bars $1.7 \times 3.5 \times 490 \text{ cm}^3$

- Split detector plane: assuming 60 mm square MCPs (53 mm active) requires two PMTs to cover $0.5 < \theta_z < 0.9 \text{ rad}$

- Adapting the TORCH optics to re-use the BaBar DIRC seems viable: much more complicated optics, but no degradation seen compared with single projection.

K. Fohl et al., NIM A876 (2017) 202