TORCH: A large-area time-of-flight detector for LHCb Phase II Upgrade

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Beyond the LHCb Phase-I Upgrade
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Outline

- TORCH concept
- Development of Microchannel Plate (MCP)-PMTs
- Test beam results
- Future prospects and summary
1. PID and the LHCb Upgrade

- The RICH system will be retained for particle ID, but with aerogel removed
- Possibility install a time-of-flight detector (TORCH) in front of RICH2 (or replacing muon station M1), most likely in LS3
LHCb particle identification

- K-π separation (1–100 GeV) is crucial for the hadronic physics of LHCb. Currently achieved with two RICH radiators: C₄F₁₀ and CF₄.
- Currently no positive kaon ID below ~10 GeV/c. Aim is to achieve this via a time of flight (ToF) measurement with a new detector (TORCH).

RICH C₄F₁₀ data
2. The TORCH R&D project

- The TORCH (Time Of internally Reflected CHeReNkov light) detector is an R&D project to develop a large-area time-of-flight system.

- TORCH combines timing information with DIRC-style reconstruction (cf. Belle TOP detectors & the PANDA DIRC) : aiming to achieve a ToF resolution ~10-15 ps (per track).

- A 5-year grant for R&D on TORCH has been awarded by the ERC: to develop customised photon detectors in collaboration with industrial partners and to provide proof-of-principle with a demonstrator ToF module.
The TORCH detector

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

- Cherenkov light production is prompt → use a plane of quartz ($\sim 5 \times 6$ m$^2$) as a source of fast signal

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

- The $\Delta$TOF requirement dictates timing single photons to a precision of 70 ps for ~30 detected photons)
Basics of the TORCH design

- Measure *angles* of photons: then reconstruct their path length $L$, make correction dispersion effects - then time of propagation
- From simulation, a $\sim 1$ mrad precision is required on the angles in both planes for intrinsic resolution of $\sim 50$ ps
- Need a photon detector with anode pixel size: $128 \times 8$ pixels over 60mm pitch: (11 microchannel plate (MCP) detectors per module)
• Micro-channel plate (MCP) photon detectors are well known for fast timing of single photon signals (~30 ps). Tube lifetime has been an issue in the past.

3. MCP development

• Anode pixel structure can in principle be adjusted according to resolution required as long as charge footprint is small enough: →tune to adapted pixel size: 128 × 8 pixels
A major TORCH focus is on MCP R&D with an industrial partner: Photek (UK).

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

- **Phase 1:** MCP single channel focuses on extended lifetime (> 5 C/cm²) and ~35ps timing resolution. **COMPLETED**

- **Phase 2:** Circular MCP with customised granularity (32x32 pixels (1/4 size) with charge sharing between neighbouring pads to get fine dimension). **COMPLETED**

- **Phase 3:** Square tubes (64x64) with high active area (>80%) and with required lifetime, granularity and time resolution. **DELIVERY SOON**
Laboratory measurements

- Lifetime requirement 5C/cm²
  - Gain drop observed
  - Recovered by increase of HV
  - Marginal loss in quantum efficiency (at 3.1 C/cm²)

- Phase 1 Photek tubes: excellent timing resolution obtained with fast laser and with commercial electronics

Lifetime test by TORCH @ CERN

Initial HV (2300V) increased by 150V
Initial gain ~6×10⁵
Photoelectron rate ≤ 0.8 MHz/cm²

Regular tests of DCR, gain, TTS, QE

T. Gys, presented at RICH2016 (Bled)
Laboratory measurements (2)

- Phase 2 tubes: tests of charge sharing between pixels.
- TORCH requirement is \( \sim 0.41 \text{mm}/\sqrt{12} = 0.12 \text{ mm} \).
- Improvement with charge division between adjacent channels \( \rightarrow x4 \) better than that required.
- See L. Castillo García et al, JINST 11 C05022 (2016)
4) Demonstrator TORCH module

- Quartz radiator (12×35×1 cm³) with matching focusing block
- Single Phase-II MCP-PMT in centre of focusing plane (4×32 pixels)
- Testbeam at CERN PS / T9
- Trigger defined by two 8×8 mm² scintillators spaced 11 m apart
- Timing ref taken from two borosilicate bars with single-channel MCP-PMT
TORCH beam test infrastructure in PS/T9

T1/T2: scintillator + timing stations
C1/C2: threshold Cherenkov counters (CO$_2$ @ 2.5bars)
Pattern folding

- Cherenkov cone results in hyperbola-like patterns
- Reflections off module sides result in folding of this pattern
- Chromatic dispersion spreads line into band
- Pattern shown here for full TORCH module, also very prevalent in testbeam

Beyond the LHCb Upgrade 29 May 2017

Direct
Two reflections
One reflection

Focusing optics and detectors

Geant simulation

Full pattern
($E_{\text{photon}} = 1.75 - 7\text{eV}$)
Cluster hit map in TORCH

- Charge weighting applied to get centroid of clusters
- Particle selection from beam telescope ToF
- Reflections clearly separated
- Proton – pion difference cleanly resolved
**Time resolution**

- Plot time measured for each cluster relative to T1 vs. vertical position along column of pixels.
- Project along timing axis relative to prediction for each column of pixels (relative to T1 as timing reference).
- Core distribution has $\sigma \approx 110$ ps. After subtraction of contribution from timing reference measure $\sim 85$ ps, approaching the target resolution of 70 ps / photon.
- Improvements possible:
  - Beam defined by small scintillators with no tracking.
  - 100ps binning in HPTDC.
- Tails under study, due to imperfect calibration and back scattering effects.
Simulation of the TORCH detector & interface to a simulation of LHCb events, plus TORCH pattern recognition in GEANT.

Obtain a start time $t_0$ from the other tracks in the event originating from the primary vertex.

Excellent particle ID performance achieved, up to and beyond 10 GeV/c (with some discrimination up to 15 GeV/c). Seems to be robust against increased luminosity.
Full-scale prototype

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

- Optical components from Nikon
  (radiator plate, focusing block)
  Detailed measurements provided by supplier, match the specifications

- Testbeam October/November
Future developments

- A proposal to mount the large-scale TORCH module inside LHCb (outside acceptance) has been discussed for winter shutdown
  - Would still have tracking for low energy particles
  - Test bench for full application
  - Require successful testbeam campaign and lots of work to be done.

- Possibility of re-use of BaBar DIRC quartz bars. Assigned bar still at SLAC and on hold for now.
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 ($1X_0 \approx 6\text{mm}$) 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
For a given photon from a PV + timing information from TORCH can open a window with width $\mu$ ps around the given timing information.

- A loose cut with window 360ps reduces combinatoric and has almost 100% efficiency of containing the correct PV

- A cut of 120ps has reasonable efficiency for correct PV, but likely to have no incorrect vertices
Summary

- TORCH is a novel concept for a DIRC-type detector to achieve high-precision time-of-flight over large areas aiming to achieve K-π separation up to 10 GeV/c and beyond (with a TOF resolution of ~15 ps per track).

- Ongoing R&D programme aims to produce suitable MCP, satisfying challenging requirements of lifetime, granularity, and active area.
  - First two phases of MCP results show promising results for lifetime, timing measurements, granularity with charge sharing.

- Testbeam results very promising
  - Performance has been shown to be very good ~approaching 70ps time resolution per photon.

- TORCH future
  - New optics half-sized module have been delivered
  - Delivery of Phase-III MCP-PMTs is very close
  - New generation of electronics being designed.
That’s all folks!

The TORCH project is 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

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

\[ \phi_0 := 822\text{mrad} \]
\[ \text{normal incidence} \]

Time differences \( t(k)-t(\pi) \)

\( \log_{10} \) scale

Particle momentum \( p \) [GeV/c]
TORCH Angular measurement ($\theta_x$)

- Need to measure angles of photons: their path length can then be reconstructed
- In $\theta_x$ typical lever arm ~ 2 m
  - Angular resolution $\approx$ 1 mrad x 2000 mm / $\sqrt{12}$
  - Coarse segmentation (~6 mm) sufficient for the transverse direction ($\theta_x$)
  - ~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
TORCH modular layout

- Dimension of quartz plane is \( \sim 5 \times 6 \text{ m}^2 \) (at \( z = 10 \text{ m} \))
- Unrealistic to cover with a single quartz plate \( \rightarrow \) evolve to modular layout

- 18 identical modules each \( 250 \times 66 \times 1 \text{ cm}^3 \)
  \( \rightarrow \) each with 11 MCPs to cover the length

- MCP photon detectors at the top and bottom edges
  \( 18 \times 11 = 198 \) units
  Each with 1024 pads
  \( \rightarrow \) 200k channels total
**Chromatic dispersion correction**

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

Time of propagation (ToP) in quartz:

\[
t = \frac{L}{v_{\text{group}}} = \frac{n_{\text{group}} L}{c}
\]

- Need to correct for the chromatic dispersion of the quartz
- Measure Cherenkov angle \( \theta_c \) and arrival time at the top of a bar radiator → can associate \( n_{\text{phase}} \) to get photon colour for K, \( \pi \), p hypotheses → use dispersion relation for \( n_{\text{group}} \)
- Reconstruct path length \( L = (t - t_0) \frac{c}{n_{\text{group}}} \) then determine ToP
- Then reconstruct ToF for K, \( \pi \), p hypotheses

**Motivation**

- Measured angle
- Particle flight path: 9.5 m
- IP: Tracking
- TORCH: Measured angle d=2 m
- LHCb Upgrade: 29 May 2017

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Customized pad layout

- Traditional multi-anode manufacturing uses multiple pins: difficult for \( 128 \times 8 \) array – plan therefore for \( 64 \times 8 \): gang together 8 pixels in coarse direction

- Have charge division between a pair of pads recovers pixel resolution from \( 64 \rightarrow 128 \) and reduces total number of channels

- TORCH pixel pads are 0.75 mm wide on a 0.88 mm pitch. Contact made to readout PCB by Anisotropic Conductive Film (ACF)
Readout Electronics

- Readout electronics are crucial to achieve desired resolution.

- Suitable front-end chip has been developed for the ALICE TOF system: NINO + HPTDC [F. Anghinolfi et al, Nucl. Instr. and Meth. A 533, (2004), 183, M. Despeisse et al., IEEE 58 (2011) 202]

- TORCH is using 32 channel NINOs, with 64 channels per board (128 ch. board in development)

- NINO-32 provides time-over-threshold information which is used to correct time walk & charge measurement - together with HPTDC time digitization
NINO analogue front end

- DAC – Setting threshold
- Input – negative phase only
- Potentiometer – threshold quick settings
- LVDS output

2xNINO - Time Over Threshold Measurement, 64-ch per board

Detector Signals

Threshold

NINO Output

Rui Gao, 23rd September 2014
TWEPP 2014, Aix En Provence, France
HPTDC board – Time to Digital conversion

LVDS input from NINO

2x HPTDC[4]
ASICs 64ch

Spartan3AN
HPTDC configuration and control
Data formatting and buffering

Power
Input: clock, trigger, serial slow control, fast control
Output: TDC data, all signals in LVDS
Readout board

LVDS I/O
Fan out 4 x clocks, 4 x triggers
and 36 pairs of LVDS signals
Standalone JTAG for TDC board
2.5v and 3.3v @ 3A max

Gigabit Ethernet

HDMI Connector
External clock and 3 bi-directional LVDS pairs,
pinout compatible with Timepix3 Telescope TLU.

Standard LEMO/ SMA interface are available
through adaptor.

Spartan6 LX45T

1Gbit DDR3 RAM

200MHz OSC

Single 5V power supply

Rui Gao, 23rd September 2014
TWEPP 2014, Aix En Provence, France
Lifetime measurements

- Use Atomic Layer Deposition (ALD) to coat atomic layers onto the MCP

- Lifetime requirement set at 5C/cm² for Phase-I MCP-PMTs

- Testing at Photek and CERN
  - Gain drop observed
  - Recovered by increase of HV
  - Marginal loss in quantum efficiency (at 3.1 C/cm²)
MCP timing resolution measured in Lab

- Phase 1 Photek tubes: timing resolution obtained with fast laser and with commercial electronics.

- Phase 2 Photek tube: timing resolution obtained with fast laser and customised NINO-32 and HPTDC electronics with HPTDC time binning set to 100 ps.
  - Correction needs to be made for integral non-linearity (INL) of the HPTDC and time-walk effects from the time-over-threshold (TOT) information from the NINO.

- All timing properties measured at an MCP gain of $1 \times 10^6$. 
MCP charge sharing (Lab)

- Tests of charge sharing between pixels. Pad dimensions 0.75 mm. Fast laser to the centre of a pixel

- TORCH requirement is $\sim 0.41 \text{mm}/\sqrt{12} = 0.12$ mm. Improvement with charge division between adjacent channels $\rightarrow x4$ better than that required

- See L. Castillo García et al, JINST 11 C05022 (2016)
Timing results continued

Pions only | Protons only | All
---|---|---
Time projection T1 (column 0) | Time projection T1 (column 0) | Time projection T1 (column 0)

~600 ps

T1 reference
Flight path 10m

T2 reference
Flight path 1m
Timing results

- Displayed as time projection per single (vertical) column
- Superimpose predictions and data
LHCb event

- Typical LHCb event, at luminosity of $10^{33}$ cm$^{-2}$ s$^{-1}$ (only photons reaching the upper edge shown)
- High multiplicity $>100$ tracks/event
- Tracks from vertex region colour-coded according to the vertex they come from (rest are secondaries)

Zoom on vertex region
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 \( t_0 \)

Example from PV of same event

\[
\sigma(t_0) = 49 \text{ ps} \sqrt{534}
\]
TORCH possible re-use of BaBar quartz bars

- BaBar DIRC quartz bars are available following SuperB cancellation: made up of 12 planar “bar-boxes” each containing 12 quartz bars 1.7 x 3.5 x 490 cm³
- Bar length (at z = 950 cm) and total area ~ 30 m² matches TORCH needs. Adapting the bars requires focusing in both projections; can use a cylindrical lens for this, at the end of each bar.
- Effect of wedge (glued to bars) is to give two separate beams: depending on whether photons reflected or not.
- Split detector plane: assuming 60 mm square MCPs (53 mm active) requires two PMTs to cover 0.5 < \( \theta_z \) < 0.9 rad
- Adapting the TORCH optics to re-use the BaBar DIRC seems viable: no degradation seen compared with single projection. Studies are ongoing.