TORCH: a novel concept for PID

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TORCH (Time Of internally Reflected CHerenkov light) is a detector concept intended for fast timing of charged particles over large areas. Currently an R&D project, under study for next upgrade of LHCb (in LS3/4). Potentially interesting for adaptation to use in a future FCC-ee detector?

Previously presented at an FCC-ee detector brainstorming meeting on 4 July 2016—slides updated here with progress made since then:

1. TORCH principle
2. R&D project
3. Application in FCC-ee?

FCC-ee workshop (CERN) 9 January 2019
1. TORCH principle

- DIRC-like detector, with a ~1 cm thick quartz radiator plate. Cherenkov light produced in the plate propagates to the edge by TIR focused via a cylindrical lens onto fast photon detectors.

- Reconstruction of the Cherenkov angle at emission allows the propagation time in the radiator plate to be corrected for dispersion i.e. it combines RICH + TOF aspects.

- Requires precise angular information (~ 1 mrad) to achieve timing resolution of ~ 70 ps/photon → 10-15 ps/track by combining ~ 30 detected p.e./track.
Signal form

- Event display of an idealised TORCH detector in simulation of sterile neutrinos (low multiplicity)

- Photon hits colour-coded to match parent track

→ TORCH is also a candidate for use in such SHiP-type experiments e.g. included in the design of proposed TauFV (considered by PBC)
Reconstruction

• Smearing from dispersion in quartz:

- Use timing information as well as spatial information from detector to separate signals from each track
- Calculate time of propagation of all photons relative to the blue track ($\pi$)
- Hits from that track peak at true time
  Hits from other tracks spread out
  (but peak in time distribution when it is calculated relative to that track)
TORCH in LHCb

- Conceived for low-momentum PID in LHCb replacing aerogel radiator of RICH system (could not handle increased occupancy)

- Nominal position of TORCH \((z = 9.5\,\text{m})\) chosen to be as close as possible to tracker and to reduce area to be covered \((\sim 30\,\text{m}^2)\)

- Original DIRC of BaBar required large water-filled standoff volume for readout, achieved \(K/\pi\) separation up to \(\sim 3.5\,\text{GeV}\) (based on Cherenkov angle, not timing)

- Belle-II TOP “time-of-propagation” detector adds timing but limited focusing \(\rightarrow 4–5\,\text{GeV}\) (see previous talk from Roberto Mussa)

- TORCH uses measured Cherenkov angle to correct timing, aiming for “ultimate” resolution \(K/\pi\) separation up to 10 GeV/c \((\Delta_{\text{TOF}} \approx 40\,\text{ps})\)
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 (others are secondaries)

- “Start time” for TOF determination can be extracted from primary tracks (see backup)

Zoom on vertex region
Modular design

- For the application in LHCb, transverse dimension of plane to be instrumented is $\sim 5 \times 6 \text{ m}^2$ (at $z = 9.5 \text{ m}$) + central hole for beam pipe

- Unrealistic to cover with a single quartz plate $\rightarrow$ modular layout developed:

  - 18 identical modules each $250 \times 66 \times 1 \text{ cm}^3$ $\rightarrow$ $\sim 300$ litres of quartz in total (less than BaBar)

  - Reflective lower edge $\rightarrow$ detectors only on top

    $18 \times 11 = 198$ detectors

    Each with 1024 pixels

    $\rightarrow 200k$ channels total

  Channel count halved by using charge sharing to improve spatial resolution
Effect of modules

- Illustrate the effect of introducing modules, using the same event
- Far fewer hit-track combinations, but reflections from sides give ambiguities, which can be resolved in the reconstruction
Performance

Isolated tracks (TOF only)  LHCb simulation: efficiency vs. $p$

- Expected performance for low-momentum particle ID from full simulation: excellent, and robust to increasing luminosity
- Results shown are from a stand-alone simulation of the TORCH detector coupled to full LHCb simulation at the upgrade (i.e. post-LS2) luminosity
- Integration of TORCH into the LHCb simulation is in progress
2. R&D project

- **Fast photon detectors** required: < 70 ps for single photons—use microchannel plate (MCP) PMTs
- Fine spatial granularity needed (~ 0.4 mm) in one dimension (due to focusing) + long lifetime (> 5 C/cm²) + large active area
  Requirements were not available in commercial tubes when R&D effort started (6 years ago)
- **R&D project** set up to develop suitable photodetector, funded by ERC: collaboration between CERN, Oxford, Bristol and UCL, with industrial partner Photek (UK); Warwick and Edinburgh have now also joined the collaboration
- Granularity and lifetime (using ALD coating) achieved in round tubes, final phase developed square tubes with large active area
  64 x 64 ch/tube!—we group pixels as required

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Custom electronics

- Full readout for prototype tubes developed based on 32 ch NINO (ALICE) and HPTDC chips

Photek MCP  Anode pads

Time-over-threshold used for charge estimate → reduce number of pixels in fine direction (to 64)
Test-beam studies

- Small prototype TORCH module made with 35 x 12 x 1 cm³ radiator plate
- Coupled to focusing block and MCP with readout electronics + timing stations
- Data taken successfully in several test-beam campaigns at the PS (T9, 5 GeV/c)
Data analysis

- Time-of-flight determined using timing stations $(T_1, T_2) \rightarrow$ separate $\pi / \pi$ components of beam
  Confirmed using Cherenkov counter

- Hits seen in MCP match expected pattern (taking into account reflections from edges)
  Difference in Cherenkov angle for $\pi$ and $\rho$ visible

Hit pattern in MCP (32 x 4 ch)

More recent data (64 x 4 ch)
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Timing performance

- Plot time measured for each cluster vs. vertical position along column of pixels
  - Reflections clearly separated
  - $p-\pi$ time-of-flight difference cleanly resolved
- Project along timing axis relative to prediction for the earliest pion signal, for each column of pixels (relative to T2 as timing reference)
- Core distribution has $\sigma \approx 100$ ps
  $\rightarrow$ approaching target resolution of 70 ps / photon
- Tails under study, due to imperfect calibration and back-scattering effects [see e.g, https://arxiv.org/abs/1812.09773]
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Full-scale prototype

• Final goal of the ERC-funded R&D project was to prototype a TORCH module accommodating 10 MCPs. They have now been delivered (Photek) (64 x 8 ch, with charge sharing).

• Highly polished synthetic quartz plate 66 × 125 × 1 cm³ (procured from Nikon).

• Mechanics completed at end of last year so far instrumented with 2 MCPs.
Prototype construction

- Required significant engineering!

During construction

Rotated vertical
3. Application in FCC-ee?

- *In the spirit of brainstorming...* I was not sure of current design for a detector at FCC-ee last time so assumed something ALEPH-like (easily scaled for other designs)

- Best place for TORCH would be just after tracking volume, $R \sim 180$ cm i.e. between TPC and ECAL

- Adapt to barrel geometry following 12-fold symmetry

- Endcap modules (if required) could be optically coupled together

- Some space required for focusing, photodetectors, electronics → place in overlap region (“readout boxes”) – *far* smaller than BaBar!

- 24 barrel modules $96 \times 220$ cm$^2 = 50$ m$^2$
  12 modules for each endcap $\sim 10$ m$^2$ (i.e. total area $\sim 2x$ LHCb design)
• Possible layout illustrated, to give idea of what would be required

• Focusing scheme should be adapted according to constraints (here arranged to lie on one side of modules only)

• Assuming 6 x 6 cm$^2$ photodetectors along edge of module → 16 tubes per module

• 48 modules → 768 tubes in total 512 channels each (using charge sharing) → 400 k total — i.e. not outrageous

• Practical details would need to be optimized: e.g. separating barrel/endcap... achieving full coverage of overlap? material budget from readout box, etc. (for LHCb the readout box can be arranged to be outside the acceptance)
Performance considerations

• **Time-of-flight** from IP to quartz plate is less in this layout than in LHCb (distance 2–3 m instead of 10 m) However, **time-of-propagation** of the Cherenkov photons in quartz is similar (distance 2–3 m)

• Total time difference of K/π is sum of the two (they add constructively) so overall performance would be somewhat degraded, but still good Could be compensated by pushing the timing/photon and granularity — simulation would be required, to be quantitative

• What is required momentum range for flavour physics PID at FCC-ee? On the Z, b fragmentation ~ 0.7 → $p_b$ ~ 30 GeV, interesting b decays typically have few – 10 daughters → $p_{\text{daughter}}$ ~ few – 10 GeV (?) Other physics cases? How well can dE/dx compete in this range?

• **Occupancy** should be much lower at FCC-ee than in LHCb However, for high luminosity operation would timing of all tracks be useful? (as it will be for pile-up suppression at HL-LHC, separately from PID aspect)

• **Material budget:** 1 cm quartz = 8% $X_0$ (plus light-weight support/enclosure) MCPs are generally insensitive to magnetic field
Conclusions

• **TORCH** is a novel detector concept designed to provide high-precision timing over large areas, pushing the limits of the DIRC technique.

• Developed in **LHCb** to provide clean K/π separation up to 10 GeV/c. The R&D project progressed well, has developed the required photodetectors and is now focused on completing the full-scale prototype module (proposal submitted to ATTRACT) + demonstrating the physics case.

• TORCH technique may be interesting for application in an **FCC-ee detector**: it has been developed to tolerate LHC-levels of radiation and occupancy, compact for integration in experiment + affordable for large area coverage. **Cost** of prototype module ~ 400 kCHF split between optics + photodetectors. Hope for economy of scale to reduce cost/module for final detector (?)

• Estimating the performance at FCC-ee would require **simulation** study. Physics requirements should be clearly defined, so design can be optimized. Happy to hear if there is interest to pursue this in the FCC-ee community!
• To determine the time-of-flight, also need a start time \( t_0 \)
• Might consider using timing information from the machine, but bunches are long and their collisions are spread in time
• Instead use the other tracks in the event from the primary vertex
• Typically 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, and procedure iterated
• Can achieve few-ps resolution on \( t_0 \)

\[ \sigma(t_0) = 49 \text{ ps} \sqrt{534} \]
MCP-PMT development

- Intrinsic **timing** performance of Phase-1 tubes measured with fast laser and single-channel commercial readout electronics
- Prototype tubes use dual-MCP in chevron configuration, 10 μm pores
  - **Lifetime** addressed by ALD (atomic layer deposition) treatment of MCP
  - As introduced by Argonne/LAPPD

Long-term test
- Blue LED illumination
- HV increased: 2300 → 2450 V

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**T. Gys et al., NIM A766 (2014) 171**

**Counts (logarithmic scale)**

- Experimental data
- Exp. Modified Gaussian
- 2nd Gaussian
- Data fit

**Laser + back-scattering effects**

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**T. Gys et al., RICH2016**

**Quantum efficiency [%]**

- On-axis
- Off-axis -5mm
- Off-axis -8mm
Spatial resolution

• Effective resolution equivalent to 0.4 mm achieved with 2x larger pixels by making use of charge-sharing between neighbouring pixels. Point-spread function adjusted to share charge over 2-3 pixels.

• Requires calibration of the relationship between pulse width and charge.

Anode segmentation of Phase-2 tube
Active area 25 x 25 mm², 32 x 4 pixels

Charge-to-width calibration

Spatial resolution measured with laser illumination (charge-weighted cluster centroid).

L. Castillo García, IPRD16
Final photon detector

• Final Phase-3 tube integrates the features that have been developed in earlier phases, in a square format with 53 x 53 mm² active area. Quartz window and AC-coupled anode, so window can be at ground.

• Readout connectors mounted on PCB, 64 x 8 pixels per tube, which is attached to tube using ACF (anisotropic conductive film).

• Delivery of final tubes from Photek planned in the coming weeks.

Bare tubes

After potting, before readout PCB is attached