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TORCH, a novel time of flight detector for LHCb upgrade II

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The plans for LHCb upgrade II in the HL LHC era include complementing the experiment's particle identification capabilities in the low momentum region up to $10-15\,\mathrm{GeV/c}$ with the novel TORCH time of flight detector. TORCH is designed to provide 15 ps timing resolution for charged particles, resulting in K/π (p/K) particle identification up to 10 (15) GeV/c momentum over a 10 m flight path. We present the results of beam and laboratory test of TORCH prototypes; the latest TORCH design for the LHCb upgrade II Framework Technical Design Report; and the simulated particle ID performance in LHCb upgrade II high luminosity running conditions.

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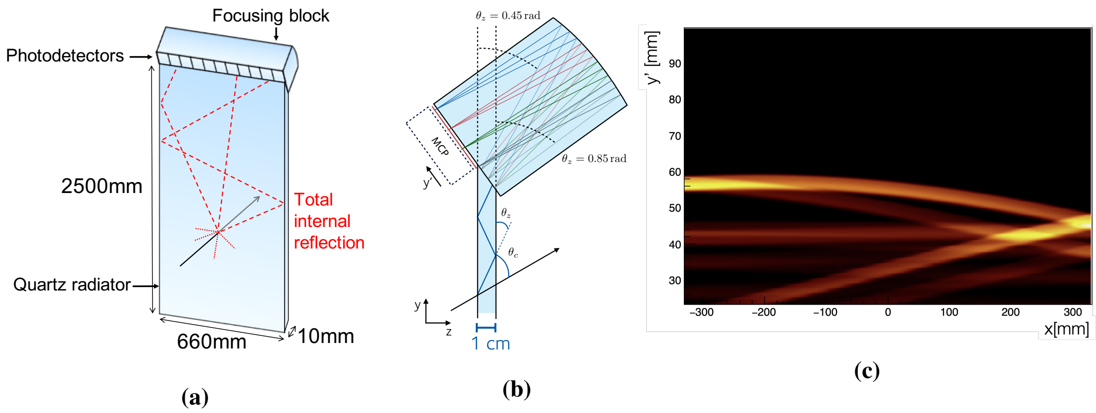


Figure 1: (a) A TORCH module with focusing block, illustrated with different photon paths (red) from the track (black) to the focusing block on top. (b) A schematic of the focusing block, which shows the translation of the photon's angle of exit from the quartz plate into the position on the MCP-PMT plane. (c) The resulting image on the detector plane for one example track. This idealised image is obtained from an analytical probability density function - the real image will be pixelated and have typically $\sim$ 30 photon hits.

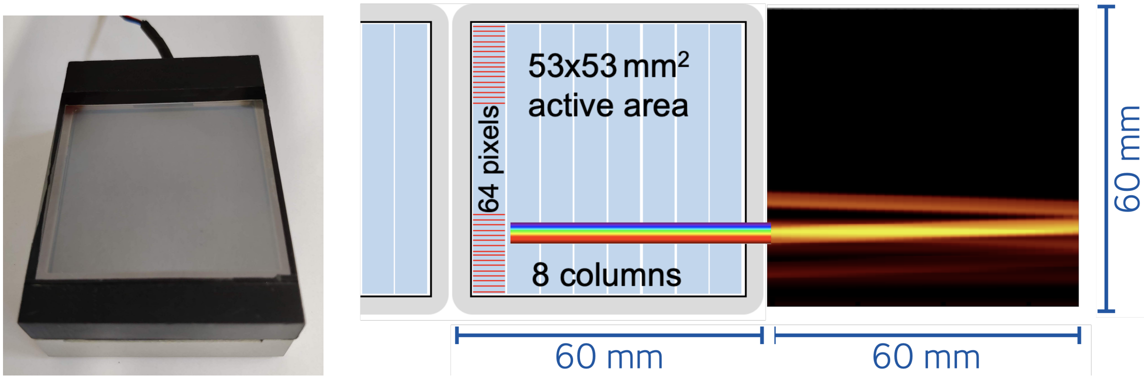
1. Introduction

TORCH (Time Of internally Reflected CHerenkov light) is a novel time of flight detector [1, 2]. It uses Cherenkov light created by charged particles that traverse its 10 mm quartz pane. This light is internally reflected and read out at one edge, where a cylindrical mirror directs it onto an array of photon detectors with excellent time resolution, as illustrated in figure 1. The method extends techniques which were pioneered by the BaBar DIRC [3] and Belle II iTOP [4, 5]. TORCH particle ID is based on measuring the time at which the charged particle traverses the quartz pane, positioned about 10 m from the interaction point where it was created. From this, the speed of the particle is inferred. When combined with momentum information from the tracking system, this provides information on the particle's mass. TORCH is designed to achieve kaon-pion (proton-kaon) separation up to a momentum of 10(15) GeV. This would perfectly complement LHCb's RICH system, which provides positive kaon (proton) ID for momenta above 10(15) GeV. TORCH is expected to be installed for LHCb upgrade II [6].

2. TORCH Design

The necessity to reconstruct the time of propagation of each photon from the track to the photon detector motivates the design of the TORCH optical system, shown in figure 1b. It allows the reconstruction of the photon's path length, and the Cherenkov angle at which it was emitted. The Cherenkov angle depends on the photon's wavelength, which determines its speed of propagation. Further details on TORCH event reconstruction can be found in [7, 8].

The design of a TORCH module is shown in figure 1a. An idealised version of the pattern on the photo detector plane, resulting from a single track, is shown in figure 1c. This is derived from an analytical PDF for the photon distribution on the detector plane [7]. The overlapping lines correspond to photon paths with different numbers of reflections on the sides of the module,



(a) **(b)**

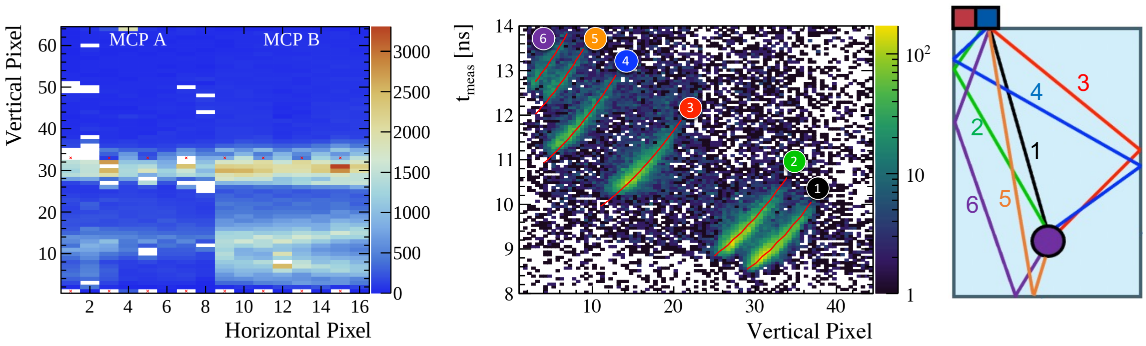
Figure 2: Subfigure (a) shows a prototype MCP-PMT built by Photek [9]. The image on the right of subfigure (b) represents the probability density function of photons hitting the detector plane from one example track, before any pixelisation effects. The subfigure illustrates the motivation for the desired resolution of 128×8 effective pixels (achieved through interpolation of 64×8 pixels using charge sharing). The finer vertical granularity is needed to resolve the wavelength of the arriving photons.

or the bottom. The precision timing information from the Micro-Channel Plate Photomultiplier Tubes (MCP-PMTs) used in TORCH disentangles these contributions, as shown in figure 3. The information on the Cherenkov angle, and thus photon wavelength and speed, is encoded primarily in the vertical direction in figure 2 (the rainbow colours in the picture are however just for illustration, the real spectrum lies in large part in the UV). This motivates the fine granularity of the MCP-PMTs in that direction. In the horizontal direction, the image varies very slowly, justifying the coarse 8-pixel binning. An effective 128×8 resolution is achieved with 64×8 physical pixels, and position interpolation based on charge sharing. Each module will be equipped with eleven MCP-PMTs.

The proposed design for use in the Upgrade II of the LHCb experiment [6] combines 18 TORCH modules to cover and area of $6\,\text{m} \times 5\,\text{m}$. When positioned at a distance of 9.5 m from the LHCb interaction point, the time-of-flight difference between 10 GeV/c pions and kaons is 35 ps, requiring a per-track time resolution of $10 - 15$ ps for three standard deviations (σ) of separation between mass hypotheses. Given $\sim$30 detected photons per track, the requirement on the single-photon time resolution is thus ~ 70 ps [10].

3. TORCH Photodetectors and Readout

Multi-channel plate photo multiplier tubes (MCP-PMTs) allow for excellent timing resolution. MCP-PMTs to meet the requirements of TORCH have been developed in collaboration with industrial partner Photek [9]. The tubes have an intrinsic pixelisation of 64×64 pads over a $53 \times 53\,\text{mm}^2$ active area, within a $60 \times 60\,\text{mm}^2$ physical footprint. The MCP-PMT anode pads are connected directly to an external printed circuit board (PCB) using anisotropic conductive film. The MCP-PMTs are read out with a granularity of 8×64 pixels, illustrated in Fig. 2b. The MCP-PMTs are designed to withstand an integrated charge of $5\,\text{C}/\text{cm}^2$ [11]. This radiation hardness is achieved through atomic layer deposition (ALD) coating of the micro-channel plates.



(a) (b) (c)

Figure 3: (a) The spatial distribution of reconstructed photon clusters on MCP-PMTss A and B. Pixels marked with a red cross are those where a time reference signals were injected. (b) The time projection of reconstructed photon clusters on MCP-PMT B. (c) Diagram with photon paths leading to the labelled features in (b). [18]

The MCP-PMTs are read out using customised electronics boards [12] that use chip-sets developed for the ALICE TOF detector [13], incorporating NINO ASICs [14], and High Performance Time to Digital Converters (HPTDCs) [15].

Laboratory tests [16] of TORCH MCP-PMTs at CERN show approximately 15%-20% peak quantum efficiency in the wavelength range 200 – 800 nm. Operating the HPTDC in high and very high resolution mode, a single-photon time resolution of the combined tube and readout system of 90 ps and 48 ps is found, respectively. The latter fulfils TORCH requirements. The next generation of TDCs is expected have an even better time resolution [17].

4. Beam tests

Several TORCH prototypes have been tested in beam tests [2, 18, 19]. The latest test [18] with a half-scale prototype was the first equipped with the final MCP-PMT design. Two MCP-PMTs were positioned in the top-left corner of the protoype, represented by the red and blue box in the diagram in figure 3b. Figure 3a shows the pattern on the detector plane resulting from 8 GeV/c protons, while figure 3b shows the distribution of hits in time and the vertical (high-resolution) pixel dimension. The time information cleanly separates out the different contributions resulting from different reflections on the sides and bottom of the quartz pane illustrated in figure 3c.

Table 1: Contributions to the single photon time resolution. The results of the analysis of the pion and proton samples are shown separately and are consistent with each other. The target performance is also shown.

Contribution	Fitted values (ps)		Target values (ps)
	Pion	Proton	
$\sigma_{\text{prop}}(t_p)$	$(8.3 \pm 0.7) \times 10^{-3} \times t_p$	$(7.6 \pm 0.5) \times 10^{-3} \times t_p$	$(3.75 \pm 0.8) \times 10^{-3} \times t_p$
σ_{MCP}	34.5 ± 8.6	31.0 ± 7.6	33
$\sigma_{\text{RO}}(N_{\text{Hits}})$	$(96.2 \pm 6.7)/\sqrt{N_{\text{Hits}}}$	$(95.0 \pm 6.0)/\sqrt{N_{\text{Hits}}}$	$60/\sqrt{N_{\text{Hits}}}$

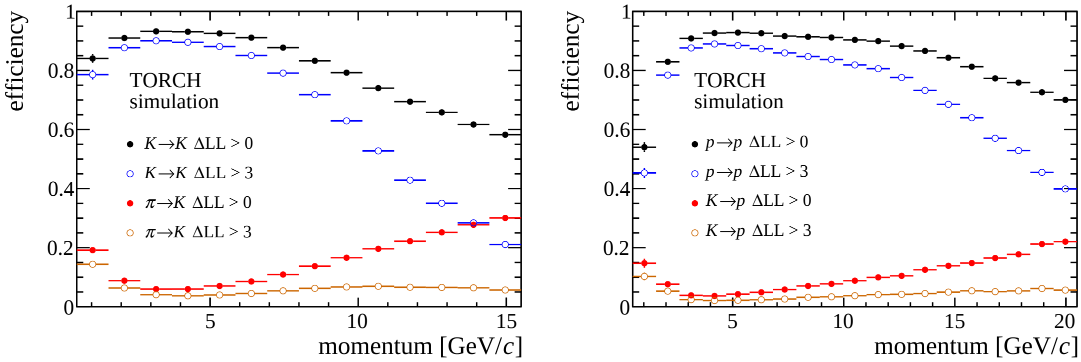


Figure 4: Simulated kaon (left) and proton (right) identification efficiency for two different $\Delta\mathrm{LL} = \log L_{K,p} - \log L_{\pi}$ requirements, at LHCb upgrade II at an instantaneous luminosity of $1.4 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

The testbeam setup allowed the study of the time resolution as a function of the photon propagation time t_p and the number of signals above threshold read out from the tube, N_{Hits}. A single photon can produce multiple hits N_{Hits} due to charge sharing. These measurements allowed a separation of three different contributions to the single-photon time resolution: one proportional to the propagation time t_p, σ_{prop} (related to the Cherenkov angle resolution); the time resolution of the readout electronics, σ_{RO}, which is assumed to be proportional to $1/\sqrt{N_{\mathrm{hits}}}$; and the intrinsic time resolution of the photo detectors, σ_{MCP}. The results are shown shown in table 1. The intrinsic time resolution of the photon detectors is excellent and within specifications. The values of σ_{RO} and σ_{prop} are expected to improve with future electronics calibrations.

5. TORCH at LHCb Upgrade II

LHCb upgrade II is planned to be installed in LHC's Long Shutdown 4 and is expected to start operation in 2035. It will operate at a luminosity of $1.4 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [6], nearly an order of magnitude higher than that of LHCb upgrade I which is currently being commissioned (2022).

The expected performance of TORCH in LHCb upgrade-II conditions has been evaluated in detailed simulation studies [20]. Figure 4 shows TORCH particle ID performance for K/π and K/p separation, in terms of the probability of the correct ($K \to K, p \to p$) and incorrect ($\pi \to K, K \to p$) particle identification. The performance is shown for two different requirements on the likelihood difference (ΔLL) of the two particle hypotheses. The figure shows good K/π separation for momenta up to 10 GeV/c, and good p/K separation up to 15 GeV/c. Further performance improvements are expected from a reoptimisation of the detector geometry in the central modules, where occupancies are highest.

The improved particle ID will benefit a large host of analyses. This includes high multiplicity decays (leading to soft momentum spectra for the final state particles) like, for example $B^0 \to DDK\pi \to 3K3\pi$ [21]; this decay can help with the interpretation of $B \to K^*\mu\mu$ in terms of Standard Model or New Physics. The substantially improved proton ID will benefit all analyses involving baryons, such as $\Lambda_b \to J/\psi K p$, the pentaquark discovery channel [22, 23]. The improved particle ID does not only increase, but also equalise the efficiency throughout the kinematic phase space, which is important for the complex amplitude analyses needed to extract the desired physics parameters. TORCH particle ID is expected to improve B flavour tagging and identification of heavy particles such as deuterons. LHCb's global event reconstruction is expected to benefit from TORCH's precision timing, which can help "disentangle" high pile-up events.

6. Summary

TORCH is a novel time of flight detector for particle ID over large areas. The concept has been proven in extensive beam and laboratory tests. Performance of TORCH prototypes is already close to specification. Planned calibration campaigns and upgrades to TORCH readout electronics are expected to lead to further improvements. It is anticipated that TORCH will be installed in LHCb upgrade II. It will provide K/π separation up to 10 GeV/c and K/p separation up to 15 GeV, filling the low-momentum gap in LHCb's current particle ID system. TORCH's precision timing is also expected to benefit LHCb's global event reconstruction.

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