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Status of the TORCH time-of-flight project

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ABSTRACT

TORCH is a time-of-flight detector, designed to provide charged π/K particle identification up to a momentum of 10 GeV/c for a 10 m flight path. To achieve this level of performance, a time resolution of 15 ps per incident particle is required. TORCH uses a plane of quartz of 1 cm thickness as a source of Cherenkov photons, which are then focussed onto square Micro-Channel Plate Photomultipliers (MCP-PMTs) of active area 53 × 53 mm^2, segmented into 8 × 128 pixels equivalent. A small-scale TORCH demonstrator with a customised MCP-PMT and associated readout electronics has been successfully operated in a 5 GeV/c mixed pion/proton beam at the CERN PS facility. Preliminary results indicate that a single-photon resolution better than 100 ps can be achieved. The expected performance of a full-scale TORCH detector for the Upgrade II of the LHCb experiment is also discussed.

1. Introduction

The TORCH (Time Of internally Reflected CHerenkov light) detector will measure the time-of-flight (ToF) of charged particles over large areas, with the aim to provide Particle IDentification (PID) of pions, kaons and protons up to 10 GeV/c momentum and beyond [1]. The difference in ToF between pions and kaons over a ∼10 m flight path at 10 GeV/c is 35 ps, hence to achieve positive identification of kaons, TORCH aims for a time resolution of ∼10–15 ps per track. A specific application of TORCH is for the LHCb Upgrade II experiment, where the detector would occupy an area of 30 m^2 in front of the current RICH 2 detector [2]. The proposed experimental arrangement is shown in Fig. 1.

TORCH combines timing measurements with DIRC-style reconstruction, a technique pioneered by the BaBar DIRC [3] and Belle II TOP [4] collaborations. The production of Cherenkov light is prompt, hence TORCH uses planes of 1 cm thick quartz as a source of fast signal, which also facilitates a modular design. Cherenkov photons travel to the periphery of the quartz plates by total internal reflection where they are reflected by a cylindrical mirror surface of a quartz block. This focuses the photons onto a plane of pixellated Micro-Channel Plate Photomultipliers (MCP-PMTs) where their positions and arrival times are measured. The expectation is that typically 30 photons will be detected per charged track, hence the required ToF resolution dictates the timing of single photons to a precision of around 70 ps.

A schematic of the TORCH geometry in the longitudinal and transverse planes is shown in Fig. 2, showing the focussing block and the LHCb modular arrangement. For every photon hit in the MCP-PMTs, the Cherenkov angle θ_c and the photon path length of propagation through the quartz L is measured. From knowledge of the dispersion relation within the quartz, a correction for chromatic dispersion is then made to the photon time of propagation. From simulation, a ∼1 mrad precision is required on the measurement of the angles in both planes to achieve the required intrinsic timing resolution [1].

2. MCP-PMT development

In order to achieve the desired 1 mrad angular precision, TORCH requires a photon detector with a fine granularity in the focussing direction and a coarse granularity in the non-focussing direction. The pixel structure of MCP-PMTs can in principle be adjusted to the resolution required provided the charge footprint is small enough. An anode granularity of 128 × 8 pixels is chosen with a 53 × 53 mm^2 active area on a 60 mm pitch. MCP-PMTs are well known for fast timing of single

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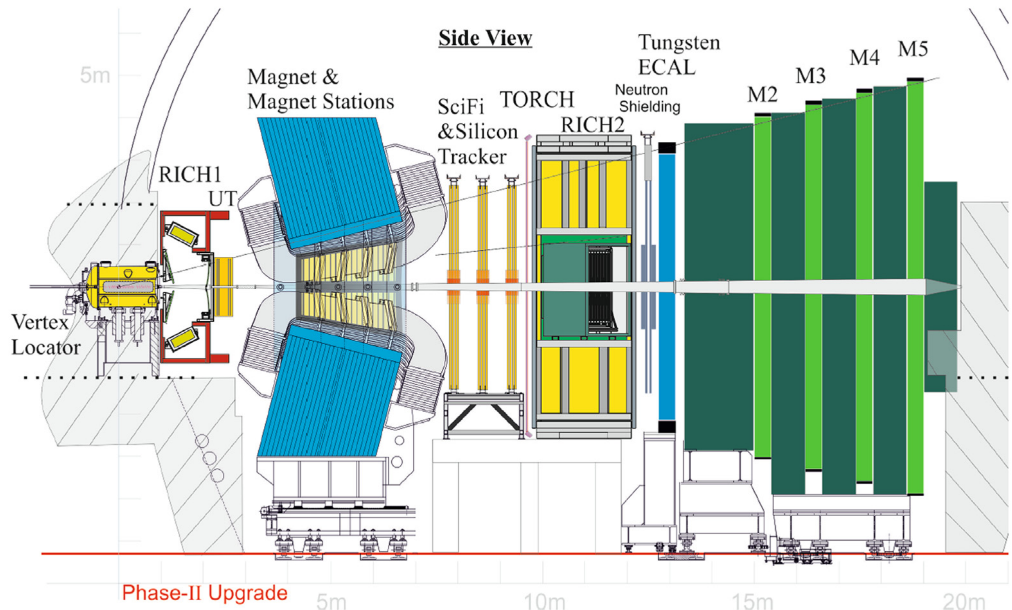

Fig. 1. A schematic of the LHCb experiment, showing TORCH located directly upstream of the RICH 2 detector.

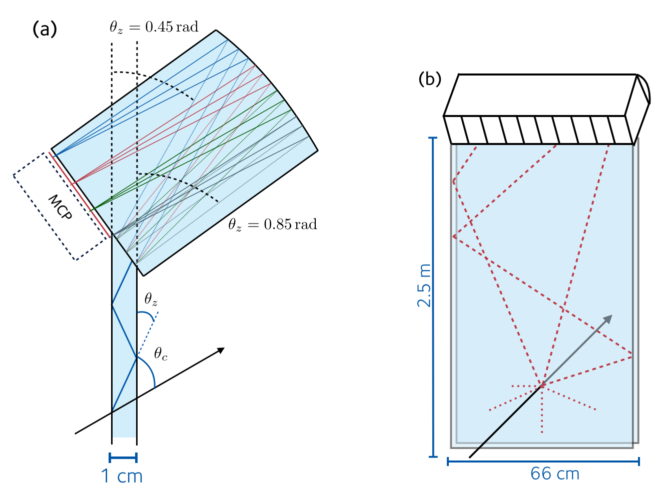

Fig. 2. Schematics of a TORCH module showing possible reflection paths: (a) the focussing block and MCP-PMT plane, (b) a single LHCb module.

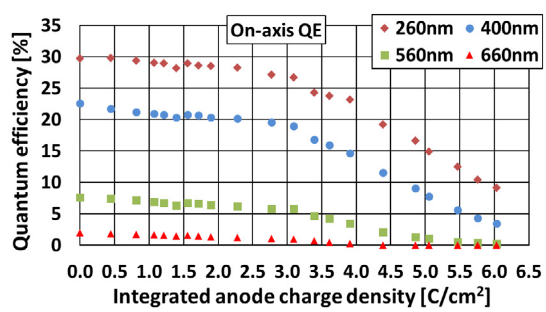

Fig. 3. The quantum efficiency of a Photek Phase 1 MCP-PMT as a function of wavelength and collected integrated charge, as measured on the tube axis.

photon signals, ∼30 ps, however tube lifetime has been an issue in the past.

A major focus of the TORCH project has been on the development of the MCP-PMTs, which has been conducted in collaboration with an industrial partner, Photek (UK). A three-phase R&D programme was defined. Phase 1 saw the development of a single-channel MCP-PMT with extended lifetime, accomplished with an atomic-layer deposition (ALD) coating of the MCPs [5], and where an excellent timing resolution of better than ∼35 ps was also achieved [6]. The extended lifetime is required for the harsh environment of the LHC, where integrated anode charges of at least 5 Ccm^{-2} are expected. Lifetime measurements have since been conducted over a period of 2.5 years using single-photon illumination from a blue LED, and are now reaching an integrated charge of 6.16 Ccm^{-2}. Fig. 3 demonstrates the results. Some loss of quantum efficiency is seen above 3 Ccm^{-2}, with a factor 2 loss at 5 Ccm^{-2}. A gain drop is also measured, but which can be recovered by an increase of MCP high voltage [7]. The MCP-PMT lifetime is close to the required performance, and it is expected that the Phase 3 tubes will improve on this.

The Phase 2 MCP-PMTs are circular in construction with a 40 mm diameter and a square 26.5×26.5 mm^2 active area containing 4×32 pixels, a quarter size of the final geometry. Beam tests on these tubes were successfully completed in 2015/16 and are reported elsewhere [8].

The final TORCH devices, the Phase 3 tubes, have high active area (>80%), the required granularity, ALD coating to give the extended lifetime, and excellent time resolution. Ten Phase 3 MCP-PMTs have been delivered from Photek and are currently under test. The MCP-PMT has a square 53×53 mm^2 active area with 64×64 pixels. The effective resolution of 128×8 pixels is achieved in the focussing and non-focussing directions by exploiting charge sharing between pixels [9] and by ganging electronically 64 pixels into 8 (or 4), respectively. The MCP-PMT anode is connected to a PCB via Anisotropic Conductive Film (ACF) onto which a readout connector is mounted. The readout configuration of the first evaluated tube has 64×4 pixels, compatible with a previous version of electronics, and used in the test-beam of November 2017. The second configuration gives 64×8 pixels per tube for use with new electronics in the test-beam of June 2018 [10].

3. Beam tests with a small-scale TORCH demonstrator

Several test-beam campaigns have been conducted between 2015–2018 at the CERN PS T9 beamline with a 5 GeV/c mixed pion/proton beam. The small-scale TORCH demonstrator [8] consists of a $12 \times 35 \times 1$ cm^3 quartz radiator plate with a matching focusing block,

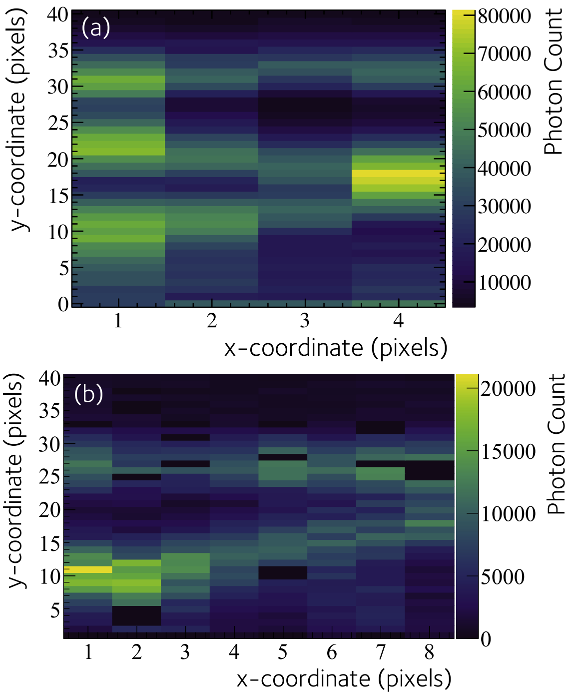

Fig. 4. The patterns of hits measured in the TORCH demonstrator with 5 GeV/c pions. (a) 64 × 4 pixel readout in November 2017 with the beam 14 cm below the quartz radiator centre-line and the MCP-PMT located in its nominal position on the focal plane, and (b) 64 × 8 pixel readout in June 2018 with the beam at the quartz centre-line and the MCP-PMT shifted 5 mm upwards with respect to configuration (a).

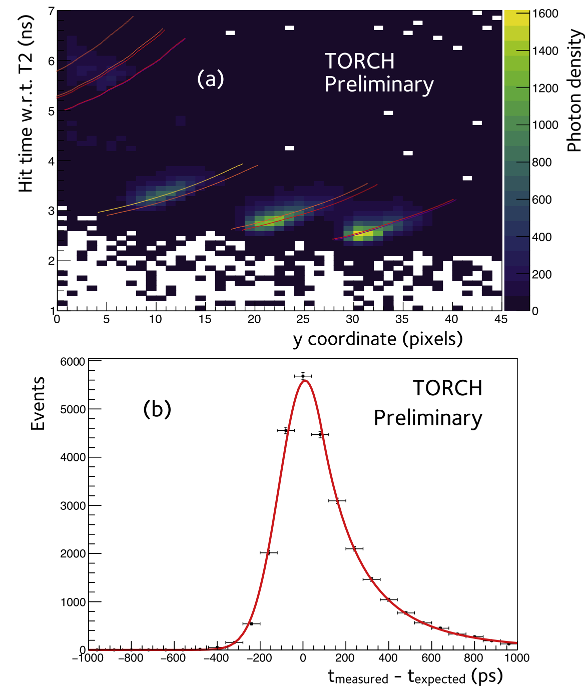

Fig. 5. (a) The time-of-arrival of single Cherenkov photons from a 5 GeV/c pion beam, relative to the T2 beam time-reference station, as a function of detected 64-wide column pixel number. The overlaid lines represent the simulated patterns for light reflected only off the front and back faces of the radiator plate (purple), light undergoing one (red), two (orange) and three (yellow) reflections off the side faces. The top left distributions correspond to multiple reflections from the bottom horizontal face. (b) The residuals between observed and simulated Cherenkov photon arrival times for pixel row 4 (November 2017 data). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

both manufactured by Schott, Germany. The radiator plate is mounted in an almost vertical position, tilted backwards by 5° with respect to the horizontal incidence of the beam.

We report here preliminary results from the November 2017 campaign, where the demonstrator is read out with a single Phase 3 MCP-PMT in the 64 × 4 pixel configuration. The customised electronics system [10] uses the NINO32 [11] and HPTDC [12] chipsets, developed for fast timing applications of the ALICE experiment. Proton–pion selection is achieved independent of TORCH using a pair of upstream Cherenkov counters, and two borosilicate finger counters (T1 and T2), separated by a ∼11 m flight path, provide a time reference.

The pattern of measured MCP-PMT hits for 5 GeV/c pions is shown in Fig. 4 (a). Here clustering has been applied over simultaneous MCP-PMT column hits to obtain the centroid position of each photon. The beam impinges approximately 14 cm below the plate centre-line and close to the plate side, a position which has been chosen to give a cleanly resolved pattern. The Cherenkov cones which are internally reflected in the quartz radiator result in hyperbola-like patterns at the MCP-PMT plane; reflections off module sides result in a folding of this pattern. Chromatic dispersion spreads the lines into bands. Since the quartz is read out by only a single MCP-PMT, the full pattern is only sampled, which accounts for the observed discontinuities.

For the timing measurement, a simultaneous correction is made for time-walk and integral non-linearities of the NINO/HPTDC electronics using a data-driven method [8]. For each single 4-wide pixel row, the measured MCP time-stamp for each cluster is plotted relative to the downstream borosilicate station (T2) versus the measured 64-wide column position. An example data distribution is shown in Fig. 5 (a) showing good agreement when compared to simulation. The distribution of residuals between the measured and simulated times of arrival is shown in Fig. 5 (b). Core distributions have resolutions (sigmas) of approximately 100–125 ps (which is photon energy and MCP-PMT row dependent). The tails are due to imperfect calibration and backscattering from the MCP top surface. The timing resolution of the timing reference is ∼50 ps and, subtracted in quadrature, gives ∼85–115 ps time resolution of the TORCH demonstrator, approaching the target resolution of 70 ps per photon. Future improvements are possible such as incorporating charge to width calibrations of the front-end electronics and reducing the current limitation imposed by the 100 ps time binning of the HPTDC.

4. Development of half-length TORCH prototype

A prototype of a half-length TORCH module, 125 × 66 × 1 cm^3 (length, width and thickness), is currently under construction. The module will be equipped with ten MCP-PMTs (∼5000 channels). The radiator plate and focussing block were both procured from Nikon, Japan. As an incremental step, the small-scale TORCH demonstrator was equipped with a single 64 × 8 pixel MCP-PMT and upgraded electronics and tested in a 5 GeV/c pion beam in June 2018. The pattern of measured MCP-PMT hits is shown in Fig. 4 (b). Results are currently being analysed, and calibrations and timing measurements are in progress. The full-scale module is planned for test-beam running in October/November 2018.

5. TORCH for the LHCb Upgrade II

The RICH system currently provides PID for the LHCb experiment [13], where discrimination of pions, kaons and protons is essential for CP violation measurements, exotic spectroscopy and particle tagging. However, LHCb has no positive kaon or proton identification below ∼10 GeV/c. Therefore the proposal is to install TORCH immediately upstream of the RICH 2 detector, where it would be located ∼9.5 m from the proton–proton interaction region [2]. Here the total area of

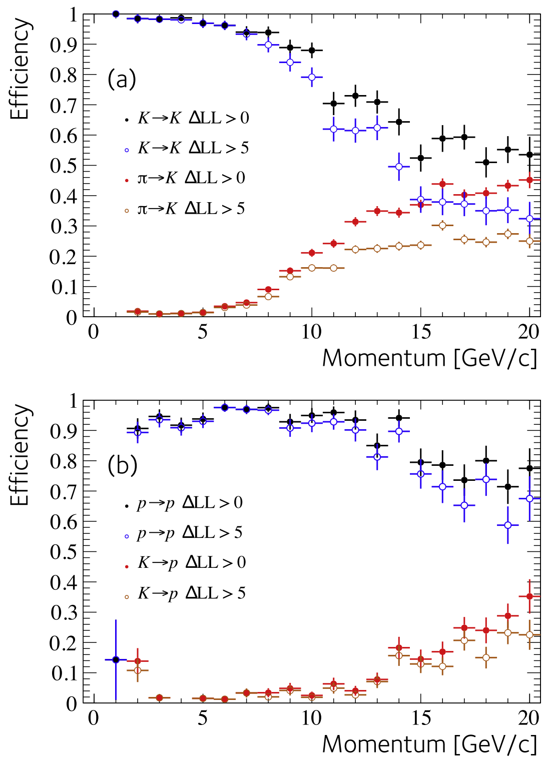

Fig. 6. The efficiency of TORCH in LHCb to positively identify (a) kaons and (b) protons as a function of momentum and the probability that they are misidentified. The curves are for two different delta-log-likelihood cuts and for a luminosity of 2×10^{33} cm^{-2} s^{-1}. The simulated sample is for heavy flavour decays in pp collisions, including pile-up.

TORCH would be 5×6 m^2, divided into 18 modules, each 66 cm wide and 2.5 m high with 11 MCP-PMTs per module.

Studies are underway to evaluate the performance of TORCH in the LHCb experiment. A luminosity of 2×10^{33} cm^{-2} s^{-1} has been simulated ($\times$ 5 the current LHCb luminosity), including collision pile-up. The track entry point in the quartz radiator of TORCH is provided by position information from the tracking system of the LHCb spectrometer. The expected hit distributions for the $\pi/K/p$ hypotheses are compared to the MCP-PMT photon spatial hits and arrival times, and log-likelihoods are then computed.

Fig. 6 shows the efficiency of TORCH to positively identify kaons and protons as a function of momentum and the probability of misidentification. Good separation between π/K/p in the 2–10 GeV/c range and beyond is observed. Studies have also started on key physics channels and tagging performance, and these will form the basis of a Technical Proposal to construct a full-scale TORCH detector for the start-up of LHC Run 4, with installation in the Long Shutdown 3 (LS3) in 2024.

6. Summary

The performance of a small-scale TORCH demonstrator in a 5 GeV/c mixed pion/proton beam has been reported. A customised 64 × 4 pixelated MCP-PMT has been prototyped, and timing resolutions of 85–115 ps per photon have been measured. With future improvements, it is hoped to achieve the desired per-photon resolution of 70 ps. A half-length TORCH module incorporating new optics is under construction, including final 64 × 8 pixelated MCP-PMTs and a new generation of electronics. Studies are underway to prepare a Technical Proposal for TORCH to be incorporated in the Upgrade-II of the LHCb experiment.

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