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The TORCH time-of-flight detector

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ABSTRACT

TORCH is a large-area time-of-flight (ToF) detector, proposed for the Upgrade-II of the LHCb experiment. It will provide charged hadron identification over a 2–20 GeV/c momentum range, given a 9.5 m flight distance from the LHC interaction point. To achieve this level of performance, a 15 ps timing resolution per track is required. A TORCH prototype module having a $1250 \times 660 \times 10\,\mathrm{mm}^3$ fused-silica radiator plate and equipped with two MCP-PMTs has been tested in a 8 GeV/c CERN test-beam. Single-photon time resolutions of between 70–100 ps have been achieved, dependent on the beam position in the radiator. The measured photon yields agree with expectations.

1. Introduction

TORCH is a time of flight detector to provide pion/kaon/proton particle identification (PID) between 2–20 GeV/c momenta over a 9.5 m flight path [1,2]. TORCH is proposed for the Upgrade-II of the LHCb experiment to complement the particle identification of the RICH system to lower momenta [3]. On the passage of a charged particle, Cherenkov photons are emitted in a 10 mm thick fused-silica (quartz) plate, and are transmitted to the periphery of the plate via total internal reflection. Here the photons are focused onto an array of customised Micro-Channel Plate (MCP-PMT) photo-detectors, developed with industrial partner Photek UK [4]. The MCP-PMTs record the position and arrival times of the Cherenkov photons, and this allows for chromatic dispersion in the quartz to be corrected. Each MCP-PMT detector has an effective granularity of 128 × 8 pixels over a $53 \times 53\,\mathrm{mm}^2$ active area, which gives a ∼1 mrad precision on the photon angular measurement. The single-photon time resolution of the MCP-PMT has been measured to be around 50 ps in the laboratory [5], including the contribution from the customised electronics-readout system [6]. The design goal for TORCH is to achieve an overall timing resolution of 15 ps per incident particle and, with an estimated 30 detected photons and a $\sqrt{N_{photons}}$ dependence assuming no correlated effects, we have set a target resolution of ∼70 ps per single photon.

2. TORCH prototyping

A TORCH prototype module (named "Proto-TORCH") has been constructed. This has a $1250 \times 660 \times 10\,\mathrm{mm}^3$ (length × width × thickness) quartz radiator plate and represents a half-length, full-width, LHCb module. Proto-TORCH is instrumented with two MCP-PMTs (labelled MCP-A and -B), each with 64 × 64 physical pixels. Pixels are then grouped electronically into 8 columns in the horizontal coordinate. Vertically, charge sharing improves the spatial measurement by up to a factor ∼2, to give an effective resolution of 128 pixels.

Beam tests were carried out in an 8 GeV/c mixed pion/proton beam in the T9 area of the CERN PS. The cones of Cherenkov radiation emitted by the incident hadrons are focused into hyperbole-like patterns on the photo-detector plane. The photon time-of-arrival for MCP-B is shown as a function of photon hit coordinate in Fig. 1, where the vertical pixel number runs from 1 to 64. Here the beam entry position

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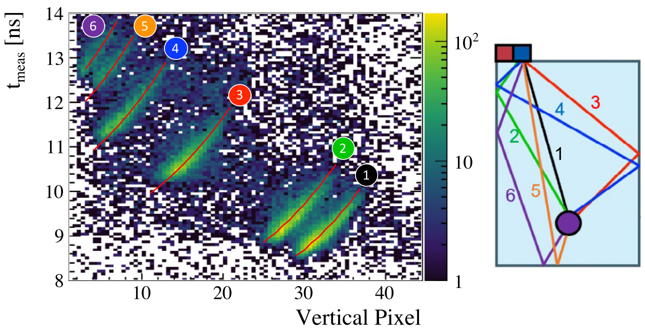

Fig. 1. (Left) The time projection of reconstructed photons as a function of the vertical pixel number, shown for a horizontal column of MCP-B, with the photon trajectories labelled. Results from simulation are shown by the solid red lines. (Right) A schematic of the photon paths observed.

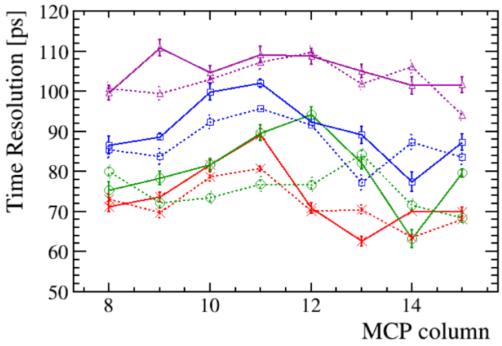

Fig. 2. The single-photon time resolution determined as a function of column number in MCP B for different beam positions from the top of the radiator plate ($y = 175$ mm (×), $y = 489$ mm (○), $y = 802$ mm (□), $y = 1115$ mm (△). The full (dotted) lines are the results from the pion (proton) samples.

in the quartz radiator is central, $x = 330$ mm, and the distance y from the top of the plate is 1115 mm, where the origin is taken at the upper corner of the radiator closest to the MCP-PMTs. The different orders of reflection (i.e. photon paths in the radiator) are seen to be very well-separated and agree with simulation. For each vertical pixel, the widths of each order with respect to the mean are measured to determine the single-photon time resolution.

The beam entry positions are varied with height in the radiator, with the beam fixed in x at 5 mm from the side edge of the quartz radiator closest to the MCPs. The single-photon time resolutions are then determined in different columns of MCP-B, shown in Fig. 2. It can be seen that the 70 ps target resolution is achieved for the beam-entry point closest to the MCPs. As expected, the resolution degrades approximately linearly for longer photon paths as the time of propagation increases. This is due to the finite size of the pixels which introduces an uncertainty in the measurement of the photon energy.

The photon counting yields are measured in data and compared to simulation in Table 1. The yields agree well with expectations if the ∼10% events which have no photon hits are excluded. The excess events with $N_{photons} = 0$ are attributed to known inefficiencies in the electronics readout when small charge deposits are shared between channels. These test-beam results indicate that TORCH can meet the design goal for LHCb, given that a fully-instrumented module would detect around 30 photons. To verify this, a future test-beam campaign is planned for the end of 2022, which will employ the fully instrumented TORCH prototype (with up to 11 MCP-PMTs).

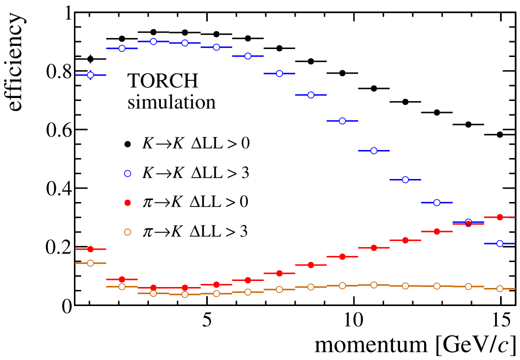

Fig. 3. The TORCH efficiency to positively identify kaons as a function of momentum and the probability that pions are misidentifed as kaons, for LHCb Upgrade II conditions at a luminosity of 1.5×10^{34} cm^{-2} s^{-1}. The plots show two different delta-log-likelihood cuts.

Table 1
The mean number of photons detected as a function of the distance from the top of the radiator in data and simulation. The final column gives the ratio of the yields when contributions from zero photons are excluded.

Position	Mean $N_{photons}$		Ratio data/simulation
y coordinate (mm)	Data	Simulation	Excluding $N_{photons} = 0$
175	2.605 ± 0.007	2.711 ± 0.017	1.075 ± 0.006
489	1.419 ± 0.005	1.570 ± 0.014	1.002 ± 0.007
802	0.937 ± 0.004	1.072 ± 0.012	0.983 ± 0.007
1115	0.677 ± 0.002	0.812 ± 0.010	0.981 ± 0.007

3. Performance at LHCb

In the LHCb Upgrade-II, TORCH will be located in front of the current RICH 2 detector, approximately 9.5 m downstream from the LHC interaction region [3]. The expected performance of the detector has been simulated at an LHC luminosity of 1.5×10^{34}cm^{-2} s^{-1}. The TORCH efficiency to positively identify kaons as a function of momentum and the probability that they are misidentified is shown in Fig. 3. It can be seen that good PID efficiency is achieved for π/K separation up to 10 GeV/c; similarly the K/p separation extends up to around 20 GeV/c. Hence TORCH will complement the PID capabilities of the LHCb upgraded experiment over the range from 2 to above 100 GeV/c.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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