ARTICLE IN PRESS

Nuclear Instruments and Methods in Physics Research A xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

The TORCH detector R & D: Status and perspectives

T. Gys[a,*], N. Brook[b], L. Castillo García[c], D. Cussans[d], K. Föhl[a], R. Forty[a], C. Frei[a], R. Gao[c], N. Harnew[c], D. Piedigrossi[a], J. Rademacker[d], A. Ros García[d], M. van Dijk[c]

[a] CERN, EP Department, Geneva 23, CH-1211 Switzerland
[b] Wessex House, Faculty of Science, University of Bath, Claverton Down, BA2 7AY Bath, United Kingdom
[c] Denys Wilkinson Laboratory, University of Oxford, Keble Road, OX1 3RH Oxford, United Kingdom
[d] H.H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, BS8 1TL Bristol , United Kingdom

ARTICLE INFO

Keywords:
Time-of-flight
Cherenkov light
Micro-channel plate photon detectors

ABSTRACT

TORCH (Timing Of internally Reflected CHerenkov photons) is a time-of-flight detector for particle identification at low momentum. It has been originally proposed for the LHCb experiment upgrade. TORCH is using plates of quartz radiator in a modular design. A fraction of the Cherenkov photons produced by charged particles passing through this radiator propagate by total internal reflection, they emerge at the edges and are subsequently focused onto fast, position-sensitive single-photon detectors. The recorded position and arrival time of the photons are used to precisely reconstruct their trajectory and propagation time in the quartz. The on-going R & D programme aims at demonstrating the TORCH basic concept through the realization of a full detector module and has been organized on the following main development lines: micro-channel plate photon detectors featuring the required granularity and lifetime, dedicated fast front-end electronics preserving the picosecond timing information provided by single photons, and high-quality quartz radiator and focussing optics minimizing photon losses. The present paper reports on the TORCH results successfully achieved in the laboratory and in charged particle beam tests. It will also introduce the latest developments towards a final full-scale module prototype.

1. Introduction

TORCH (Timing Of internally Reflected CHerenkov photons) [1] is a time-of-flight detector originally proposed for the upgrade of the LHCb experiment [2,3]. TORCH would extend into the low momentum range (2–10 GeV/c) the LHCb particle identification capabilities currently provided by two gaseous ring-imaging Cherenkov detectors [4]. The TORCH design is inspired by the BaBar DIRC [5], Belle-II iTOP [6] and PANDA disc DIRC [7] concepts and involves the use of 10 mm-thick plates of quartz. Charged particles passing through a plate produce Cherenkov photons, some of which are trapped within the plate by total internal reflection, they emerge at the edges, and are focused onto micro-channel plate (MCP) photon detectors [8] where their arrival is timed (Fig. 1). The focusing element, made of quartz, uses a cylindrical mirror that converts the total internal reflection angle θ_z of the photons into a spatial coordinate on the MCPs. The other (azimuthal) propagation angle θ_x of the photons is converted to the other (transverse) MCP spatial coordinate. With the knowledge of the photon arrival time and position, the photon trajectory and the particle Cherenkov angle θ_c can be reconstructed, and after correction for chromatic effects, the photon propagation time in the quartz can be estimated [9].

The TORCH requires the development of MCPs with a measured transit time spread better than 50 ps (after electronic signal processing) for single photons. An asymmetric anode segmentation of ~0.4 mm×6.4 mm for a 2 ″×2 ″ square photon detector provides an angular precision of 1 mrad for θ_z and θ_x, respectively. This yields a per-photon uncertainty on the reconstructed time of propagation of ~50 ps. The resulting expectation on the overall per-photon time resolution is therefore ~70 ps. Combining the information from 30 detected photons will provide a ~15 ps time resolution per track. This corresponds to a 3σ separation between 10 GeV/c kaons and pions resulting from a time-of-flight over a distance of 10 m. The TORCH photon detectors must also survive 5–10 years in a high radiation and high occupancy environment. For a gain of 5×10^5, and for 100 tracks per event and 30 detected photons per track every 25 ns, the instantaneous average detected photon rate is expected to be up to 10 MHz/cm^2, corresponding to an anode current of ~1 μA/cm^2 and to an integrated anode charge per year of at least 1 C/cm^2.

* Corresponding author.
E-mail address: Thierry.Gys@cern.ch (T. Gys).

http://dx.doi.org/10.1016/j.nima.2017.02.060
Received 1 November 2016; Received in revised form 8 February 2017; Accepted 20 February 2017

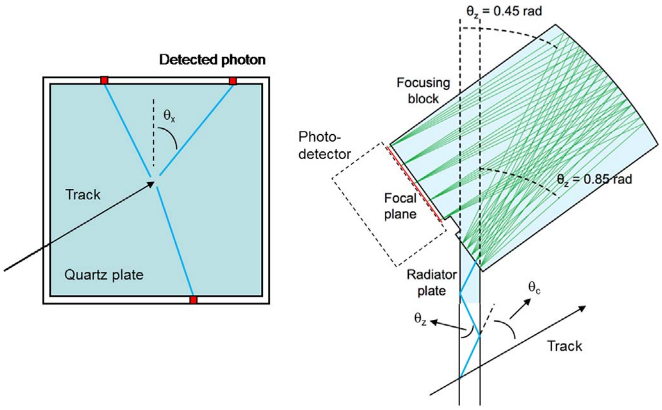

Fig. 1. Schematic principle of the TORCH detector – xy projection (left) and yz projection (right).

2. Micro-channel plate tube developments

The development of MCP tubes for TORCH is being carried out in close collaboration with an industrial partner, Photek Ltd. [10]. The R & D is organized in three phases.

Phase-I tubes implement MCPs processed with an atomic layer deposition technique [11] providing extended lifetime. The tubes are circular, 25 mm in active diameter and equipped with a single-channel anode. Their intrinsic performance has been first calibrated in terms of gain, pulse height distribution and timing resolution [12]. The tubes have been subsequently subjected to accelerated ageing tests. Following preliminary measurements performed by the manufacturer on similar prototypes [13], ageing tests have been carried out at CERN. A Phase-I tube operated at an initial gain of ~100 fC (~6×10^5) is exposed to high light intensity using a stabilized blue (428 nm) DC LED source. Assuming a uniform light distribution, the initial intensity level corresponds to a photoelectron rate of ≤1 MHz/cm^2 and a total anode current of ≤500 nA equivalent to an accumulated charge density rate of ≤10 mC/cm^2/day. The evolution of the tube anode current in function of integrated anode charge density is displayed in Fig. 2.

Figure 2 shows that the MCP gain has decreased by a factor of 3 over an integrated anode charge density of ~2 C/cm^2. At that point, the initial gain was recovered by increasing the high voltage by 150 V. The anode current monitoring is interrupted for periodic measurements of the MCP gain and the photocathode quantum efficiency over the wavelength range 200–800 nm. As illustrated in Fig. 3, the quantum efficiency at 400 nm is essentially flat until 3 C/cm^2 and then a slight fall-off is seen.

Photek Phase-II tube prototypes are equipped with a segmented anode that provides the spatial precision as required for TORCH. These tubes are circular and have an active input diameter of 40 mm. The anode consists of an array of 32×4 pixels each 0.8 mm×6.4 mm in size,

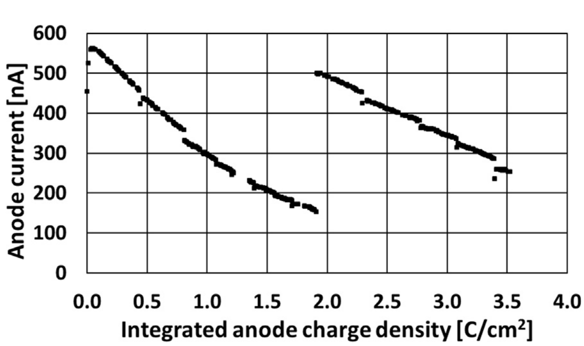

Fig. 2. Anode current as a function of the integrated anode charge density for a Photek Phase-I tube under high illumination. At a charge density of ~2 C/cm^2, the initial gain was recovered through an increase of the tube operating voltage. See text for details.

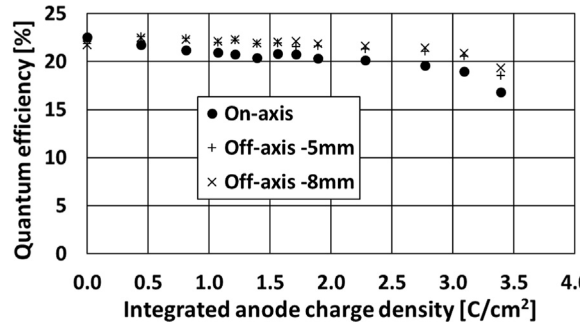

Fig. 3. On- and off-axis quantum efficiency at 400 nm wavelength as a function of the integrated anode charge density.

and is interfaced to the readout electronics by a printed circuit board. Pixels are connected to metallized pads on that board through an anisotropic conductive film. The front-end electronics (see [14] and references therein) consist of a fast amplifier-discriminator (NINO ASIC) providing a digital output pulse with time-over-threshold measurement of the input charge. This pulse is input to a time digitizer (HPTDC ASIC). In the Phase-II tube, the signature of a detected photon signal is in the form of a pixel cluster. The average number of pixels per cluster is 3–4 for the operating parameters used. This number essentially depends on the MCP gain and the NINO threshold settings. The charge induced in each pixel of the cluster is used to calculate the cluster centroid. In this way, a spatial precision of order 0.1 mm or better is achieved [15]. This anode design combined with a charge sharing technique fulfils the TORCH requirements with the advantage of a reduced number of pixels and readout channels. The arrival time of the photon on the MCP tube is calculated from the average within a cluster of the pixel time stamps each weighted by the corresponding deposited charge. When measured in the laboratory with a pulsed laser operated in single photon regime and the HPTDC chip running in 100 ps mode, time precisions of a single pixel reach 80 ps [15].

Photek Phase-III tubes [10] will combine the features of extended lifetime and spatial precision in 2″×2″ square devices that can be close-packed to optimize surface coverage. The anode is segmented as an array of 64×8 pixels each 0.8 mm×6.4 mm in size. These full-scale prototypes are expected to be delivered early in 2017.

3. Beam tests

A scaled-down "mini-TORCH" detector prototype has been tested in various charged particle beam facilities at CERN. The Cherenkov radiator is a quartz plate of dimensions 35(H)×12(W)×1(T) cm^3 and is coupled to matching focussing optics also made of quartz (see Fig. 4). The output surface of the optics block can accommodate two 2″×2″ square tubes.

The mini-TORCH is instrumented with one Phase-II prototype tube covering a square active surface of 1″×1″ (Fig. 5). The 32×4=128 channels are read out with 4 NINO32 and 4 HPTDC ASICs [16]. The HPTDC chips are operated in high resolution mode (100 ps time bin). The mini-TORCH prototype has been installed at the CERN PS facility that provides a low-momentum (≤10 GeV/c) mixed beam of pions and protons. Two external timing stations (T1 and T2) provide start- and stop-time references. They each consist of a Cherenkov radiator bar made of borosilicate, tilted with respect to the particle beam to optimize the time response. Each bar is coupled to a single-channel MCP-PMT read out with a fast amplifier and a constant-fraction discriminator. Stations T1 and T2 have been calibrated with a collimated high-momentum particle beam at the CERN SPS. The intrinsic time jitter per station has been measured to be ~35 ps. Station T1 is located upstream at 10 m distance from mini-TORCH, and station T2 downstream at 1 m distance. The time reference signals

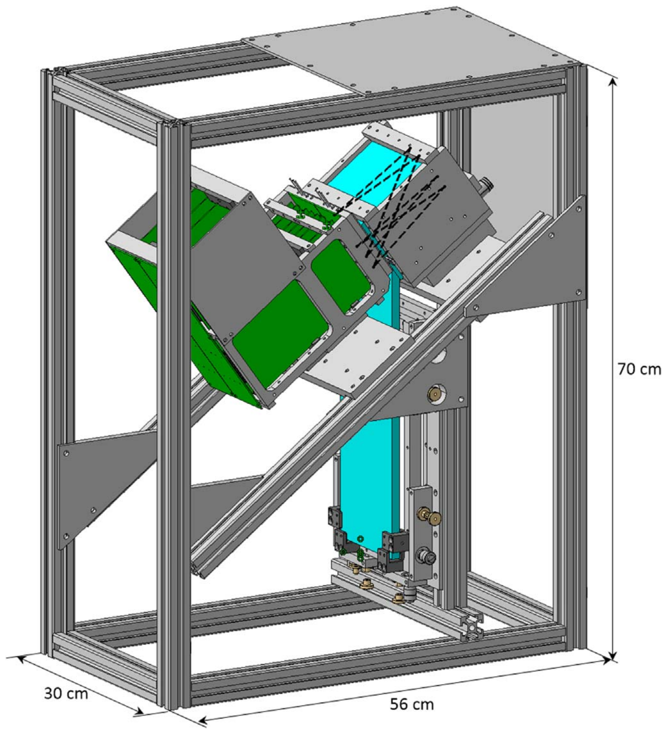

Fig. 4. Perspective drawing of the mini-TORCH installed in its mechanical support structure.

Fig. 5. Photograph of a Phase-II MCP-PMT and its readout electronics mounted on a supporting chariot.

are input to the mini-TORCH readout electronics. The time difference T1-T2 is used to select and separate the particle species for analysis purposes. The beam trigger is generated from the coincidence signal of two scintillator systems located close to the T1 and T2 stations. These scintillators are 8×8 mm^2 in size and also define the track position and angle. There is no high-precision tracking detector installed.

Figure 6 shows the time projection pattern from mini-TORCH generated by 5 GeV/c pions when time reference T2 is used. Each data

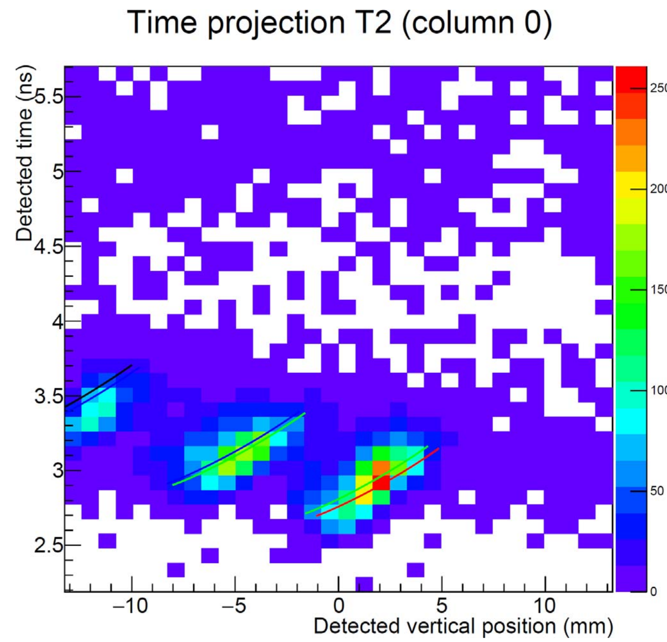

Fig. 6. Time projection patterns as observed in the mini-TORCH prototype for 5 GeV/c pions passing through the edge of the quartz radiator. The superimposed lines are described in the text.

point refers to a photon detected in one pixel column of the MCP tube anode. The horizontal coordinate of the point is the pixel cluster centroid while the vertical coordinate is the cluster time. Three populations are clearly visible. The expected ideal patterns are superposed as lines and refer to photons that directly reach the focussing optics block (red line), or that undergo one reflection (green lines), two reflections (blue lines) or three reflections (black line) off the radiator sides before reaching the block.

The differences between observed and predicted times for the detected photons, for all pixel columns, are reproduced in Fig. 7. The standard deviations of the main peaks range from ~117 ps to ~127 ps and represent the overall per-photon time resolution. This resolution is affected by the HPTDC operating mode of 100 ps, the reference time resolution and the relatively poor spatial track resolution. Hence the measured values only provide an upper limit on the intrinsic time resolution. The tails are attributed to uncertainties in the estimates of

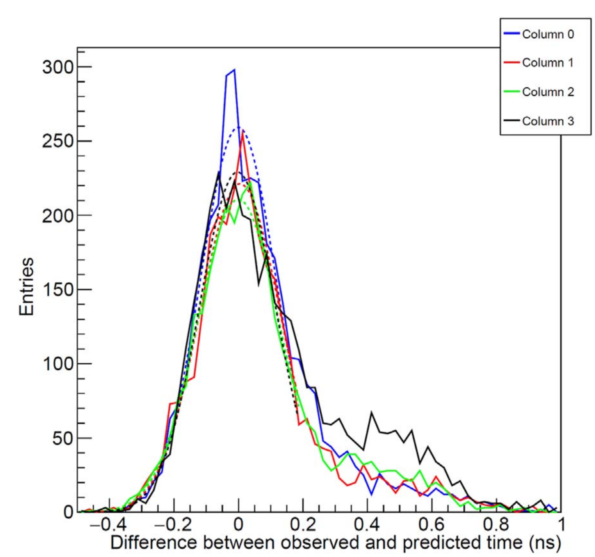

Fig. 7. Difference between observed and predicted times for the photons detected in mini-TORCH for 5 GeV/c pions, separated by pixel column number.

the MCP charge signals input to the NINO chips and to residual time walk effects from the NINO chips that cannot be fully corrected for.

4. Conclusions and perspectives

The TORCH detector R & D has shown significant progress in various fields of activities. Laboratory and beam test results demonstrate that time and spatial resolutions are approaching the target values. The procurement of a quartz radiator plate and a focussing block to equip a TORCH module prototype is underway. The radiator plate dimensions will be 125(H)×66(W)×1(T) cm^3 and the focussing block will be made out of a single quartz piece. This quartz structure will require a new dedicated holding mechanics. Another iteration of readout electronics is being designed [17] with the aim of instrumenting the TORCH module with 10 Phase-III photon detectors. Performance simulations and studies towards a full-scale TORCH detector covering a surface of 6(W)×5(H) m^2 are being pursued. They include the possibility to populate the outside region of the TORCH detector with BaBar DIRC bar boxes [18].

Acknowledgements

Support from the European Research Council in funding the TORCH R & D project is gratefully acknowledged (ERC-2011-AdG, 291175-TORCH). The authors also thank the industrial partner Photek Ltd.

References

[1] M. Charles, R. Forty, TORCH: time of flight identification with Cherenkov radiation, Nucl. Instrum. Methds A 639 (1) (2011) 173.
[2] The LHCb Collaboration, Letter of Intent for the LHCb Upgrade, CERN/LHCC 2011-001, LHCb LoI (7 March 2011).
[3] The LHCb Collaboration, LHCb PID Upgrade Technical Design Report, CERN/LHCC 2013-022, LHCb TDR 14 (28 November 2013).
[4] A. Papanestis et al., Performance of the LHCb RICH detectors during the LHC Run II, Nucl. Instrum. Methods A, these proceedings.
[5] I. Adam, et al., The DIRC particle identification system for the BaBar experiment, Nucl. Instrum. Methods A 538 (1–3) (2005) 281.
[6] J. Fast et al., The Belle II imaging Time-of-Propagation (iTOP) Detector, Nucl. Instrum. Methods A, these proceedings.
[7] M. Düren et al., The Endcap Disc DIRC of PANDA, Nucl. Instrum. Methods A, these proceedings.
[8] T. Gys, Micro-channel plates and vacuum detectors, Nucl. Instrum. Methods A 787 (2015) 254.
[9] M.W.U. van Dijk, et al., TORCH—a Cherenkov based time-of-flight detector, Nucl. Instrum. Methods A 766 (2014) 118.
[10] J. Milnes et al., The TORCH PMT: a close packing, long life MCP-PMT for Cherenkov applications with a novel high granularity multi-anode, Nucl. Instrum. Methods A, these proceedings.
[11] D.R. Beaulieu, et al., Nano-engineered ultra-high-gain microchannel plates, Nucl. Instrum. Methods A 607 (1) (2009) 81.
[12] L. Castillo García, et al., Micro-channel plate photon detector studies for the TORCH detector, Nucl. Instrum. Methods A 787 (2015) 197.
[13] T.M. Conneely, et al., Extended lifetime MCP-PMTs: Characterisation and lifetime measurements of ALD coated microchannel plates, in a sealed photomultiplier tube, Nucl. Instrum. Methods A 732 (2013) 388.
[14] R. Gao, et al., Development of precision Time-of-Flight electronics for LHCb TORCH, J. Instrum. 9 (02) (2014) C02025.
[15] L. Castillo García, et al., Development, characterization and beam tests of a small-scale TORCH prototype module, J. Instrum. 11 (05) (2016) C05022.
[16] R. Gao, et al., Development of TORCH readout electronics for customised MCPs, J. Instrum. 11 (04) (2016) C04012.
[17] R. Gao et al., Precision Electronics for a System of Custom MCPs in the TORCH Time of Flight Detector, proceedings of TWEPP 2016, to be published in JINST.
[18] K. Föhl et al., Performance simulation of BaBar DIRC bar boxes in TORCH, Nucl. Instrum. Methods A, these proceedings.