Development, characterization and beam tests of a small-scale TORCH prototype module

2016 JINST 11 C05022

(http://iopscience.iop.org/1748-0221/11/05/C05022)

Published by IOP Publishing for Sissa Medialab

Received: *March 11, 2016*
Accepted: *May 2, 2016*
Published: *May 25, 2016*

International Workshop on Fast Cherenkov Detectors - Photon detection, DIRC design and DAQ
November 11–13, 2015, Giessen, Germany

Development, characterization and beam tests of a small-scale TORCH prototype module

L. Castillo García,[a,b,1] N. Brook,[c] T.Conneely,[d] D. Cussans,[e] K. Föhl,[b] R. Forty,[b] C. Frei,[b] R. Gao,[f] T. Gys,[b] N. Harnew,[f] J. Milnes,[d] D. Piedigrossi,[b] A. Ros García[e] and M. van Dijk[e]

[a]*Laboratory For High Energy Physics, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland*
[b]*EP Department, CERN, CH-1211, Geneva 23, Switzerland*
[c]*Mathematical & Physical Sciences Faculty Office, University College London, Gower Street, London, WC1E 6BT, United Kingdom*
[d]*Photek Ltd., St. Leonards-on-Sea, Castleham Road, East Sussex, TN38 9NS, United Kingdom*
[e]*H.H. Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol, BS8 1TL, United Kingdom*
[f]*Department of Physics, University of Oxford, Keble Road, Oxford, OX1 3RH, United Kingdom*

E-mail: lucia.castillo.garcia@cern.ch

Abstract: Within the TORCH (Time Of internally Reflected CHerenkov light) R&D project, a small-scale TORCH prototype module is currently under study. Circular-shaped micro-channel plate photon detectors with finely segmented square anodes (32×32 channels) have been produced for TORCH requirements in industrial partnership. A new generation of custom multi-channel electronics based on the 32-channel NINO and HPTDC ASICs has been developed. The performance of the photon detector coupled to these customized electronics has been assessed in the laboratory and is reported on. A time resolution of 80 ps and a spatial resolution of 0.03 mm have been measured. Finally, tests of the TORCH prototype module illuminated with laser light and in a charged particle beam will be highlighted.

Keywords: Instrumentation and methods for time-of-flight (TOF) spectroscopy; Particle identification methods; Cherenkov detectors; Photon detectors for UV, visible and IR photons (vacuum) (photomultipliers, HPDs, others)

[1]Corresponding author.

doi:10.1088/1748-0221/11/05/C05022

2016 JINST 11 C05022

Contents

2016 JINST 11 C05022

1 Introduction

The TORCH detector [1–3] requires the use of micro-channel plate (MCP) photon detectors with asymmetrically segmented anodes of 8×128 pads of dimensions $6.6 \times 0.4\,\text{mm}^2$, respectively. Circular-shaped MCP prototypes with finely segmented anodes (32×32 pads) have been manufactured in collaboration with Photek Ltd.[1] [4]. The active area is $26.5 \times 26.5\,\text{mm}^2$. The anode is connected to an interface printed circuit board (PCB) using anisotropic conductive film. This PCB merges the pads by groups of 8 in the coarse direction leading to an asymmetric segmentation of 4×32 pads representing a quarter size of the final requirement. A charge-sharing technique is used to achieve the spatial resolution of $0.4/\sqrt{12}\,\text{mm}$ as required by TORCH with half the number of pads in the fine direction. These tubes were characterized in the laboratory with a pulsed laser diode[2] in single photon regime. Custom electronics have been designed and produced for testing the multi-anode MCP photon detectors for TORCH. A small-scale TORCH prototype module consisting of a quartz radiator plate of dimensions $10 \times 120 \times 350\,\text{mm}^3$ and a focusing block with a cylindrical mirror has been developed. The TORCH prototype module together with the MCP photon detectors and electronics were characterized with laser light and in a charged-particle beam.

[1] http://www.photek.com/.
[2] Optical head model PiL040, digital control unit EIG1000D from PiLas, D-12489, Berlin, Germany.

2 Photon detector and electronics performance

2.1 Light intensity level and MCP gain estimate

A laser light spot is focused between two MCP anode pads in the fine direction. Neutral density filters are used to attenuate the light to the level of single photons. At a tube operating voltage of +3800 V the photoelectron charge cloud is spread over four pads. The light intensity level and the MCP gain are calibrated from charge spectra. The analogue signals from four adjacent pads in the fine direction are read out with a fast oscilloscope. Charge spectra are recorded simultaneously from the four pads, shown in figure 1. The central pads receive the largest charges whereas the edge pads see less charge. The average number of photoelectrons is inferred from Poisson statistics and a Gaussian fit of the pedestal peak of each individual pad and amounts to 0.24 ± 0.02. The MCP gain at +3800 V is estimated from the position of the first photoelectron peak with respect to the pedestal position and is found to be 1.6×10^6 electrons, corresponding to the sum of the average charges from the four pads.

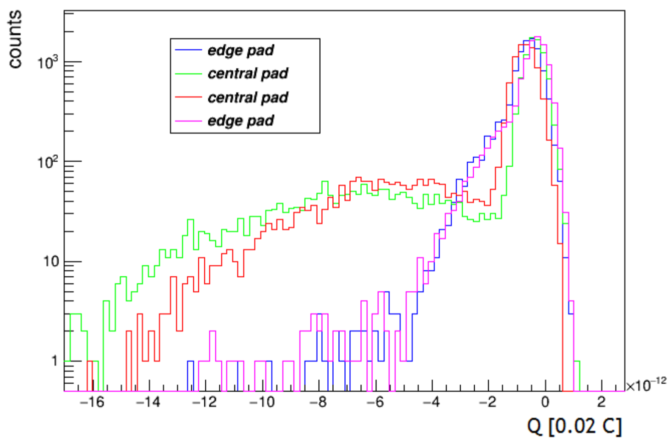

Figure 1. Charge spectra of four pads of the multi-anode MCP tube recorded using a fast oscilloscope.

2.2 Time resolution

The timing performance of the MCP tubes has been assessed using a new generation of custom made multi-channel electronics with increased channel count [5]. This readout system is based on a scalable design using 32-channel NINO [6] and HPTDC [7, 8] chips originally developed for the ALICE TOF detector [9]. The electronics consists of separate NINO and HPTDC boards, each incorporating two ASIC chips, a readout board and back-plane adaptor board. The NINO amplifies and discriminates the analogue signal from the MCP and provides a Time-Over-Threshold (TOT) measurement for time walk correction. Output signals from the NINO chips are routed to HPTDC chips where both the signal leading and trailing edges are time-digitized. The HPTDCs are operated in a resolution mode offering a 100 ps time bin precision.

In the laboratory, laser light is transported through monomode fibers and an asymmetric splitter allows to illuminate both the customized MCP device and a single-channel MCP tube which provides the time reference. Neutral density filters attenuate the light to the single photon level on the customized MCP and to the multiphoton regime on the single-channel MCP which provides a

2016 JINST 11 C05022

fast reference timing with a resolution of $\sigma = 20\,\text{ps}$. This fast signal is read out by a commercial amplifier and a constant fraction discriminator[3] (CFD) and is injected into a test channel of the NINO electronics.

2.2.1 Time walk calibration

MCP signals vary in amplitude due to intrinsic gain fluctuations. The leading edge time depends on the signal amplitude and the use of the pulse width information provided by the NINO chips allows time walk correction. Figure 2 (left) shows a 2D scatter plot of the pulse width versus the leading edge time, and the time walk calibration curve is then determined. The vertical axis is divided into slices of 1 ns and its projection onto the horizontal axis (time distribution) is then fitted with a Gaussian. For all slices the width values and the positions of the Gaussians are plotted and fitted with a cubic spline function. The calibration curve for a single NINO channel is superposed to the data in figure 2, where the coloured points correspond to experimental data and the black curve corresponds to the fit. This calibration is used for global time walk corrections assuming all channels behave similarly. Ideally, each NINO channel should have its own calibration curve.

The photoelectron time distribution is measured from the difference between the leading edge of the signal on a channel and that of the reference signal. Time distributions before and after correction are shown in figure 2 (right). Due to the small gap of 0.2 mm between the photocathode and the MCP input face, most of the back-scattered photoelectrons populate the main peak, resulting in an asymmetric distribution. Consequently, data are fitted with an exponentially-modified Gaussian [10]. The time resolution is defined as the standard deviation of the unmodified Gaussian. An additional single Gaussian accounts for the relaxation pulse of the laser, delayed 150 ps from the main peak. A time resolution of 80 ps is achieved after time walk correction. This resolution includes the jitter from the electronics chain.

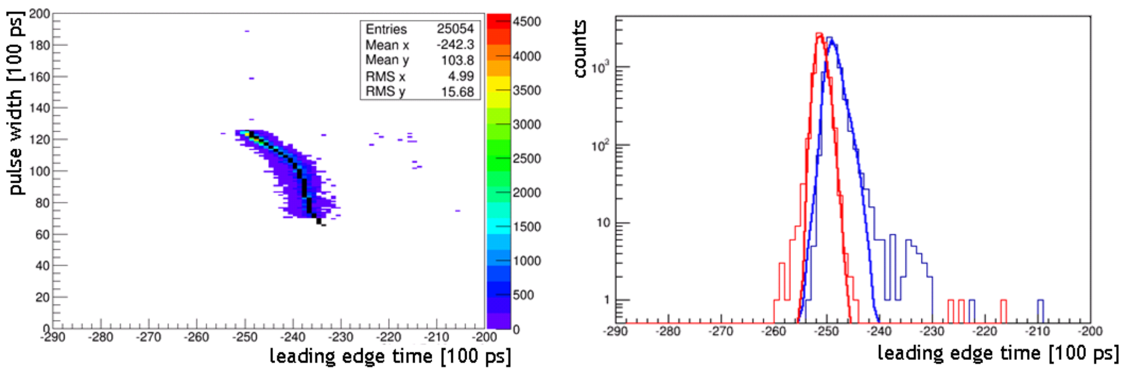

Figure 2. TOT plot (left) and time distributions in logarithmic scale before (blue) and after (red) time walk correction (right).

2.3 Spatial resolution

A similar configuration is used for spatial scans. The laser source is aligned with the centre of a pad and is moved across several pads in the fine direction by steps of half a pitch (0.4 mm). For each spatial position, the pulse width in each pad is recorded.

[3]Model 9327 from ORTEC, Oak Ridge, TN37831-0895, U.S.A..

2016 JINST 11 C05022

2.3.1 Charge-to-width calibration

A pulse generator is used to inject charges into the electronics. The charge values are first calibrated using a fast oscilloscope. For each injected charge, the widths of the NINO pulses are then measured with the full readout electronics chain. This calibration is performed on several adjacent NINO channels. Figure 3 (left) shows the dependence of the pulse width on the input charge for a single NINO channel. Data are fitted with a model that has been used in the TOT calibration of the Timepix chip [11].

The position of the laser spot is estimated using a centroid algorithm by weighting each hit position with the charge which is calculated from the charge-to-width calibration and using the analytical fitting model. A position resolution of 0.03 mm is achieved (figure 3 (right)) and is to be compared with the required value of 0.12 mm. The required precision on the measurement of the photon propagation angle in TORCH is 1 mrad and the obtained spatial resolution contributes as 0.29 mrad.

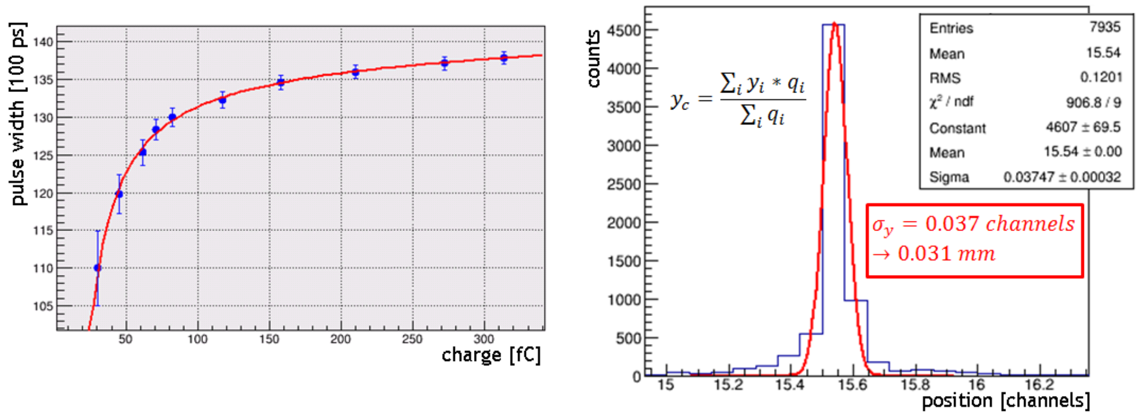

Figure 3. Charge-to-width calibration curve for a single NINO channel (left). Position histogram and resolution obtained with a centroid algorithm (right).

3 Small-scale TORCH prototype module development

3.1 Light transmission and simulation studies

Optical components of the small-scale TORCH prototype module have been manufactured by Schott Switzerland.[4] The light transmission in the UV region at the interface between the radiator plate and the focusing block has been studied. In particular, the optical quality of various glass samples using different glues has been optimized [12]. Following these investigations, a silicone glue which transmits 85% at 220 nm, PACTAN 8030, has been used for the optical coupling.

The quality of the focusing optics has also been investigated and verified by simulation using Mathematica software [13]. The air gap between the exit surface of the focusing block and the entrance window of the MCP is 0.5 mm and the window thickness is 9 mm. Rays in the angular range of 0.45–0.85 rad are generated and focused via the cylindrical mirror at the focal plane ~ 1.3 mm

[4] http://www.schott.com/advanced_optics/english/products/optical-materials/index.html.

inside the optical window. The resulting photon spread at the exit of the optical window in the fine direction is $\sigma_y < 0.4$ mm which degrades the spatial precision in the fine direction. The final photon detectors for TORCH will have smaller window thickness in order to not suffer from mismatch of focal plane and photocathode.

3.2 Laboratory tests

The small-scale TORCH prototype has first been characterized in the laboratory. The prototype was assembled and mounted inside a dedicated light-tight housing. It was mechanically coupled to the circular-shape multi-channel MCP device which was half instrumented with custom readout electronics. Collimated laser light was injected in the quartz radiator from its bottom edge and propagated via total internal reflection to the focusing block at the top and there reflected off the cylindrical mirror. Figure 4 (left) shows the laser pattern at the exit of the focusing block and the MCP area instrumented with electronics. Figure 4 (right) displays the corresponding hit map.

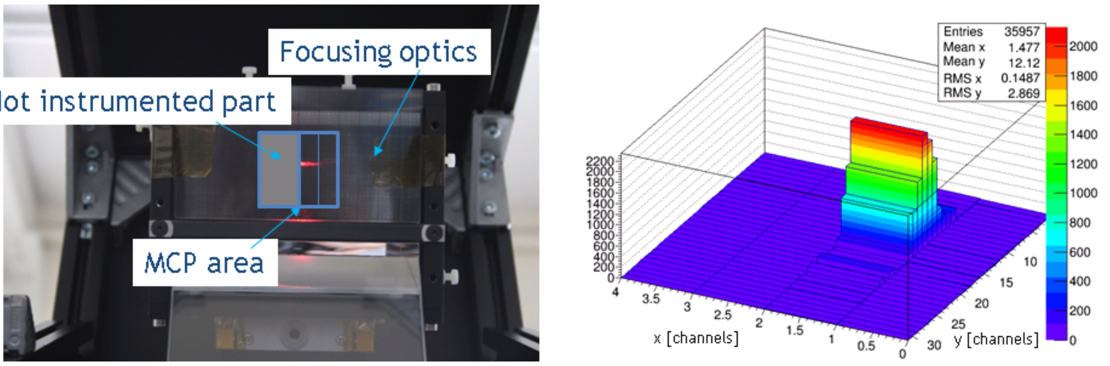

Figure 4. Laser arrangement of the small-scale TORCH prototype module together with the custom MCP device and multi-channel electronics (left) and the resulting channel hit map (right).

4 Test beam studies

Beam tests at the CERN SPS facility have been undertaken in May and July 2015.

4.1 TORCH prototype module performance

The layout of the TORCH experimental area at the SPS-H8 is shown in figure 5. The tests were performed with a high-momentum (180 GeV/c) charged-particle beam. A pixel telescope from the LHCb VELO group [14] was used to provide particle track information. A trigger logic unit [15] was used to synchronise the telescope with the TORCH electronics. The coincidence signal from two scintillators in the VELO telescope provided the trigger signal.

The time reference signal was provided by Cherenkov photons generated in a borosilicate bar ($8 \times 8 \times 100\,\text{mm}^3$) with blackened surfaces coupled to a single-channel MCP, read out with a fast amplifier and CFD. This reference signal was injected into a test channel of the NINO electronics. The borosilicate bar provides a start time and was installed in a small light-tight box mounted on the telescope infrastructure and located $\sim$ 1 m upstream from the TORCH prototype. This station was aligned with respect to the beam axis using the telescope translation and rotation stage system.

2016 JINST 11 C05022

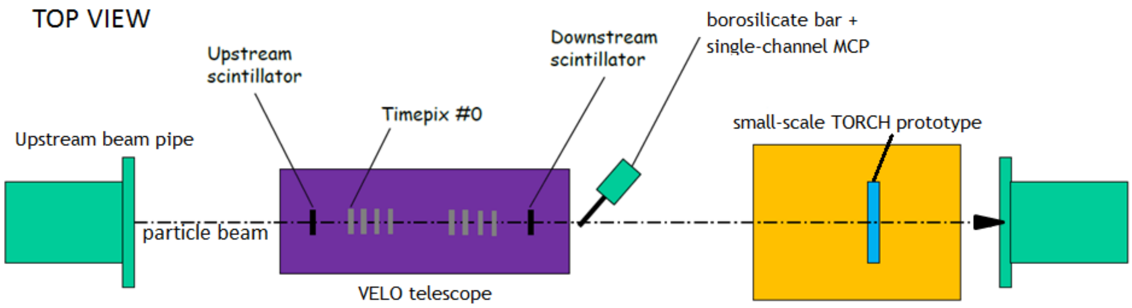

Figure 5. A schematic of the test beam infrastructure at the CERN SPS.

The data acquisition system interface was based on LabVIEW. Data were recorded for various TORCH configurations and NINO thresholds. The TORCH prototype could be translated horizontally and vertically. The nominal configuration corresponded to the beam crossing the quartz plate at its centre in both horizontal and vertical directions.

4.1.1 Preliminary results

The timing distribution of a single channel is shown in figure 6. The time walk correction, as previously introduced in subsection 2.2.1, was applied offline to the TORCH raw data. A time resolution of 220 ps is achieved for single photons. This resolution represents the single-channel response with no correction for reconstruction. Hence, the value of 220 ps includes contributions from:

- Chromatic dispersion
- Emission point error
- Track position.

The electronics contribution to the timing resolution is measured using two available NIM signals from the CFD and delaying one with respect to the other. Both signals were then injected into the test channel of the NINO electronics. The electronics jitter can be inferred from the distribution of the time difference between the leading edge of each signal. The jitter of 60 ps, already scaled by $1/\sqrt{2}$, is dominated by the HPTDC time bin precision of 100 ps.

4.2 Performance of the start time station

During a second beam test, two similar start time stations have been used in conjunction to determine the contribution of a single station to the overall time resolution achieved with the TORCH prototype. Both single-channel MCPs have been pre-calibrated in the laboratory to operate at the same gain of 1.5×10^5 electrons. The two-station system was mounted on the telescope infrastructure and x-y and rotation scans were performed to align the system with respect to the beam (figure 7 (left)). Each timing station was instrumented with a charge preamplifier to measure the pulse height spectrum and estimate the photon yield. For the timing measurements, each timing station was coupled to an amplifier/CFD and the output signals were delayed with respect to each other. Both signals

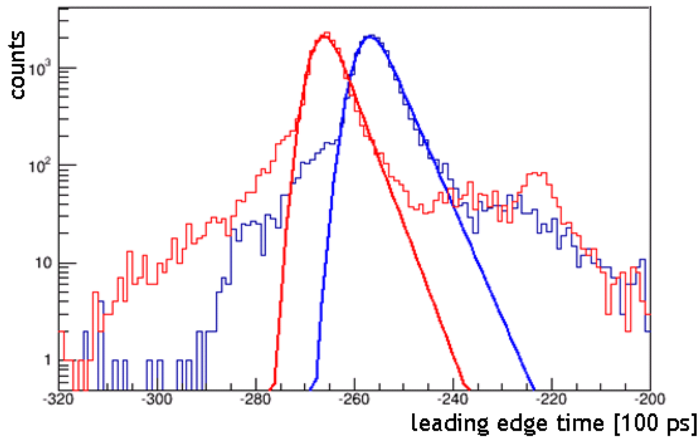

Figure 6. Timing distributions before (blue) and after (red) time walk correction from a single channel measured with the TORCH prototype module in a charged-particle beam. An offset in time is introduced for graphical display.

are input to a commercial time to amplitude converter[5] module and time jitter distributions are recorded using a multi-channel analyser. The coincidence signal from the two scintillators of the pixel telescope was used as a trigger.

The photon yield and time jitter of the timing stations have been assessed. The average detected photon yield of a single station is found to be 1.7 photoelectrons. The time difference distribution in figure 7 (right) is fitted with a Gaussian; the time resolution of a single station is given by the standard deviation of the Gaussian scaled by $1/\sqrt{2}$. This resolution is found to be ~ 50 ps.

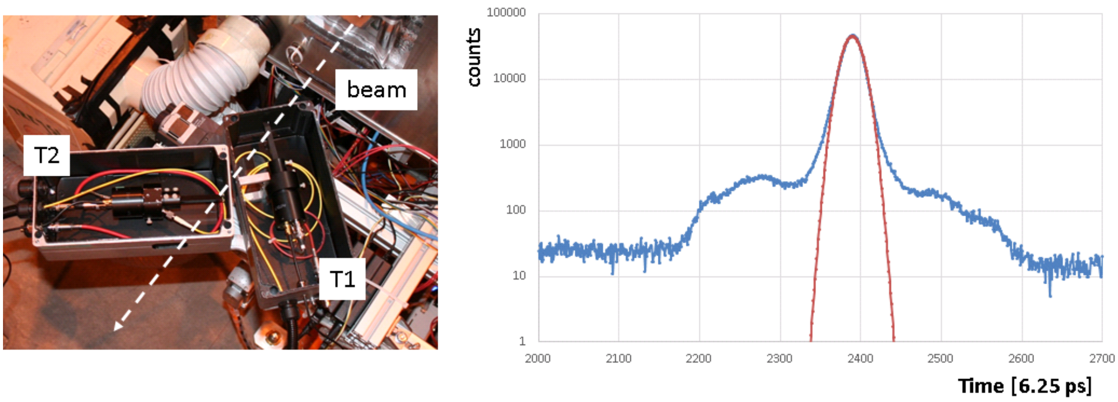

Figure 7. The configuration of the timing stations in the beam test (left). Time difference distribution of borosilicate bars with blackened surfaces (right).

A second configuration of the Cherenkov radiators was tested in which unblackened borosilicate bars were installed in place of the previous blackened bars. In this configuration, an average detected photon yield of 8.5 photoelectrons was measured. The corresponding single-station time resolution was found to be about 30 ps.

[5]Model 566 from ORTEC, Oak Ridge, TN37831-0895, U.S.A..

2016 JINST 11 C05022

5 Discussion

The performance of MCP prototypes customized for TORCH has been investigated using NINO-HPTDC readout electronics. A timing resolution of 80 ps is achieved in the laboratory for a single channel. The position resolution is found to be 0.03 mm, a value that already fulfils the TORCH requirements.

A TORCH prototype module was tested in a charged-particle beam. The time distribution of a single NINO channel gives a 220 ps resolution and full reconstruction of the TORCH data is on-going. The electronics jitter of 60 ps measured from the time reference signal is not currently a significant factor in the overall time resolution.

A time reference station has been calibrated in the same infrastructure, giving a time jitter of 50 ps. A modified version of this station with unblackened borosilicate bars results in an improved time resolution of 30 ps. This configuration is now the baseline option for future beam tests.

Acknowledgments

Support from the European Research Council in funding the TORCH R&D project is gratefully acknowledged (ERC-2011-AdG, 291175-TORCH, http://cordis.europa.eu/projects/rcn/103813_en.html). The TORCH group also acknowledges the LHCb VELO group for their help in using the pixel telescope.

References

[1] LHCb collaboration, M.J. Charles and R. Forty, *TORCH: Time of Flight Identification with Cherenkov Radiation*, *Nucl. Instrum. Meth.* **A 639** (2011) 173 [arXiv:1009.3793].

[2] M.W.U. van Dijk et al., *TORCH — a Cherenkov based time-of-flight detector*, *Nucl. Instrum. Meth.* **A 766** (2014) 118.

[3] K. Föhl et al., *TORCH — Cherenkov and Time-of-Flight PID Detector for the LHCb upgrade at CERN*, this workshop.

[4] T.M. Conneely et al., *The TORCH PMT: a close packing, multi-anode, long life MCP-PMT for Cherenkov applications*, 2015 *JINST* **10** C05003.

[5] R. Gao et al., *Development of scalable electronics for the TORCH time-of-flight detector*, 2015 *JINST* **10** C02028.

[6] M. Despeisse et al., *Multi-Channel Amplifier-Discriminator for Highly Time-Resolved Detection*, *IEEE Trans. Nucl. Sci.* **58** (2011) 202.

[7] M. Mota et al., *A flexible multi-channel high-resolution time-to-digital converter ASIC*, *IEEE Trans. Nucl. Sci.* **2** (2000) 155.

[8] J. Christiansen, *HPTDC High Performance Time to Digital Converter*, version 2.2 (2004) for HPTDC version 1.3 https://edms.cern.ch/file/599848/2.2/hptdc_manual_ver2.2.pdf.

[9] P. Antonioli, *The ALICE time-of-flight system*, *Nucl. Phys. Proc. Suppl.* **B 125** (2003) 193.

[10] I.G. McWilliam and H.C. Bolton, *Instrumental peak distortion*, *Anal. Chem.* **41** (1969) 1755.

[11] J. Jakubek, *Precise energy calibration of pixel detector working in time-over-threshold mode*, *Nucl. Instr. Meth.* **A 633** (2011) S262.

2016 JINST 11 C05022

[12] L. Castillo García et al., *Micro-channel plate photon detector studies for the TORCH detector*, *Nucl. Instrum. Meth.* **A 787** (2015) 197.

[13] Optica3 package of Mathematica, http://www.opticasoftware.com/.

[14] K. Akiba et al., *The Timepix Telescope for High Performance Particle Tracking*, *Nucl. Instrum. Meth.* **A 723** (2013) 47 [arXiv:1304.5175].

[15] AIDA mini TLU, http://www.ohwr.org/projects/fmc-mtlu/wiki.

2016 JINST 11 C05022