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Status of the TORCH time-of-flight detector

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Abstract: The TORCH time-of-flight detector is designed for large-area coverage, up to 30 m^2, to provide particle identification between 2-10 GeV/c momentum over a flight distance of 10 m. The arrival times from Cherenkov photons produced within a quartz radiator plate of 10 mm thickness are combined to achieve a 15 ps time-of-flight resolution per incident particle. Micro-Channel Plate Photomultiplier Tube (MCP-PMT) detectors of 53 $\times$ 53 mm^2 active area have been developed with industrial partners for the TORCH application. The MCP-PMT is read out using charge division to give a 128 $\times$ 8 effective granularity. Laboratory results of development MCP-PMTs will be described, and testbeam studies using a small-scale TORCH prototype module will be presented.

Keywords: Cherenkov detectors, Particle identification methods, Photon detectors for UV, visible and IR photons (vacuum), Timing detectors.

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Contents

1 Introduction

The Timing Of internally Reflected CHerenkov photons (TORCH) is a high-precision time-of-flight detector suitable for large-area applications and covering the particle momentum range up to 10 GeV/c [1, 2]. Cherenkov photons, produced in a fused silica radiator of 1 cm thickness, propagate by total internal reflection to focussing optics at the periphery of the detector. There the photons are detected by fast photodetectors where their arrival times are measured. A schematic of the TORCH modular layout is shown in figure 1.

At 10 GeV/c momentum the time of flight difference between a pion and kaon is 35 ps over a distance of 10 m, hence a time resolution of about 10-15 ps per track is required to give a 3-sigma separation. Given around 30 detected Cherenkov photons per track, a time resolution of $\sim$70 ps per photon is therefore necessary. To achieve this, simulation has shown that a 1 mrad resolution of the angular measurement of each photon is also required [1].

To meet the above requirements, Micro-Channel Plate Photomultiplier Tube (MCP-PMT) photon detectors have been developed with industrial partners to have customized geometry and which are robust against large doses of integrated charge, up to 5 C/cm^2. To achieve the milliradian precision, the detectors must have a 128 $\times$ 8 effective granularity over a 53 $\times$ 53 mm^2 active area.

In this paper the performance of the MCP-PMTs and the multi-channel electronics readout system will be summarised. The construction of a TORCH demonstrator module and its operation in a CERN test-beam will also be described.

2 The MCP-PMT photon detectors

To conform to the stringent TORCH requirements, customised MCP-PMT detectors have been produced by our industrial partners, Photek Ltd[1]. MCP lifetime had historically been problematic, with tubes having severe loss of gain and quantum efficiency when exposed to

[1] Photek Ltd., 26 Castleham Road, St Leonards on Sea, East Sussex, TN38 9NS, United Kingdom.

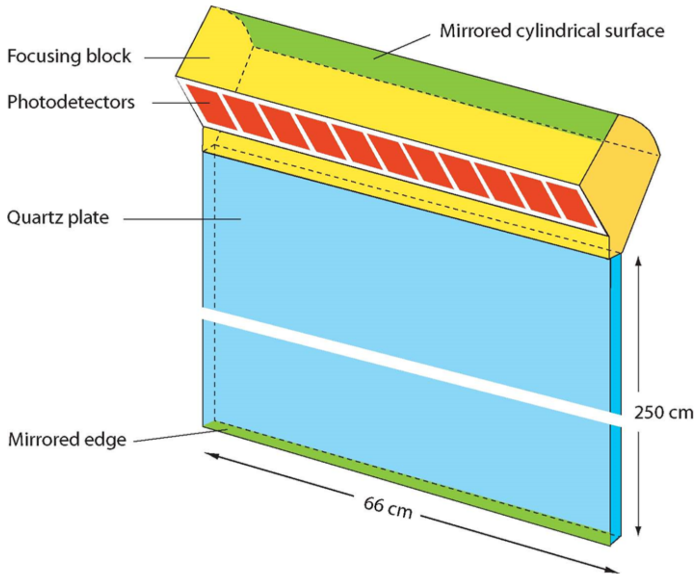

Figure 1. Schematic of a TORCH module [2].

photon doses giving significantly less than $\sim 0.1\,\mathrm{C/cm^2}$ [3, 4]. Another issue was the coarse granularity of commercially available tubes which did not fulfil TORCH requirements. The major challenges for the TORCH MCP-PMT development was therefore to overcome the lifetime issue, with satisfactory tube operation after accumulation of around $5\,\mathrm{C/cm^2}$ integrated charge, and to manufacture an MCP-PMT with customised fine-grained 128×8 granularity, housed within a square $53 \times 53\,\mathrm{mm^2}$ (2 inch $\times$ 2 inch) active area.

In actuality the final TORCH design has a 64×64 pixel pattern and a novel charge-sharing technique is used in the fine dimension to give an equivalent 128 pixel resolution over the 2 inch width. The charge sharing relies on capacitive coupling to produce a smooth well-defined charge footprint on the anode [5]. This has the advantage of halving the number of anode pads in the confined area and also halving the number of readout channels, hence saving cost and complexity. In the coarse dimension, each of eight consecutive pixels are ganged together in the external electronics, giving eight logical pixels.

At the inception of the project, a three-phase programme of R&D was defined. For Phase 1, five circular 25 mm diameter single-channel MCP-PMTs with atomic-layer deposition (ALD) coating were produced. A single tube was lifetime-tested at CERN with LED illumination and, after running for approximately three years, the device had reached $3.5\,\mathrm{C/cm^2}$ with little drop in quantum efficiency [2], and around a factor 2 drop at $5\,\mathrm{C/cm^2}$ [6]. Figure 2 shows the measured quantum efficiency as a function of charge accumulation. The MCP-PMT timing performance was also studied, shown in figure 3. A time resolution of 23 ps is inferred from an exponentially-modified Gaussian fit to the main peak [7]. A second broader Gaussian describes the asymmetry caused by effects of back-scattering and relaxation after-pulsing of the laser which provides the start signal.

For the Phase 2 development, five 40 mm diameter multi-channel high-granularity MCP-PMTs, with the required TORCH spatial and timing resolutions, were produced and tested.

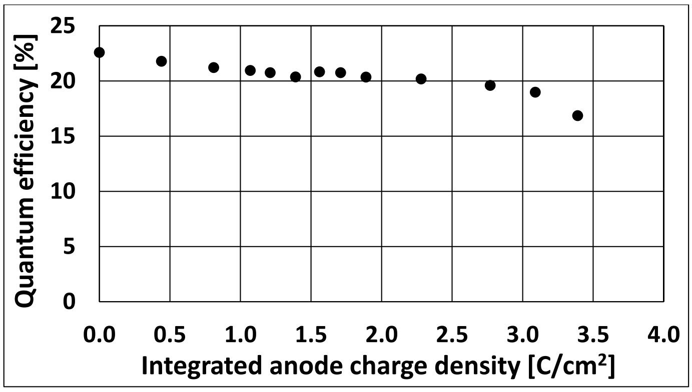

Figure 2. Photocathode efficiency measured on-axis as a function of integrated charge collection for a Phase 1 Photek ALD-coated MCP [2].

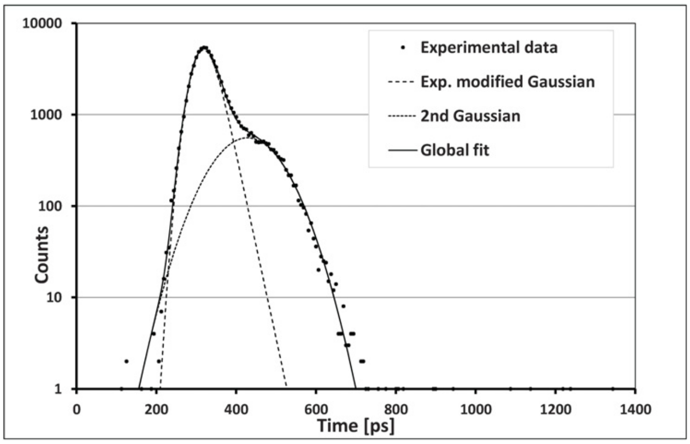

Figure 3. Timing distribution of a Photek Phase 1 MCP tube [7]. Note the vertical logarithmic scale. An exponentially-modified Gaussian fit (described in the text) gives a timing resolution of 23 ps.

These tubes have 32 $\times$ 32 pixels, filling a square quarter area, 26.5 $\times$ 26.5 mm^2. The pad size is 0.728 $\times$ 0.728 mm^2 with a pitch of 0.828 $\times$ 0.828 mm^2, matching the 64 $\times$ 64 pattern of the final TORCH design. Electrical contact to the readout PCB board is via Anisotropic Conductive Film (ACF), a commercial product which conducts in one direction and not in the other. The spatial resolution of the Phase 2 tubes measured with laser illumination, using cluster centroiding with charge weighting, is demonstrated in figure 4. The resolution is significantly better than the $\sim$100 μm required for TORCH [8].

The production of ten final MCP-PMT photon detectors in a square tube body with the required lifetime, granularity and timing resolution, was completed in May 2017. These tubes are currently under test and will be the subject of a future paper.

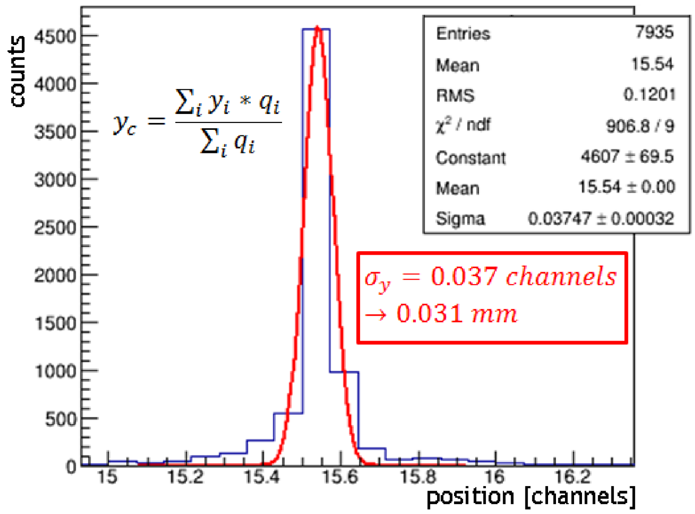

Figure 4. Position measurement of a laser spot with a Photek Phase 2 MCP-PMT tube [8]. A Gaussian fit gives a spatial resolution of 31 μm.

3 The TORCH prototype module and readout system

A scaled-down version of a TORCH module, shown in figure 5(left), has been constructed, and used in all the test-beam studies described in section 4. The demonstrator module consists of a quartz plate of 350 mm length, 120 mm width and 10 mm thickness together with an aluminized focussing block, both procured from Schott Germany[2]. The radiator quartz plate is positioned vertically, glued to the focussing block, supported from a mounting frame, and enclosed in a light-tight vessel. The optical geometry of the focussing block is shown in figure 6. A single Phase 2 MCP-PMT is mounted to the focussing block with a small air gap separating them.

The MCP-PMT is read out by a fully-customised electronics system [9]. The front-end amplifier and discriminator board houses a pair of 32-channel NINO ASICs [10], which give time-over-threshold (TOT) information, in a 64-channel configuration. The NINO-32 board is then connected to a TDC board containing a pair of HPTDC chips [11] operated in 32-channel mode, which digitise the signals with 100 ps binning. The performance of the MCP-PMT charge-sharing principle and timing relies heavily on the TOT electronics performance and calibration. A photograph of the electronics boards connected together, and before mounting on the TORCH prototype module, is shown in figure 5(right).

4 Beam tests and characterization

The prototype TORCH module was operated at the CERN PS-T9 area for a two year programme of running (Dec 2014 to Dec 2016) [2]. The beam was composed of a mixture of pions and protons at 5 GeV/c momentum. The particle identification could be independently determined using dedicated timing stations, T1 and T2, which allowed the pion-

[2]Schott Ltd, Hattenbergstrasse 10, 55122 Mainz, Germany.

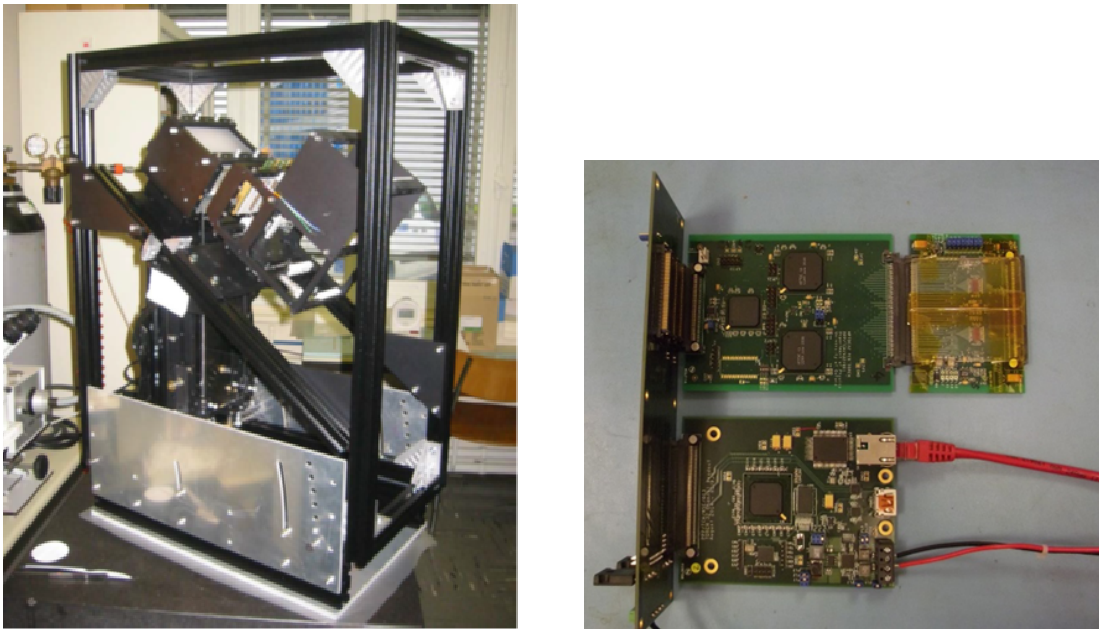

Figure 5. Photographs of (left) the scaled-down TORCH module, and (right) the TORCH 64-channel electronics readout system; anticlockwise from top right, the NINO Board, HPTDC Board, backplane and readout board.

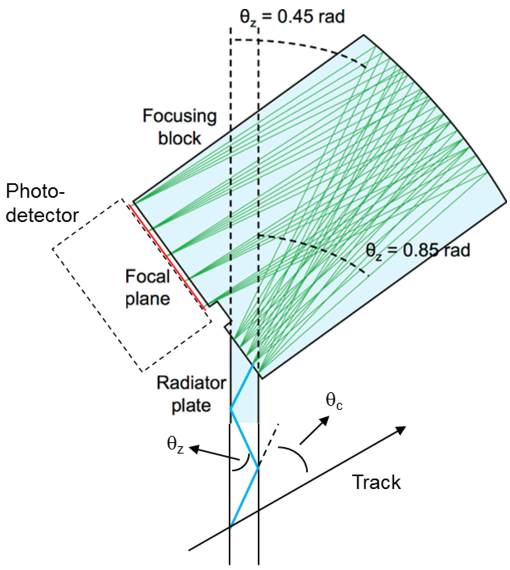

Figure 6. The optics of the focussing block showing the angular geometry and the extremities of the photon paths for the range of beam impact points and angles.

proton components of the beam to be separated. The stations each had a single-channel MCP-PMT mounted to a small borosilicate bar; T1 was located 10 m upstream and T2 located 1 m behind the TORCH demonstrator. T1 therefore provided a better separation of pion-proton time differences with respect to the TORCH timing measurement, whereas T2 provided a better time resolution due to a significantly shorter cable length.

The primary goals of the beam tests were to get experience with the Photek Phase 2 MCP-PMT, the associated electronics, and the performance of the optical system. A commercial device, the 32 × 32 channel Planacon MCP-PMT[3] was also tested. This tube has a nominal 2 inch × 2 inch square active area, similar in size to the planned Phase 3 MCP-PMT from Photek, however with pixel size a factor four larger than required for the eventual TORCH detector. For both types of MCP-PMTs, pixels were read out with the NINO-32 and HPTDC system. The electronics were calibrated for time-walk, time-over-threshold and TDC integrated non-linearities, using a data-driven method [12]. A clustering algorithm based on charge division was used to calculate the spatial hit location. The analysis relies on the measurement of the photon-by-photon Cherenkov angle determination and the arrival time of the photon, and then correcting for chromatic dispersion in the quartz radiator [1, 13].

Figures 7 (left) and (right) show hit patterns in the Photek Phase 2 MCP-PMT for 5 GeV/c pions and protons, respectively. Hits seen in the MCP-PMT match the expected pattern (taking into account reflections from the edges of the quartz plate). The small difference in Cherenkov angle for pions and protons is visible. The time difference measured for each MCP-PMT cluster with respect to station T1 is plotted versus the vertical position (fine direction) along one column of pixels in figure 8, and compared to Monte Carlo predictions. The reflections are clearly separated and the pion-proton time-of-flight difference of about 600 ps is cleanly resolved. Residuals of the measured times relative to the predicted curves are then calculated for selected pions (using the T2 timing station as reference), and shown in figure 9 (left). The distributions give a core distribution with a standard deviation of about 110 ps, averaged over the column of pixels. This is before subtraction of the contribution from the timing reference itself and, with this subtraction, we approach the target resolution of 70 ps/photon [12]. Small tails seen in the timing distribution are due to imperfections in the calibration and back-scattering effects. Hence we have demonstrated the TORCH principle to achieve the desired timing resolution.

The measurements above were repeated using the Photonis Planacon 32 × 32 MCP-PMT in the 2016 test-beam period. As before, projecting along the timing axis relative to the prediction for the earliest pion signal for each column of pixels (using the T2 timing station as reference) gives a core distribution which is largely unchanged from before, with a standard deviation close to 110 ps, shown in figure 9 (right). Hence, despite the coarser (× 4) granularity of the Planacon with respect to the Photek MCP-PMT, the timing performance could be maintained in this particular TORCH configuration. This is because working experience over the two beam periods gave significant improvements in calibration methods and better experimental control. These new techniques will be incorporated in any future

[3]Photonis USA, Lancaster, PA 17601-5688, USA.

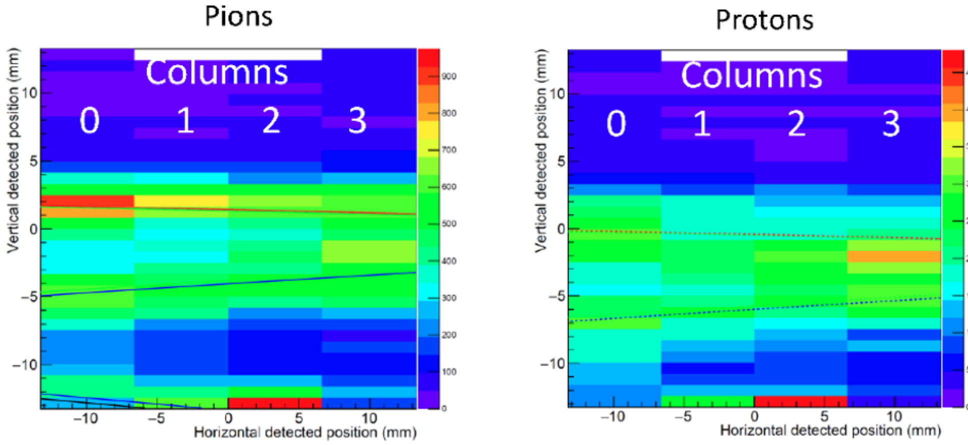

Figure 7. Data from the test beam showing hit patterns in the Photek Phase 2 MCP-PMT for (left) selected pions and (right) protons. The overlaid lines represent the simulated patterns.

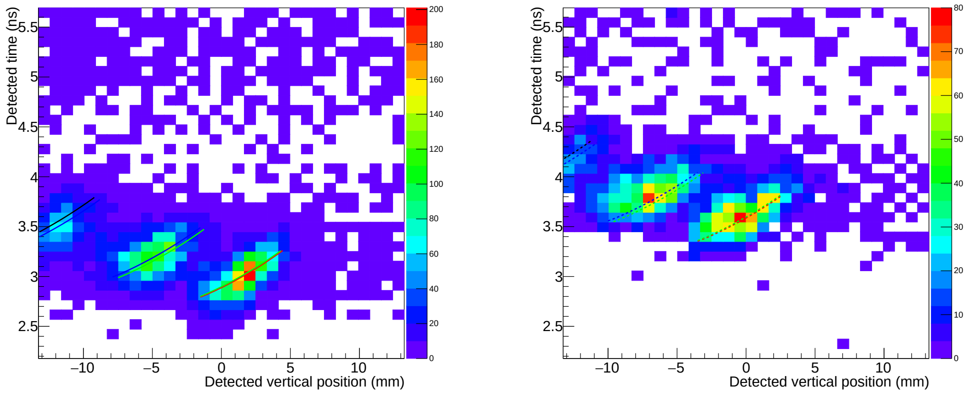

Figure 8. Data from the test beam showing the reconstructed time distribution with respect to the upstream T1 timing station versus vertical position in the four columns of pixels in the Photek Phase 2 MCP-PMT for (left) selected pions and (right) protons. The overlaid lines represent the simulated patterns for photons undergoing no reflection off the 1 cm side faces of the quartz radiator plane (red), a single reflection (green), double reflection (blue) and triple reflection (black).

operation with the Photek tube.

5 Conclusions and future work

In summary, TORCH is a novel detector concept designed to achieve a time-of-flight resolution of 15 ps, providing a $K - \pi$ separation up to 10 GeV/c momentum over a 10 m flight path. A small-scale TORCH prototype detector has been evaluated in a CERN test-beam, that includes a customised MCP-PMT which satisfies the TORCH requirements of lifetime, granularity and active area. The TORCH concept has been demonstrated.

Towards the next R&D phase, the design and construction of a half-length, full-width, prototype TORCH module is currently underway. The quartz radiator plate, 1250 mm

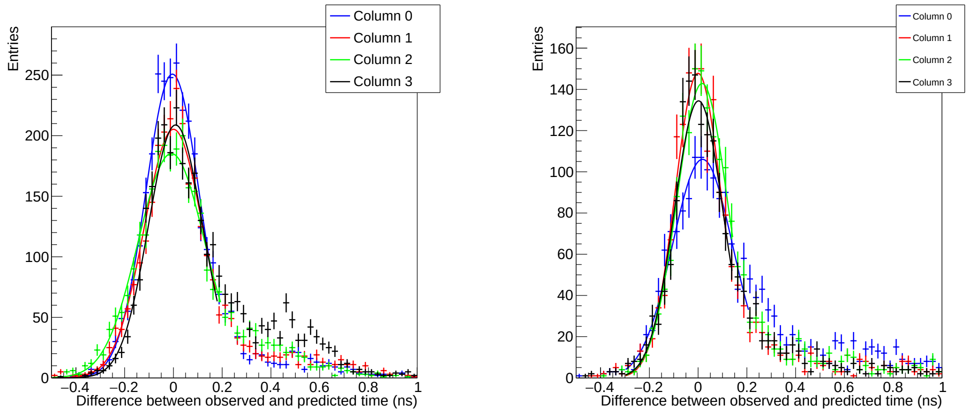

Figure 9. The difference between observed and predicted times for pions for four MCP-PMT columns: (left) the Photek Phase 2 MCP-PMT and (right) the Planacon 32 × 32 MCP-PMT.

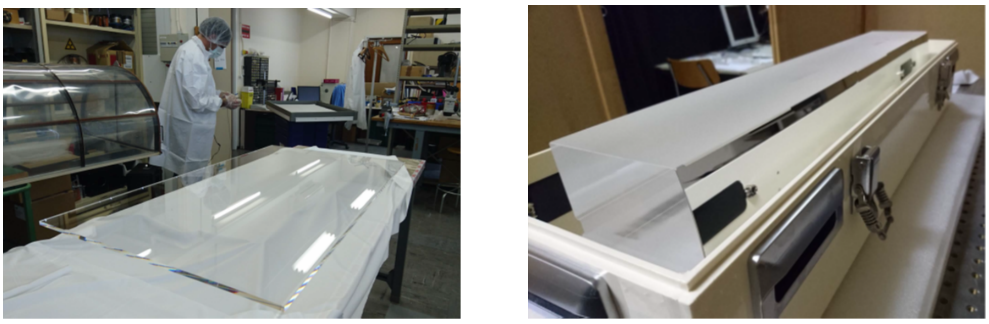

Figure 10. Photographs of (left) the TORCH half-length radiator plate and (right) the focussing block.

length, 660 mm width and 10 mm thickness, and the aluminized focussing block, have been delivered from Nikon (Japan)[4]. Photographs of the optical components are shown in figure 10. The electronics system to equip the ten Phase 3 MCP-PMTs (5000 channels) is currently being tested. The TORCH module will be demonstrated in a CERN test-beam during 2018.

In parallel, simulation studies are proceeding on the TORCH performance in the LHCb experiment, in particular the implications of occupancies at high luminosities. A possible detector arrangement is shown in figure 11, which re-uses the quartz radiator bars of the BaBar experiment and which surround the central TORCH modules [14]. Figure 12 shows the efficiency for TORCH to positively identify kaons as a function of momentum and the probability that pions are misidentified as kaons. Good performance is observed for a luminosity of 1×10^{33} cm^{-2}s^{-1} (which is $\times 5$ the current nominal LHCb luminosity); the reduced efficiency below 5 GeV/c will be restored with improved treatment of particle tracking through the LHCb spectrometer magnet. This work will form the basis of a Technical Proposal to construct a full-scale TORCH detector for the start-up of LHC Run 4,

[4]Nikon Corporation, Shinagawa Intercity Tower, 2-15-3 Konan, Minato-ku, Tokyo 108-6290, Japan.

for installation in the Long Shutdown 3 (LS3).

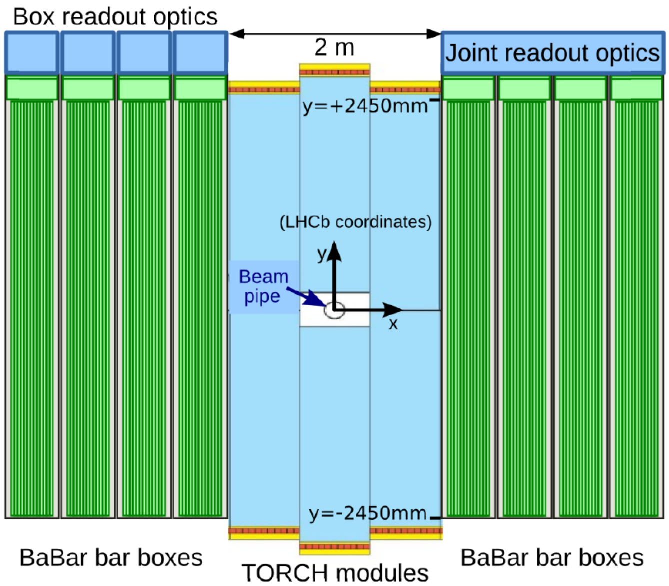

Figure 11. A possible TORCH configuration for LHCb. TORCH modules are located around the beam pipe, with the areas to the left and right each being covered with four BaBar bar boxes.

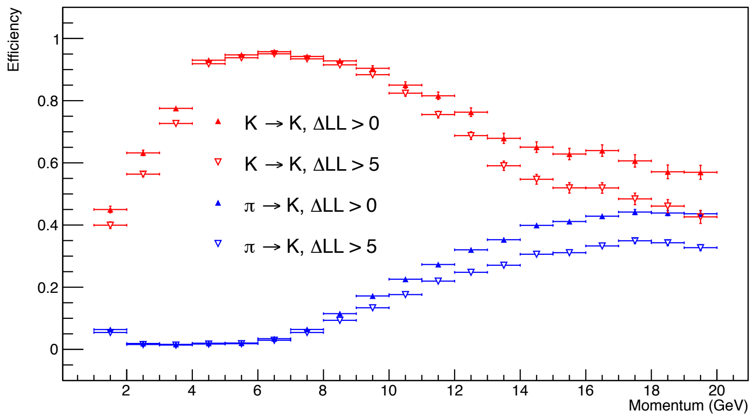

Figure 12. The efficiency in LHCb for TORCH to positively identify kaons as a function of momentum and the probability that pions are misidentied as kaons. The curves are for two different delta-log-likelihood cuts and for a luminosity of 1×10^{33} cm^{-2}s^{-1}.

Acknowledgments

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