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TORCH: A Cherenkov based time-of-flight detector.

N. H. Brook, E. N. Cowie*, **David Cussans, M. W. U. Van Dijk**
School of Physics, HH Wills Physics Laboratory
University of Bristol, Tyndall Avenue
Bristol BS8 1TL
United Kingdom
E-mail: Euan.Cowie@bristol.ac.uk; N.Brook@bristol.ac.uk; David.Cussans@bristol.ac.uk; M.VanDijk@bristol.ac.uk

L. Castillo-Garcia[ab], C. D'Ambrosio[a], R. Forty[a], C. Frei[a], T. Gys[a] D. Piedigrossi[a]
[a]*European Organization for Nuclear Research(CERN)*
CH-1211, Geneva 23
Switzerland
[b]*Laboratory for High Energy Physics, Ecole Polytechnique Fédérale de Lausanne*
CH-1015 Lausanne
Switzerland
E-mail: lucia.castillo.garcia@cern.ch, carmelo.d'ambrosio@cern.ch, roger.forty@cern.ch, thierry.gys@cern.ch, didier.piedigrossi@cern.ch

R. Gao, N. Harnew
Denys Wilkinson Laboratory, University of Oxford
Keble Road, Oxford OX1 3RH
United Kingdom
E-mail: r.gao1@physics.ox.ac.uk, n.harnew1@physics.ox.ac.uk

TORCH is a novel high-precision time-of-flight detector suitable for large area applications and covering the momentum range up to 10 GeV/c. The concept uses Cherenkov photons produced in a fused silica radiator which are propagated to focussing optics coupled to fast photodetectors. For this purpose, custom MCP-PMTs are being produced in collaboration with industrial partners. The development is divided into three phases. Phase 1 addresses the lifetime requirements for TORCH, Phase 2 will customize the MCP-PMT granularity and Phase 3 will deliver prototypes that meet the TORCH requirements. Phase 1 devices have been successfully delivered and initial tests show stable gain performance for integrated anode current >5 C/cm^2 and a single photon time resolution of $\leq$ 30 ps. Initial simulations indicate the single photon timing resolution of the TORCH detector will be $\sim$70 ps.

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1. Introduction

The TORCH [1] (Time Of internally Reflected Cherenkov light) detector is a proposed upgrade for extending the particle identification (PID) capability of the LHCb experiment [2] in the momentum range up to 10 GeV/c. Optimal pion-kaon separation plays an important role in LHCb physics for rare heavy-flavour decays and flavour tagging [3]. TORCH will be located 9.5 m from the interaction point, directly upstream of the RICH-2 detector. A schematic of the TORCH design is shown in Figure 1.

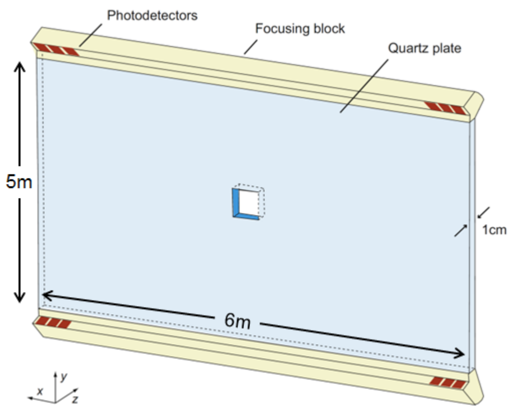

Figure 1: The TORCH detector design. Particles pass through the quartz plate producing Cherenkov radiation which is reflected to the photodetectors via focussing optics. Dimensions shown are for the TORCH detector located 9.5 m from the interaction point of LHCb.

2. The TORCH Concept

The TORCH detector will measure the time-of-flight (ToF) of a traversing particle by detecting the emitted Cherenkov light. The ToF difference between pions and kaons as a function of momentum over a path length of 9.5 m is shown in Figure 2. At 10 GeV/c this difference dictates a required ToF resolution of 10-15 ps per track for 3σ π/K separation. To achieve this, TORCH will utilise a Detection of Internally Reflected Cherenkov radiation (DIRC [4]) design with a 10 mm fused silica radiator plate. Photons produced are totally internally reflected to focussing optics along the top and bottom edges of the plate. The focussing optics map the photon propagation angle onto a position on the detector plane where the photons are read out using fast photodetectors. For this, the TORCH collaboration is developing custom Micro-Channel Plate Photomultiplier Tubes (MCP-PMTs) through industrial partnership with Photek Ltd.[1] Commercially available devices have also been tested [7].

The geometrical principle of TORCH maps the acceptance of the LHCb spectrometer, $\pm$300 mrad in the horizontal plane and $\pm$250 mrad in the vertical. At the proposed location of 9.5 m downstream of the interaction point, the radiator has dimensions of 6 x 5 m^2. To optimise the parameters of the geometrical design, a full simulation using the GEANT-4 framework [5] is ongoing. It is

[1] Photek Ltd., 26 Castleham Road, St Leonards on Sea, TN38 9NS, UK

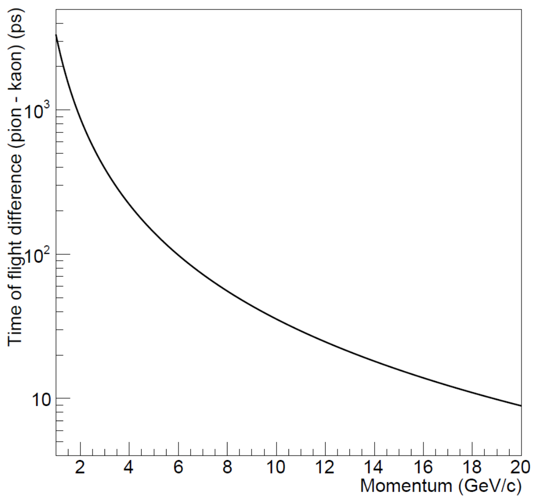

Figure 2: The time-of-flight difference between pions and kaons as a function of momentum over a flight distance of 9.5m.

expected ~30 photons per track will result, giving a timing resolution per photon of ~70 ps, as required.

The TORCH MCP-PMT will have a pitch of 60 mm and an active area of 53 x 53 mm^2. The active area will be segmented into coarse and fine directions of 8 x 128 pixels, respectively. A schematic of the MCP-PMT layout is shown in Figure 3. The simulations show that the contribution to the total timing uncertainty resulting from this geometrical and pixel layout is $\sigma \simeq 55$ ps per photon [6].

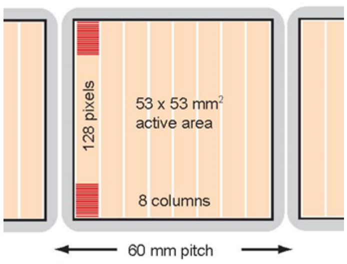

Figure 3: Schematic of the required TORCH MCP-PMT granularity and pitch [2]. Options regarding implementation are in progress.

To precisely calculate the photon path length through the radiator, the focussing light guide must accurately map θ_z, defined in Figure 4, onto a position on the MCP-PMT active surface. The angular acceptance of the focussing block, also shown in Figure 4, is 0.45 rad $\leq \theta_z \leq$ 0.85 rad. In the focussing direction the MCP-PMT is divided into 128 pixels, resulting in an angular resolution per pixel of ~1 mrad. This resolution is required for the necessary precision in the measurement of photon path length and to later allow for the correction of chromatic dispersion of the photons.

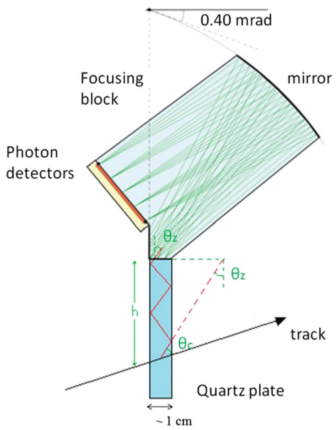

Figure 4: A cross section of the TORCH optical design. The angle θ_z is mapped by a mirror onto a position on the photodetector surface.

3. The MCP-PMT Development

The MCP-PMT is central to the performance of TORCH. Firstly the device must show stable gain performance throughout the lifetime of the experiment, in the case of the LHCb upgrade a minimum of 5 C/cm^2 integrated anode charge. Secondly it must satisfy the granularity requirements of 8 x 128 pixels, as shown in Figure 3. Finally it must have excellent time resolution, $\leq$ 50 ps for single photons. In previously reported work, commercially available devices have been tested for suitability of timing performance and resolutions of $\leq$40 ps have been achieved [7]. To reach the challenging requirements of TORCH, development of the custom MCP-PMT is being undertaken in three distinct phases.

3.1 Phase 1 - Single Channel Long Lifetime MCP-PMT

Phase 1 has focussed on producing Microchannel Plate (MCP) devices with stable gain performance up to 5 C/cm^2 integrated anode charge. To achieve this, the process of Atomic Layer Deposition (ALD) on the MCPs has been utilized. The devices produced are single pixel, round tubes of 1" diameter. One of the MCP-PMTs underwent ageing tests at Photek Ltd. [8], the results of which are shown in Figure 5. The ALD coated devices show an initial drop in gain with increasing collected charge which stabilises after 2.5 C cm^{-2}. Such a drop can be compensated by use of a higher operating voltage. The uncoated control MCP-PMT shows a sharp decrease in performance after an integrated charge of $\mathcal{O}(100\,\text{mC/cm}^2)$

The phase 1 MCP-PMTs have also been studied for their intrinsic timing performance with initial studies demonstrating a FWHM of around 68 ps [7]. Verification of these results was carried out using a picosecond pulsed laser diode. The time difference between the laser trigger signal, which was delayed, and arrival time of the MCP-PMT signal is shown in Figure 6. A primary peak and tail to later times are clearly visible; these contributions result from promptly detected and backscattered photoelectrons, respectively.

The distribution of Figure 6 is fitted with a double Gaussian to account for the primary signal and the backscattered component, respectively. The FWHM of the peak is around 70 ps which is compatible with the initial studies and those carried out by Photek [7][8].

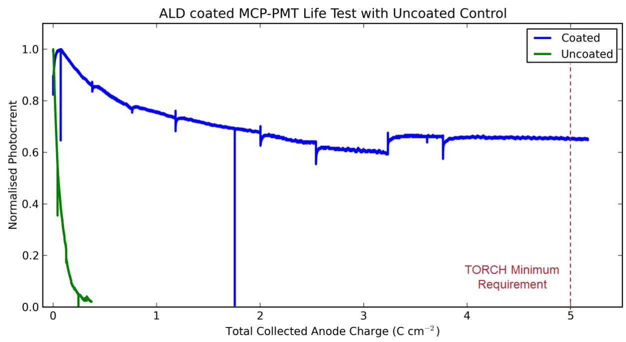

Figure 5: Initial measurement of gain as a function of integrated anode charge. After an initial decrease, the photocathode response is shown to be stable and fully satisfying TORCH requirements. The uncoated MCP-PMT is seen to degrade after $\mathcal{O}(100\,\mathrm{mC/cm^2})$ [8]

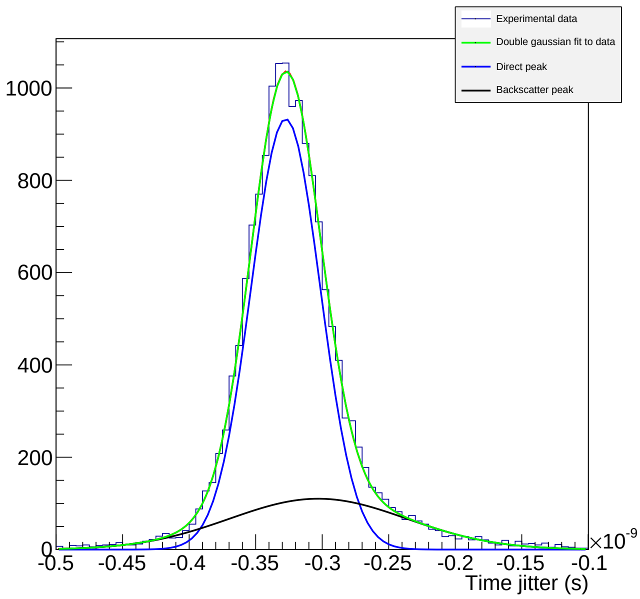

Figure 6: Timing distribution for the phase 1 MCP-PMT showing the time of arrival of the signal relative to the laser trigger. The distribution shown is inclusive of detector resolution, trigger jitter and the timing spread of the laser pulse.

Further tests are under way to check the gain and timing uniformity across the MCP-PMT surface. Gain uniformities of $\sim$15% over the surface of the ALD-coated large area MCPs developed for the LAPPD project have been observed [9]. In contrast, devices tested for use in the PANDA DIRCs show notable non-uniformity across the surface [10].

3.2 Phase 2 - High Granularity MCP-PMT

The phase 2 tubes are currently being manufactured and will feature a highly granular anode structure. They will be of circular geometry 40 mm diameter, with a square active area of 25 x 25 mm^2 containing 32 x 32 pixels. This gives a pixel pitch of $\sim$780 μm. To achieve the required pitch of the TORCH device, pixels in one direction will be ganged together and nearest neighbour charge sharing will be employed in the other. This will result in an effective pixel pitch of 6.6 mm and $\sim$415 μm, respectively. These devices will not feature the ALD coating for improved lifetime.

The performance of the charge sharing principle has been simulated using Ansys Maxwell [11] electromagnetic simulation package. To reach the required improvement in granularity the error on the reconstructed position must be ≤ 0.15 mm. The uncertainty on the reconstructed position of a photon hit as a function of gain and electronics threshold is shown in Figure 7, where the signal discrimination properties of the NINO chip [12] have been assumed. As inferred from Figure 7, for optimal operation of the electronics a minimum threshold of 50 fC is required. As such, the MCP-PMTs will need to be run with a minimum gain of 1 x 10^6 electrons. Operation at higher gain could improve the timing resolution, but would also result in a faster accumulation of integrated anode charge and hence in faster ageing of the MCP-PMTs. Further details of this study were presented at this conference [13].

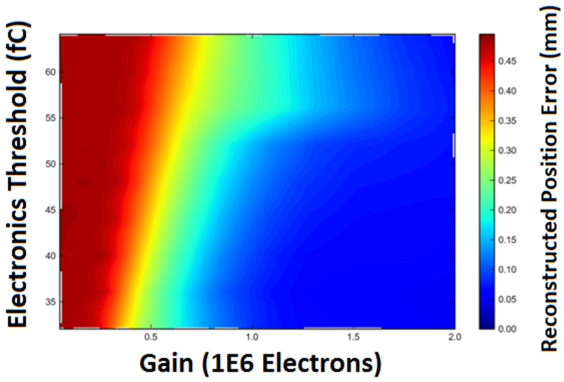

Figure 7: The uncertainty in reconstructed photon position with charge sharing. The electronics threshold should be a minimum of 50 fC to reach the required timing resolution [13].

3.3 Phase 3 - Full Prototype MCP-PMTs

The final phase of development will result in a prototype MCP-PMT fulfilling the TORCH requirements, with a pitch of 60 mm, active area of 53 x 53 mm^2 and an effective granularity of 8 x 128 pixels. The efficacy of the charge sharing devices tested in phase 2 will determine if the granularity will be achieved through a 64 x 64 pixel anode operated as in phase 2, or if the device will use 8 x 128 pixels. The phase 3 devices will also have the ALD coating for long lifetime performance. Aspects of the design are being finalised by Photek Ltd. and will be tested prior to the final prototypes being dispatched.

4. Electronics

The electronics readout system is essential to achieve the challenging timing resolution required by TORCH. Coupled to the MCP-PMT will be a combination of two custom ASICs: NINO [16] and HPTDC [17]. Tests carried out with the 8-channel NINO and HPTDC in so-called

Very High Resolution mode gives a resolution of 40 ps using electronic test pulses. Combining these electronics with a commercially available Planacon XP85012[2] MCP-PMT in laboratory tests gives a timing resolution of $\leq$ 90 ps [14] and in a test-beam gives around 130 ps [15].

To improve the performance of the electronics and meet the granularity requirements, development will focus on use of the 32-channel NINO in a 64-channel front-end board design. This new NINO allows for a greater channel density and excellent time resolution. To achieve fast and reliable timing resolution the NINO threshold must be $\geq$ 50 fC, giving a timing jitter on the leading edge of the NINO pulse of 8-10 ps [12].

The NINO will be paired with the HPTDC run in so-called High Resolution mode, with the possibility to run a subset of channels using the Very High resolution mode. A comparison between the HPTDC operational modes is shown in Figure 8. Comparing modes shows a decrease in timing resolution from 17 ps to 34 ps, with the benefit of increasing channel density to 16 per chip [17].

Mode	Resolution (RMS)
Low resolution	0.34 bin (265 ps)
Medium resolution	0.44 bin (86ps)
High resolution	0.65 bin (64ps)
High resolution DLL tap adjust INL table correction	0.35 bin (34ps)
Very high resolution	2.4 bin (58ps)
Very high resolution DLL tap adjust INL table correction	0.72 bin (17 ps)

Figure 8: The time resolution of the HPTDC chip for given operational modes [17]. Original tests were carried out in Very High Resolution mode, future work will be carried out in High Resolution mode, with the possibility to run a subset of channels using Very High resolution mode.

The electronics will be combined with a prototype module of a reduced-size TORCH design and will be deployed in a test-beam at the end of 2014.

5. Conclusions

TORCH is a novel detector concept to provide charged particle identification up to 10 GeV/c momentum and is proposed for the LHCb experiment. An ambitious programme of R&D work will culminate in a prototype TORCH module to demonstrate the feasibility of the full-scale design.

Development of the MCP-PMTs required to meet the TORCH programme is progressing. Phase 1 devices have shown excellent timing resolution and gain stability at an integrated anode charge in excess of 5 C/cm^2. The development of the highly granular Phase 2 device is well under way and prototypes will be delivered during summer 2014. A third-phase device, matching the full specifications for use in the final TORCH detector, will follow in 2015.

A 64-channel front-end electronics board, featuring 32-channel NINO chips, is being developed. Such a board will accommodate the increased channel density of the final TORCH MCP-PMT. Combining the measured timing resolution of the MCP-PMT with those of the electronics and optical simulation, a resolution of $\sim$70 ps is anticipated.

[2]Manufactured by Photonis USA Inc.

A prototype module is currently being prepared for deployment in a test-beam at CERN later in the year. Upon successful completion of the R&D phase a proposal will be submitted to include TORCH within the LHCb experiment.

Acknowledgements

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