The TORCH project

R. Forty

CERN, Geneva, Switzerland

E-mail: Roger.Forty@cern.ch

ABSTRACT: TORCH is a DIRC-style detector concept designed for high-precision time-of-flight measurements over large areas. It has been proposed for the upgrade of the LHCb experiment to complement the particle identification capabilities of the RICH detectors, covering the momentum region 1.5–10 GeV/c for K–π separation. The current status of the detector design and R&D is presented.

KEYWORDS: Instrumentation and methods for time-of-flight (TOF) spectroscopy; Particle identification methods

1On behalf of the TORCH collaboration.
1 Introduction

The LHCb experiment is one of the four major experiments at the LHC, and has been running successfully over the last three years [1]. It is designed for the study of flavour physics, in particular the CP violation and rare decays of hadrons containing the $b$ and $c$ quarks. The experiment has taken over the exploration of this field following the pioneering studies at the B factory experiments, and combines the enormous statistics available at a hadron collider with precision vertexing and high quality particle identification. The experiment is a key element of the exploitation of the LHC, with a sensitivity to new physics through quantum loop effects which extends to higher mass scales than the direct searches for new particles at ATLAS and CMS, and which will provide crucial input to understanding the nature of new physics once it has been found.

TORCH (Time Of internally Reflected CHerenkov light) is a detector that is proposed for the upgrade of LHCb [2]. It is a DIRC-style detector concept, focusing on time-of-flight measurement with very high resolution (10–15 ps per track), to cover the region 1.5–10 GeV/c in $K-\pi$ separation. For the implementation in LHCb, at a position of 9.5 m from the interaction point, the required height is 4.9 m and the total area to be covered is $\sim 30 \text{ m}^2$.

The TORCH detector development for LHCb places requirements on the photon detectors which exceed those of available commercial devices. While the required time resolution of about 50 ps per photon has been demonstrated for micro-channel plate photomultiplier tubes (MCP-PMTs), the granularity and lifetime requirements of TORCH are beyond what is currently available. An R&D project has therefore been instigated, focused on developing suitable photon detectors, and has received funding from the European Union over four years [3]. The final deliverable of that project will be a prototype TORCH module, including suitable radiator and optical system equipped with about 10 MCP-PMT tubes satisfying all of the detector requirements.
Figure 1. (a) Clearly resolved oscillations between the $B_0^0$ and its antiparticle [4]. (b) Observation of $D^0$–$\bar{D}^0$ mixing, from the time-dependence of the wrong-sign fraction in the $K\pi$ decay mode, with over 9 standard deviation significance [5].

2 The LHCb upgrade

Over the last three years a data set corresponding to an integrated luminosity of 3 fb$^{-1}$ has been recorded by LHCb in proton-proton collisions, and has so far produced over 160 physics publications. Some selected highlights of the physics output include the world’s best measurements of $B_0^0$–$\bar{B}_0^0$ and $D^0$–$\bar{D}^0$ oscillations, illustrated in figure 1, and the first observation of CP violation in the $B_0^0$ system shown in figure 2. First evidence was seen for the very rare decay $B_0^0 \rightarrow \mu^+\mu^-$, with a branching ratio of $\sim 3 \times 10^{-9}$, which is very sensitive to new physics (but was found to be in good agreement with the Standard Model expectation). Indications have also been seen for CP violation in charm decays, and for discrepancies in the angular distributions in $B_0^0 \rightarrow K^{*0}\mu^+\mu^-$ decays, but more data will be required to clarify these effects [7].

The LHC accelerator is currently shut down for consolidation of the connections between its superconducting magnets, and will start up again in 2015 at almost twice the energy (13 TeV). It is expected that the run will last for another three years, by which time LHCb will have more than doubled its data set. After that point the data-doubling time will become too long, so it is planned to upgrade the experiment to increase the data rate by an order of magnitude, to collect a total of at least 50 fb$^{-1}$ of data [8]. The main focus of the upgrade is to remove the bottleneck in the trigger (the hardware trigger level), which currently prevents the experiment from running at higher luminosity. This will be achieved by reading out all detectors at the 40 MHz bunch crossing rate of the LHC, and performing the trigger in software in a large CPU farm. The upgrade has been approved, and will be installed in the second long shutdown of the LHC, expected to take place in 2019. The physics goals of the LHCb upgrade have been presented in detail in ref. [7].

Particle identification is crucial to the physics performed at LHCb, where separating the different types of charged hadrons is essential for the study of hadronic final states. It is currently provided by a RICH system consisting of three radiators (silica aerogel, C$_4$F$_{10}$ gas and CF$_4$ gas) in two vessels, RICH1 and RICH2, visible in figure 3. These detectors will be modified for the upgrade, in particular the photon detectors and their electronics have to be replaced to satisfy the 40 MHz readout requirement [9]. But in addition, it has been found that in the high-occupancy en-
Figure 2. Observation of CP violation in two-body charmless $B$ decays: (a, b) with selection tuned for $B^0 \rightarrow K^+ \pi^-$ decays, where the raw CP asymmetry can be seen between the $B^0$ and $\bar{B}^0$ peaks, and (c, d) with selection tuned for $B^0_s \rightarrow K^+ \pi^-$ decays [6].

The environment of the upgrade, the aerogel radiator is no longer effective (as it produces few detectable photons, spread over very large rings) and it will therefore be removed. This will leave the experiment with an excellent RICH system for particle identification above the kaon threshold in C$_4$F$_{10}$ gas ($\sim 9.3$ GeV/c), but without positive $K$–$\pi$ separation below that momentum. A time-of-flight based system, TORCH, has therefore been proposed to cover the low-momentum region, and replace the role of the aerogel radiator in the upgrade.

The physics that will be enabled by TORCH in LHCb follows from extending the particle identification capability to full momentum coverage at the lower end of the spectrum (only tracks with $p > 1.5$ GeV/c make it through the spectrometer dipole field). This low-momentum coverage is important for multibody final states, as typical momenta of the decay products peak around 10 GeV/c. It will also strengthen the concept of the LHCb upgrade as a general-purpose detector for the forward region, complementing the central high-$p_T$ experiments ATLAS and CMS. They cover the pseudorapidity range $|\eta| < 2.5$ with excellent detection capability, but LHCb extends that coverage to the forward region $2 < \eta < 5$. A particular case where the lower momentum coverage will be crucial is for flavour tagging: the determination of whether a given $b$ (or $c$) hadron was produced as particle or antiparticle. This is required for time-dependent CP violation measurements, for example. One of the most powerful tags is of opposite-side kaons coming from the $b \rightarrow c \rightarrow s$ decay chain, for which the charge of the resulting kaon tags the production state of the $b$ (or $\bar{b}$) produced in conjunction with the signal $b$ hadron. Such tracks typically have momenta of a few GeV/c, so extending the positive particle ID below 10 GeV/c will have a significant impact on the total tagging power.
The proposed location for the TORCH detector in LHCb is at a position along the beam axis of $z = 9.5$ m, where $z = 0$ is the nominal interaction point, as illustrated in figure 3. The difference in time-of-flight (TOF) between kaons and pions over this distance is shown in figure 4(a), and corresponds to about 40 ps at 10 GeV/c. Very high resolution is therefore required, with a target of 10–15 ps per track. The nominal particle identification performance of such TOF is shown in figure 4(b), illustrating how it would complement the gas radiators of the RICH system.

A DIRC-style detector is proposed, with a thin plane of quartz (synthetic fused silica) used as radiator, to provide prompt Cherenkov photons. They then propagate by total internal reflection to the edges of the plane, where they are detected and their arrival time measured precisely. For a quartz thickness of 1 cm, and assuming a reasonable quantum efficiency for the photon detector, about 30 photons can be detected per track, leading to a required resolution per photon of about 70 ps. We assume that 50 ps intrinsic time resolution (RMS) can be achieved on the time measurement of the photons, using MCP-PMTs: better resolution than this has already been demonstrated for single photon detection [10], although extending such performance to a large system will be an interesting challenge.

The time-of-propagation of the photon in the quartz plate has also to be determined to within 50 ps, so that its combination in quadrature with the intrinsic time resolution matches the overall 70 ps resolution requirement per photon. The effect of dispersion in the quartz smears the time-of-propagation depending on the photon wavelength, and has to be corrected for. This is achieved in the TORCH concept by measuring the Cherenkov angle at emission of the photon, and thus determining the refractive index $n_{\text{phase}}$. The group velocity is used to determine the time of propagation, and this is related to the phase velocity by $n_{\text{group}} = n_{\text{phase}} - \lambda \cdot dn_{\text{phase}} / d\lambda$ (at wavelength $\lambda$), which then, together with the dispersion relationship, determines the time of propagation. High angular
precision is required to perform this reconstruction, of about 1 mrad in each projection, despite the focus of the concept being on TOF. Note that for a saturated track the difference in Cherenkov angle between photons with energy 3 and 5 eV (spanning the expected sensitive region of the photocathode) is about 24 mrad, demonstrating the importance of the dispersion correction. Timing was used in the BaBar DIRC to suppress background [11], and in the FDIRC R&D to improve the Cherenkov angle resolution [12], while in TORCH the measured Cherenkov angle is used to improve the timing resolution.

The initial TORCH concept used a full plane of quartz with photon detectors around its edge, so that the measurement of the photon angle is simple, using the detection point and the track impact point. In the projection corresponding to the plane only coarse pixellization of the photon detector is required, of order 6 mm. The other angle is determined by focusing the photons onto the photon detector with a focusing element, that consists of a cylindrical mirror (shown in figure 5). Assuming a range of 400 mrad in angle ($\theta_z$) has to be covered, then about 128 pixels are required in this projection to achieve the required 1 mrad precision.

A linear array of square photon detectors is assumed, as shown in figure 5. The highest granularity MCP PMT available commercially is the Planacon\(^1\) with $32 \times 32$ channels in an active area 53 mm x 53 mm. We assume the same layout for the photon detector, but with adapted pixellization of the anode to give $8 \times 128$ pixels, as shown in figure 6(a). The quantum efficiency versus photon energy assumed in the simulation is shown in figure 6(b).

The time-of-propagation of the photons within the quartz is also, of course, sensitive to the particle type at low momentum: this is the source of $K-\pi$ separation exploited in the TOP detector for Belle II [13]. At 10 GeV/c the difference in Cherenkov angle between a pion and kaon is about 1 mrad. Fortunately the difference in time-of-propagation has the same sign as that of the

---

\(^1\)Burle/Photonis, Lancaster PA 17601–5688, US.
TOF separation, and acts to increase the overall performance of the system. Good charged particle tracking will be required so that the track angular and momentum resolution does not limit the performance in the reconstruction, but this will be available in LHCb. The “start time” for the TOF measurement will be determined from other tracks coming from the same primary $pp$ vertex as the signal decay under study: in LHCb there are a large number of such tracks, mostly pions, so the TORCH reconstruction technique can be reversed to calculate their time-of-flight on the assumption that they are pions; the few non-pion tracks give outliers from the time distribution which can be rejected. In this way the start-time can be determined with high precision (typically a few ps).  

Synchronisation of the TORCH modules to match this precision will require attention; an alternative approach is to use timing information from the LHC machine, with correction for the measured primary vertex position.

---

**Figure 5.** Schematic layout of the TORCH detector, showing the focusing block attached to the edge of the 1 cm-thick quartz radiator plate; its cylindrical mirror focuses the Cherenkov light onto a linear array of photon detectors [8].

**Figure 6.** (a) Layout of photon detectors assumed for TORCH, with an active area of 53 mm × 53 mm instrumented with 8 × 128 pixels. (b) Quantum efficiency versus photon energy assumed in the simulation; the dashed line indicates the effect of the transmission limitation from the optical epoxy used in the assembly of the BaBar DIRC.
Figure 7. Event display of a low multiplicity event with three tracks passing through TORCH. The impact points of the tracks on the quartz plane are shown in the central panel, and the detected photon signals in the four outer panels, one for each edge. In the latter, the vertical axis gives the angle of the photon, $\theta_z$, while the horizontal axis gives the position along the coordinate of the corresponding edge; the photon hits are colour coded to match the tracks. Dispersion in the quartz is not included here, for the purposes of illustration.

The pattern of photon signals that would be detected for a low-multiplicity event is displayed in figure 7. As can be seen, the photons from a given track form hyperbola-like images in the photon detectors along each edge of the plane, with the width of the hyperbola depending on how close the track is to the edge. This figure was made without including dispersion in the quartz, for illustration. When dispersion is included, the images become less easily identified by eye, as shown in figure 8 (a), which corresponds to the same image as the upper edge of figure 7.

Use of timing information as well as the spatial information from the detector can help to separate the signals from each track. In figure 8 (b) the time-of-propagation of the photons in the quartz is calculated with respect to one of the tracks (the one marked in blue in the figure). As can be seen, hits from that track peak at the true time, while the hits from other tracks are spread out, but would peak in the time distribution when calculated with respect to the correct track. This is the essence of the pattern recognition approach, to make all track-hit combinations, calculate the corresponding photon energy from the Cherenkov angle, and reject those that fall outside the bandwidth of the photon detector that was shown in figure 6 (b). The assignment of photons to tracks is then optimized, by maximizing an overall likelihood for the event.
Figure 8. (a) The same event display as the upper panel of the previous figure, but now with the effect of dispersion in the quartz included. (b) Difference in reconstructed and true time-of-propagation of the photons in the quartz plate, when calculated with respect to the track coloured blue.

Covering the full $5 \times 6 \text{m}^2$ area required for the LHCb acceptance with a single plane of quartz is of course not feasible in practice, not least because of the hole required for the beam pipe. Simulation studies are therefore being made of a modular layout, where the full plane is replaced with a number of identical modules placed side-by-side. The layout shown in figure 5 has the dimensions of one such module, out of 18 that would be required to cover the full acceptance, giving a total of 198 photon detector units. Such a modular layout has the advantage of reducing the number of tracks that contribute to the signal in a given module, but on the other hand there are ambiguities introduced by possible reflections off the sides of the module. For a given track-hit combination, there are typically a number of solutions with zero, one or more reflections off a module edge that will still give a physical reconstructed Cherenkov angle, so these need to be taken into account in the reconstruction. The effect of such modular construction is illustrated in figure 9 for a simulated LHCb event. Initial studies show that such ambiguities can be handled successfully, but the optimization of the module width is still in progress.

The performance of this approach has been studied using the full simulation of LHCb events, interfaced to a simplified description of the TORCH detector itself. The resulting particle identification performance is shown in figure 10, and matches well the requirement of covering the momentum region $1.5$–$10 \text{GeV}/c$, even at the high luminosity of the LHCb upgrade. Full GEANT simulation of the TORCH detector is now in progress [14].
Figure 9. Event display of a realistic event in LHCb: (a) the photon signals seen on the upper edge of the quartz plate, when the plate is considered to be a single piece; photons from one track (a kaon) have been emphasized. Dispersion in the quartz is not included here, for the purposes of illustration. (b) The track impact points on the quartz plate; the extent of a single module has been marked with a dashed rectangle. (c) The image detected in that module, for the same event as in (a), but now taking the reflections on the module edges into account.

4 R&D project

The environment at the proton-proton collisions of the LHC is challenging, with high multiplicity events of order 100 tracks every 25 ns bunch crossing (i.e. 40 MHz crossing rate). This leads to severe requirements for the photon detectors in terms of rate capability (> 10 MHz/cm²) and integrated charge (> 5 C/cm²), beyond the lifetime of previous MCP-PMTs. The TORCH R&D project was therefore set up, focusing on the development of a suitable MCP-PMT satisfying the granularity, lifetime, and active-area requirements for TORCH. The TORCH collaboration involves groups from CERN and Bristol and Oxford Universities (a subset of the groups that work on the RICH system of LHCb). A successful application was made to the European Research Council
Figure 10. Kaon detection efficiency and pion misidentification rate as a function of momentum, determined by interfacing a simplified description of the TORCH detector to a full simulation of LHCb events at nominal luminosity ($2 \times 10^{32}$ cm$^{-2}$s$^{-1}$); the dashed lines show the corresponding distributions at the ten-times higher luminosity expected in the LHCb upgrade, illustrating that the performance is robust [8].

for R&D funding. In the first year of the project to date an industrial partner has been selected following a tendering process$^3$ and first prototype MCP tubes have been produced. They are single-channel, round tubes, with excellent time resolution measured $\sim 25$ ps. Their MCPs have been coated using an atomic-layer deposition (ALD) process, which is expected to solve the lifetime issue. First results look very promising, and long-term life testing is underway. The next phase will be to provide the high granularity required, and then finally square tubes that satisfy both high granularity and long lifetime. These will be used to instrument a prototype TORCH module, which is the final deliverable of the R&D project.

In parallel with this activity, work is underway on the readout electronics, using commercial MCP tubes which have been studied in the lab and in test-beam measurements. The electronics are based on the NINO front-end amplifier/discriminator ASIC that was originally developed for the TOF system of ALICE, along with the HPTDC chip for digitization [15]. Custom electronics boards have been developed using the 8-channel NINO chip, and the performance studied [16, 17]. It is planned to move to the 32-channel version of the NINO for the next round of tests, and a sample of those chips have been acquired.

5 Conclusions

TORCH is a novel concept for a DIRC-type detector, to achieve high-precision time-of-flight over large areas. It has been proposed for the upgrade of LHCb, to complement the high-momentum particle identification provided by the RICH system. The target resolution is 70 ps per detected Cherenkov photon, to give 10–15 ps per charged track, and provide clear $K$–$\pi$ separation up to

$^3$Photek, St. Leonards on Sea, U.K.
The ongoing R&D programme aims to produce a suitable MCP-PMT photon detector within the next 2–3 years, satisfying the challenging requirements of lifetime, granularity and active area. A prototype module will then be prepared to demonstrate the concept. On successful completion of the R&D, a proposal for implementation in LHCb will follow.

Acknowledgments

I would like to thank the organizers for an excellent workshop. Ideas for TORCH have been cross-fertilized with input from the DIRC community, including the FDIRC, TOP, and PANDA studies. The support of the European Research Council is gratefully acknowledged in the funding of this work (call identifier: ERC-2011-AdG, 291175-TORCH).

References

[1] LHCb collaboration, *The LHCb Detector at the LHC*, 2008 JINST 3 S08005.

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

[3] ERC Advanced Grant No. 291175, http://cordis.europa.eu/projects/rcn/103813.en.html.

[4] LHCb collaboration, *Precision measurement of the $B^0_s$-$\bar{B}^0_s$ oscillation frequency with the decay $B^0_s \to D^- \pi^+$*, New J. Phys. 15 (2013) 053021 [arXiv:1304.4741].

[5] LHCb collaboration, *Observation of $D^0$–$\bar{D}^0$ oscillations*, Phys. Rev. Lett. 110 (2013) 101802 [arXiv:1211.1230].

[6] LHCb collaboration, *First observation of CP violation in the decays of $B^0_d$ mesons*, Phys. Rev. Lett. 110 (2013) 221601 [arXiv:1304.6173].

[7] LHCb collaboration, *Implications of LHCb measurements and future prospects*, Eur. Phys. J. C 73 (2013) 2373 [arXiv:1208.3355].

[8] LHCb collaboration, *Letter of Intent for the LHCb Upgrade*, CERN-LHCC-2011-001 (7 March 2011); LHCb collaboration, *Framework TDR for the LHCb Upgrade: Technical Design Report*, CERN-LHCC-2012-007 (25 May 2012).

[9] LHCb collaboration, *LHCb PID Upgrade Technical Design Report*, CERN-LHCC-2013-022 (28 November 2013).

[10] L. Castillo Garcia, *Timing performance of a MCP photon detector read out with multichannel electronics for the TORCH system*, in proceedings of 14th ICATPP Conference, Como, Italy, 23–27 September 2013.

[11] BABAR-DIRC collaboration, I. Adam et al., *The DIRC particle identification system for the BaBar experiment*, Nucl. Instrum. Meth. A 538 (2005) 281.

[12] J. Benitez et al., *Status of the Fast Focusing DIRC (fDIRC)*, Nucl. Instrum. Meth. A 595 (2008) 104.

[13] K. Inami, *TOP counter for particle identification at Belle II experiment*, presented at RICH 2013, Shonan Village, Japan, 2–6 December 2013.

[14] M. van Dijk, *TORCH, a Cherenkov based time of flight detector*, presented at RICH 2013, Shonan Village, Japan, 2–6 December 2013.
[15] F. Anghinolfi et al., *NINO: An ultra-fast and low-power front-end amplifier/discriminator ASIC designed for the multigap resistive plate chamber*, Nucl. Instrum. Meth. A 533 (2004) 183;
M. Mota et al., *A flexible multi-channel high-resolution Time-to-Digital Converter ASIC*, IEEE Nucl. Sci. Conf. R. 2 (2000) 155.

[16] R. Gao et al., *Development of precision time-of-flight electronics for LHCb TORCH*, in proceedings of TWEPP 2013, Perugia, Italy, 23–27 September 2013.

[17] N. Harnew, *TORCH: A large-area detector for precision time-of-flight measurements*, presented at Fast Timing Workshop, Erice, Italy, 20–22 November 2013.