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TORCH: A large-area detector for precision time-of-flight measurements at LHCb

N. Harnew[1]

The University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, UK

Abstract

The TORCH (Time Of internally Reflected CHerenkov light) is an innovative high-precision time-of-flight detector which is suitable for large areas, up to tens of square metres, and is being developed for the upgraded LHCb experiment. The TORCH provides a time-of-flight measurement from the imaging of photons emitted in a 1 cm thick quartz radiator, based on the Cherenkov principle. The photons propagate by total internal reflection to the edge of the quartz plane and are then focused onto an array of Micro-Channel Plate (MCP) photon detectors at the periphery of the detector. The goal is to achieve a timing resolution of 15 ps per particle over a flight distance of 10 m. This will allow particle identification in the challenging momentum region up to 20 GeV/c. Commercial MCPs have been tested in the laboratory and demonstrate the required timing precision. An electronics readout system based on the NINO and HPTDC chipset is being developed to evaluate an 8×8 channel TORCH prototype. The simulated performance of the TORCH detector for LHCb is also presented.

Keywords: TORCH, Cherenkov, Time-of-flight, LHCb experiment, MCP

1. Introduction

The LHCb experiment [1] is a forward spectrometer, operating at the CERN *pp* Large Hadron Collider (LHC). LHCb is optimized for the study of heavy-flavour hadron production, for which the angular distribution of the produced hadrons is predominantly forward-backward peaked. The experiment will measure the CKM parameters of the Unitarity Triangle with high precision, and is designed to discover physics beyond the Standard Model. The spectrometer covers the rapidity range $1.9 < \eta < 4.9$, a region which is unique amongst the LHC experiments. Despite LHCb covering only ~4% of the solid angle, the experiment captures approximately 40% of the heavy-quark production cross-section.

Prior to 2017, LHCb will have collected an estimated $5\,\text{fb}^{-1}$ of integrated luminosity. The detector will be upgraded in 2018 to increase the data-set by an order of magnitude, up to $50\,\text{fb}^{-1}$ [2]. To achieve this, a major trigger improvement will be necessary to allow operation at a five-fold increase in luminosity. All

[1]On behalf of the LHCb RICH and TORCH collaborations
Email address: n.harnew1@physics.ox.ac.uk (N. Harnew)

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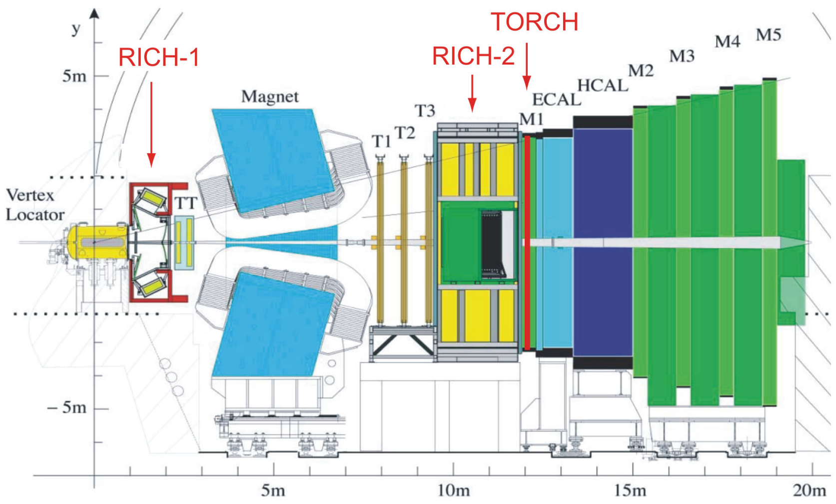

Fig. 1. The upgraded LHCb detector highlighting the locations of the RICH-1, RICH-2 and TORCH detectors.

electronics channels will be read out at 40 MHz to an off-detector first-level software trigger operating on a CPU farm.

A robust particle identification (PID) system is also a vital component of the upgraded LHCb detector. Several key physics channels which involve kaons rely on two Ring Imaging Cherenkov (RICH) detectors to reject copious backgrounds from multiple-track combinatorics and events with similar decay topologies. Especially important for the upgrade are the very rare decays $B_s \to \phi\phi$, $B_s \to \phi\gamma$, $B \to \phi K^0_S$, as well as the family of channels $B \to DK$. The PID is also crucial for the kaon tagging performance of the experiment, especially for momenta up to 10 GeV/c.

The key momentum range for PID is from p ~2 GeV/c up to ~100 GeV/c [3]. The upstream RICH-1 detector currently has aerogel and C_4F_{10} gas radiators, covering momenta from ~2 to 10 GeV/c and ~10 to 60 GeV/c, respectively. The downstream RICH-2 detector has a CF_4 gas radiator and covers up to ~100 GeV/c. The RICH system will be retained in the upgraded LHCb experiment but with the photon detectors replaced. However the aerogel is less effective at high luminosity due to its low photon yield (a mean of 5.5 photons per saturated track [1]) and, coupled with the increased background at high luminosity, would compromise the crucial low-momentum PID. In the upgraded detector, the aerogel will therefore be removed, and the PID system will be augmented by a novel detector based on time-of-flight to identify low momentum particles: the TORCH (Time Of internally Reflected CHerenkov light) [4]. Figure 1 shows a schematic of the upgraded PID system within the LHCb detector, highlighting the location of the TORCH and the RICH detectors.

The TORCH will cover the low momentum range below ~10 GeV/c (i.e. below the kaon threshold in the C_4F_{10} gas radiator). At this momentum the π/K time-of-flight difference over a 10 m flight path from the interaction region is 37 ps. Hence, three sigma π/K separation and positive proton separation up to 10 GeV/c requires a time-of-flight resolution of better than 15 ps per track.

The TORCH detector combines time-of-flight and RICH detection techniques. Cherenkov light is prompt, hence a 1 cm-thick plane of quartz is used as a source of simultaneously emitted photons to measure the time-of-flight of tracks. The photons propagate by total internal reflection to the edge of the quartz plane, in a manner similar to a DIRC detector [5]. The photons then traverse into a focusing element at the periphery of the detector and are reflected from a mirrored cylindrical surface onto an array of pixellated Micro-Channel Plate (MCP) photon detectors. This is illustrated in Fig. 2. The time-of-propagation of the photons in the quartz plate depends on the particle type that produces them, as different velocities give different Cherenkov angles and therefore different path lengths. The requirement to achieve a time resolution of 15 ps per track, together with the expected number of detected photons per track of around 30, dictates a

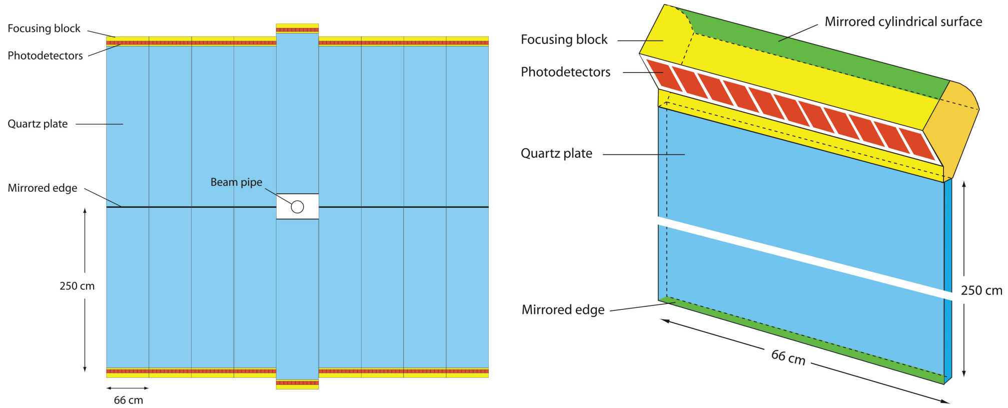

Fig. 2. Schematic layout of the TORCH detector, (Left) showing the front view of the 18 identical modules, and (Right) an isometric view of a single module.

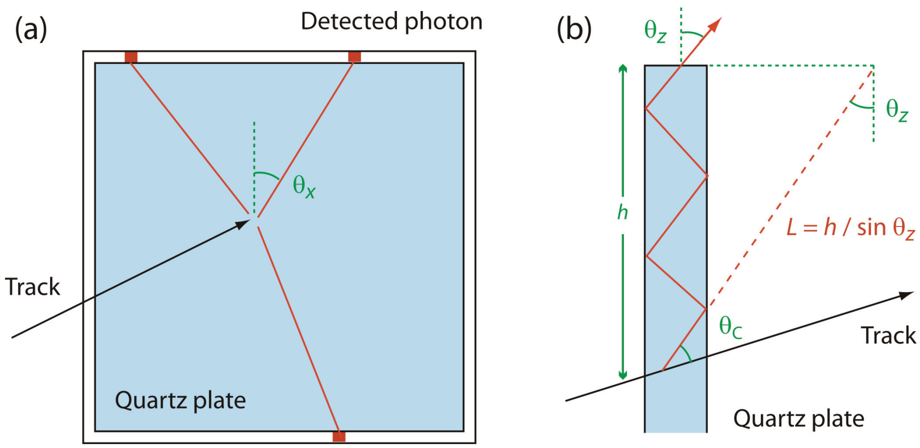

Fig. 3. Schematic to illustrate the reconstruction of photon trajectories (a) in the transverse (x, y) projection, where the filled squares indicate detected photon hits, (b) in the (y, z) projection.

70 ps resolution of the single photon time measurement.

Due to the chromatic dispersion of quartz, we must not only measure the time-of-flight, but also correct for the spread of photon speed due to the variation of refractive index with photon wavelength. This is achieved by accurately measuring the photon angle with the MCPs. When combined with the known track direction, the Cherenkov emission angle can then be determined. The wavelength of the photon is inferred from this information, allowing the dispersion to be corrected for. This concept is closely related to other ongoing R&D projects for future PID detectors, the TOP detector for Belle II [10, 7] and the endcap DIRC for PANDA [8], which similarly rely on the recent development of fast photodetectors. The distinction of the TORCH is time-of-flight rather than time-of-propagation, and the TORCH performance is optimized for higher momenta.

2. Detector operation and layout

A modular TORCH arrangement has been designed and is shown in Fig. 2. The method for reconstructing the photon paths is illustrated in Fig. 3. The angle of the photon within the plane of the quartz plate, θ_x, is determined from knowledge of the emission point on the track and the detection point at the photodetector, as in Fig. 3(a). The angle perpendicular to the plane, θ_z, shown in Fig. 3(b), is determined by focusing the photons onto the pixellated photodetectors using the optical element shown in Fig. 4 at the edge of the plate.

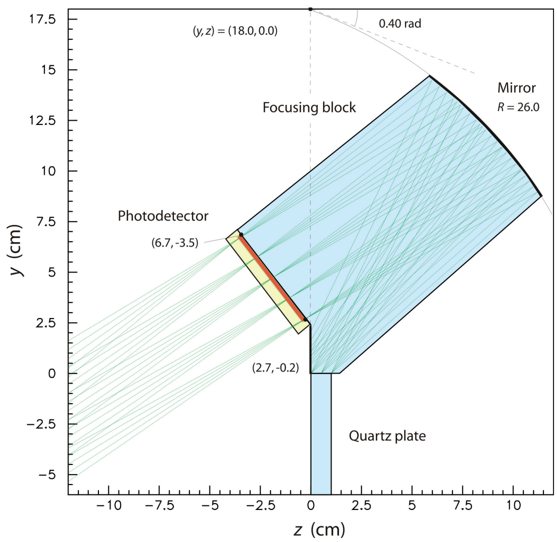

Fig. 4. Cross-section through the focusing element, attached to the edge of the quartz plate. The focusing of photons is indicated for five illustrative angles between 450 and 850 mrad, emerging at different points across the edge of the plate.

This method relies on the fact that the photon angle is unchanged as it reflects off the two faces of the quartz while travelling across the plane, via total internal reflection.

The arrival time and position of a photon on the photodetector plane is measured, the angle θ_z is then inferred, and the photon's trajectory is calculated assuming it was emitted by the track at the midpoint in z of its path through the quartz plate. Given measurements of the track path and momentum from the tracking system and knowledge of the optical properties of quartz, this is sufficient information to extract the mass from the time difference between the track leaving the primary vertex (PV) and the photon being detected. The production time of the particle (t_0) can be precisely determined from the combination of times measured by TORCH from the other particles produced at the same vertex in the interaction. Here we take advantage of the high pion multiplicity and use other tracks from the same event primary vertex to fix the relative timing.

Both angles θ_x and θ_z need to be determined with a precision of about 1 mrad in order to reconstruct the photon propagation time with a precision of about 50 ps. This angular precision can be easily achieved in θ_x with coarse pixellization of ~1 cm pitch, due to a long lever arm. In the other projection the pixel size needs to be finer by a factor of 10 or more. To develop the design of the detector we have taken the parameters of a commercially available MCP, as illustrated in Fig. 5, but adjusting the anode pixel size to suit our application. MCPs with a 10 μm pore size (i.e. the diameter of the microchannel) have been demonstrated to provide a resolution of 30 ps for single photons [9] and superior to the 25 μm pore size [10].

In practice, it is unrealistic to cover the whole plane with a single quartz plate so the TORCH has evolved to a modular layout, as was indicated in Fig. 2. The dimension of the quartz plane is ~5×6 m^2 (at z = 10 m). There are 18 identical modules, each $250 \times 66 \times 1$ cm^3, giving ~300 litres of quartz in total.

3. R&D on the photodetector and electronics readout

An MCP which is potentially suitable for the TORCH is the *Planacon* Burle-Photonis XP85022 [11], where a resolution of 34 ps has previously been achieved [12, 13]. This is a 59 mm square unit with ~80% active coverage. There are 32×32 pixels/unit, each 1.6 mm square in the commercial version. The channel gain uniformity is excellent ~1:1.5 and it is robust against magnetic fields (~1 T). Another great advantage of the MCP is that the anode pixel layout can in principle be designed to suit the application, but which will require collaboration with industry. The LHCb requirement for the granularity of the TORCH is 128×8, assuming the Planacon footprint. A pore size of 25 micron is currently commercially available, however

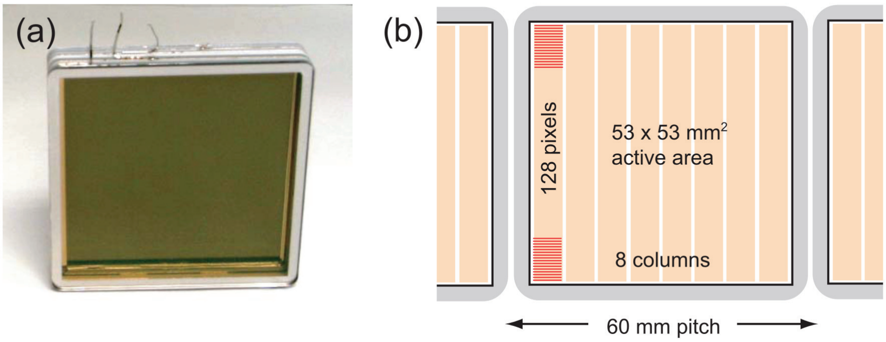

Fig. 5. (a) Photograph of the Planacon XP85022 MCP from Burle-Photonis, which has 32 × 32 square pixels. (b) Schematic of the photodetector layout for the TORCH, with Planacon-sized MCPs placed side-by-side and with fine pixellization in one direction and coarse in the other.

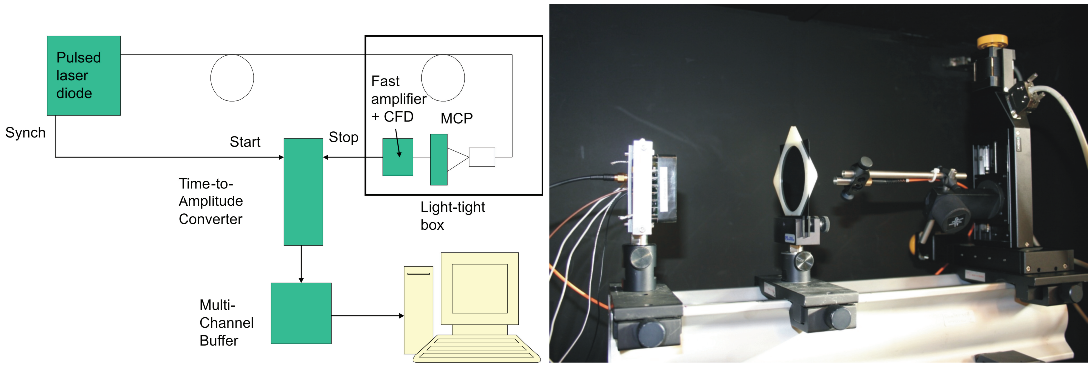

Fig. 6. (Left) A schematic the laboratory test set-up to study the timing properties of the XP85012-A1 MCP, (Right) a photograph of the laser and MCP.

evolving to 10 micron would improve the timing resolution and magnetic field response (although the latter property is not so important for the LHCb application). It is also essential to ensure good lifetime for the tubes, which has been an issue with MCPs in the past [14, 15]. The TORCH design has 18 identical modules with 11 Planacon-sized MCPs per module, giving a total of 198 MCP units and ~200k channels.

R&D is in progress to test the suitability of the MCP to meet the TORCH requirements [16]. A pair of 64-channel 8×8 Burle-Photonis XP85012-A1's (25 micron pore diameter) have been tested in the laboratory using commercially available single-channel electronics. The timing properties have been investigated with a pulsed blue (400 nm) laser with a ~20 ps intrinsic resolution, which has been set up to emit single photons. The laser and MCP are used to respectively start/stop a fast NIM-based time-to-amplitude converter. A schematic of the readout system is shown in Fig. 6 (left) and a photograph of the MCP/laser set-up is shown in Fig. 6 (right).

First results from the laboratory tests are shown in Fig. 7. A pulse-height spectrum from the MCP is displayed in Fig. 7 (left). Here the gain of the MCP is 5×10^5 with a mean number of photoelectrons of ~0.51. The spectrum is fitted with a distribution constructed from a linear sum of zero to five photons whose relative contributions are based on Poisson statistics, and incorporating Gaussian resolution functions for the photon peaks (with widths $\sigma_N = \sqrt{N}\sigma_1$ with $N = 1$ to 5) and pedestal. Fig. 7 (right) shows the measured MCP timing distribution, demonstrating an excellent resolution of 46 ps when fitted with a Gaussian function.

An MCP readout system is being developed based on the NINO and HPTDC chip-sets [17], which have been employed in the ALICE ToF system. These devices have been used to measure time-of-flights down to a resolution of 30 ps by independent researchers in space/medical applications [18]. Current NINO chips

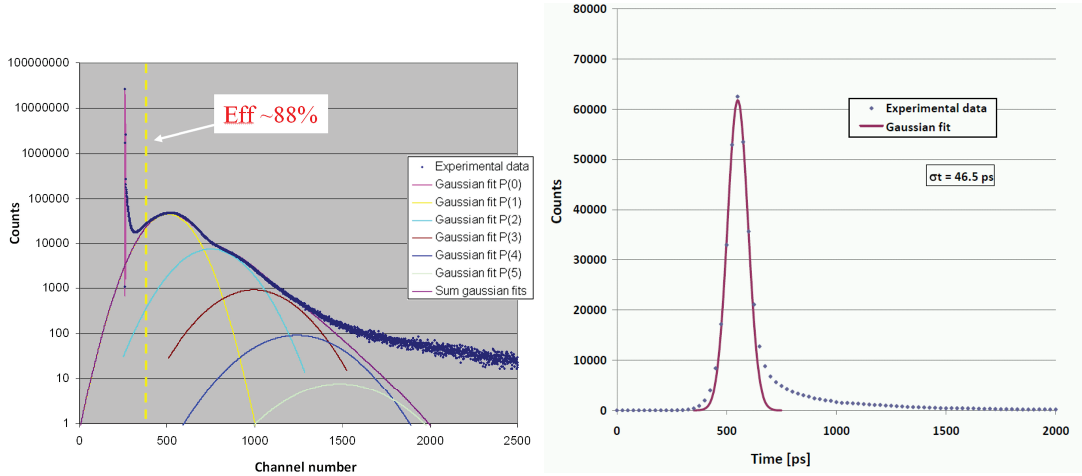

Fig. 7. (Left) The pulse height spectrum of the MCP, fitted with a sum of zero to five photons with relative contributions based on Poisson statistics. The single photon efficiency determined from the fit is 88%. (Right) The MCP timing distribution, demonstrating a 46 ps resolution when fitted with a simple Gaussian.

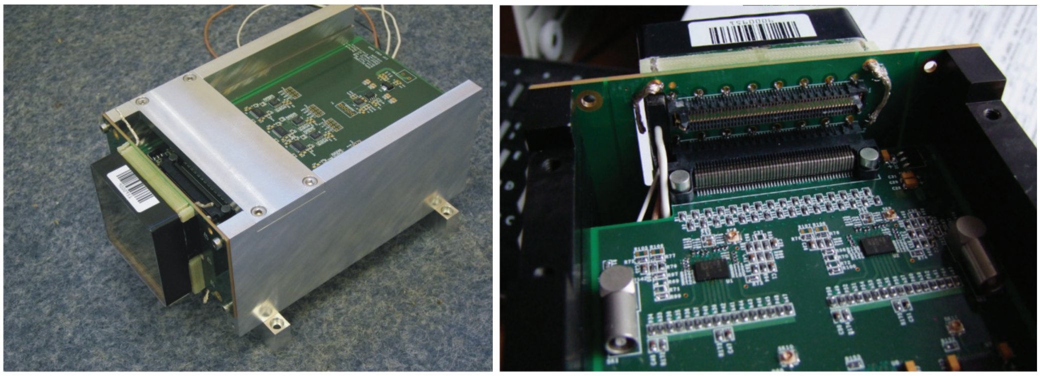

Fig. 8. (Left) A photograph of the NINO/HPTDC readout card coupled to 8×8 Burle-Photonis XP85012-A1, (Right) the readout board, showing the two NINO chips.

have eight channels, however 32-channel versions have also been fabricated, possibly progressing to 64 channels in the next iteration. To provide proof-of-principle verification of the MCP readout, a multi-layer PCB test board incorporating eight 8-channel NINO/HPTDC chips has been fabricated. This system will be used to read out the 8×8 Planacon in the laboratory and later in a CERN test-beam. A photograph of the readout card coupled to an MCP, together with a close-up of the NINO board, is shown in Fig. 8. Using test pulses, a jitter of 14-20 ps (channel dependent) has been measured in the laboratory. For the LHCb upgrade, a customized 1024-channel MCP would need to be equipped with sixteen 64-channel NINO chips.

4. Performance of the TORCH

Figure 9 (left) shows the performance of the different components of the LHCb PID system, as calculated for isolated tracks, in terms of the significance (in number of Gaussian sigmas) for K-π separation as a function of momentum. The assumed resolutions per photon and photon yields per track are (70 ps, 1.6 mrad, 0.7 mrad) and (30, 16, 12) for (TORCH, RICH-1, RICH-2), respectively. The TORCH calculation assumes a single plane of quartz covering the spectrometer acceptance. It is evident that excellent particle identification can be achieved with a combination of TORCH and RICH subdetectors over the full momentum range of interest. The actual performance will depend on backgrounds and the details of pattern recognition.

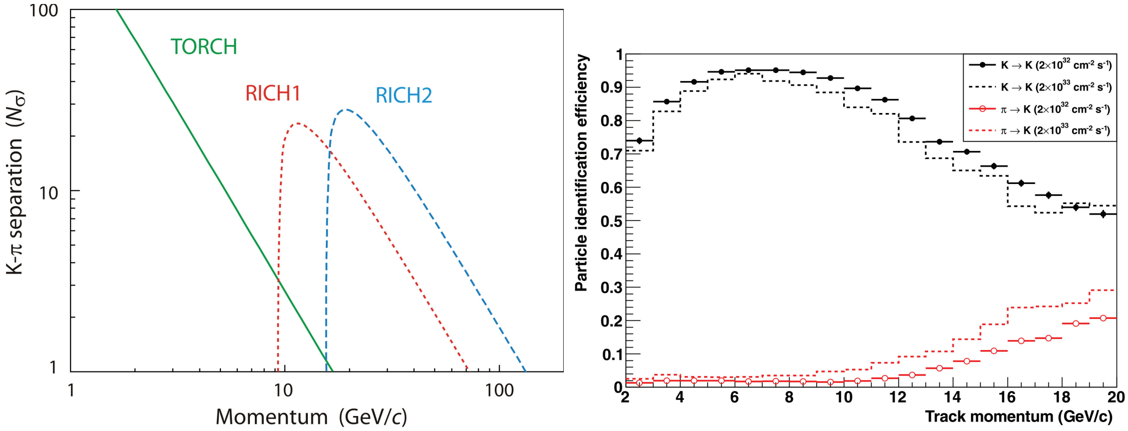

Fig. 9. (Left) Calculated performance (in sigma separation) of the components of the PID system versus momentum, for isolated tracks. (Right) Stand-alone TORCH identification efficiencies of well-measured charged tracks which are matched to a primary vertex. The plot shows the efficiency for a kaon track to be identified correctly (black) or incorrectly (red). The ID and misID efficiencies are also shown for two different luminosities, $2 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ (points) and $2 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$ (dotted lines).

The stand-alone PID performance of the TORCH has also been studied in a realistic LHC *pp* environment using tracks generated in a full simulation of the LHCb detector. Here the TORCH simulation has again assumed the simple conceptual design of a single plane of quartz with a small cut-out around the beam pipe. The total resolution of the photon propagation time includes contributions from the photon emission point, the finite MCP pixel size, and also from the intrinsic time resolution of the photodetector, assumed to be 40 ps. From these studies, it has been found that the intrinsic arrival time resolution per photon is 50 ps and, including the timing resolution of the MCP, gives a combined resolution of 70 ps per photon as required. For an average of ~30 photons per event, a 15 ps resolution per track is thus achieved.

The TORCH PID efficiencies and misidentification fractions for pions and kaons generated in the full simulation are shown in Fig. 9 (right). Excellent π-K separation is achieved up to 10 GeV/c and beyond, with some discriminating power up to 20 GeV/c. The figure also compares two luminosities: $2 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}$ (nominal LHCb) and $2 \times 10^{33}\text{cm}^{-2}\text{s}^{-1}$ (upgraded LHCb). It can be seen that the TORCH is robust to high luminosity running, up to twice that planned for the LHCb upgrade. Detailed simulation of the modular layout is now in progress.

5. Conclusions and future work

The TORCH is a novel detector concept proposed for the upgrade of the LHCb experiment. With a time-of-flight resolution of ~15 ps per track, excellent π/K separation can be achieved up to 10 GeV/c and beyond. R&D for the TORCH is in progress, currently focusing on the MCP photon detector and the readout electronics. The physics impact of the TORCH is under study using detailed simulation. A Letter of Intent for the LHCb upgrade has been submitted.

Future work involves R&D to achieve a suitable MCP anode pad structure that will be designed and developed with industry. The timing resolution, cross-talk properties and lifetime will be studied. The electronics readout will also be developed to run at a 40 MHz rate transmitted off-detector. The quartz thickness of the TORCH will be optimized, retaining good photon yield as well as mechanical stability. The focusing block will also be designed and prototyped. Following these developments, we plan to construct a complete TORCH module and study its performance in a test-beam. We are hopeful that this will be completed for the Technical Proposal of the LHCb upgrade, which is planned for submission in ~2 years time.

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