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TORCH — A CHERENKOV-BASED TIME-OF-FLIGHT DETECTOR*

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TORCH is an innovative high-precision time-of-flight system to provide particle identification in the difficult intermediate momentum region up to 10 GeV/c. It is also suitable for large-area applications. The detector provides a time-of-flight measurement from the imaging of Cherenkov photons emitted in a 1 cm thick quartz radiator. The photons propagate by total internal reflection to the edge of the quartz plate, where they are focused onto an array of photon detectors at the periphery. A time-of-flight resolution of about 10–15 ps per incident charged particle needs to be achieved for a three sigma kaon–pion separation up to 10 GeV/c momentum for the TORCH located 9.5 m from the interaction point. Given ~ 30 detected photons per incident charged particle, this requires measuring the time-of-arrival of individual photons to about 70 ps. This paper will describe the design of a TORCH prototype involving a number of ground-breaking and challenging techniques.

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1. Introduction

TORCH (Time Of internally Reflected CHerenkov light) has been proposed [1] for the LHCb upgrade to provide charged particle identification (PID) in the low momentum regime (up to 10 GeV/c). The TORCH detector will supplement the current PID system after removal of the aerogel in RICH-1, which currently performs this task [2]. Optimal kaon–pion separation in the low momentum region is important to LHCb physics for rare B hadronic decays and flavour tagging [2]. It is currently proposed to locate TORCH 9.5 m from the interaction point, in front of the RICH-2 detector. The LHCb upgrade is scheduled to be installed during the LHC Long Shutdown 2 (LS2) in 2018 although TORCH may come later.

2. Conceptual design of TORCH

In TORCH, the Time-of-Flight (TOF) of a traversing particle is measured by detecting the emitted Cherenkov light. The difference in TOF between kaons and pions of identical momentum p over distance z is given by

$$t_K - t_\pi = \frac{z}{c}\frac{1}{2p^2}\left(m_K^2 - m_\pi^2\right) \,. \tag{1}$$

Here t_K and t_π are the respective times of flight of a kaon (of mass m_K) and a pion (of mass m_π). The calculated TOF difference is shown in Fig. 1 for a 9.5 m flight path. For three sigma separation between kaons and pions, a per-

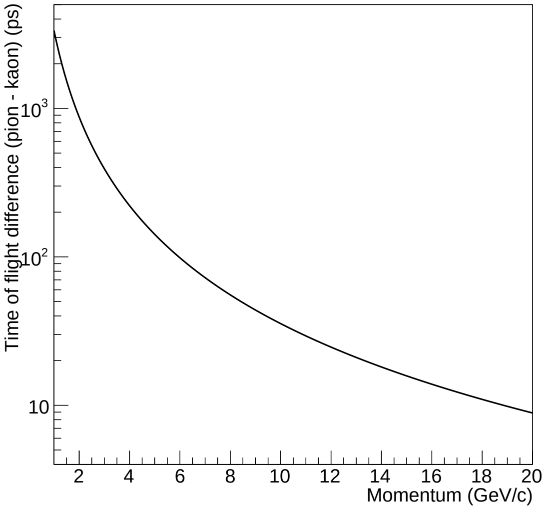

Fig. 1. Calculated time-of-flight difference between a pion and a kaon over 9.5 m.

track time resolution of 10–15 ps is thus required. To reach this resolution, a DIRC-style concept [3] has been proposed for TORCH, using a 1 cm thick plate of quartz (synthetic fused silica) as a Cherenkov radiator. The photons are propagated to the top and bottom edges of the plate by total internal reflection. A reflecting block then focuses these onto the detector plane.

The number of detected photons directly relates to the intrinsic time resolution of the detector. Given about 30 photons per track [4], and assuming standard $\sqrt{N}$ statistics, this leads to a required intrinsic time resolution for each photon of about 70 ps.

The choice of quartz as a medium for both the radiator plate and the focussing block is driven by the high photon yield ($n \approx 1.5$), its ability to hold a very high polish, and its radiation hardness. These factors are crucial in minimizing loss of photons that reach the detector plane. Further consideration is given to Rayleigh scattering, the reflectivity of the mirror surface in the focussing block and a spectral cutoff in the UV, typically around 150–200 nm [3]. The exact requirements on these factors are currently under study using GEANT4 [5] (see Fig. 2). The physical properties used in these studies originate in existing and proposed DIRC detectors, at BaBar [3] and PANDA [6]. The size of the radiator is dictated by the angular acceptance of LHCb, ±0.3 rad in the horizontal plane and ±0.25 rad in the vertical plane. At the proposed downstream location at 9.5 m this would lead to a rectangular quartz plate of 5 × 6 m.

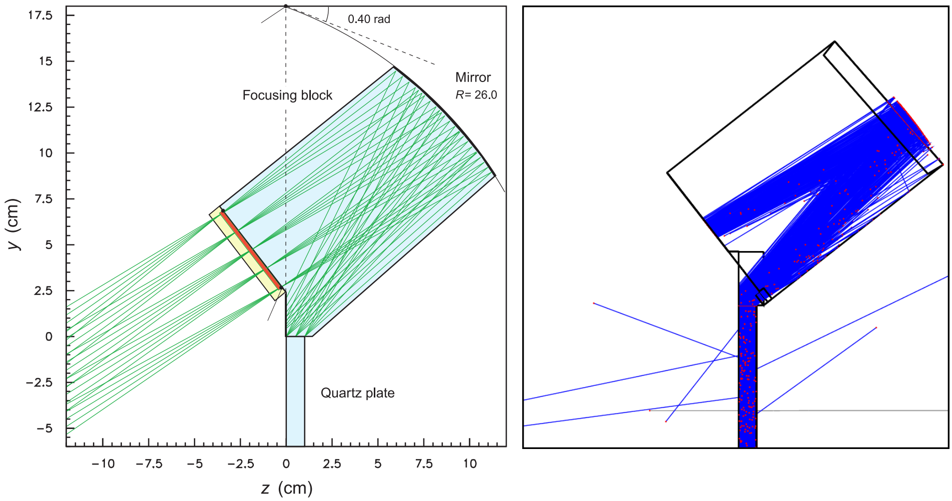

Fig. 2. (Left) Cross-section of the focussing block [4]. (Right) Reproduction of the focussing block with cylindrical mirror in GEANT4. Photon tracks outside of focussing block and radiator plate caused by diffuse reflection off rough surface and Rayleigh scattering.

Each detector will be a 59 × 59 mm micro-channel plate photomultiplier tube (MCP-PMT) with an active area of 53 × 53 mm. The layout of the detector plane is shown in Fig. 3.

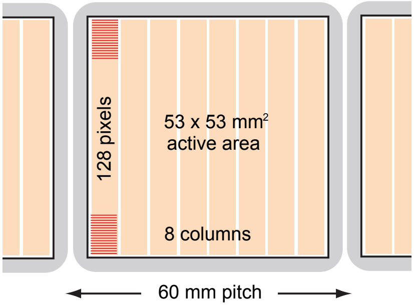

Fig. 3. Schematic of the layout of the photodetector plane for TORCH [1].

In order to measure the arrival time of photons that hit the detector plane, it is necessary to precisely calculate the path length travelled by the photons within the plate and focussing element. To achieve this, information from tracking is used to infer at which point and with which direction the particle traverses the plate. The added effect of angular straggling on the direction of the particle is actively being studied, and will be accounted for in future designs of TORCH.

Due to the focussing block, the vertical dimension at the detector plane is a direct measure for the angle of the photon path with the vertical axis (θ_z). Combining track information with the photon hit position then allows for precise calculation of the path length of the photon. The focussing block has been designed to accept θ_z angles between 0.45 and 0.85 rad. This optimizes the trade-off between total internal reflection, reflective losses and dispersion. With the detector plane divided vertically into 128 pixels this gives an expected resolution on θ_z of about 1 mrad. In the horizontal dimension, coarse pixelisation of the order of 6 mm (8 pixels per detector) is sufficient because there is no focussing and the photons are spread over a greater number of detectors. The error introduced in the calculation of the path length because of pixelisation results in an additional spread in the reconstructed propagation time of the photons. Initial studies show this effect to be ~ 55 ps [7].

3. Time-of-flight calculation

Calculating the TOF of each particle consists of two stages. First, each photon is timed individually. Using the time of propagation through the quartz of photons relative to each other allows for association of the photons with their parent particle. The position where the photon is detected combined with the projected hit position of the parent particle on the plate determines the direction of the photon at production. Combining this with the known trajectory of the parent particle allows the Cherenkov angle of the photon to be calculated. This information can then be used to correct for the effect of chromatic dispersion on the timing of the particle.

To calculate the time of flight, the start time must be calculated. This is done by assuming that particles originating from a single primary vertex are all pions. The few non-pion tracks give outliers in the histogram of the reconstructed start time t_0 for a primary vertex and can be rejected. The t_0 associated with all the particles originating from the same vertex can now be calculated, with an expected time spread of a few picoseconds [7]. The combined reconstructed time information of each single photon associated with a parent particle is combined into the time of arrival of the parent particle at the plate, and together with t_0 this yields the time of flight from the interaction point.

4. Photon detectors and electronics

A customised MCP-PMT that serves the requirements of the TORCH application is currently under development by the Photek company[1]. This three year development project aims to finish around the end of 2015 [8]. The programme will result in a 59×59 mm square MCP with an active area of 53×53 mm. The design is as outlined in Sec. 2 with 128×8 pixels, as shown in Fig. 3.

The expected lifetime of MCPs has been a concern and hence this aspect is an important part of the TORCH MCP-PMT development programme [9]. Recent developments using a special ALD-coating have extended the lifetime of the detectors [10]. Several long-lifetime tubes have been delivered as part of the TORCH programme and are currently undergoing extensive testing. For a single channel device, a time resolution of < 30 ps has been achieved [11].

The front-end electronics system that is planned for TORCH is currently under development [12]. The experimental readout is based on the NINO-8 chipset [13], which provides a time-over-threshold (TOT) measurement, in conjunction with a high precision time to digital converter (HPTDC) [14]. Using a commercially available 8×8 channel Planacon MCP (XP85012-A1[2]) with this setup, an overall time resolution of 90 ps is achieved [15]. It

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

[2] Photonis USA, XP85012 Planacon Photon Detector, Rev11-Jan2013. Available: `http://www.photonis.com/attachment.php?id_attachment=40`

is anticipated that TORCH will use a 32-channel version of the NINO. It is expected that further improvements in the readout system will bring the overall single photon time resolution down to the required 70 ps.

5. Modular design of TORCH

Covering the full area of TORCH (5 × 6 m) with a single plate of quartz is not feasible, so a modular design is proposed [1]. This would feature 18 modules of dimensions $66 \times 250 \times 1$ cm^3, so that a single module covers half the height of the TORCH detector. A conceptual drawing is shown in Fig. 4.

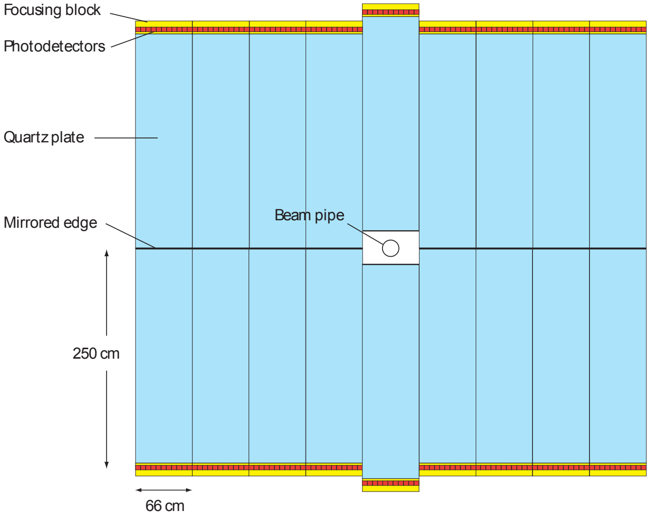

Fig. 4. Schematic layout of the TORCH detector, showing the front view of the 18 identical modules [1].

The mirrored edge in the middle of the detector and at the sides of each plate (see Fig. 4) will introduce ambiguities in the reconstruction. The edge of each module at the middle of the radiator plate separates the photons that are going upwards from the photons that are going downward. Reflections on the sides will fold up the curve that would otherwise emerge, as shown in Fig. 5.

One other possible implementation of a modular design that is currently under investigation comes with the possible availability of the quartz used in the former BaBar DIRC. Use of this quartz would circumvent part of the difficult procurement and polishing process at the cost of requiring an optical re-design of the current focussing block.

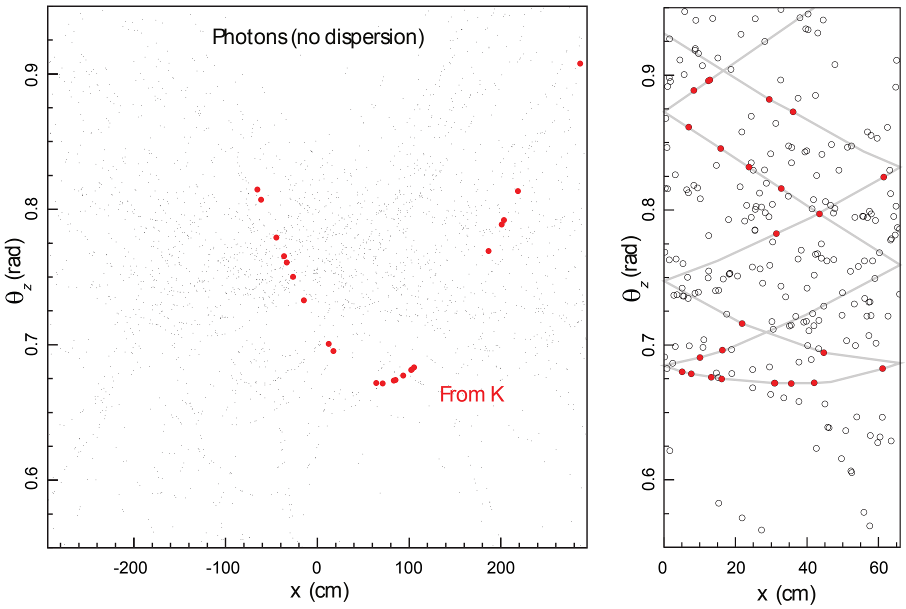

Fig. 5. Detector display for a single event. (Left) The photons originating from a single kaon have been highlighted in red for the single plate design. The remaining dots are for photons originating from other particles in the same event. (Right) The same photons for a single kaon have been highlighted (full circles), the remaining photons (open circles) represent photons from other particles, for a single module in the modular design.

6. Conclusion

The TORCH detector will provide charged particle identification in the <10 GeV$/c$ momentum range and is proposed as an upgrade to the LHCb experiment. The programme of R&D and simulation work will culminate in a prototype TORCH module to demonstrate the feasibility of the full-scale project. Based on initial measurements the aim of < 70 ps single photon resolution should be attainable. The lifetime issues with MCP detectors are being addressed. Planning and development for testbeam near the end of 2014 is ongoing.

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