

The TORCH time-of-flight detector for Upgrade II of the LHCb experiment

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Abstract

The TORCH (Time Of internally Reflected Cherenkov light) detector is proposed for the high-luminosity Upgrade II of the LHCb experiment. The aim of TORCH is to measure time-of-flight with a 15 ps resolution per charged-particle, providing particle identification over the momentum range 2–15 GeV/c. TORCH is to be located approximately 9.5 m downstream of the LHCb interaction point, and comprises 18 modules of highly-polished 1 cm-thick quartz plates, each of 250 × 66 cm². Cherenkov photons, radiated in the quartz, are focused onto an array of fast-timing micro-channel-plate detectors (MCP-PMTs) that each have a pixelation of 8 × 64 within an active area of 5.3 × 5.3 cm². Test-beam studies have previously shown that a timing resolution better than 100 ps per single photon can be achieved on a half-height module. Recent advances in the development of a 16 × 96 pixelated MCP-PMT are described. A full-height module is being developed with a light-weight carbon-fibre support structure. A novel exo-skeleton jiggling system is used to bond the optical elements and support each module during installation.

Keywords: Particle identification, Time-of-flight

1. Introduction

The TORCH detector is a large-area time-of-flight detector [1], which is proposed for inclusion in the phase II upgrade of the LHCb experiment [2]. The detector would be installed in 2033–2034 and is designed to operate at instantaneous luminosities of 1–1.5 × 10³⁴ cm⁻²s⁻¹ during the high luminosity era of the LHC (HL-LHC).

In the existing LHCb experiment pions, kaons and protons are separated using two gaseous ring-imaging Cherenkov

(RICH) detectors [3]. For momentum less than about 10 GeV/c, kaons and protons are both below threshold in the RICH radiators and it is only possible to separate light from heavy particles by operating the detectors in a veto mode. TORCH is designed to provide active separation between the different charged hadrons in this momentum range. TORCH is also able to separate lighter hadrons from deuteron and helium nuclei up to even larger momentum, and provides timing information that can more generally be used to improve event reconstruction.

The time-of-flight difference for different species of charge-hadron between the interaction region and the nominal position of the TORCH detector, positioned between the downstream tracking detectors and the RICH 2 detector (at 9.5 m from the interaction point), is shown in Fig. 1. To achieve good separation

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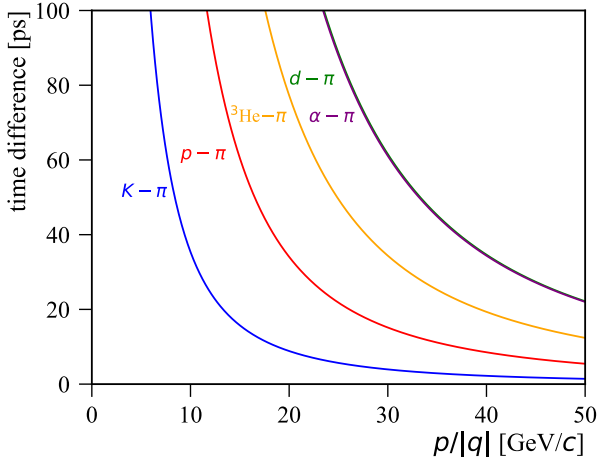


Figure 1: Time-of-flight difference between different charged particles and charged pions as a function of the ratio of the particle momentum to its charge. Deuteron and α particles are not separable using time-of-flight alone, but can be separated based on their photon yields.

25 rating power in the desired momentum range, particles must be
 26 timed to ~ 15 ps. The prompt production of Cherenkov photons in an array of quartz plates is used to provide a fast timing
 27 signal. The geometry of the proposed detector is illustrated
 28 in Fig. 2. The detector is arranged in 18 modules that each
 29 comprise a $250 \times 66 \times 1$ cm³ radiator. Cherenkov photons are
 30 propagated to the periphery of the module by total internal reflection,
 31 where they are focused by a cylindrical focusing block
 32 onto an array of fast-timing photon detectors. Photons with the
 33 same angle in the focusing plane are focused to a common point
 34 on the photon detector plane. It is necessary to reconstruct the
 35 photon emission time with a 70 ps precision to reach the desired
 36 resolution per charged particle, given ~ 30 photons are detected
 37 per track.

39 A half-height prototype of a TORCH module has previously
 40 been tested in a charged particle beam at the CERN PS [4].
 41 Results from this partial prototype are discussed below, along
 42 with plans to assemble a full-height prototype that can be used
 43 in beam tests next year.

44 2. Status of R&D

45 2.1. Cherenkov radiators

46 The half-height prototype uses a single piece of $125 \times 66 \times$
 47 1 cm³ synthetic fused silica as a radiator ($n = 1.49$ at 300 nm)
 48 and is equipped with a focusing block with a single cylindrical
 49 mirrored surface. The fused-silica pieces are produced by
 50 Nikon glass (Kanagawa, Japan) and have surface finishes that
 51 meet the TORCH requirements; the plate has surface thickness
 52 variations < 3 μ m and a surface roughness < 5 \AA . Two
 53 additional $62.5 \times 66 \times 1$ cm³ radiator pieces have recently been
 54 acquired to construct the full-height module. In the half-height
 55 prototype, the radiator is bonded with a PACTAN 8030 silicone
 56 adhesive to the focusing block [5]. In a full-scale module, the
 57 pieces are planned to be bonded with structural adhesive.

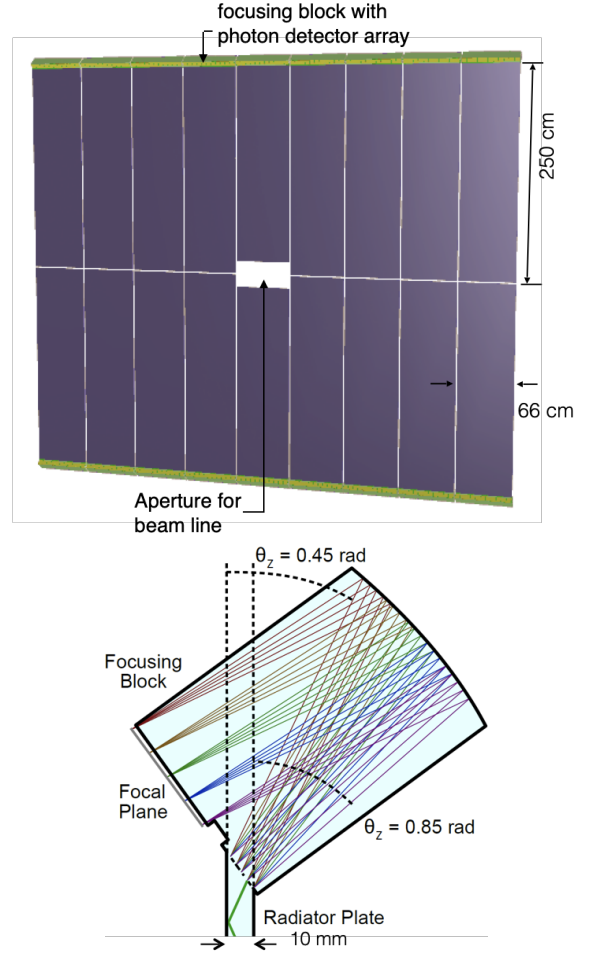


Figure 2: Torch detector geometry showing (top) the module arrangement and (bottom) the focusing block with its cylindrical mirror. The coloured paths indicate the path of photons with fixed angle from the radiator plate to the detector plane.

58 2.2. Mechanical design

59 For the full detector, it is essential to minimise the amount
 60 of material in front of the TORCH radiator and the downstream
 61 LHCb sub-detectors such that the material budget is dominated
 62 by the 8% X_0 of the 1 cm thickness of the quartz radiator. To
 63 achieve this, the mechanical support inside the detector accep-
 64 tance will be a light-weight carbon fibre structure. A prototype
 65 of this structure has been designed and is currently under con-
 66 struction. The prototype is designed to support a full-height
 67 $250 \times 66 \times 1$ cm³ radiator and to accommodate the existing read-
 68 out electronics, which are described below.

A CAD view of the carbon fibre support is shown in Fig. 3. Contact between the support structure and the fused-silica is kept minimal to avoid photon loss. Dedicated mechanics have also been developed for the gluing and jiggging of the radiator plates, along with an exo-skeleton to support the detector during handling.

For the final detector, it will be necessary to slim down the mechanical support structure to reduce the depth of the full assembly. Within the detector acceptance, it is hoped the extent

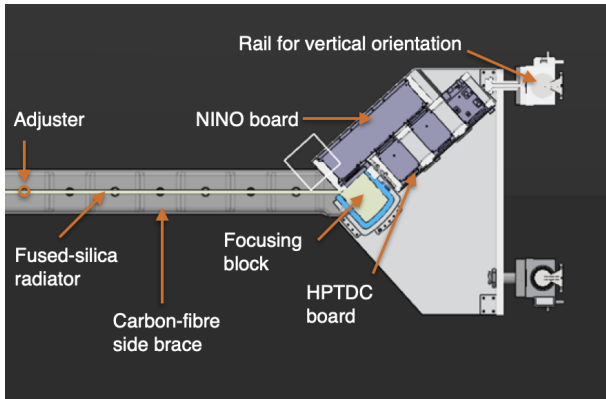


Figure 3: Design of light-weight carbon-fibre structure designed to support a $250 \times 66 \times 1 \text{ cm}^3$ fused-silica radiator and to accommodate the existing TORCH electronics.

of the detector can be limited to $< 10 \text{ cm}$. To facilitate a better packing of the detector and its electronics, the focusing block will be modified by introducing an additional plane mirror. This will allow the electronics to be stacked vertically and reduce the depth of the detector along the LHC beam line.

2.3. Photon detectors

The fast-timing photon detectors used in the existing TORCH prototype are custom microchannel-plate PMTs (MCP-PMTs) produced by Photek Ltd [6]. The MCP-PMTs have an active area of 5.3-by-5.3 cm and a 64×64 pad arrangement. The pads are electronically ganged to form a 8×64 pixel configuration. The anode of the MCP-PMT is capacitively coupled to the readout, which is mounted on an external PCB and connected via anisotropic conductive film. The MCP is treated via atomic layer deposition to achieve an extended lifetime of $> 5 \text{ Ccm}^{-2}$. Charge-sharing between neighbouring pads in the fine-pixel direction is used to achieve an effective 8×128 pixel resolution.

A new prototype MCP-PMT, with a 16×96 pixel configuration and a directly coupled anode, has been developed in order to reduce the charge sharing between pixels and the per-channel occupancy of the detector. The new MCP-PMT is currently under test at Photek. Further development will also be needed, in the context of DRD4 [7], to develop devices with improved rate capability and lifetime to cope with the high rates expected in the HL-LHC running conditions. Silicon photomultipliers (SiPMs) might provide an alternative solution in the highest occupancy region of the detectors. Given the expected neutron fluences it may be necessary to operate the SiPMs at cryogenic temperatures.

2.4. Front-end electronics

The existing TORCH prototype uses electronics based on the NINO [8] and HPTDC [9] ASICs. These are connected via a backplane to a readout card that transmits data off detector via gigabit ethernet. The electronics are described in more detail in Ref. [10].

The data packets from the HPTDC include the time-of-arrival and time-over-threshold of the signal. The latter is needed to

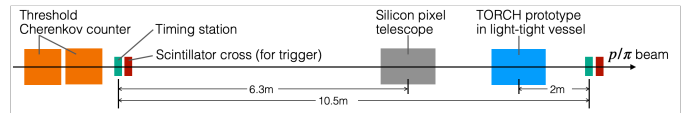


Figure 4: Layout of the TORCH beam test in the T9 area.

correct for sizable time-walk effects in the NINO. Offline, the data is also corrected for integral-non-linearity (INL) in the HPTDC. A dedicated calibration system has been developed to calibrate time-walk and INL for the 2022 test beam data.

For the final detector, the NINO and HPTDC will be replaced by the combined FastRICH ASIC that is described elsewhere in these proceedings. The FastRICH uses a constant-fraction-discriminator to account for time-walk effects, removing the need to transmit time-over-threshold information and reducing the bandwidth needed to transmit data off detector. The FastRICH also offers finer TDC binning of 25 ps compared to the 100 ps binning used in the HPTDC and lower overall power consumption. Data transmission off-detector will be via lpGBT/VTRX+ [11].

3. Detector performance

The performance of half-scale prototype has been studied extensively in beam tests at the CERN PS in 2018 and in 2022. In 2018, the prototype was equipped with two MCP-PMTs. In 2022, the number of MCP-PMTs was increased to six. The results of the 2018 beam test are described in Ref. [4]. The analysis of the 2022 data is ongoing.

The two beam tests were carried out in the PS T9 area using a mixed proton/pion beam with momenta ranging from 3 to 10 GeV/c, with the configuration shown in Fig. 4. The beam line was instrumented with: the prototype TORCH detector; a pair Cherenkov threshold counters, which could be used to separate protons from pions in the beam; a EUDET/AIDA silicon pixel telescope [12]; and a pair of timing stations. The timing stations comprise a borosilicate finger connected to a single-channel MCP-PMT that is used to provide a time stamp upstream and downstream of the prototype TORCH detector. They are equipped with crossed scintillators with an $0.8 \times 0.8 \text{ cm}^2$ active area that are used to provide a trigger to the detector readout via an AIDA trigger logic unit [13]. The time references from the timing stations are fanned out and injected into the HPTDC boards on eight channels per MCP-PMT. The TORCH prototype is mounted on a translation table to allow measurements to be taken with the beam incident on different parts of the radiator.

Figure 5 shows the pattern seen on the detector plane in the 2022 beam test when the beam entered the detector towards the centre of the quartz radiator. The Cherenkov emission, combined with the focusing optics, results in a band image that includes photons that directly reach the detector plane and cases where photons reflect from the sides or bottom of the radiator.

A GEANT4 simulation is used to compare the observed pattern to the expected arrival position/time of Cherenkov photons in the beam test data. The resulting resolution, as a function of

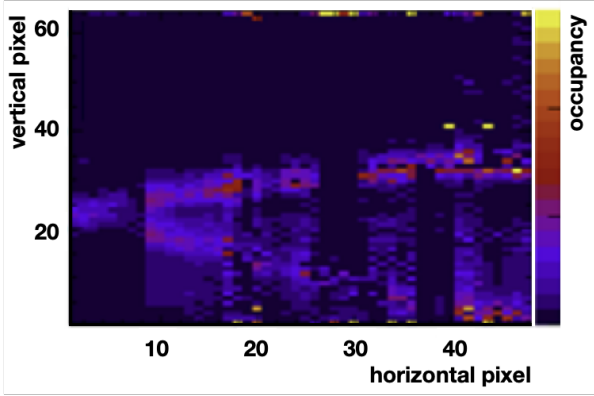


Figure 5: Pattern seen on the detector plane during the 2022 beam test when the beam is incident at the centre of the TORCH radiator.

the number of reflections undergone in the plate by the photons is shown in Fig. 6. The number of reflections is dominated by reflections from the front/rear faces of the radiator plate. The single photon resolution is expected to scale as

$$\sigma_{\text{total}}^2 = \sigma_{\text{const}}^2 + (\sigma_{\text{prop}} \cdot t_{\text{prop}})^2. \quad (1)$$

The constant term is due to the intrinsic resolution of the MCP-PMT and the electronics. Laboratory measurements of this resolution have been performed with a 405 nm picosecond pulsed laser. Selecting data with constant time-over-threshold yields a resolution of ~ 50 ps. The linear dependence on the photon propagation time, t_{prop} , arises due to chromatic dispersion. The size of σ_{prop} is determined by the finite pixel size, which is chosen to provide an approximately 1 mrad resolution on the Cherenkov angle. The resulting performance is close to the expected precision of the TORCH detector. For short propagation times, resolutions better than 100ps are achieved. The time resolution is expected to improve further with improved calibration of INL and time walk.

4. Summary

The TORCH detector is a precision time-of-flight detector that aims to improve the particle identification performance of the LHCb experiment as part of its phase II upgrade programme. Prompt timing is provided by Cherenkov emission in fused-silica radiator plates. A half-scale prototype has been constructed and used in beam tests at the CERN PS. Timing precision close to the TORCH requirements was obtained with the prototype. A full-height module is currently being constructed for use in beam tests next year. The full-height module will feature a light-weight holding structure designed to minimise the amount of material present in the final detector.

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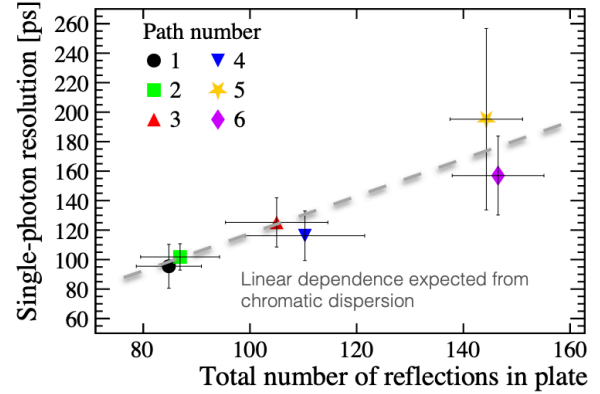


Figure 6: Time resolution as a function of the estimated number of reflections photons undergo in the fused-silica radiator. The markers correspond to a situation with: (one) a direct path between the emission point and detected position, (two) one reflection from the near side of the radiator plate, (three) on reflection from the far side of the plate, (four) two reflections from the sides of the plate, (five) one reflection from the bottom face of the plate and (six) one reflection from the bottom face and one reflection from a side face of the plate. Reproduced from Ref. [4].

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