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New developments from the TORCH R&D project

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ABSTRACT

TORCH is a large-area and high-precision time-of-flight detector, designed to provide charged particle identification over a 2–20 GeV/c momentum range. The TORCH detector comprises a 10 mm thick quartz radiator, instrumented with photon detectors, which precisely time and measure the arrival positions of the Cherenkov photons. The photon detectors are micro-channel plate photo-multiplier tubes (MCP-PMTs) comprising a finely segmented anode of 64×64 anode pads, electronically ganged into 64×8 pixels, over a $53 \times 53\,\mathrm{mm}^2$ area, an excellent intrinsic time resolution of ~ 30 ps, and a long lifetime of up to $\gtrsim 5\,\mathrm{C/cm}^2$. The current version of the MCP-PMTs used by TORCH have been developed with an industrial partner, Photek Ltd, to satisfy the stringent requirements of the detector. The TORCH R&D programme has successfully demonstrated the detector concept through extensive laboratory and beam tests. A TORCH prototype has been constructed and has yielded encouraging results when exposed to low momentum charged hadrons. Characteristic patterns of Cherenkov photons have been recorded, illustrating the required spatial accuracy and timing resolution of 70 ps per photon. Both laboratory and beam test results are approaching the design goals of the TORCH detector.

1. Introduction

TORCH (Time Of Internally Reflected CHerenkov light) is a proposed Time-Of-Flight (TOF) detector, designed to perform Particle IDentification (PID) of pions, kaons and protons in the 2–20 GeV/c momentum range. The detector exploits the prompt emission of Cherenkov radiation when charged hadrons traverse a quartz radiator. The Cherenkov photons are transported to the periphery of the radiator via total internal reflection, where they are reflected off a cylindrical mirrored surface and focused onto an array of fast-timing photon detectors. This is illustrated in Fig. 1.

The photon detectors measure the arrival time and position of the photons which can then be used to calculate the Cherenkov angle and photon path length. The Cherenkov angle is used to correct for chromatic dispersion effects in the quartz radiator. The time of entry of the hadron in the quartz can be determined by adding information from a tracking system. Using the arrival time on the photon detector plane and the path length from the photon detectors, the time of propagation and the TOF of the hadron can be inferred [1]. The full detector would comprise a number of modules (18 for LHCb) and is now included in the Upgrade II plans for the LHCb experiment [2].

Over the ~ 9.5 m flight path proposed for the TORCH, the difference in the ToF of kaons and pions at a momentum of 10 GeV/c is ~ 35 ps. To gain a statistical significance of 3 standard deviations (3σ) between pions and kaons, a per-track timing resolution of 10–15 ps is required. Given that TORCH expects to detect on average about 30 photons per charged particle track, to achieve this separation, a timing resolution of 70 ps per photon is required. There are two major contributors to the single photon time resolution: the intrinsic time resolution of photon detectors and the readout electronics; and the resolution on the photon path and photon energy reconstruction. With each of these contributions being ~ 50 ps, the required photon resolution of 70 ps can be achieved.

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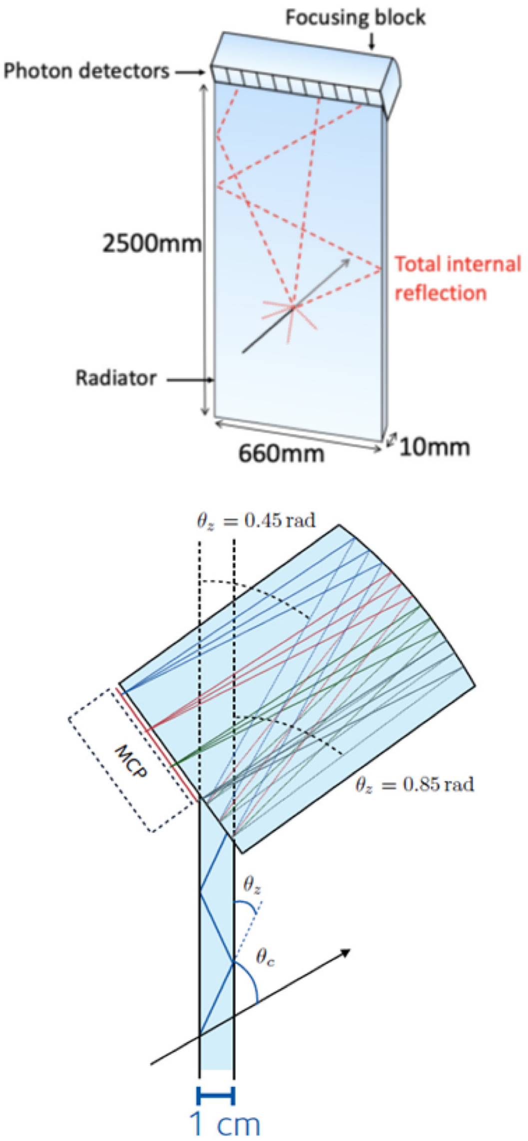

Fig. 1. Layout of one TORCH module from the (top) front and from the (bottom) side. Each image shows how a Cherenkov photon, when emitted by a charged hadron in the quartz radiator, may propagate to the periphery of the detector via total internal reflection. The side view then illustrates how Cherenkov photons will be focused onto an array photon detectors by a cylindrical mirror at the very edge of the focusing block. A cylindrical mirror ensures that different wavelengths of light are focused onto different positions on the detector (MCP) plane.

The TORCH detector and its components have been tested both in laboratory and test beam scenarios. A TORCH prototype, proto-TORCH, has shown results for the timing resolution that approaches the design goal for a full implementation of the TORCH detector [3]. Complementary lab tests were also undertaken, with the aim of measuring the gain, quantum efficiency and timing resolution of the TORCH MCP-PMTs when coupled to a readout electronics chain. The TORCH photon detectors and TORCH electronics are discussed in Sections 2 and 3 respectively. Laboratory setup and results are then reported in Section 4, with the proto-TORCH test beam outlined in Section 5.

2. TORCH photon detectors

TORCH uses multi-anode micro-channel-plate photo-multiplier-tubes (MCP-PMTs) for fast timing of single photons. The MCP-PMT prototypes have been developed with an industrial partner, Photek (UK). The MCP-PMTs are square tubes with a 53 × 53 mm^2 active area in a 60 × 60 mm^2 casing. The square shape and dimensions are chosen to optimise the photon coverage of the MCP-PMTs. The MCP-PMTs contain a finely segmented anode to provide a granularity of 64 × 64 anode pads, with the pads being electronically ganged together in the non-focusing (horizontal) direction. Charge sharing is then exploited in the focusing (vertical) direction to obtain the effective 128 × 8 pixel granularity required for TORCH [4]. In LHCb, the photon detectors will be subject to single photon event rates of $> 10\,\text{MHz/cm}^2$ and an accumulated charge of $> 5\,\text{C/cm}^2$. To meet these requirements, the MCP-PMTs are coated with a layer of material with enhanced secondary electron emission in a method known as Atomic Layer Deposition (ALD). The use of ALD has been shown to extend the lifetime of MCPs beyond the required $> 5\,\text{C/cm}^2$ for TORCH [5]. To connect the MCP-PMT anode to the external TORCH electronics, an anisotropic conductive film coupling is used.

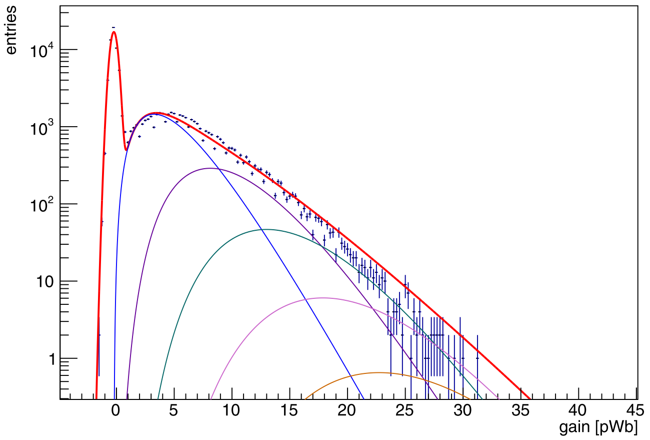

Fig. 2. Charge measured on a pixel. The data are fitted with a model comprising a pedestal and contributions from one or more photons, represented by the coloured lines. Single photon contributions are modelled with a polya function.

3. TORCH readout electronics

TORCH makes use of custom readout electronics [6] based on the NINO [7] and High Performance TDC (HPTDC) [8] application-specific integrated circuits (ASICs), originally designed for the ALICE ToF detector [9]. As a single-photon is incident on the MCP, the resulting photoelectron is converted into an analogue charge signal, which can be shared across a cluster of pixels due to charge spread. The signal is passed to the NINO where it is amplified and discriminated according to a programmable threshold. The signal output from the NINO is then passed to the HPTDC, which can be operated either in high resolution mode (100 ps time bins) or very high resolution mode (25 ps time bins). The TDC time stamps the leading and trailing edges of the signal to obtain a time over threshold. The time over threshold gives an estimate of the charge deposited in each pixel and is input to a clustering algorithm.

4. Characterisation of TORCH MCP-PMTs in the lab

A lab test-stand at CERN was used to measure the time resolution of the MCP-PMT and TORCH readout electronics, gain and Quantum Efficiency (QE) across the MCP-PMT. To estimate photo-electron gain in a MCP-PMT, a collimated pulsed laser (with a wavelength of 400 nm and a time FWHM of 20 ps) with a light spot size of $\sim 20\ \mu\text{m}$ is used to illuminate a spot on the MCP-PMT pixel array. While the light spot size is much smaller than the size of a single pixel ($0.8 \times 6.4\,\text{mm}^2$), the electron charge image spreads out to neighbouring pixels, due to

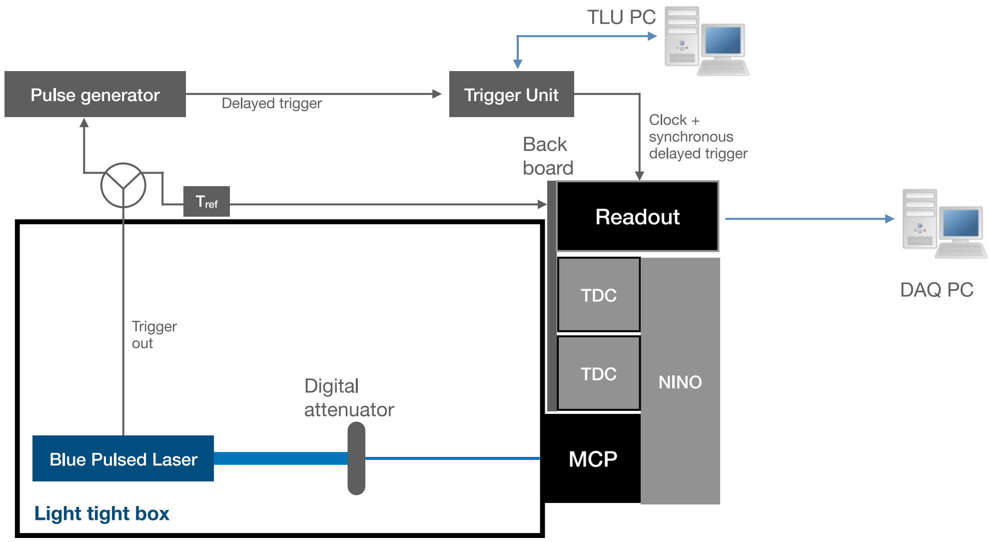

Fig. 3. Test setup at CERN measurements of the intrinsic MCP-PMT + readout electronics time resolution. Blue light from the laser is pulsed through a mono-mode optical fibre cable into a light tight box where it passes through a digital attenuator before it is incident on the MCP-PMT.

the capacitive coupling of the anode. An analogue breakout board is attached to these four pixels on the MCP, corresponding to the position of the laser light spot, and an oscilloscope is used to read the charge deposited on the pixels. The distribution of the charge deposited on each pixel is then fitted with a Gaussian distribution on the pedestal peak and a polya function convoluted with a Poisson distribution, to model the contribution to the deposited charge from one or more photoelectrons [10]. This is shown for one pixel position on the MCP in Fig. 2. The gain was measured under different conditions and positions on each MCP. This was done to facilitate studies of time resolution at different operation gains of the MCP-PMT.

To determine the time resolution, light from the pulsed laser diode is propagated through a mono-mode optical fibre cable into a light tight box. The light then passes through a digital attenuator before it is incident on the MCP-PMT. The MCP-PMT is then attached to the readout electronics, with an AIDA Trigger Logic Unit used for trigger synchronisation with other devices. The setup used to measure the time resolution is shown in Fig. 3. The HPTDC was operated in high and very high resolution mode with the MCP-PMT operated at a gain of 10^6, determined via the method described above. The integrated non-linear (INL) response of the HPTDC was corrected using a large number of events collected with a diffuse light source. Events triggered with constant time-over-threshold values are assumed to have constant amplitude to first order, and were selected to eliminate effects of a time-walk on the NINO chips. The effect of the time-walk can also be corrected for using time over threshold information (which is correlated to the charge deposited in a pixel). The leading edge of a distribution of signal lead time, corrected for INL, is fitted with a Gaussian distribution to estimate the time resolution contribution of the MCP-PMT and readout electronics. The trailing edge of the distribution is omitted from the fit as it is heavily affected by electron back-scattering from the MCP-PMT faceplate and the relaxation pulse of the laser. Example fits are shown in Fig. 4. The fits give a standard deviation (time resolution) of 90.0 ± 3.0 (47.5 ± 0.7), with the HPTDC run in high (very high) resolution mode. The latter result is within the requirement of TORCH. The next generation of TDCs are expected to have even finer time bins of $\sim 10\,\text{ps}$ [11].

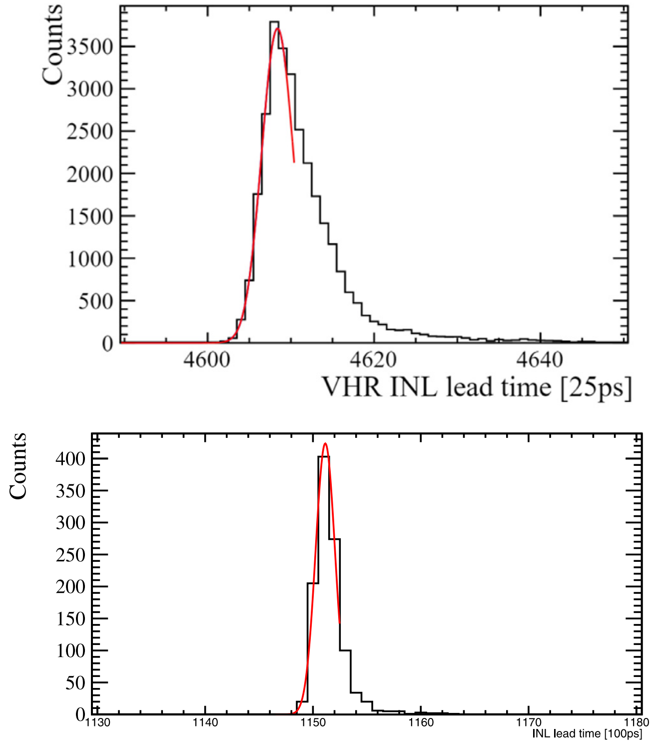

Fig. 4. Leading edge distribution of constant time-over-threshold signals from the TORCH readout chain for (top) very high and (bottom) high resolution mode of the HPTDC. The left-hand side of the distribution is fitted with a Gaussian function. The right-hand side of the distribution contains contributions from electron back-scattering and a relaxation pulses of the laser.

The QE of the MCP-PMTs is measured in the wavelength range 200–800 nm in steps of 20 nm using a xenon lamp and a monochromator with a calibrated PIN photodiode as a reference. Light from the xenon lamp is collimated to a spot of 6 mm in diameter, at several positions across the MCP-PMTs to check for uniformity. Measurements from the photodiode are used to account for variations in the intensity of the light source at different wavelengths. Measurements showed approximately 15%–20% peak QE across all TORCH MCP-PMTs. As example, the measured QE of one MCP-PMT is shown in Fig. 5.

5. Beam test results

In November 2018, a test beam campaign was conducted to evaluate the proto-TORCH module, which is a half height, full width version

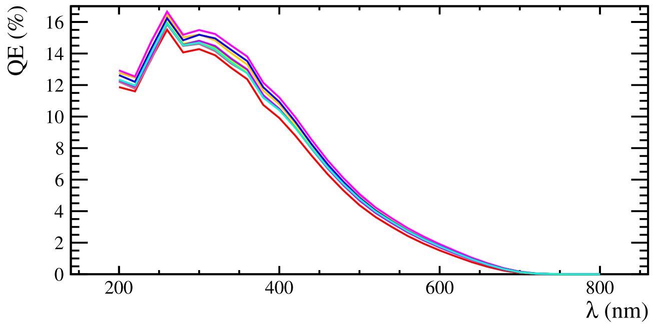

Fig. 5. Measurements of the MCP-PMT quantum efficiency at different wavelengths of light. Coloured lines represent different QE measurements at different positions on the MCP-PMT anode.

of a module designed for the LHCb experiment. It was instrumented with two MCP-PMTs, later referred to as Tube A and Tube B. The beam-test took place at the CERN PS East Hall T9 facility and made use of an 8 GeV/c mixed beam of pions and protons. One of the aims was to measure the single-photon time resolution of proto-TORCH. The test beam setup made use of two CO_2 threshold Cherenkov counters, two timing stations and a EUDET [12] pixel telescope to define beam. The timing stations use borosilicate fingers that radiate Cherenkov photons which are detected by single-channel MCP-PMTs. The two timing stations are placed 11 m apart with one placed 10 m upstream and one placed 1 m downstream (following beam direction) of proto-TORCH. The Cherenkov counters are used to provide independent PID of particles in the beam. Measurements of single-photon time resolution were taken whilst varying the beam's entry point on the proto-TORCH quartz radiator. Positions labelled by 1, 3, 4 and 5 are 5 mm away from the edge of the quartz plate and correspond to a distance of 175 mm, 489 mm, 802 mm and 1115 mm from the top of the quartz radiator, respectively. Position 2 is 60 mm across and 175 mm from the top of the radiator, while position 6 is half-way across and 1115 mm away from the top of the quartz radiator.

The TORCH image forms a hyperbola-like pattern on the detector plane that is folded on itself by reflections off the sides of the detector. Different photon paths can arrive at the same horizontal pixel coordinate but will be separated in time and vertical pixel position. This is shown in Fig. 6(a) where bands of photons with different paths can be seen on a column of pixels for a single horizontal pixel position on Tube B. The different paths are illustrated in Fig. 6(b) and correspond to the bands in Fig. 6(a). The single-photon time resolution can then be measured by determining the width of these bands. For one order reflection, the distribution of photon arrival time in a vertical pixel is fitted with a Crystal Ball model to determine the resolution, $\sigma^2_{\text{measured}}$. The full TORCH resolution can be determined as:

$$\sigma^2_{\text{TORCH}} = \sigma^2_{\text{measured}} - \sigma^2_{\text{ref.}} - \sigma^2_{\text{beam}},$$

where the measured resolution from the fit is corrected for the resolution of the timing stations, $\sigma^2_{\text{ref.}}$, and the resolution due to the finite beam size, σ^2_{beam}. The time resolution for different positions of the beam incident on the quartz radiator is shown in Fig. 7. The time resolution is larger at beam positions further away from the photon-detector plane due to the effect of chromatic dispersion. The single-photon time resolution approaches the 70 ps goal for TORCH at beam positions close to the photon-detector plane.

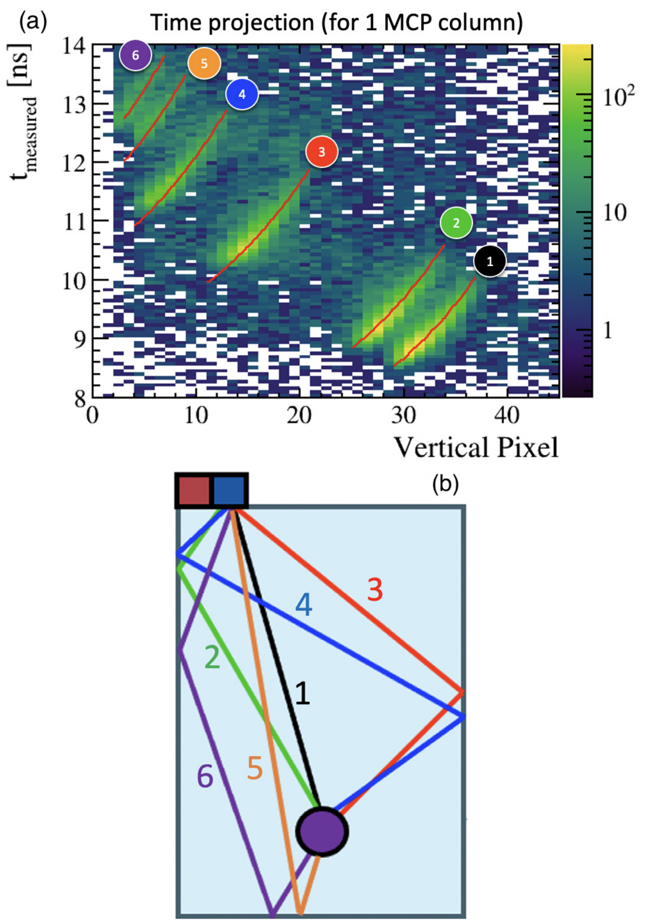

Fig. 6. (a) Photon arrival time on a single horizontal pixel as a function of a pixel in one column. Red lines over the bands show the expected position of the band from simulation. The width of the band can be measured to determine the single-photon time resolution. (b) Six possible paths a photon can take in the radiator, corresponding to the bands shown in (a).

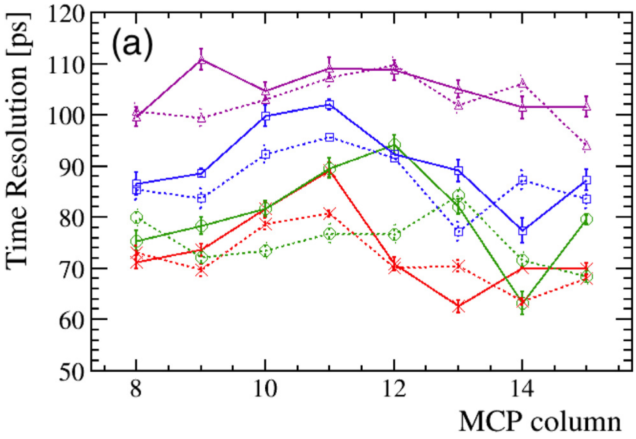

Fig. 7. Single-photon time resolution as a function of the column number on the Tube B pixel array. Solid line represents measurements for pions and dashed line represents measurements for protons. Different coloured lines correspond to different beam entry positions, noted in text as: 1 (red ×), 3 (green ∘), 4 (blue □) and 5 (purple △).

6. Conclusions

The TORCH is a proposed TOF detector developed to provide charged-particle identification, in the LHCb detector, for momentum between 2 and 20 GeV/c. Studies were conducted in the lab to measure the components of the single-photon time resolution. The measured time resolution in the high and very high resolution modes of the HPTDC were 90.0 ± 3.0 and 47.5 ± 0.7 ps respectively, which shows that the TORCH design goals are achievable. Studies were also undertaken with the use of a TORCH prototype, proto-TORCH, in a beam test in 2018 using the CERN PS. The beam test showed that the single-photon time resolution approaches the desired 70 ps and backs up the results taken from the lab tests. Together, the laboratory studies and the 2018 proto-TORCH beam test demonstrate performance that is rapidly approaching TORCH design goal and this is expected to improve with better calibration of the readout electronics. A future beam-test is planned in late 2022, aiming to use a fully instrumented TORCH prototype module.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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