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A precision time of flight readout system for the TORCH prototype detector

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Abstract: The TORCH detector provides low-momentum particle identification, combining Time of Flight (TOF) and Cherenkov techniques to achieve charged particle pi/K/p separation between 2–20 GeV/c over a flight distance of 10 m. The measurement requires a timing resolution of 70 ps for single Cherenkov photons. For precision photon detection, customised Micro-Channel Plate Photomultiplier Tubes (MCP-PMTs) with high precision TOF measurement electronics have been developed. The electronics measures time-over-threshold from the MCP-PMT and features a 10-Gigabit Ethernet readout. This paper reports the design and performance of a 5120-channel system which currently instruments a pair of MCP-PMTs, but has the capacity to read out ten customised MCP-PMT devices in the future.

Keywords: Cherenkov detectors; Electronic detector readout concepts (solid-state); Front-end electronics for detector readout; Timing detectors

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2022 JINST 17 C05015

Contents

1 Introduction **1**

2 Electronics development **2**
- 2.1 Proto-TORCH 2
- 2.2 Dataflow 2
- 2.3 Electronics design 3

3 Test-beam **4**

4 The development of a 10 Gbps readout scheme **5**

5 Future work **5**

1 Introduction

The Time Of internally Reflected CHerenkov light (TORCH) detector [1] is being developed to identify B-meson decay products for the Upgrade II of the LHCb experiment [2], and has wider applications in future particle physics experiments. The TORCH detector measures Time-Of-Flight (TOF) using the Cherenkov technique to achieve positive π/K/p separation up to 10 GeV/c over a flight path of approximately 10 m from the interaction region. In LHCb, Cherenkov photons are generated when a charged particle traverses a 10 mm-thick quartz plate of overall dimension $5 \times 6\,\mathrm{m}^2$, segmented into 18 individual modules, as shown in figure 1. The photons propagate by total internal reflection to the periphery of the plate, where they are focused onto an array of Micro Channel Plate (MCP) photomultiplier detectors. The MCPs measure the position and time of arrival of the photons. In order to achieve the required π/K separation, the measurement requires a timing resolution of 70 ps per single Cherenkov photon.

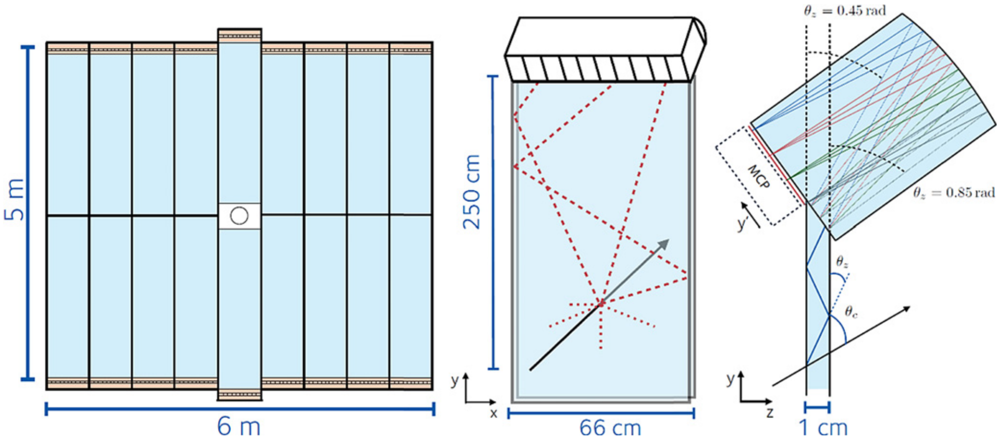

Figure 1. (Left) The proposed TORCH detector for LHCb Upgrade II with 18 modules, (centre) a module with focusing block and MCP at the periphery of the plate, (right) a side-view of the plate, focusing block and MCP.

2022 JINST 17 C05015

2 Electronics development

2.1 Proto-TORCH

In order to demonstrate the performance of TORCH detector, a prototype named "Proto-TORCH" has been developed with a 66 cm × 125 cm quartz plate and a focusing block. The optics has been installed in a mechanical structure incorporating a cooling system, as shown in figure 2. The prototype is designed to accommodate up to 10 MCP-PMT photon detectors with 5120 channels in total, although only two MCPs are currently instrumented. The customised MCP-PMT [3] has a $53 \times 53\,\text{mm}^2$ active area within a $60 \times 60\,\text{mm}^2$ physical dimension, providing a 64×64 channel physical granularity. The channels are externally connected together in groups of eight in the non-focussing coordinate and a charge-sharing technique between pairs of adjacent channels is adopted in the focussing coordinate in order to achieve the 8×128 granularity requirement for the angular precision [1]. The MCPs and the electronics described in this paper are located in the top compartment of the Proto-TORCH, as indicated in figure 2.

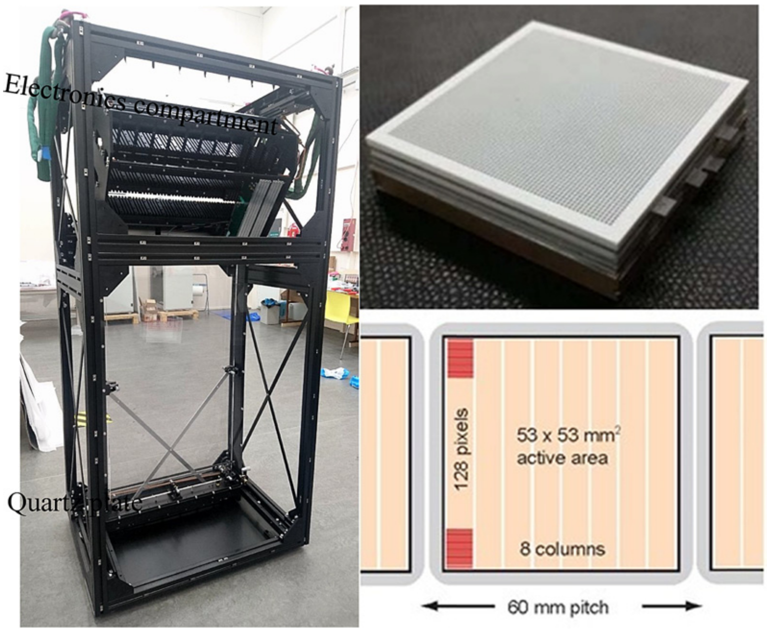

Figure 2. (Left) Proto-TORCH with a quartz plate, focusing block and two electronics modules located at the top. (Top-right) Photograph of the custom TORCH MCP, showing the back-side with 64 × 64 output pads (bottom-right) diagram of the TORCH MCP dimensions showing the effective granularity.

2.2 Dataflow

Figure 3 shows the dataflow of the electronics system. The input signals are first amplified and measured for Time-Over-Threshold (TOT) in NINO [4] ASICs located on the *NINO board*. The measurement results are then digitised in High Performance Time to Digital Convertor (HPTDC)

2022 JINST 17 C05015

ASICs [5] on the *HPTDC board* for both arrival time and TOT, the latter giving a pulse width for time-walk corrections, used in offline processing to improve the timing resolution. A *readout board* collects digitised data from four HPTDC boards and formats them into Ethernet packets to be sent to a DAQ PC. The readout board also decodes configure-and-control commands from the DAQ PC and forwards them to the corresponding NINO and HPTDC boards. The readout board uses Ethernet MAC protocol for simple and efficient data transmission.

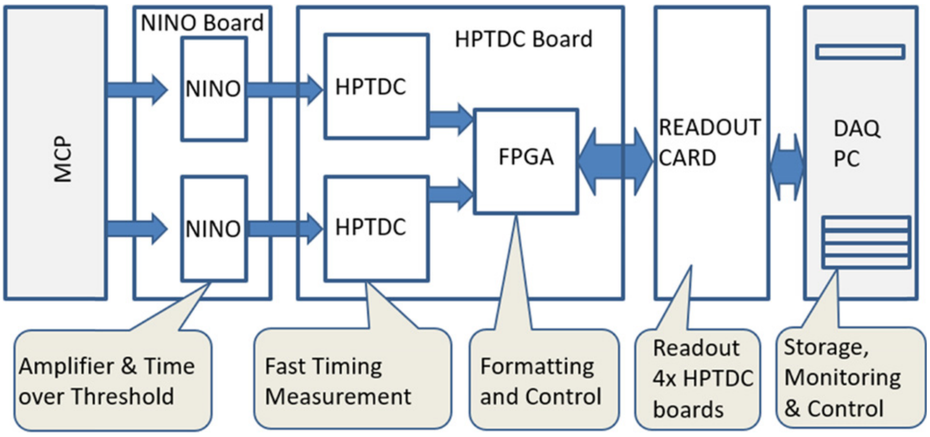

Figure 3. Dataflow diagram: signals are processed through NINO and HPTDC chips, then transmitted to a DAQ PC beyond the readout board.

2.3 Electronics design

A modular electronics system providing up to 256 channels per system in a 4-board × 64-channel arrangement has been reported previously [6]. The more recent MCP-PMT detector has an 8 × 64 layout, hence the electronics system has been scaled up, and also fits the new mechanical and optical footprint of Proto-TORCH. Figure 4 shows a photograph of the scaled-up system. As indicated in the photograph, the MCP-PMT is connected to a NINO board through one of the four connectors mounted on its side. A single NINO board consists of four 32-channel chips, in total 128 channels, and the board is connected to two 64-channel HPTDC boards. Typically, four HPTDC boards are connected to a single readout board through a backplane.

Several challenges were faced in designing the NINO and HPTDC boards. Firstly, the mechanical layout requires long signal tracks on the NINO board, which is prone to noise pick-up. Therefore, the length of the analogue PCB traces carrying the signal between MCP and NINO are kept to their minimum length. After the TOT conversion in the NINO chip, the signals are in LVDS form, which are significantly less sensitive to common-mode noise. An analogue ground plane is located under the analogue-signal traces providing shielding and a return current path in order to reduce noise pickup and emission. Secondly, in order to characterise the variation of channel-to-channel

2022 JINST 17 C05015

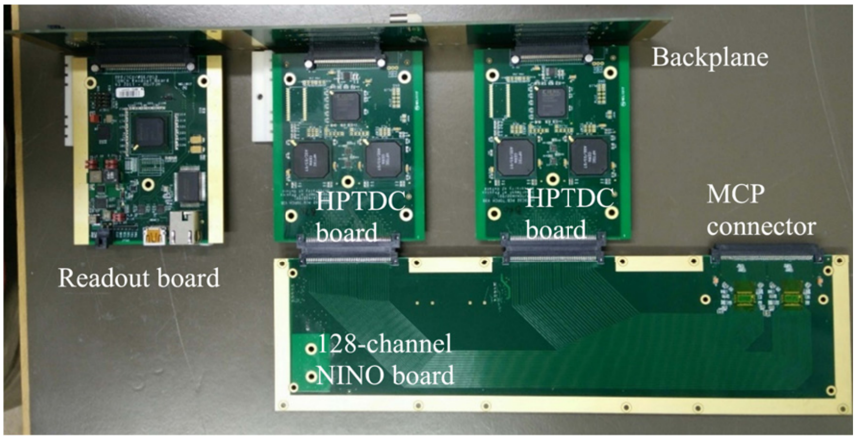

Figure 4. A photograph of the TORCH electronics boards.

arrival time, the propagation delays in the PCBs are extracted from the entry pins on the MCP connector to the HPTDC input pin. The delays are later compensated for in analysis to minimise the offsets introduced by the electronics. Finally, the HPTDC timing resolution is sensitive to power supply ripple; <1 mV peak-ripple power supplies were used to give good performance.

The readout board uses a single Gigabit Ethernet link for data transmission in both directions. The readout board also has a HDMI connector to communicate with an AIDA Trigger Logic Unit (TLU) [7] for synchronisation with other devices. Each 8×64-channel MCP needs four NINO boards, eight HPTDC boards, two readout boards joined together by a backplane and read out by two 1 Gbps Ethernet links. During operation, the DAQ PC first initialises the system by configuring the HPTDCs and setting thresholds for the NINOs. Once data-taking starts, the HPTDC measures the photon arrival time and TOT when a trigger signal has been received. The output data from the HPTDCs are buffered in an on-board FPGA and serialised into 8 lanes before being transferred to the readout board. The readout board receives the 8 lanes of serialised data from each of the four HPTDC boards and formats them into fixed-length Ethernet packets.

As previously discussed, the readout system is interfaced to an AIDA TLU, which distributes clock, as well as trigger and enable signals to all readout boards. The readout boards can also raise a busy signal to the TLU if a maximum trigger rate has been reached. These TLU communication signals are in differential form and transmitted in an HDMI cable, which provides adequate quality and shielding, and at the same time low cost.

3 Test-beam

In 2018, a test-beam campaign [8] was carried out with Proto-TORCH using a pair of MCP-PMTs that were instrumented with the electronics reported in this paper. Figure 5 (left) shows the distribution of photon arrival times as a function of pixel position on the MCP-PMTs. The best achieved time resolution is 89.1 ± 1.3 ps per single photon; for comparison, the intrinsic time resolution, measured by injecting two consecutive electrical pulses from a pulse generator into the electronics system, is 41.5 ps, [9]. Multiple reflections from a single particle hit can been seen from

2022 JINST 17 C05015

the reconstructed plot; the different possible photon paths for the reflections are shown in figure 5 (right). We expect the resolution to be improved with further calibration of time-over-threshold responses of the NINO chips.

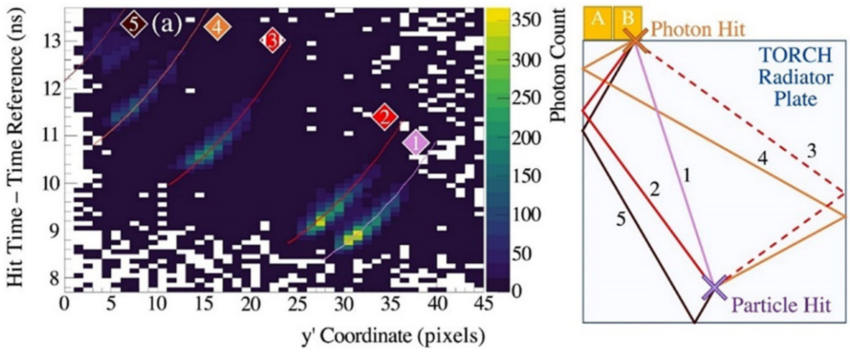

Figure 5. (Left) MCP measured time versus pixel position (in the focussing coordinate) from 8 GeV/c pions in the test-beam, showing multiple reflections in the radiator, (right) the possible photon paths. The plots are taken from [8].

4 The development of a 10 Gbps readout scheme

In the previously described system, the four readout boards were connected to a DAQ PC via a 1 Gbit Ethernet hub; the PC requested data from a single readout board, each in turn, to avoid data collision and saturating the 1 Gbps bandwidth limit on the network interface. This meant that the readout boards had to store data in buffers until data transfer. With a 10% occupancy, the system ran at a maximum 80 kHz trigger rate. Additional readout boards will significantly degrade performance due to dead time on start/stop data transfer, hence such a scheme is not suitable for the Proto-TORCH fully instrumented with 10 MCPs. We therefore developed new firmware and DAQ software to support simultaneous data transfer with multiple readout boards. We have also introduced a 10 Gbps Ethernet switch and a 10 Gbps Ethernet interface on the DAQ PC. In the updated system, the DAQ PC can request data from multiple readout boards simultaneously, while the switch takes care of routing, traffic control and buffering. In a 20 readout-board system with one 10 Gbps network interface, again assuming 10% hit occupancy, the system is capable of running at a 240 kHz trigger rate. The developed readout system has been tested in the laboratory with built-in data emulator to gauge its performance.

5 Future work

A dedicated calibration system is currently being commissioned to provide time-over-threshold responses in the NINO. A further test-beam campaign is planned in 2022 with Proto-TORCH instrumented with the 10 MCPs and the electronics system consisting of 40 NINO boards, 80 HPTDC boards, 20 readout boards and 10 backplanes, in total 5120 channels. Whilst the electronics system fits the purpose for the test-beam, the 100 ps bin resolution used for the operation of the HPTDC (in 32-channel mode) will limit the ultimate performance. The readout system also needs to be radiation tolerant for the final detector.

2022 JINST 17 C05015

To move away from the limitation of legacy ASICs, the next-generation TORCH electronics system is being developed, based on the latest technology developments with the PicoTDC [10], FastIC [11] and lpGBT [12]. This new development will improve the TORCH timing resolution, the channel density, as well as integration with DAQ structures in the LHCb experiment.

Acknowledgments

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