R & D status for the LHCb TORCH project

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WORKSHOP ON FAST CHERENKOV DETECTORS - PHOTON DETECTION,
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R & D status for the LHCb TORCH project

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ABSTRACT: The TORCH detector is proposed for the low-momentum particle identification upgrade of the LHCb experiment. It combines time-of-flight and Cherenkov techniques to achieve positive π/K/p separation up to 10GeV/c. This requires a timing resolution $\leqslant$70ps for single photons. The present paper reports on the status of a preliminary R&D using commercially-available micro-channel plate tubes and readout electronics based on existing front-end chips.

KEYWORDS: Particle identification methods; Cherenkov detectors; Timing detectors; Photon detectors for UV, visible and IR photons (vacuum)

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1 Introduction

The TORCH (Time Of internally Reflected Cherenkov light) detector [1] is proposed for the low-momentum particle identification upgrade of the LHCb experiment [2]. This detector relies on the detection of Cherenkov photons from a 1 cm-thick plane of quartz, segmented in small identical modules (figure 1), to measure the time-of-flight of charged particles. The photons propagate by total internal reflection to the edge of the plane, in a manner similar to a DIRC detector [3]. They are then focused onto an array of Micro-Channel Plate (MCP) photon detectors located at the periphery (figure 2). The time-of-propagation of the photons in the quartz plate also depends on the particle type that produced them, as particles with different velocities give a different Cherenkov angle and therefore a different path length. This effect combines constructively with the time-of-flight difference, and enhances the separation power.

Three sigma K/π separation and positive proton separation up to 10GeV/c require a time-of-flight resolution of about 15ps per track, at a distance of $\sim$10m from the interaction region. This time resolution, together with the expected number of detected photons per track of around 30, imposes a 70ps resolution in the single-photon time measurement. This value includes the intrinsic contributions of the photon detector and of the readout electronics. The present paper reports on the status of the R&D in which commercially-available MCPs and readout electronics based on existing front-end chips are investigated.

2 R&D status

2.1 Photon detectors

MCPs are currently the best choice for fast timing of single photons. These vacuum devices feature high gain, short transit time spread (TTS) together with low noise. This latter is essentially dominated by dark counts. The TORCH design requires the development of MCPs with a TTS better than 50ps for single photons and a finely segmented anode. From simulation studies, it is found that a 128-channel segmentation in one dimension ($\sim$0.4mm) and an angular dynamic range of 400mrad correspond to an uncertainty per-photon on the time of propagation of O(70ps) whereas in the other dimension the required granularity is much looser ($\sim$6.5mm).

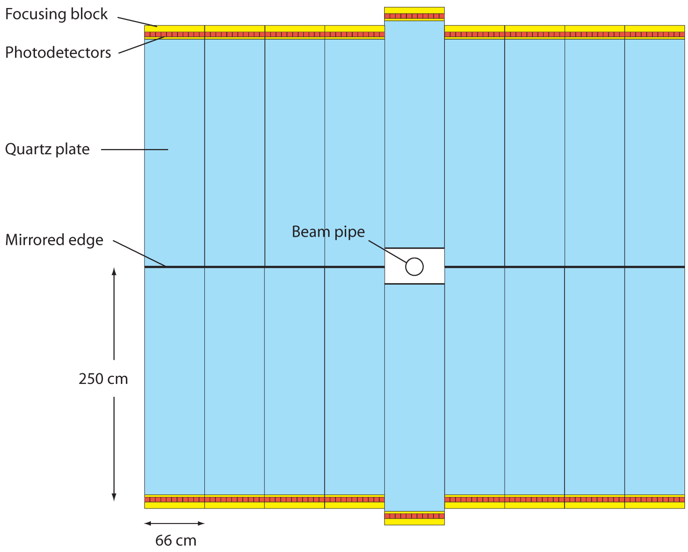

Figure 1. Schematic layout (front view) of the TORCH detector (from ref. [2]).

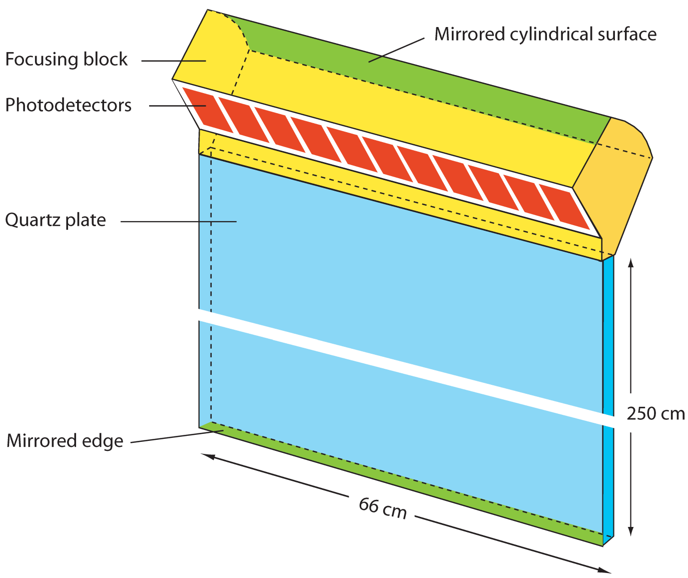

Figure 2. Isometric view of a single TORCH module (from ref. [2]).

Commercially-available MCPs close to satisfying the above requirements are the Planacons manufactured by Photonis USA.[1] These square photon detectors of $53\times53\text{mm}^2$ active area are available in two anode versions, with either 8x8 or 32x32 pads. They are equipped with two MCPs in chevron configuration with 25μm channel pore diameter and an overall gain of up to 10^6. Two units of the 8x8 type (model XP85012) are being tested in the laboratory [4].

The experimental setup used for pulse height measurements is sketched in figure 3. The light

[1]Photonis USA Pennsylvania, Inc. (formerly Burle Industries, Inc.), 1000 New Holland Avenue, Lancaster, PA 17601-5688, USA.

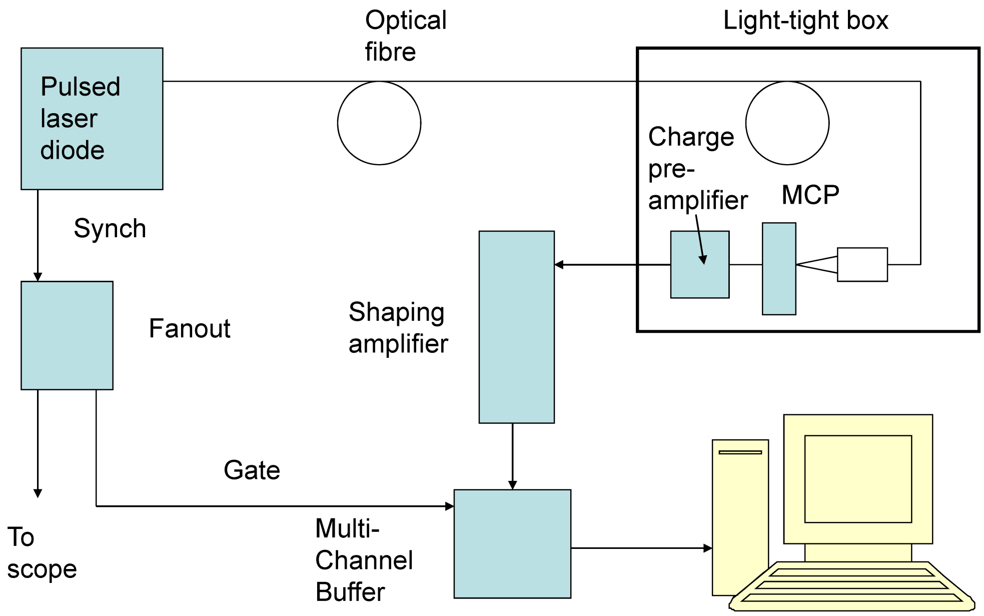

Figure 3. Experimental setup for pulse height measurements.

source is a pulsed laser diode from ALS[2] emitting a pulse of ∼20ps FWHM at 405nm. The light is attenuated through neutral density filters to an average level <1 photoelectron equivalent per pulse, and subsequently focused and collimated. The resulting spot size on the MCP input face is ∼200μm FWHM. Single-channel electronics[3] are used to read out the output signal from one pad while all other pads are connected to ground. The output pad signal is read out using a charge preamplifier connected to a spectroscopy amplifier with shaping time 0.5μs. Data are recorded in a multi-channel buffer.

The MCP is operated at a rather moderate gain range of 6-8$\times 10^5$. The MCP gain (in electrons) and the laser pulse intensity (in photoelectrons) are calibrated through a fit of the pulse height spectrum assuming a standard Poisson distribution model [4]. The data points and the fit are in very good agreement up to five photoelectrons (figure 4). For TORCH, it is important to keep the average number μ of photoelectrons per pulse well below unity, to ensure that the MCP performance is assessed for single photoelectrons.

TTS measurements (figure 5) are performed with a 1GHz timing amplifier and constant fraction discriminator (CFD). The start time is provided by the laser synchronization signal, and the stop time by the output signal from the CFD.

A typical TTS distribution is reproduced on figure 6 and consists of three parts (from left to right): a main prompt peak, a shoulder and a long tail. The main peak represents the measured intrinsic time response of the MCP and the readout electronics. The shoulder is unambiguously attributed to the laser operating mode, as its relative amplitude is seen to increase with the laser intensity. In addition, the shoulder time position and width fully agree with the laser data sheets. The long tail originates essentially from photoelectron transit time spread from the photocathode

[2] Advanced Laser Diode Systems GmbH, Schwarzschildstr. 6, D-12489 Berlin, Germany.
[3] ORTEC Advanced Measurement Technology, Inc., 801 South Illinois Ave., Oak Ridge, TN 37831-0895, USA.

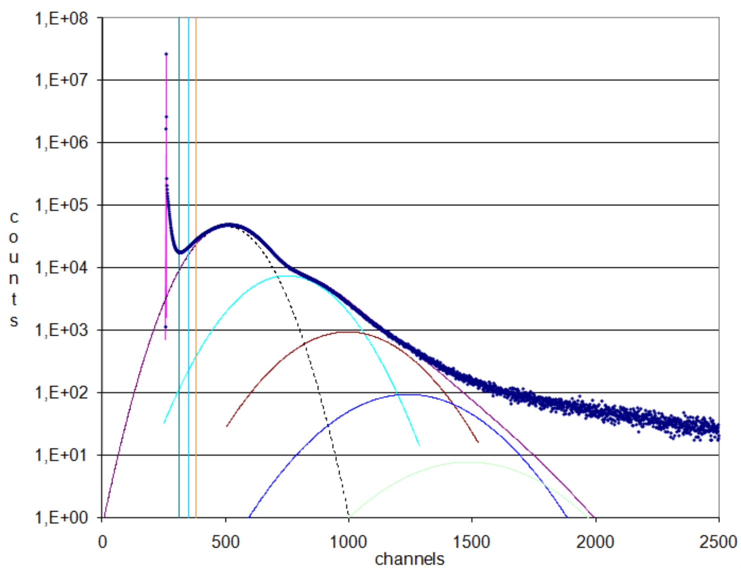

Figure 4. Typical pulse height spectrum (from ref. [4])

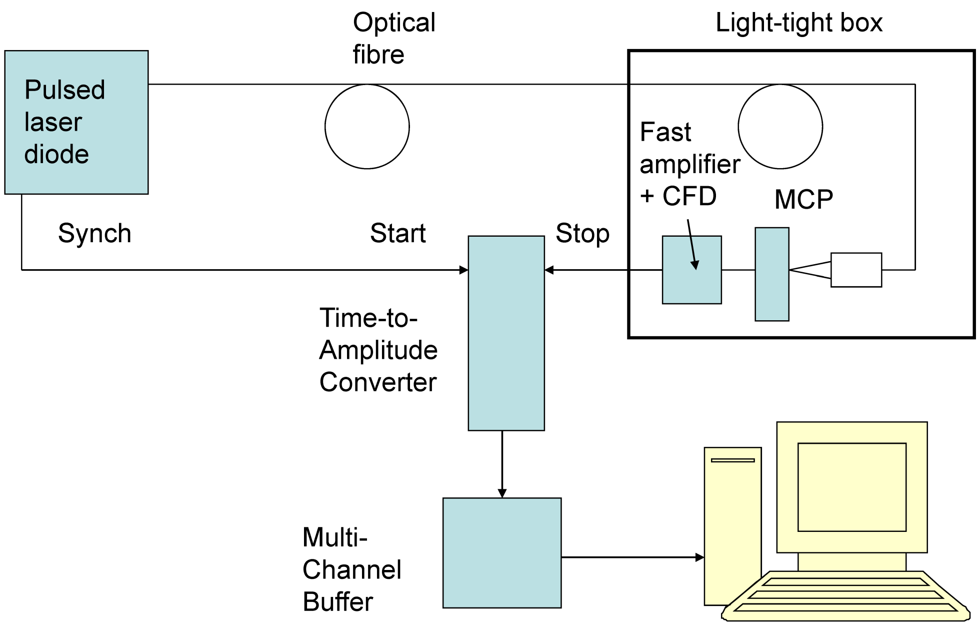

Figure 5. Experimental setup for timing measurements.

to the MCP input, and from photoelectron back-scattering effects at the MCP input surface. The resulting timing values depend on the gap distance between the photocathode and the MCP input and on the voltage difference between them. In this respect, the tested Planacons are not optimized since this distance is rather large (~4.5mm). The end-point time position of the tail is consistent with photoelectron elastic scattering normal to the MCP input surface.

The TTS distribution is fitted with two Gaussians and yields a typical timing resolution <40ps for the main peak. TTS measurements are performed with various discrimination thresholds at

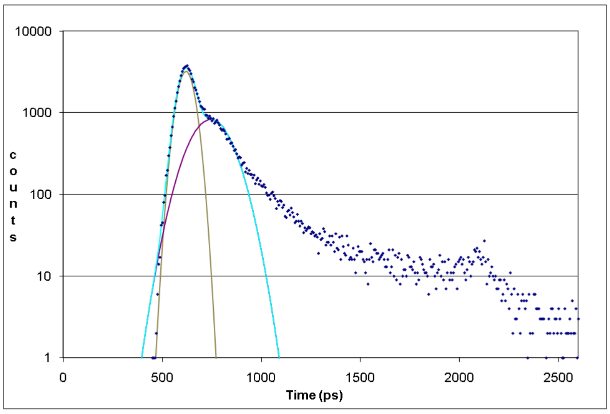

Figure 6. Typical TTS distribution (from ref. [4])

the CFD input. The threshold values are adjusted to prevent the CFD from triggering on low-level noise, and to optimize the performance (see vertical colour lines in figure 4). For a detected photoelectron, and depending on the threshold values, the resulting efficiencies of producing a valid timing output are estimated to range from 88 to 97%.

All reported results have been achieved for a laser illumination at the geometrical centre of the pad. As expected from charge-sharing effects, the pulse height and efficiency decrease at the pad boundary (edge and corner). However, thanks to the low-noise readout electronics, TTS values remain comparable [4]. For a low discrimination threshold of 22.5fC, these values range from 41 to 48ps with an efficiency exceeding 80% if the MCP output charge is equally shared between two pads, and with an efficiency exceeding 70% if this charge is equally shared between four pads.

The point spread function (PSF) is studied using X-Y translation stages to scan the laser light spot along the axial lines of the pad. The PSF amounts to $\sim$1.2mm FWHM at the anode level. In the current Planacon model, the gap distance between MCP output and anode is $\sim$3.5mm. The PSF value would be reduced with a shorter gap distance, and would in this case closely match the fine granularity of 0.4 mm required by the TORCH design.

2.2 Readout electronics

Multi-channel MCP readout electronics are being actively investigated. A potential candidate for the front-end chip is the NINO ASIC [5] that has been developed for the ALICE time-of-flight system [6]. Each NINO channel has a differential input, a fast amplifier stage with $<$1ns peaking time to minimize time jitter, an adjustable discriminator threshold and an output pulse width dependent on the charge of the input signal. Through this time-over-threshold technique, slewing corrections can be applied. Current NINO chips have 8 channels; however a 32-channel version exists and has also been successfully tested, possibly progressing to 64 channels in the next iteration.

The NINO chipset is combined with a multi-channel high-precision time digitization electronics that measure both the leading and trailing edge of the input signal. This is achieved by the ASIC known as the HPTDC [7, 8] that features a 25ps time bin width when configured in high-resolution mode.

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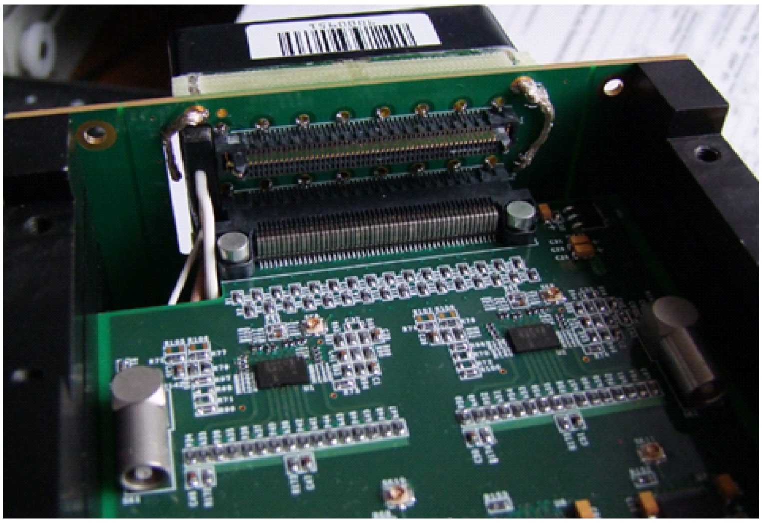

Figure 7. Photograph of a front-end NINO board connected to a Planacon tube.

To provide proof-of-principle verification of the MCP readout, multi-layer printed circuit boards have been fabricated. Each board incorporates two NINO chips that allow the readout of 16 pads of the Planacon. Preliminary electrical tests with an oscilloscope result in time jitters ranging from 12 to 20ps for all channels on the board. More extensive tests with the board connected to a Planacon (figure 7) are on-going.

In parallel with the above activity, a new version of printed circuit board has been designed, laid out and manufactured. This board version includes in addition to the two NINO chips, two HPTDC chips controlled by a Field-Programmable Gate Array (FPGA). Four such NINO/HPTDC boards will be connected to a Planacon tube on the front-end, and on the back-end to an interface/clock board that includes an FPGA for data formatting, Ethernet MAC driving a PHY chip and clock and trigger fan-out. The design and layout of this interface/clock board are nearing completion.

3 Conclusions and perspectives

The preliminary R&D phase described in the present paper shows that the TORCH requirements for the photon detector time response are basically fulfilled by commercially-available MCP tubes. A single-photon time resolution $<$40ps is achieved with an efficiency of $\sim$90% of producing a valid timing output. The MCP is operated at a rather modest gain of $\sim 7\times10^5$, a key condition to ensure good lifetime for the tube. At the LHCb upgrade luminosity [2], it is estimated that 100 tracks will traverse TORCH every 25ns, with each track producing $\sim$30 detected photons on average. Assuming a MCP gain of 5×10^5, the corresponding integrated charge at the MCP anode is in the range 1-5C/cm^2/year. This is a stringent requirement. However, recent progress has been made to extend the lifetime of MCP tubes through the optimization of the manufacturing steps and/or the minimization of degradation effects caused by ion feed-back and residual gases [9]. Finally, customisation of MCPs with internal geometry (e.g. smaller gap distances) and anode segmentation adequate to the TORCH will involve close collaboration with industry.

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Front-end readout boards populated with NINO ASICs have been developed. Preliminary results are very encouraging. The performance of the boards connected to an MCP tube is currently under thorough investigation. For the final 1024-channel MCP, a single device would need sixteen 64-channel NINO chips, and this electronics modularity would require additional study.

The current R&D programme is being extended towards the following aspects:

- Extension of the current TORCH simulation framework by e.g. switching to the updated/modular detector design and adding a tail to the time resolution curve to mimic photoelectron transit time spreads and backscattering effects. The quartz thickness is a crucial parameter, and the compromise will be between good photon yield, minimizing the uncertainty on the position of the photon emission, and overall mechanical stability.

- Integration of the TORCH simulation within a full GEANT framework, in order to introduce e.g. multiple scattering effects that smear the track angle and more realistic track timing and propagation through the magnetic field.

- Prototyping of quartz plates and focussing optics, with emphasis on the ability to polish the quartz surface over a large area, in order to maintain less than a 1mrad uncertainty after multiple internal reflections. The mechanical mounting of the quartz is crucial, as well as its coupling to the focussing block.

The proof-of-principle of the TORCH should be demonstrated using test beam, in view of the Technical Design Report for the LHCb Upgrade on a timescale of the next two years.

Acknowledgments

Support from the LHCb Collaboration is gratefully acknowledged.

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