Prospects for a precision timing upgrade of the CMS PbWO crystal electromagnetic calorimeter for the HL-LHC

Published by IOP Publishing for Sissa Medialab

Received: *January 7, 2018*
Accepted: *February 23, 2018*
Published: *April 3, 2018*

CHEF2017 — Calorimetry for the High Energy Frontier
2–6 October 2017
Lyon, France

Prospects for a precision timing upgrade of the CMS PbWO crystal electromagnetic calorimeter for the HL-LHC

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Abstract: The upgrade of the Compact Muon Solenoid (CMS) crystal electromagnetic calorimeter (ECAL), which will operate at the High Luminosity Large Hadron Collider (HL-LHC), will achieve a timing resolution of around 30 ps for high energy photons and electrons. In this talk we will discuss the benefits of precision timing for the ECAL event reconstruction at HL-LHC. Simulation studies focused on the timing properties of $PbWO_4$ crystals, as well as the impact of the photosensors and the readout electronics on the timing performance, will be presented. Test beam studies intended to measure the timing performance of the $PbWO_4$ crystals with different photosensors and readout electronics will be shown.

Keywords: Calorimeters; Timing detectors

2018 JINST 13 C04003

https://doi.org/10.1088/1748-0221/13/04/C04003

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1 Introduction

The Compact Muon Solenoid (CMS) experiment [1] is a general purpose experiment at the Large Hadron Collider (LHC) at CERN, designed to search for the Standard Model (SM) Higgs boson and for new physics beyond the SM. Many of these searches involve electrons or photons in their final state, and the electromagnetic calorimeter (ECAL) plays an essential role in their reconstruction and identification. The CMS ECAL [2] has been designed to achieve an excellent energy resolution and to guarantee good hermeticity. The ECAL is a homogeneous and hermetic calorimeter containing 61200 lead tungstate ($PbWO_4$) scintillating crystals mounted in the barrel (EB), closed at each end by endcaps (EE) each containing 7324 crystals. The scintillation light is detected by avalanche photodiodes (APDs) in EB and by vacuum phototriodes (VPTs) in EE.

The current LHC data-taking is expected to accumulate a few hundred inverse femtobarns of proton-proton collisions before the LHC will be upgraded to provide a higher instantaneous luminosity, referred to as the High-Luminosity LHC (HL-LHC) [3]. The HL-LHC is expected to provide about 3 inverse attobarn of integrated luminosity, exploiting a higher instantaneous luminosity, but thus having higher rates of simultaneous proton-proton collisions, called pile-up (PU), up to and exceeding 140 PU. Likewise the triggered event rates will increase further which requires upgrades to the readout and trigger electronics of the existing ECAL, while radiation damage in the endcaps require a complete replacement of the EE.

In order to cope with the harsh environment of HL-LHC and mitigate the effects of high PU, it will be possible to exploit not only the excellent energy resolution of the ECAL, but also the very good time resolution.

The upgrade plans will be briefly discussed, and a detailed explanation of precision timing and its use will be given in the following document.

2 ECAL and HL-LHC

For the HL-LHC, given the big reduction in transparency in the highly irradiated crystals in the endcap, the EE will be replaced with a highly granular silicon calorimeter [4]. The EB crystals will be maintained, but the electronics will be replaced. The expected instantaneous luminosity increase is about a factor 4: from the current 40-50 vertices per event to 140 vertices per event, or more, in HL-LHC.

New CMS trigger requirements, in particular related to additional latency (from the current 6.4 μs to 12.5 μs) resulting from tracking information in the first stages of the triggering system (L1), and the increased L1 maximum trigger rate (from 100 kHz to 750 kHz), will require a replacement of the EB electronics. In addition, in order to maintain the excellent energy resolution, both the photodetectors and the crystals will be cooled from the current 18°C to 9°C to reduce the increased noise in the APD due to radiation damage. These changes in the electronics will maintain not only the energy resolution, but will improve the time resolution, achieving around 30 ps of accuracy for 50 GeV electrons and photons.

3 Timing performances, use and upgrade

Several aspects determine the time resolution of an electromagnetic shower in a homogeneous crystal calorimeter:

- intrinsic electromagnetic shower fluctuations, both in terms of longitudinal shower fluctuations, scintillation rise and decay time, and light propagation (as shown in figure 1),
- photodetector and electronics, in particular the noise (dark current and electronic noise),
- data acquisition (DAQ), mainly related to the clock distribution.

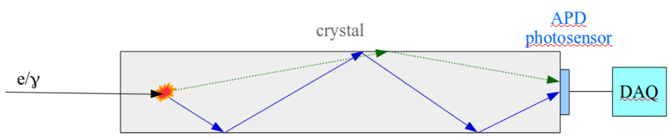

Figure 1. Example of light propagation inside a crystal and effect on time resolution. Optical ray paths are shown inside the crystal.

The intrinsic time resolution of the ECAL crystals has been measured in test beams, obtaining a constant term of the time resolution as a function of the amplitude of about 20 ps, measured using neighboring crystals from the same electromagnetic shower. In CMS, the time resolution is measured using decays of the Z boson to electron-positron pairs. Studying close by crystals from the same electromagnetic shower a constant term of 70 ps is measured, while looking at crystals from different clock distribution regions the constant term is about 150 ps [5, 6]. The performance in CMS with respect to test beam is the challenge that will need to be addressed in order to exploit as much as possible the capabilities of the ECAL.

Good timing resolution from the ECAL can be used to mitigate the effect of high PU in several ways:

- subtraction of neutral energy from PU in electron and photon clusters, associating energy deposits asynchronous with respect to the electron and photon ones
- identification of PU jets, then originating from different vertices
- vertex assignment in high PU environment, mainly for photons

In particular, time information can be used in di-photon searches to triangulate the vertex and assign the correct one in a high PU environment. The correct vertex assignment is needed in order not to introduce additional smearing for narrow resonances di-photon searches. The relative width for a di-photon resonance can be expressed as in equation (3.1), where the energy resolution from each single photon ($\frac{\Delta E_\gamma}{E_\gamma}$) is added in quadrature to a term describing the uncertainty on the angle between the two photons ($\frac{\Delta\theta_{\gamma\gamma}}{tan(\theta_{\gamma\gamma}/2)}$). This last component depends on the knowledge of the vertex from which photons originated: with a time resolution of about 30 ps it is possible to get 1 cm spatial resolution, that is the required goal to keep the angular component of the mass resolution under control.

$$\frac{\Delta m_{\gamma\gamma}}{m_{\gamma\gamma}} = \frac{1}{2}\left[\frac{\Delta E_{\gamma 1}}{E_{\gamma 1}} \oplus \frac{\Delta E_{\gamma 2}}{E_{\gamma 2}} \oplus \frac{\Delta\theta_{\gamma\gamma}}{tan\left(\theta_{\gamma\gamma}/2\right)}\right], \tag{3.1}$$

The new Very Front End (VFE) will be based on a dual gain Trans Impedence Amplifier (TIA), with the goal to preserve the fast signal information to optimize time resolution [7]. The ADC sampling rate will be increased to 160 MHz, with respect to the current 40 MHz. In addition, since the clock distribution has a crucial role, care will be needed in order to ensure clock jitter stability below 10 ps on a large distributed system.

4 Test beam results

Test beams have been performed since 2015 at the CERN SPS H4 facility to study intrinsic $PbWO_4$ timing capabilities and new electronics. A matrix of 25 ECAL barrel crystals with associated APDs has been tested with different VFE configurations. The signals have been readout either by a fast digitizer (CAEN V1742, 5 GHz) or by dedicated readout chips. The time has been extracted from a fit to the pulse shape, while Micro-Channel Plate (MCP) detectors have been used as time reference, given their excellent time resolution ($\sigma_t \sim 20$ ps). A prototype of the new VFE with TIA has been implemented using discrete components and the predicted performance has been achieved: with a 160 MHz sampling rate the expected timing resolution for HL-LHC data-taking conditions, as shown in figure 2.

5 Conclusion

The ECAL upgrade program to cope with HL-LHC data-taking conditions has been described, with particular emphasis on improving the timing resolution to maintain the excellent performance for precision physics and discovery.

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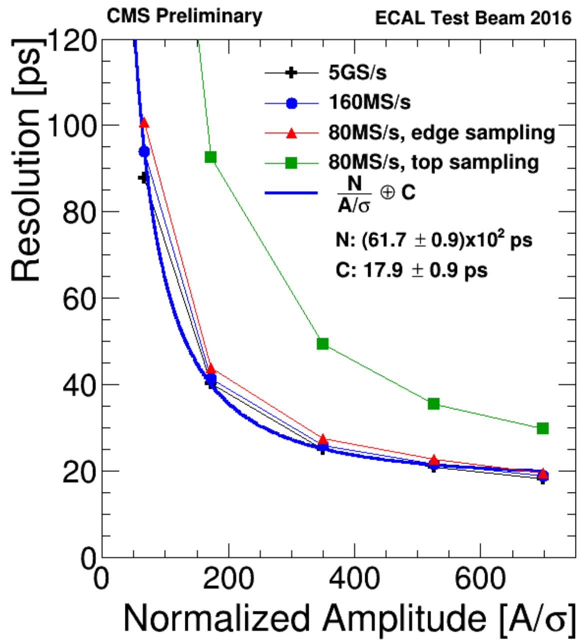

Figure 2. Time resolution measured with TIA implemented by means of discrete components as a function of the pulse amplitude divided by the electronic noise (A/σ). The timing performance of the new electronics has been evaluated for a crystal at the centre of the matrix, comparing the time of the APD pulse at the rear face of the crystal with a reference measurement made at the front face, measured using a MCP. The signal is acquired at a sampling frequency of 5 GHz and different sampling frequencies have been emulated: no significant resolution degradation is observed when changing from a high sampling frequency to 160 MHz, and a resolution of 30 ps is achievable at A/$\sigma \sim 250$, which corresponds to a 25 GeV photon at the start of the HL-LHC (σ = 100 MeV), and a 60 GeV photon at the end of HL-LHC data taking (σ = 240 MeV). The 160 MHz sampling allows to achieve both time and energy resolution goals.

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