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CMS CR -2017/282

The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

22 September 2017 (v4, 01 October 2017)

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

Badder Marzocchi for the CMS Collaboration

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Presented at *NDIP17 8th International Conference on New Developments In Photodetection*

Prospects for a precision timing upgrade of the CMS $PbWO_4$ 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 on the timing properties of PbWO crystals, as well as the impact of the photosensors and the readout electronics on the timing performance, will be presented. Test beam studies on the timing performance of $PbWO_4$ crystals with various photosensors and readout electronics will be shown.

Keywords: CMS, Electromagnetic Calorimeter, APD, Timing, HL-LHC

1. Introduction

The electromagnetic calorimeter (ECAL) of the Compact Muon Solenoid Experiment (CMS) [1] is currently operating at the Large Hadron Collider (LHC) [2] with proton-proton collisions at 13 TeV center-of-mass energy and at a bunch spacing of 25 ns, at an instantaneous luminosity in the range of up to $1.7{\times}10^{34}$ $cm^{-2}s^{-1}$. Following upgrades to the LHC accelerator complex in Long Shutdown 3 (2024-6), the High-Luminosity LHC (HL-LHC) [3, 4] will increase the instantaneous luminosity by about a factor 2 to 5 from current levels, with the goal to accumulate a total of at least 3 ab^{-1} of data. The higher instantaneous luminosity will result in around 200 concurrent interactions per LHC bunch crossing, termed pileup, spread over a luminous region of a few centimetres along the beam axis, and of about few 100 ps in time. This will present significant challenges to the reconstruction algorithms currently in use in CMS.

Pileup mitigation can be substantially improved by means of precision time-tagging of calorimeter clusters. This is achieved by associating them to primary vertices via 4D triangulation [5]. Fig. 1 shows the improvement on the vertices identification when the timing information is exploited, with 200 pileup concurrent simulated interactions. Assuming 20 ps timing resolution, the 4D triangulation vertexing allows the effective pileup to be reduced to the current Run II levels, thus restoring the vertex reconstruction efficiency.

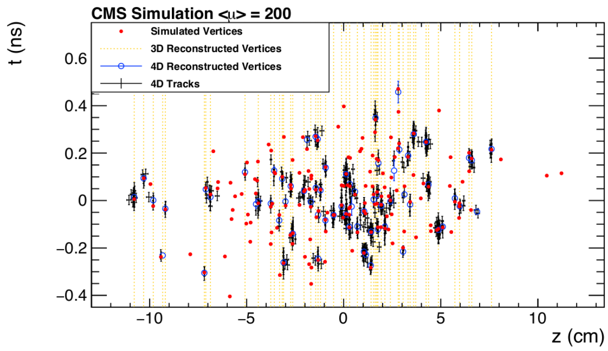

Figure 1: Comparison between standard vertexing and 4D-vertexing in the simulation, with 200 pileup interactions.

2. ECAL Timing Performance

The CMS Electromagnetic Calorimeter is a compact, homogeneous, hermetic and fine grained calorimeter made of 75848 lead tungstate ($PbWO_4$) scintillating crystals (radiation length of 0.89 cm, Molière radius of 2.19 cm, 25 ns scintillating time) embedded in 3.8 T magnetic field. The lead tungstate material has been chosen because of its radiation resilience. Scintillating light is read by avalanche photodiodes (APDs) in the barrel (EB) and vacuum phototriodes (VPTs) in the endcaps (EE). The lead tungstate crystals intrinsic light yield is 100 γ/MeV, resulting in 4 p.e./MeV detected by the APDs. The APDs (Hamamatsu S8148) [6, 7] are operated at gain 50 with 380 V bias. The ECAL detector was designed for excellent energy resolution for electrons and photons with energies up to 1.5 TeV. The excellent resolution achieved to date has played a key role in the discovery of the Higgs boson through the $H\to\gamma\gamma$ decay channel and in the measurement of its properties [8].

The timing of ECAL energy deposits is extracted from the measured pulse shape. This includes the finite decay time of the scintillation light (90% of light emitted within 25 ns) as well as the signal pre-amplifier, which involves a shaping time

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of 43 ns. The pulse is digitized by a sampling ADC running at 40 MHz and ten amplitude samples, with 25 ns spacing, are recorded. Fig. 2 [9] shows an example ECAL pulse shape with the 10 digitized samples. The readout phase is adjusted such that the signal peaks on the sixth sample and the first three samples are used to measure the pedestal.

The timing performance has been measured at the test beams and in situ using electromagnetic (e.m.) showers arising from Z→ee decays [10]. At the test beam a constant term in the time resolution of 20 ps has been measured using neighbouring crystals from the same e.m. shower. However, in CMS, a larger constant term is observed, reaching up to 150 ps for electrons from Z→ee decays. This is understood to be mainly as a result of two contributions. The first contribution comes from channel to channel uncertainties in the timing calibration, which is derived from physics events. The second contribution arises from the clock distribution system, which distributes the precision LHC clock signal between different regions of the ECAL. This large increase in the constant term illustrates the challenges that must be overcome to achieve a stable 30 ps resolution during HL-LHC operation..

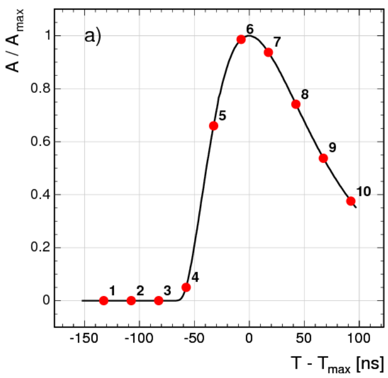

Figure 2: Pulse shape sampling with current CMS ECAL electronics.

3. ECAL Barrel upgrade

A substantial upgrade of the full CMS detector is required, to maintain its performance during the HL-LHC phase. Different strategies are foreseen for EB and EE, since in the EE region the radiation dose is roughly two orders of magnitude larger with respect to EB. The endcaps will be completely replaced by a high-granularity silicon-based detector [11], while the EB lead tungstate crystals and APDs will remain (they will maintain their performance), but a full upgrade of the readout electronics is required. This paper focuses on the design and testing of the upgraded readout electronics for EB.

The basic readout unit of EB detector is a "trigger tower" (TT), i.e. a matrix of 25 crystals read out by APDs. The APDs are connected, through a passive connector (motherboard), to the very front-end (VFE) electronics which contains pulse amplification (MGPA preamplifier), shaping (43 ns shaping time) and digitization functions (12 bit ADC). Each VFE has 5 channels, and 5 VFE are needed for each TT. Amplified and shaped signals from the VFE are passed to the front-end (FE) card which forms the trigger primitives and transmits trigger and data signals to the off-detector electronics via high-speed optical links. The full 5x5 matrix is read out at 40 MHz rate, while the crystals triggered events are read out at 100 kHz rate. This readout scheme is sketched in Fig. 3.

The main motivation for the upgrade of the EB electronics is to match the increased Level-1 trigger requirements for the HL-LHC phase. These requirements, which foresee a maximum Level-1 trigger rate of 750 kHz and a trigger latency of about 12.5 μs, are needed to maintain the current triggering thresholds at HL-LHC. Since the current EB readout buffering and bandwidth are not enough to satisfy these requirements, it is necessary to completely replace the VFE, FE and off-detector electronics.

The upgrade is also a good opportunity to mitigate several radiation and pileup induced effects that affect ECAL performance: mitigate the radiation-induced increase in APD noise, improve the rejection of direct hadronic interactions in the APDs ("spikes"), and improve the timing resolution of the electronics.

In order to mitigate the increase in APDs dark current, induced by the hadronic damage, an upgrade of the cooling system is foreseen, as the dark current is strongly dependent on the temperature. The plan is to reduce the cooling temperature from current 18°C down to 9°C, reducing the APD dark current by a factor of 2 and the electronic noise by a factor of $\sqrt{2}$.

In addition, it is highly desirable to design the pulse shaping and digitization in the upgraded VFE to provide precise timing measurement capabilities. Because of the fast scintillating signal (~25 ns), the best way to improve the VFE timing performance is to reduce the shaping time. Therefore, it is foreseen to use a trans-impedance amplifier (TIA), instead of the current MGPA preamplifier, an ADC with 12 bit resolution and 160 MHz sampling, including data compression, and a trigger-less streaming front end system, with a precision sampling clock distribution and high speed data transmission towards the off-detector. The TIA is designed with a very fast dual gain trans-impedance amplifier, preserving the pulse shape, focused on achieving optimal time resolution.

4. EB upgrade test beam

In order to test the performance of the upgraded electronics readout, a matrix of 30 $PbWO_4$ crystals has been built and tested with high energy electron and pion beams (between 20 and 200 GeV) in the H4 beam line at CERN SPS. The matrix has been equipped with the first prototypes of the trans-impedance amplifier architecture. The goals of this test beam, which took place in Summer 2016, were: a detailed study of APD pulse shapes, for both scintillation and spike events, the measurement of the temperature dependence of the pulse shape, and the determination of the timing resolution of $PbWO_4$ crystals equipped with the new electronics prototypes. For these measurements, the signal output has been sampled using a high-frequency digitizer, operating at 5 GS/s.

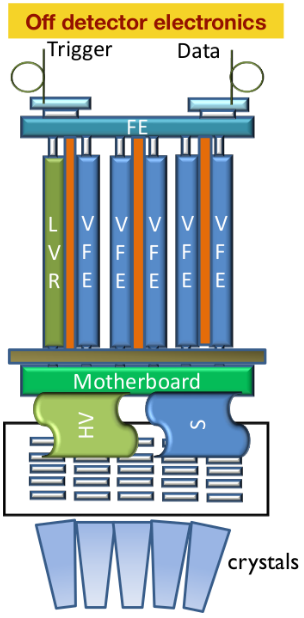

Figure 3: Schematic representation of CMS ECAL Barrel readout electronics.

Pulse shape studies: a detailed study of the pulse shapes as a function of the beam energy and the cooling temperature has been performed. Several electron runs have been taken on the same crystals varying the beam energy and lowering the temperature from 18 to 6°C. The average pulse shapes acquired can be seen in Fig. 4. A good stability of the amplitude, as a function of the beam energy, and of the rising edge of the pulse, as a function of the temperature, have been verified.

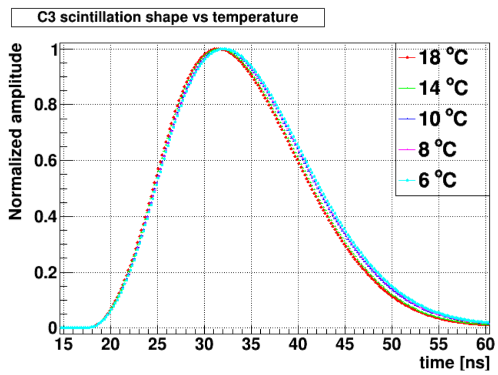

Figure 4: Average pulse shapes for electron beams impinging on the central crystal of the prototype matrix. The pulse shapes, acquired at different temperatures, are shown in different colors.

Spike rejection: spike signals in the APDs have been induced using high energy hadron beams. Fig. 5 shows a comparison of APD pulse shapes induced by spike and scintillation signals. The TIA architecture applies minimal shaping to the APD pulse, therefore the characteristic difference between the pulse shapes of spike and scintillation induced signals can be clearly seen [12].

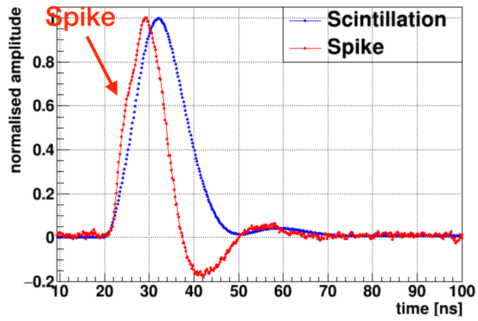

Figure 5: Comparison of the average TIA analog output signals for spike and scintillation events. The pulse shape for spike (scintillation) events is shown in red (blue).

Timing performance: the timing performance of the new electronics has been evaluated for a crystal at the centre of the matrix. The timing resolution, measured with high energy electrons, is obtained by 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 Micro-Channel plate (MCP) with an intrinsic resolution of 20 ps. The time of the APD is extracted using a template fit to the pulse shape. Since the signal is acquired at high sampling frequency (5 GS/s), different sampling frequencies have been emulated and the corresponding timing performance compared. Fig. 6 shows the timing resolution as a function of the pulse amplitude divided by the electronic noise (A/σ). The blue line is the fit to the 160 MS/s experimental points, which is the baseline sampling frequency of the TIA architecture. It can be seen that no significant resolution degradation is observed when passing from high sampling frequency (black points) to 160 MS/s, and that 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, and a 60 GeV photon at the end of HL-LHC data taking. The plot illustrates why 160 MS/s sampling is required - the timing resolution obtained for 80 MS/s sampling is strongly dependent on the sampling phase.

5. Conclusion

The CMS electromagnetic calorimeter is performing well during LHC Run II data taking, yielding precise energy measurements of electrons and photons, which play a leading role in many analyses crucial to the CMS physics program. For the future High Luminosity phase of LHC, an upgrade of the detector will be needed to maintain the same performance in an environment with unprecedented levels of pileup and radiation. A first prototype of the upgrade detector has been built and tested with high energy electron beams at the CERN SPS beam line. This prototype has been equipped with a first version of the upgraded VFE boards. Preliminary results demonstrate good performance for many of the key features for the upgraded

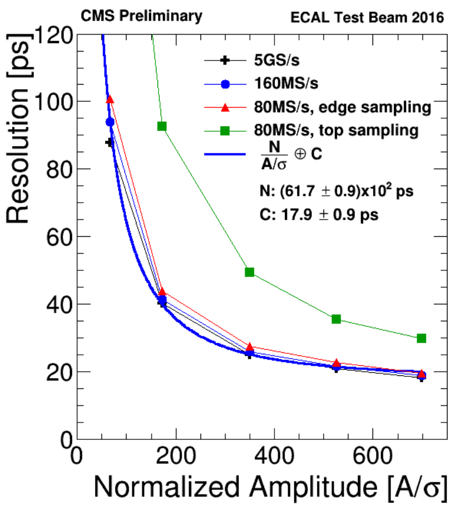

Figure 6: Timing resolution as a function of normalized amplitude for different sampling frequencies.

detector: stability in energy and temperature measurement, discrimination between spike and scintillation signals, timing performance.
Further tests are foreseen in the next several years. The test matrix will be equipped with evolved prototypes of the VFE and FE readout boards, and the performance of the upgraded detector in HL-LHC conditions will be extrapolated from the results of these tests.

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