The Compact Muon Solenoid Experiment
Conference Report

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19 June 2017 (v2, 28 June 2017)

The CMS ECAL Upgrade for Precision Crystal Calorimetry at the HL-LHC

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Abstract

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Presented at *TIPP2017 International Conference on Technology and Instrumentation in Particle Physics 2017*

The CMS ECAL upgrade for precision crystals calorimetry at the HL-LHC

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Abstract. The electromagnetic calorimeter (ECAL) of the Compact Muon Solenoid Experiment (CMS) is operating at the Large Hadron Collider (LHC) in 2016 with proton-proton collisions at 13 TeV center-of-mass energy and at a bunch spacing of 25 ns. Challenging running conditions for CMS are expected after the High-Luminosity upgrade of the LHC (HL-LHC). We review the design and R&D studies for the CMS ECAL crystal calorimeter upgrade and present first test beam studies. Particular challenges at HL-LHC are the harsh radiation environment, the increasing data rates and the extreme level of pile-up events, with up to 200 simultaneous proton-proton (p-p) collisions. We also report on the R&D for the new readout and trigger electronics, which must be upgraded due to the increased trigger and latency requirements at the HL-LHC.

Keywords: Calorimeter, Radiation-hard detectors, Scintillators, Front-end electronics for detector readout

Introduction

The physics goals for the HL-LHC phase (Phase II) [1,2] foresee precise measurements of the Higgs boson couplings and studies of rare SM processes, crucial for searches for new physics. To successfully exploit these data which will be collected during the HL-LHC phase, it is necessary to reduce the effects of the increased simultaneous interactions per bunch crossing (pileup (PU)). At the same time the calorimeters should provide performance similar to that delivered so far but with beam intensities that will result in 200 PU arising from a peak instantaneous luminosity of $5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$. This will be a particularly difficult challenge for the endcap region (EE), due to the fact that the radiation levels will change by a factor of 100 between $|\eta| = 1.48$ and $|\eta| = 3.0$. The dose and fluence levels will result in significant loss to the crystal light transmission and VPT (Vacuum Photo Triode) performance. In the barrel region (EB) we will also have to cope with the increased PU, along with increasing APD (Avalanche Photo Diode) noise (see fig. 2(c)) resulting from increased dark current, the dominant effect for $\mathcal{L}_{int} > 1000 \text{fb}^{-1}$ (see fig. 2(b)). These effects require that the CMS detector [3] will be upgraded including a replacement of EE and the upgrade of EB.

1 The CMS Electromagnetic Calorimeter (ECAL)

The CMS ECAL is a compact homogeneous calorimeter (see fig. 1) containing 75848 lead-tungstate (PbWO_4) scintillating crystals, located inside the CMS superconducting solenoid. The EB covers a pseudorapidity range $|\eta| = 1.48$ while the two EE cover $1.48 < |\eta| < 3.0$. The scintillation light is detected by APDs in the EB and by VPTs in the two EE. A preshower detector (ES), based on lead absorbers equipped with silicon strip sensors, is placed in front of the EE crystals and covers the $1.65 < |\eta| < 2.6$ range. The ECAL energy resolution is crucial not only for the reconstruction and measurement of Higgs-boson decays, for example $\text{H} \rightarrow \gamma\gamma$, but also for many other CMS analyses. At the same time, as already mentioned, the performance is affected by PU. ECAL has excellent performance at 13 TeV [4] and in particular the photon energy resolution was 1-3% in EB and 2.5-4.5% in EE+ES.

Fig. 1. The CMS Electromagnetic Calorimeter (ECAL). EB section comprises 61200 crystals and EE section comprises 14648 crystals. Copyright 2017 CERN for the benefit of the CMS Collaboration. CC-BY-4.0 license.

2 ECAL Barrel Upgrade

The existing EB on-detector electronics (see fig. 2(a)), is organized into groups of 5×5 crystals readout by APDs and form a trigger tower (TT). The energy from the APDs of all 25 crystals is readout at 40 MHz through a motherboard and 5 VFE cards. The VFEs contain ASICs that perform pulse amplification, shaping and digitization functions. Digital signals from the 5 VFE cards are sent to a

Fig. 2. (a) Schematic of CMS ECAL readout electronics (crystals (at the bottom), the motherboard, 5 VFE boards, and 1 FE board). (b) Expected APD dark current (I_{dark}) level in EB versus integrated luminosity at both $|\eta| = 0$ (blue curves) and $|\eta| = 1.45$ (purple curves) for operating temperatures of $18^\circ C$ or at $8^\circ C$. (c) Expected noise level in EB versus integrated luminosity at $|\eta| = 1.45$ for operating temperatures of $18^\circ C$ (red curves) or at $8^\circ C$ (blue curves), with the present electronics (continuous line, shaping time $t = 43 ns$), or the upgraded electronics (dotted line, $t = 20 ns$). Copyright 2017 CERN for the benefit of the CMS Collaboration. CC-BY-4.0 license.

single FE card where the trigger primitive (TP) is formed. This TP is essentially the summed energy from the 5×5 crystals, together with some basic information on the shape of the shower in these crystals. The TP is transmitted via a Gbit optical link at 40 MHz to the off-detector trigger cards. The FE card also features a memory, to store the individual crystal energies until reception of an external level-1 (L1) trigger signal. At this point a second Gbit optical link multiplexes the individual crystal energies to the off-detector readout boards. Figure 2(a) shows that the $PbWO_4$ crystals, the APDs, the motherboards, and the overall mechanical structure will not be upgraded. Both FE and VFE electronics readout will be replaced to satisfy the increased Phase II L1 trigger latency ($12.5 \mu s$ c.f. $4.8 \mu s$) and accept rate (750 kHz c.f. 100 kHz) requirements and to cope with the increased HL-LHC performance. The VFEs will maintain similar purpose, but decreasing the shaping time (43 ns c.f. 20 ns) and the digitisation to reduce out-of-time PU contamination, electronics noise and anomalous APD signals (spikes) [5]. The FE card will readout individual crystal energies at 40 MHz, moving most processing off-detector, so the off-detector electronics needs to be upgraded to accommodate higher transfer rates and to generate TP.

2.1 Motivations

The ECAL EB upgrade [6] is driven by the Phase II L1 trigger requirements as well as the spike mitigation can be improved using a single crystal granularity not yet available at L1. Currently the spikes are rejected at L1 using an algorithm whose performance will degrade significantly during the HL-LHC scenario. How-

ever, with an upgraded electronics we will be able to apply more sophisticated filtering algorithms in the VFE. Decreasing the shaping time and increasing the digitization frequency will improve the discrimination between "normal" signals and those from the (faster) spikes (see fig. 3(b)). Furthermore, because of the increasing APD noise that will significantly degrade the electromagnetic resolution (see fig. 2(c)), we will mitigate this effect by cooling the crystals, and therefore the APDs, and by optimising pulse shaping with new VFEs. The APD dark current is strongly dependent on temperature so by reducing the temperature of the EB from 18°C to 8°C the dark current will reduce by a factor of 2.5, resulting in a noise decrease of 35%.

Fig. 3. (a) New VFE boards with Trans-impedance Amplifier (TIA) pulse shaper/preamplifier as re-designed ASICs. (b) Comparison of APD pulse shape for spike and scintillation events. The pulse shape for spike (scintillation) events is shown in red (blue). (c) Timing resolution as a function of normalized amplitude for different sampling frequencies. Copyright 2017 CERN for the benefit of the CMS Collaboration. CC-BY-4.0 license.

3 Timing performance

Precision timing will improve the vertex localisation for high energy photons, and in particular the vertex resolution for $H \rightarrow \gamma\gamma$ decays will benefit from this. The current efficiency of localising the vertex is ~ 70 -80% but with the current EB timing precision it would be reduced to less than 30% at 200 PU. An improvement up to ~ 70 % can be achieved for photons with $|\Delta\eta| > 0.8$, but to get this important increase the VFE ASIC design, the sampling rate, and the clock distribution should be upgraded to approach the 30 ps timing precision. As pulse shaper/preamplifier ASIC option a trans-impedance amplifier (TIA) (see fig. 3(a)) has been chosen and tested. TIA architecture is mainly digital and does not apply a shaping to the APD pulse. It measures the APD signal with high bandwidth and is optimized for sampling/digitization up to 160 MHz. Its

performance has been confirmed during 2016 beam tests at the H4 beam line at CERN SPS with high energy electrons ($20 < E_e < 250$ GeV). The timing performance of the new electronics has been evaluated for a single crystal, at the centre of a 5×5 PbWO₄ crystal matrix, that has been readout by prototype VFE with discrete component TIA. Different sampling frequencies have been emulated and finally the APD timing has been extracted through a template fit to pulse shape. Figure 3(c) reports the very promising results achieved at 160 MHz: $\sigma \sim 30$ ps at normalized amplitude (A/σ) of 250 corresponding at 25 GeV photon with 100 MeV noise (at HL-LHC start) and 60 GeV photon with 240 MeV noise (at HL-LHC end).

4 Conclusions

The ECAL performance at 13 TeV is excellent but the harsh and challenging conditions of the HL-LHC necessitate a complete replacement of EE and a partial upgrade of EB to maintain this performance comparable to the Run II ones. To mitigate the increased APD noise due to radiation damage, the EB operating temperature will be lowered from 18°C to 8°C. Reading single-crystal information at 40 MHz through transimpedance amplifiers will provide much more information to the off-detector electronics. This will be used in the L1 trigger to mitigate anomalous signals in the APDs and reduce the effects of pileup. Higher-precision timing information than presently available will mitigate pileup even further and result in an overall EB performance that is comparable to that in present CMS operation. However a more precise time-of-flight measurement of photons ($\sigma \sim 30$ ps) will play a key role during HL-LHC to get the same angular resolution in $H \rightarrow \gamma\gamma$ analysis as in Run II.

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