The Compact Muon Solenoid Experiment

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High precision electromagnetic calorimetry with 40 MHz readout: the CMS crystal ECAL for the High-Luminosity LHC

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Abstract

The electromagnetic calorimeter (ECAL) of the Compact Muon Solenoid Experiment (CMS) will be upgraded to meet the challenging running conditions expected after the High-Luminosity upgrade of the LHC (HL-LHC). 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 collisions. The detector will have to sustain an instantaneous luminosity of above $5 \times 10^{34} \text{ cm}^2 \text{ s}^{-1}$, maintaining a performance similar to the one of LHC Run I for an integrated luminosity of 3 to 5 ab^{-1} . This poses stringent requirements on the radiation resistance of detector components, the readout and data transfer from the front end to the back end electronics, as well as the latency of the trigger system. The barrel region of the CMS ECAL will be able to retain the current lead tungstate crystals and avalanche photodiode detectors which will meet the energy measurement performance requirements throughout the operational lifetime of the HL-LHC. To improve the physics performance of CMS under severe pile-up conditions, the timing precision of the CMS ECAL will be improved to reach around 30 ps for energies down to 10 GeV. The very front end readout will utilize trans-impedance amplifiers to optimally utilize the excellent timing performance of the ECAL crystals. The detector will be fully read out without any noise suppression at the LHC collision rate of 40 MHz. A powerful back-end electronics will reconstruct the amplitude and time of each of the 60000 channels of the ECAL barrel in real time. We will present the status of the R and D of the readout and back-end electronics, report on the latest beam tests with pre-production prototypes, and describe the expected performance of the upgraded detector.

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High precision electromagnetic calorimetry with 40 MHz readout: the CMS crystal ECAL for the High-Luminosity LHC

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Abstract—The electromagnetic calorimeter (ECAL) of the Compact Muon Solenoid Experiment (CMS) will be upgraded to meet the challenging running conditions expected after the high luminosity upgrade of the LHC (HL-LHC). Particular challenges at the 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 collisions. The detector will have to sustain an instantaneous luminosity of $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, while maintaining a performance similar to what was achieved at LHC Run I, but for an integrated luminosity of 3 to 5 ab^{-1} . This poses stringent requirements on the radiation resistance of detector components, the readout and data transfer from the front-end to the back-end off-detector electronics, as well as the latency of the trigger system. The barrel region of the CMS ECAL will be able to retain the current lead tungstate crystals and avalanche photodiode detectors which will meet the energy measurement performance requirements throughout the operational lifetime of the HL-LHC. To improve the physics performance of CMS under severe pile-up conditions, the timing precision of the CMS ECAL will be improved to reach around 30 ps for energies down to 10 GeV. The very-front-end readout will utilize trans-impedance amplifiers to optimally take advantage of the excellent timing performance of the ECAL crystals. The detector will be fully read out, without any noise suppression, at the LHC collision rate of 40 MHz. Powerful back-end electronics will reconstruct the amplitude and time of each of the ~ 60000 channels of the ECAL barrel in real time. We present the status of the R&D of the readout and back-end electronics, report on the latest beam tests with pre-production prototypes, and describe the expected performance of the upgraded detector.

I. INTRODUCTION

The Compact Muon Solenoid (CMS) Experiment is a general-purpose particle detector experiment at the Large Hadron Collider (LHC) at the CERN laboratory in Geneva, Switzerland [1]. The CMS detector was designed to study proton-proton collisions, with the goals of elucidating the origin of electroweak symmetry breaking and discovering new physics at the high energy frontier.

II. CMS ECAL AT LHC

The CMS electromagnetic calorimeter (ECAL) is a high-resolution, hermetic, and homogeneous detector made of

75,848 scintillating lead tungstate crystals, located inside the CMS superconducting solenoid [2]. The exceptional precision of the CMS ECAL, as well as its timing performance, are invaluable tools for the discovery of new physics at the LHC. The high resolution CMS ECAL was a crucial component in the discovery of the Higgs boson, in particular in the $H \rightarrow \gamma\gamma$ channel.

The ECAL crystals are organized into a central barrel (EB) region, with coverage in pseudorapidity $|\eta| < 1.479$, and two endcap regions (EE) with coverage $1.479 < |\eta| < 3.0$. A preshower detector consisting of two planes of silicon sensors interleaved with a total of $3X_0$ of lead is located in front of EE. Figure 1a shows a schematic of the ECAL, highlighting its division into barrel, endcap and preshower detectors. In the barrel, the crystals are organized into modules and supermodules of 1700 crystals, and the scintillation light is detected by avalanche photo-diodes (APDs). Figure 1b shows a photo from the installation of the 36 ECAL supermodules in CMS. The ECAL design provides the fast response time, fine granularity, excellent energy resolution and radiation hardness that are required at the LHC. For instance, in the EB, an energy resolution of about 1% is achieved for unconverted or late-converting photons in the tens of GeV energy range. The remaining barrel photons have a resolution of about 1.3% up to a pseudorapidity of $|\eta| = 1$, rising to about 2.5% at $|\eta| = 1.4$ [3].

A schematic of the current EB readout electronics is depicted in Figure 1c. For each EB crystal, two APDs are mounted on the rear face and connected in parallel to form one readout unit per crystal. The APDs are connected to a passive motherboard, which distributes the high voltage and low voltage and interconnects the APDs to the very-front-end (VFE) cards. Each VFE card has five readout channels made up of a multi-gain pre-amplifier (MGPA) with 43 ns shaping time and a 12-bit analog-to-digital converter (ADC). The VFE cards are capable of operating at a rate of up to 40 MHz. The digitized signals from five VFE cards (5×5 crystals) form a trigger tower (TT) and are passed to a front-

Fig. 1: (a) Schematic of the CMS ECAL, highlighting a barrel supermodule in green, the endcap dees in blue, and the preshower in red. (b) Photo from the installation of the 36 ECAL supermodules in CMS. (c) Schematic of CMS ECAL readout electronics, depicting crystals (at the bottom), the motherboard, 5 VFE boards, and 1 FE board.

end (FE) card as a single readout unit. The FE cards calculate the trigger primitives from the transverse energy deposited in a TT and a single bit to qualify the energy deposit. The trigger primitives are transmitted optically off-detector to a trigger concentrator card in the underground service cavern at a rate of 40 MHz. In addition, the FE cards also contain the digital latency buffer and primary event buffer. The per-crystal information is buffered in the FE for transmission to the data concentrator card. Only channels above an energy threshold, associated with a cluster of deposits, are read out at a rate of 100 kHz. Data and trigger information are read out through separate links. The VFE and FE were fabricated with $0.25\ \mu\text{m}$ radiation-hard CMOS technology. All boards were tested to resist the radiation environment for the entire duration of the LHC. Thus far, we have observed only a very low failure rate of $<1\%$ of non-operational ECAL channels, and no failures attributed to radiation damage.

III. HIGH-LUMINOSITY LHC

The LHC was designed to provide 500 fb^{-1} of 14 TeV proton collisions, over 10 years, at a peak instantaneous luminosity of $\sim 1 \times 10^{34}\text{ cm}^{-2}\text{s}^{-1}$. Beyond that point, the high luminosity LHC (HL-LHC) will provide unprecedented instantaneous ($5 \times 10^{34}\text{ cm}^{-2}\text{s}^{-1}$) and integrated luminosity (3000 fb^{-1}) until 2035, in a highly challenging environment [4]. The physics goals for the HL-LHC include precision measurements of the Higgs boson couplings and studies of rare SM processes, both of which may provide insight into the nature of potential new physics, as well as direct searches for new phenomena. An important benchmark for the HL-LHC is the measurement of the Higgs self-coupling through di-Higgs production, for which the final state with two b quarks and two photons may be the most sensitive. Maintaining the excellent performance of the CMS ECAL will be crucial for this measurement.

IV. CMS ECAL LONGEVITY

The CMS ECAL will face a challenging environment at the HL-LHC: higher event pile-up (PU) from multiple interactions per bunch crossing (average PU will increase from 50 to 140), higher radiation levels ($\times 6$) for the crystals and photo-detectors, and a higher rate of anomalous signals in the APDs. The most significant damage to the lead tungstate crystals arises from hadron irradiation. Although hadron damage does not affect the underlying scintillation mechanism, it creates permanent defects, which decrease crystal transparency and shift the transparency band edge towards longer wavelengths, thus attenuating transmission [5]. Figure 2a shows the expected decrease in relative light output from simulation studies, as a function of η and integrated luminosity, going from LHC Run 1 conditions (red) to the end of the HL-LHC (cyan). We observe that the relative light output remains acceptable ($> 50\%$) for the EB crystals, but there will be significant damage to the EE crystals. Figure 2b depicts the effect that this loss of light output has on the constant term of the energy resolution, which dominates the resolution at higher energies, as a function of μ_{ind} . The radiation-induced absorption coefficient, μ_{ind} , is a measure of crystal transmission loss, with EB crystals expected to have $\mu_{\text{ind}} < 2\text{ m}^{-1}$ and EE crystals larger values. The EB crystals, exposed to less radiation in the central region, will continue to perform well with good energy resolution throughout the HL-LHC. However, the EE will have to be replaced entirely, due to significant degradation in performance. The EE upgrade is outside the scope of this report but has been described elsewhere.

V. CMS ECAL BARREL AT THE HL-LHC

Although the EB crystals and APDs will continue to perform well, an upgrade of the EB is planned to mitigate the challenges of the HL-LHC [4]. The primary motivations for the upgrade are the latency and bandwidth requirements of the upgraded CMS trigger system, which will be improved

Fig. 2: (a) Expectation of the relative light output S/S_0 of the ECAL crystals for electron showers of 50 GeV as a function of η for various aging conditions. (b) Test beam results for hadron irradiated crystals for the degradation of the constant term of the energy resolution, compared with predictions from Geant4 simulation (dotted line). (c) The dark current for ECAL APDs at $|\eta| = 1.45$ operated at 18 °C (red), at 9 °C (blue), and at 9 °C until LS4 and then at a lower temperature of 6 °C afterwards (purple). The vertical shaded lines indicate long shutdowns.

to accommodate the higher event rates at the HL-LHC. The EB readout electronics must be upgraded in order to accommodate the increase in Level-1 (L1) trigger rate (100 kHz at LHC compared to 750 kHz at HL-LHC) and latency (5 μs at LHC compared to 12.5 μs at HL-LHC) planned for the upgraded CMS trigger system [4]. The upgrade of the EB readout electronics will necessitate the removal, refurbishment, reinstallation and recommissioning of the 36 EB supermodules during the third long LHC shutdown (LS3). The crystals, APDs, motherboards, and overall mechanical structure of the EB will remain the same, while the VFE, FE, and off-detector electronics will be replaced. Additional improvements that are foreseen for the EB upgrade include: reduction of the increasing APD noise due to dark current; improvements in anomalous signal rejection and PU mitigation; precision timing for vertex determination.

A. APD noise

Although the APDs are expected to remain operational through the HL-LHC, the APD dark current increases with integrated luminosity, resulting in higher noise levels. The APD noise is expected to increase from 40 MeV per channel during the initial commissioning period of ECAL to 400 MeV per channel at the end of the HL-LHC. To mitigate this effect, the EB operating temperature will be reduced from 18 °C to 9 °C, since the dark current scales logarithmically with temperature. The operating temperature may be further reduced to 6 °C during LS4. Figure 2c shows the increase in dark current induced APD noise if the EB continues to be operated at 18 °C (red), the mitigation at 9 °C (blue), and the further improvement by reducing to 6 °C (purple). Reducing the EB operating temperature will require careful planning of services, as well as optimization of thermal insulation to avoid

condensation. A further reduction in the impact of noise can be attained by shortening the signal shaping time in the VFE.

B. Anomalous signal rejection

Anomalous signals ("spikes"), consisting of isolated large signals with equivalent energies that can exceed 100 GeV, have been observed in the EB [6]. The spikes arise when particles from pp collisions directly strike the APDs and very occasionally interact to produce secondary particles that cause large anomalous signals through direct ionization. The spikes have been observed at a rate that is proportional to the collision rate, and as such pose a potential problem for triggering at high luminosities. The spikes can be distinguished from true scintillation signals from electromagnetic (EM) showers using the topology of the deposits in EB, since the spikes occur in a single channel. The pulse shape of the spikes is also different from EM showers, arriving earlier in time and with a shorter pulse since the spike signals do not include the response time of the scintillation light. Figure 3a compares the pulse shapes for a spike signal and a true scintillation signal from an EM shower. Currently, spikes are rejected at L1 using a coarse topological algorithm. Without an upgrade, the efficiency of these rejection algorithms will degrade to unacceptable levels due to the higher collision rate, noise and PU at the HL-LHC. In order to reduce spikes to a negligible level (< 1 kHz above 20 GeV), a L1 spike rejection efficiency of better than 99.9% is needed. The upgraded electronics will allow us to apply more sophisticated filtering algorithms in the VFE since single crystal data will be made available at the trigger level. For instance, a topological variable known as the Swiss-cross is used offline to reject spikes. The Swiss-cross (Figure 3b) is defined as $1 - E_4/E_1$, where E_1 is the energy of the central crystal of a 3×3 array, and E_4 is the total energy of the four adjacent crystals in the 3×3 array.

Fig. 3: (a) Pulse shapes for a spike (blue) and a scintillation signal from an EM shower (red) from simulation. (b) Distribution of the “Swiss-cross” variable for ECAL seed crystals with $E_T > 3 \text{ GeV}$. The open histogram shows all hits, including APD spikes. The shaded histogram includes hits that have less than 1% of their energy from spikes. (c) EB timing resolution as a function of the noise-normalized amplitude (A/σ), as measured at a test beam.

C. Precision timing

Maintaining reconstruction performance in a high PU environment is one of the main challenges at the HL-LHC. The vertex finding efficiency for $H \rightarrow \gamma\gamma$ events will degrade to levels that will significantly affect the $H \rightarrow \gamma\gamma$ mass resolution if no intervention is made. In particular, the $H \rightarrow \gamma\gamma$ vertex efficiency will degrade to 40% for PU greater than 140, compared to 80% in LHC Run 1. However, the vertex efficiency can be restored with precision timing, employing a 4D vertex reconstruction technique which will effectively reduce the impact of PU. The intrinsic timing resolution of the EB crystals and APDs was measured to be $< 30 \text{ ps}$ at a CERN test beam, as depicted in Figure 3c. With 30 ps timing, the vertex efficiency for $H \rightarrow \gamma\gamma$ can be recovered to 55%, and further improved to 75% if coupled with charged track precision timing. The upgraded EB system is designed to approach the intrinsic 30 ps timing precision of the crystals and APDs for high energy EM signals.

VI. UPGRADE OF THE ECAL BARREL ELECTRONICS

The upgrade of the EB electronics will entail a replacement of the on-detector VFE and FE cards, as well as the off-detector electronics. The upgrade will be optimized such that the basic performance specifications of the current system will be maintained. With this Phase-II upgrade, the continued performance of the CMS detector will be guaranteed for 30 years of operation and 4.5 ab^{-1} of integrated luminosity.

A. Very-Front-End Electronics

The VFE will maintain a similar purpose, but the shaping time and sampling rate will be optimized for HL-LHC conditions. A shortening of the shaping time in the VFE will significantly reduce the effective noise from PU and electronics noise, while also allowing for better spike discrimination. Shorter shaping time will also improve the determination of

the pulse arrival time for spike rejection, pileup suppression, and vertex association. The pulse shaping and preamplification will be performed with a trans-impedance amplifier (TIA), which was chosen for its excellent time resolution. The TIA maintains the integrity of the APD signal shape, with an output bandwidth of 50 MHz. The TIA will have two gain ranges, a dynamic range of 50 MeV to 2 TeV, and a least significant bit of 50 MeV. For digitization, a 12-bit resolution, dual-channel ADC with gain selection logic will be employed at a sampling rate of 160 MHz. This combination of TIA and ADC was selected to optimize the timing performance of the upgraded system. The TIA will be implemented with 130 nm CMOS technology, while the ADC will be fabricated with 65 nm CMOS. Figure 4a shows the TIA timing performance measured at a test beam. A timing resolution of 30 ps can be attained with the TIA with a 160 MHz sampling rate for a noise-normalized amplitude (A/σ) of 250, which implies 30 ps timing resolution for 25 GeV photons at the beginning of the HL-LHC ($\sigma = 100 \text{ MeV}$) and 60 GeV photons at the end of the HL-LHC ($\sigma = 240 \text{ MeV}$).

B. Front-End and Off-Detector Electronics

The upgraded FE and off-detector electronics will read data from all crystals, with a longer data pipeline for the increased trigger latency. The new streaming FE card will become a pipeline, transferring most of the processing to the off-detector electronics. The new FE will be fabricated with 65 nm CMOS technology. High speed, radiation-hard 10 Gb/s Versatile optical links with the Gigabit Transceiver (GBT) chipset will allow the transmission of all channels from the FE to the off-detector electronics. The same stream will be utilized for trigger and data. The GBT bandwidth permits a full-granularity readout for the trigger. There will be no noise suppression performed in the VFE or FE, resulting in

Fig. 4: (a) Timing resolution as a function of noise-normalized amplitude obtained at test beam using prototype TIA electronics. (b) Energy resolution $\sigma_{\text{eff}}(E)/E$ for photons from simulated $H \rightarrow \gamma\gamma$ events, for different integrated luminosities and PU, showing the resolution improvement provided by the upgrade.

~ 30 Gb/s per TT (25 channels) after data compression, which requires four 10 Gb/s links.

The off-detector electronics will be upgraded to accept the higher rates, including single crystal readout. In addition, the generation of trigger primitives will be shifted off-detector in the service cavern. As such, the upgraded processors need not be radiation-hard, and commercially available FPGAs can be utilized. The L1 trigger pipeline will also be moved off-detector, allowing for an arbitrary trigger latency. Moreover, the trigger, data and controls may be grouped in single card in the off-detector electronics. An additional benefit of this new readout scheme is the ability to apply more advanced topological filtering, utilizing single crystal data, to reject spikes at the trigger level, similar to the filtering methods that are currently applied offline. The possibility of further low level processing of the data to associate clusters of energy deposits in the back-end is currently being studied.

In addition, the new ASICs for the VFE and FE will require a different bias voltage than what is currently supplied, necessitating an upgrade for the low-voltage regulator card (LVR).

C. Performance with EB Upgrade

With the Phase-II upgrade to the EB electronics and the lowering of the EB operating temperature, the EB will maintain its excellent energy resolution for measuring electrons and photons through the HL-LHC. Figure 4b shows the energy resolution for simulated $H \rightarrow \gamma\gamma$ events, for various integrated luminosity and PU scenarios. It is expected that with the interventions described above, the energy resolution with 1000 fb⁻¹ and an average PU of 140 will be similar to the energy resolution at the beginning of the LHC.

VII. CONCLUSION

The CMS ECAL barrel crystals, APDs, and electronics are performing well at the LHC. However, the challenging

conditions of the HL-LHC will require more bandwidth and a longer data pipeline to accommodate the higher event rates. In addition, performance of the ECAL will be augmented with improved spike rejection at the hardware trigger level, mitigation of the increasing APD noise, as well as precision timing for vertex determination. This will require the full refurbishment of the EB electronics during the Phase-II upgrade program of CMS. The upgrade will entail new VFE and FE electronics to cope with the increase data rate, noise, pileup, and spikes. The off-detector electronics will be upgraded to cope with the higher output bandwidth from the FE and to generate trigger primitives. Moreover, the off-detector electronics will implement more sophisticated algorithms, utilizing single crystal data, to improve spike rejection at the trigger level. Lastly, the EB will be operated cooler to mitigate the increased APD noise due to the radiation-induced dark current. With this upgrade, the CMS ECAL barrel will continue its excellent performance through HL-LHC.

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