The Compact Muon Solenoid Experiment

Conference Report

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Performance of the CMS precision electromagnetic calorimeter at the LHC Run II and prospects for high-luminosity LHC

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Abstract

The Compact Muon Solenoid (CMS) electromagnetic calorimeter (ECAL) is a high-performance calorimeter which will operate also at the High Luminosity Large Hadron Collider (HL-LHC). This talk will describe the strategies that have been employed to maintain the excellent performance of the CMS ECAL throughout Run 2. Performance results from the 2015-2016 data taking periods will be shown and an outlook on the expected Run 2 performance in the years to come will be provided. The status and plans for the upgraded ECAL barrel electronics for the HL-LHC will be presented, based on recent results from simulations, laboratory tests, and test beam measurements of prototype devices.

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Performance of the CMS precision electromagnetic calorimeter at the LHC Run II and prospects for high-luminosity LHC

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The Compact Muon Solenoid (CMS) electromagnetic calorimeter (ECAL) is a high-performance calorimeter which will operate also at the High Luminosity Large Hadron Collider (HL-LHC). This talk will describe the strategies that have been employed to maintain the excellent performance of the CMS ECAL throughout Run 2. Performance results from the 2015-2016 data taking periods will be shown and an outlook on the expected Run 2 performance in the years to come will be provided. The status and plans for the upgraded ECAL barrel electronics for the HL-LHC will be presented, based on recent results from simulations, laboratory tests, and test beam measurements of prototype devices.

Keywords: CMS, Electromagnetic calorimeter, HL-LHC, APD

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1. Introduction

The electromagnetic calorimeter (ECAL) of the Compact Muon Solenoid (CMS) experiment [1] is a high-resolution, hermetic, homogeneous and compact detector made of 75848 lead tungstate ($PbWO_4$) scintillating crystals arranged in a cylindrical structure around the LHC [2] interaction point.

The lead tungstate crystals are radiation tolerant, have fast scintillation ($\sim 75\%$ in 25 ns), density $\rho = 8.28 \text{ g/cm}^3$, short radiation length ($X_0 = 0.89 \text{ cm}$) and small Moliere radius ($R_M = 2.2 \text{ cm}$).

In the barrel (EB) covering the region $|\eta| < 1.48$, the scintillation light from the crystals is read out by avalanche photodiodes (APDs) while in the two endcaps (EE) extending the coverage to $1.48 < |\eta| < 3.0$, it is read out by vacuum phototriodes (VPTs). The pre-shower (ES) region with $1.65 < |\eta| < 2.6$ is instead made of 2 layers of Pb/Si strips, with about 140000 read-out channels.

2. ECAL at the LHC Run 2

The ECAL occupies an important role in many CMS physics analyses at the LHC. The excellent ECAL energy resolution played a key role in the discovery of the Higgs boson in LHC Run 1 through the $H \rightarrow \gamma\gamma$ decay channel and in the measurement of its couplings to other particles [3]. An high performance electromagnetic calorimetry is crucial also for many analyses of physics beyond the Standard Model (BSM), such as high-mass resonances or detection of final states with energetic photons or electrons [4], and for SM precision measurements [5].

The ECAL must then provide an high energy resolution, a high

position resolution for reconstructed deposits, a good timing resolution and a fast and efficient readout for online selection. The CMS ECAL is giving an excellent performance, with a photon energy resolution of 1 – 3% in EB and of 2.5 – 4.5% in EE. The energy resolution is given by:

$$\frac{\sigma_E}{E} = \frac{2.8\%}{\sqrt{E(\text{GeV})}} \oplus \frac{0.128}{E(\text{GeV})} \oplus 0.3\%$$

where the first term is the stochastic term due to shower development, the second one is the noise term and the last constant term is due to stability, uniformity, monitoring and calibration effects. These values are taken from a test beam with ideal conditions (without magnetic field, tracker, bremsstrahlung radiations or conversions) and they are different for data.

Electrons and photons deposit energy over several crystals (70% in one crystal and 97% in a 3×3 array). The energy of an electron or a photon is then collected by cluster algorithms, obtained by summing the single energy deposits in each crystal belonging to the electromagnetic cluster as:

$$E_{e,\gamma} = F_{e,\gamma} \cdot [G \cdot \sum_i [S_i(t) \cdot c_i \cdot \mathcal{A}_i] + E_{ES}].$$

The $F_{e,\gamma}$ are corrections to the supercluster energy to account for energy containment effects, G is the global energy scale from ADC to GeV, $S_i(t)$ are laser monitoring corrections, c_i are intercalibrations constants and $\mathcal{A}_i$ pulse amplitudes. They are described in the following section.

The current period of data taking, LHC Run 2, is characterised by an instantaneous luminosity of up to $1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and an average number of concurrent interactions per bunch crossing (pileup) of up to 50. These values are approximately a factor of two larger than those experienced in Run 1, and exceed the original design parameters of the LHC, so the performance of the ECAL will have to deal with the LHC luminosity and pileup increases.

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Figure 1: Relative response to laser light injected in the ECAL crystals, averaged over all crystals in bins of pseudorapidity, for the LHC Run 1 and Run 2 data taking periods with magnetic field at 3.8 T. The response change observed in the ECAL channels is up to 10% in the barrel, it reaches up to 50% at $\eta \sim 2.5$, the limit of the tracker acceptance, and is up to 90% in the region closest to the beam pipe. The recovery of the crystal response during the periods without collisions is visible. The bottom plot shows the instantaneous LHC luminosity delivered during this time period.

3. ECAL current performance

New techniques have been developed to maintain the ECAL energy resolution and trigger performance at higher pileup, like a more efficient electromagnetic trigger algorithm and a new method for pulse shape reconstruction.

The new multifit pulse shape reconstruction mitigate the effect of out-of-time (OOT) pile-up events, under the high luminosity conditions of Run 2. The pulse shape is modeled as the sum of one in-time signal amplitude and up to 9 OOT amplitudes (one per bunch crossing), estimated minimizing the χ^2 distribution,

$$\chi^2 = \sum_{i=1}^{10} \frac{(\sum_{j=1}^M \mathcal{A}_j \times p_{ij} - S_i)^2}{\sigma_{S_i}^2},$$

for a best description of the in-time shape. The $\mathcal{A}_j$ are the amplitudes from the pulse at bunch cross j , the p_{ij} are the pulses, the S_i are the digitized amplitudes and the σ_{S_i} are the noise covariance matrix.

The energy response of the detector is precisely calibrated and monitored at regular intervals.

The radiation exposure causes crystal transparency losses. This loss is time dependent and the crystals partially recover the initial transparency in absence of irradiation (during inter-fills and shut-downs). The transparency is monitored with a laser system injecting light in every crystal every 40 minutes (Fig. 1) and the monitoring corrections are obtained and applied promptly (in ~ 48 hours). The stability of the response after applying the monitoring corrections is assessed comparing the energy measured in ECAL to the track momentum measured in the silicon tracker (E/p) of single electrons from W/Z bosons decays and using the π^0 invariant mass (Fig. 2).

To equalize the response of each crystal to the deposited energy, relative and absolute calibrations are performed. The relative crystal by crystal intercalibrations use different methods:

- the ϕ -symmetry method equalizes the average energy in channels located at a constant value of η , based on the expectation that the total deposited transverse energy should be the same in all crystals at the same pseudorapidity;
- the π^0/η mass method exploits the invariant mass of unconverted photons arising from π^0 and η decays to intercalibrate the channel response;
- the E/p method compares the energy measured in ECAL to the momentum measured in tracker for isolated electrons from W and Z boson decays.

The intercalibration constants from each method are then combined to provide a weighted average intercalibration constant for each channel.

The Z mass peak in a single η -ring is exploited to correct the relative scale between different η -rings.

The global energy scale is also given by the $Z \rightarrow ee$ invariant mass, used to fix the overall absolute calibration matching data to a detailed simulation of the detector for EB and EE separately.

The supercluster energy is corrected using a multivariate approach that maximally exploits η , ϕ and cluster shapes variables of photons. These energy corrections are optimized using a Boosted Decision Tree (BDT) implementation trained on MC simulation and are tuned separately for electrons and photons to account for the differences in the way they interact with the material in front of the ECAL.

4. ECAL barrel upgrade for the HL-LHC

The LHC program foresees a high-luminosity phase (HL-LHC) [6] starting from 2026. The proposed operating scenario for the HL-LHC is to provide collisions with an instantaneous luminosity of at least $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and to accumulate a total dataset of about 3000 fb^{-1} over a further 10 years of operation. The expected pileup is a factor of four larger than the current Run 2 values, and unprecedented levels of radiation, up to six times higher than for LHC, will be experienced. The HL-LHC will then be an highly challenging environment and to retain performance comparable to Run 2 the trigger rate will need to be increased.

The ECAL needs an upgrade strategy different for EB and EE, since the radiation dose will be 100 times bigger in the EE. The radiation-induced loss of crystal response in the forward regions of CMS will require a complete replacement of the ECAL endcaps prior to the HL-LHC. The EE will then be fully replaced by a high-granularity silicon calorimeter (HGCAL) [7]. The luminosity increase also poses significant challenges to the operation of the barrel photodetectors. The EB crystals and APDs [8] will remain operational, but there will be a partial upgrade of the electronics, that will necessitate the removal, re-installation and re-commissioning of 36 EB super-modules during the long shutdown 3 (LS3).

The current EB electronics is composed of readout units, very-front-end (VFE) and front-end (FE) boards. The basic readout unit is made of a 5×5 crystal matrix and is the building block

for the on-detector electronics. Each VFE has 5 identical read-out channels with a pre-amplifier (MGPA) with 43 ns shaping time and a 12 bit ADC with sampling rate of 40 MHz. The FE electronics take care of data pipeline and transmission, generates trigger primitives with 5x5 crystal granularity and separate the readout for data and trigger.

The new on-detector and off-detector electronics will be required to satisfy a trigger latency of $12.5\mu\text{s}$ (about a factor of two increase with respect to the current one) to achieve a CMS Level-1 (L1) trigger accept rate of about 750 kHz (about 7.5 times higher than the current one), so the VFE and FE cards will be replaced.

The predicted neutron fluence at the HL-LHC is about 2×10^{14} n/cm² in the most irradiated regions of the ECAL barrel. Recent studies [9] have shown that the APDs will remain operational under such conditions, however the dark current increases linearly with the neutron fluence, and the readout noise will have an increase of about a factor 10 after 3000 fb⁻¹, corresponding to ~ 400 MeV/channel. To mitigate the APD dark current, a reduction of the operating temperature is foreseen, from the current 18°C to 8 – 10°C, which will reduce the induced noise by about 35% (Fig. 3). The temperature reduction will require an upgrade of the cooling system. The cooling supply to the ECAL cooling plant, currently with water at 14°C, will be required to have chilled water at 6°C for operations at 9°C.

The new on-detector ASICs will be designed to perform the functions of pulse amplification, shaping and digitization of the signal at a faster sampling rate of 160 MHz, and will allow to maintain the best possible energy resolution for the HL-LHC. The new designs of the VFE boards will involve also a shortening of the signal shaping time from 43 ns to about 20 ns, that will help in reducing the APD noise, which goes like $\sqrt{t}$. These ASICs will also improve the suppression of signals caused by direct ionization of the APDs (spikes). These signals are energy deposits in a single APD with a shorter pulse than an EM shower, which is spread over several crystal. The performance of the current spike rejection algorithm at L1 will not be sufficient at the HL-LHC, where the expected spike rate is as much as one per bunch crossing. A reduction of the pulse shaping time from 43 to about 20 ns and the use of single crystals information at the L1 trigger will provide additional handles to keep a similar performance as during Phase 1 operations. Recent developments in radiation hard optical links (IpGBT) will permit the amplification, digitization and transmission of data from all ECAL readout channels to new off-detector electronics, where processors are capable of processing these data with more complex and better-performing algorithms than are currently possible, like a more granular clustering, a better spatial resolution and a better tracks-cluster association with approximated tracks available at L1. The off-detector electronics will have to accommodate higher transfer rates and to generate trigger primitives. This will allow the exploitation of the full ECAL granularity in the Level-1 trigger. Such an upgrade will greatly improve the rejection of APD spikes (Fig. 4), which would otherwise dominate the available trigger bandwidth, as well as improving PU mitigation at Level-1.

The on-detector readout will be designed also with the aim of

Figure 2: Stability of the relative energy scale measured from the E/p of single electrons from W/Z decays (top) or from the π^0 invariant mass distribution (bottom), plotted as a function of time. The error bars represent the statistical errors on the relative E/p scale (top) and on the π^0 fitted peak position (bottom). The plots show the data with (green points) and without (red points) light monitoring corrections applied. The right-hand panels show the projected relative energy scales.

Figure 3: APDs noise as a function of integrated luminosity. The dark current for APDs operating at 18°C (9°C) is shown by the red (blue) curve. The solid (dashed) lines show a shaping time of 43 (20) ns.

Figure 4: Average pulse shapes from APD spike (red) and scintillation signal (blue). The amplitude samples from the digitization at 160 MHz sampling frequency are shown as dots and squares.

exploiting the excellent intrinsic timing resolution of the crystals, in order to discriminate between energy deposits arising from different overlapping events based on their time-of-flight. The short shaping time (20 ns) and the fast sampling rate (160 MHz) will allow to approach the intrinsic timing capacity of the detector (~ 30 ps from test beam measurements). Timing of high energy photons with 30 ps precision can be exploited to keep the same $H \rightarrow \gamma\gamma$ vertex assignment efficiency as in Run 2 (Fig. 5).

5. Conclusions

The CMS electromagnetic calorimeter has been giving excellent performance throughout LHC Run 2 data taking. It is crucial for many CMS physics analyses at the LHC thanks to its precise measurements of electrons and photons energies. In the future years, an upgrade of the detector will be needed for the High Luminosity LHC to maintain performance comparable to Run 2 in an environment with unprecedented levels of pileup and radiation. Test beam measurements of prototype devices are being carried out, providing the upgrade strategy for the barrel and the extrapolation of the future performance. The main changes for the ECAL EB will be the replacement of VFE, FE and off-detector electronics, an upgrade of the cooling system with an operating temperature of 8 – 10°C, the use of single crystal information in the Level-1 trigger, a new design for VFE electronics with a shorter pulse shaping at 20 ns and a faster sampling rate of 160 MHz, 12 bit ADCs with two gains and new FE boards with radiation hard optical links (lpGBT).

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Figure 5: Timing resolution as a function of normalized amplitude for different sampling frequencies. The 160 MHz sampling rate is shown in blue.

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