The Compact Muon Solenoid Experiment

Conference Report

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

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The CMS electromagnetic calorimeter barrel upgrade for High-Luminosity LHC

Maria Margherita Obertino for the CMS Collaboration

Abstract

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The CMS electromagnetic calorimeter barrel upgrade for High-Luminosity LHC

M. M. Obertino on behalf of the CMS Collaboration

Abstract—The High Luminosity LHC (HL-LHC) will provide unprecedented instantaneous and integrated luminosity. The lead tungstate crystals forming the barrel part of the CMS Electromagnetic Calorimeter (ECAL) will still perform well, even after the expected 3000 fb^{-1} at the end of HL-LHC. The avalanche photodiodes (APDs) used to detect the scintillation light have recently been exposed to the levels of radiation expected at the end of HL-LHC. Although they will continue to be operational, there will be some increase in noise due to radiation-induced dark-currents. Triggering CMS with ~ 140 pileup events necessitates a change of the front-end electronics. New developments in high-speed optical links will allow single-crystal readout at 40 MHz. This will provide maximum flexibility and enhanced triggering possibilities when used in conjunction with upgraded off-detector processors. The very-front-end system will also be upgraded, to provide improved rejection of anomalous signals in the APDs as well as to mitigate the increase in APD noise. We are also considering lowering the ECAL barrel operating temperature from 18 degrees C to about 8-10 degrees C, in order to increase the scintillation light output and reduce the APD dark current.

I. INTRODUCTION

The electromagnetic calorimeter (ECAL) [1] of the Compact Muon Solenoid (CMS) experiment [2] at CERN is a homogeneous, quasi-hermetic detector made of 75848 lead-tungstate (PbWO_4) scintillating crystals, organized in a barrel (EB), with pseudorapidity coverage up to $|\eta|=1.48$, closed by two endcaps (EE) that extend up to $|\eta| < 3$. A preshower detector (ES) comprising two planes of silicon sensors interleaved with lead absorber is located in front of each endcap, at $1.65 < |\eta| < 2.6$, to help in π^0/γ separation.

Thanks to its excellent energy resolution, response linearity and electron and photon identification capability [3], ECAL has played a crucial role in many analyses performed with the data collected during the LHC Run1, and notably in the discovery and in the study of the properties of the Higgs boson through its two photon decay [4].

As the majority of the CMS apparatus, the electromagnetic calorimeter was designed to operate over ten years of data-taking at LHC, corresponding to a total integrated luminosity of 500 fb^{-1} , and at a maximum instantaneous luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. A major upgrade of the LHC accelerator, which is scheduled to take place between 2023 and 2025, will allow to operate at a leveled instantaneous luminosity of $5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and to accumulate $\sim 3000 \text{ fb}^{-1}$ in about ten years of running. This phase, termed High Luminosity LHC (HL-LHC),

represents a challenge for the detectors due to a high radiation dose (up to 300 kGy in ECAL at $|\eta|=2.6$) and to the high number of pileup interactions per beam crossing (~ 140). To maintain performance similar to the one delivered during the LHC Run1 several parts of the CMS apparatus need to be upgraded. In this report we will focus on the changes required for the ECAL barrel. A more comprehensive description of the upgrade plan for the CMS calorimeter system, which also includes the proposed replacement of the endcap part of ECAL, can be found in [5].

II. THE ECAL BARREL

The ECAL barrel is made of 62000 PbWO_4 crystals with the scintillation light read out by two avalanche photodiodes (APD) in parallel, mounted on the rear face of each crystal. The readout electronics is organized in two logical levels, one positioned inside the detector (the Front End System), immediately behind the crystals, the other in the underground service cavern (Off Detector Electronics). The connection between the two parts is made via optical fibers.

The basic element of the Front End System is the Trigger Tower (TT) designed to readout 25 crystals (Fig.1). It consists of a Motherboard (MB), 5 Very Front End Cards (VFE), a Low Voltage Regulator Board (LVR) and a Front End Card (FE).

Fig. 1. Current design of the ECAL Barrel Front End readout electronics.

Motherboards are passive devices that provide the flat surface where the VFE and the LVB are mounted. They distribute the regulated analog and digital voltage provided by the LVR to the VFEs, filter and distribute the high voltage to the APDs and drive their signal to the electronic chain.

The Very Front End Cards comprise five identical and independent read-out channels which process the signal from five crystals simultaneously. Each channel consists of a Multi Gain Pre-Amplifier (MGPA) and a multi-channel analog-to-digital converter (ADC). The MGPA contains a preamplifier

and three parallel amplifier stages with nominal gains 1, 6, and 12 that shape and amplify the photodetector signal. The shaping is done by a CR-RC filter with a shaping time of 43 ns. The 3 analog output signals of the MGPA are digitized in parallel by a 40 MHz 12-bit ADC (AD41240). A digital logic internal to the ADC automatically selects as output the signal of the highest, not saturated gain.

The digitized signals from the five VFEs belonging to the same TT are passed to the FE board where the trigger primitives are calculated by summing the energy of the corresponding 25 crystals; this sum is sent to the CMS trigger system at 40 MHz. The crystal information is buffered in the FE with a maximum latency of 6.4 μ s and a maximum Level 1 accept rate of about 150 kHz. The digital signal processing for the trigger primitive generation and the RAM for the digital pipeline and the primary event buffers are included in the FENIX ASIC functionalities. Two independent optical links are used to transfer the crystal data and the trigger primitives from each FE board to the Data Concentrator Cards (TCC) and to the Trigger Concentrator Cards (TCC), respectively. The clock is distributed to the front-ends through token rings controlled by the Clock and Control System (CCS).

The LVR, VFE and FE ASICs are fabricated in 250 nm CMOS technology and were qualified to resist the radiation environment of ECAL for at least ten years of operation.

III. RADIATION EFFECTS ON CRYSTALS AND PHOTODETECTORS

Radiation affects the ECAL barrel response and performance mainly through two different effects: the reduction of the crystal transparency due to the formation of color centers and the increase of the APD leakage current due to the damage of the silicon bulk.

A. Radiation damage in PbWO_4 crystals

Lead tungstate crystals are subject to damage due to electromagnetic and hadron irradiation. Both type of radiation do not alter the scintillation mechanism but reduce the crystal transparency through the formation of color centers which absorb part of the scintillation light.

Transparency loss induced by ionizing electromagnetic radiation largely recovers through spontaneous annealing at room temperature [6]. The light output tends towards an equilibrium level, which depends on the dose rate. During LHC running the response variation of the ECAL channels is tracked by means of a laser monitoring system [7] based on the injection of laser light at 447 nm (440 nm in 2011), close to the emission peak of PbWO_4 scintillation light. This system cycles through all 75848 crystals every 40 minute. The changes observed during 2011-2012 running are shown in Fig. 2. They are less than 6% in the EB and reach 30% in the most forward EE regions used for electron and photon reconstruction ($|\eta| < 2.5$). The laser monitoring system was successfully employed to correct for these variations in channel response allowing ECAL to maintain excellent performance during the entire LHC Run1 [8].

The dominant concern for HL-LHC is the loss of response due to hadron irradiation. High-energy protons and pions cause a loss of light transmission in PbWO_4 , which is permanent at room temperature. The cumulative nature of this damage

implies that the light output from the calorimeter crystals is expected to decrease with irradiation. The effect of charged

Fig. 2. CMS ECAL relative response to laser light versus time, averaged over all crystals in one given pseudorapidity bin, for the 2011 and 2012 data taking (top panel). Instantaneous luminosity versus time (bottom panel).

hadrons has been studied on crystals irradiated with pions and protons from the CERN Proton Synchrotron [9], [10]. An extensive test-beam campaign on the irradiated crystals has been performed and the worsening of the energy resolution with the increasing dose has been observed [11]. Based on these measurements, a model of crystal ageing has been developed. This study has shown that radiation damage is not problematic in the ECAL Barrel, even in the highest η region where the expected crystals output loss after 3000 fb^{-1} is $\sim 40\%$, less than what was experienced by the most forward part of the endcaps during the LHC Run1.

B. Radiation-induced aging of APDs

The APDs are silicon photodiodes with internal gain, developed and produced by Hamamatsu Photonics in collaboration with CMS. They are currently operated at gain 50 ($V_{\text{BIAS}} \sim 380 \text{ V}$) and at a temperature of 18°C . As with all silicon devices, they are sensitive to γ and hadron damage [12]. The γ radiation causes an increase in the surface current and decreases the quantum efficiency. ECAL APDs were screened for potential damage with a ^{60}Co source up to 5 kGy [13], as a preventive measure for channel failure due to surface defects. In addition they have a Si_3N_4 coating, which is more radiation hard than SiO_2 , and a guard ring to protect against surface damage. Therefore, the principal concern for the HL-LHC is hadron irradiation which creates defects in the silicon bulk and consequently induces an increase of the APD dark current and of the detector noise. Previous studies [12], [13] had proven the radiation hardness of the APDs up to a fluence of $4 \cdot 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$. A new campaign of irradiation studies has been performed in order to assess the APD longevity up to the HL-LHC requirement. Specifically, ten APDs were irradiated at the TAPIRO reactor at ENEA Casaccia up to a fluence of $1.5 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$. The dark current was found to increase linearly with the neutron fluence and a shift of the gain versus bias voltage curve to higher values has been observed. The voltage change needed to compensate for

the gain shift is ~ 20 - 30 V for the most highly irradiated devices and does not recover in time. This effect is not considered problematic since bias voltage shifts can be easily compensated for by the ECAL high voltage system [14]. The evolution of the APD dark current in the ECAL channels was also measured during the LHC Run1 as shown in Fig. 3, together with the LHC delivered luminosity as a function of time. These data confirm the linearity in the rate of creation of defects in the APD with neutron fluence. The observed dark current variation corresponds to an increase of the electronics noise of about 0.2-0.3 ADC counts, depending on η . Fig. 3 also shows that during technical stops and winter shutdowns part of the APD defects anneals and the current reduces.

Fig. 3. Evolution of the dark current of APDs installed in the ECAL Barrel for different pseudorapidity during the LHC Run1. The red points show the LHC delivered luminosity as a function of time.

Neutrons dominate the hadron spectrum behind the ECAL crystals. For a delivered luminosity of 3000 fb^{-1} the neutron fluence predicted with the FLUKA simulation [15] varies from $1.2 \cdot 10^{14}$ to $2.4 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ for η values between 0 and 1.45. The expected dark current of a pair of APDs at gain 50 at $\eta=1.45$, considering only the permanent bulk damage, is 200-250 μA . With the present electronics the corresponding increase of the preamplifier noise, which depends on the square root of the APD bulk current times the shaping time, is expected to be of the order of ~ 9 ADC counts (Fig. 4). This means that after 3000 fb^{-1} , the noise levels in EB will reach almost 350 MeV per channel at $\eta=1.45$ (1 ADC count corresponds to about 40 MeV). Considering that electromagnetic showers in ECAL are typically reconstructed summing the energy of at least a 5×5 crystal matrix, the level of electronics noise will be the limiting factor of the EB energy resolution for photons after 1500 fb^{-1} .

A substantial reduction of the dark current can be achieved by cooling the APDs, thus reducing the electronic noise contribution to the resolution. Specifically, a decrease of the ECAL operating temperature from 18°C to 8°C will halve the APD dark current and consequently will reduce the noise by about 30%. Fig. 5 presents the expected noise levels in the detector at lower temperature and it shows that operating the APDs at 8°C after 3000 fb^{-1} corresponds in terms of noise to

operating at 18°C after about 1000 - 1200 fb^{-1} . The lower temperature also reduces the risk of APD self-heating.

Fig. 4. Expected noise with current ECAL electronics as a function of LHC integrated luminosity in the center of the Barrel ($\eta=0$) and at the edge ($\eta=1.45$). The expected noise is shown also in the case of the decreasing of the ECAL operating temperature to 8°C .

The proposed operating condition will affect the crystals response, too. At 8°C the light yield increases of $\sim 25\%$ but the spontaneous PbWO_4 light output recovery from gamma irradiation is less effective. The combination of these two effects leads to a light output larger at 8°C by about 10% compared to 18°C . The dynamics of the PbWO_4 radiation damage at 8°C will be studied in detail in order to optimize the operating temperature of the calorimeter for the HL-LHC operation.

IV. ECAL BARREL ELECTRONICS UPGRADE

Accelerated aging tests performed on the present ECAL Barrel electronics showed that the single components can survive the HL-LHC radiation environment. Consequently, the MBs will not be replaced to avoid the risk of disturbing the cooling block and cooling system joints. However, radiation hardness is not the only concern. Notably, the current FE card cannot meet the requirements of the HL-LHC CMS L1 trigger system, which foresees an increase of the latency up to $20 \mu\text{s}$ and an increase of the bandwidth up to 1 MHz . By replacing the FE boards and the off-detector electronics and by profiting of the new 10 Gb/s optical links currently under development at CERN [16], ECAL will be able to readout all the 61200 crystals at 40 MHz . This will allow major functions currently implemented in the Front End Electronics to be moved off detector where commercially available FPGAs can be employed. These new processors will be powerful enough to accommodate all functions presently performed by DCC, TCC and CCS. Moreover, the new architecture will allow calculating the trigger primitives off detector providing the possibility to develop more sophisticated algorithms based on individual crystal information also for the Level 1 calorimeter trigger.

By including the VFE in the upgrade, pulse shaping and

sampling could be optimized to mitigate the effect of the increased APD noise and of the pileup and to improve timing resolution.

The upgrade of the VFE and FE cards will allow producing the new ASICs in 130 nm or 65 nm CMOS technology characterized by a higher radiation tolerance and a lower power consumption than the 250 nm CMOS technology currently used. New ASICs will require a different bias voltage from that presently supplied by the low voltage regulator card. The LVR will be redesigned and should exploit the radiation hard “point of load” DC-DC converters, that have recently been developed for use in the LHC experiments [17]. These compact devices are highly efficient and have low noise output. They will reduce the power consumption of the front end to about 50 kW (around half of the present value) and the amount of copper cabling required for power transmission.

For the control and distribution of the clock, trigger commands and FE and VFE settings and configurations the GBTX control bus will be used, simplifying the existing scheme driven by a specific control board (CCS). Each control link will serve a group of 25 crystals in the barrel. An additional redundant link would also be highly desirable to facilitate recovery from a bad link.

Fig. 3 shows a possible new design of the Trigger Tower. The individual boards will maintain the same form of the present electronics in order to fit in the same physical space and use the existing services whenever is possible.

Fig. 5. A possible new architecture for the upgrade of the ECAL Barrel readout electronics.

Two substantial improvements that would be introduced by the new FE design are discussed in the paragraphs A and B of this section.

A. Improved online mitigation of anomalous signals

Large isolated signals were observed in the ECAL Barrel during the LHC Run1. They are characterized by a pulse shape shorter in time than the normal scintillation signal and involve only one channel whereas an electromagnetic shower typically deposits at least 20% of its energy in neighboring crystals [1]. These deposits, named “spikes”, were understood to be associated with particles striking the APDs and interacting in the silicon bulk through direct ionization. Extensive studies of their properties in data have been carried out and various algorithms have been developed to flag and remove them. Notably, during the LHC Run1 their rate was reduced to a manageable level by exploiting an additional functionality of

the Front End Card, i.e. the possibility to set the Strip Fine-Grained Veto Bit (sFGVB) based on the level of isolation of the detected signal [18]. Since their rate is proportional to the luminosity, spikes represent an important issue for triggering CMS in higher luminosity scenarios, like the HL-LHC one.

The full event readout at 40 MHz foreseen by the new architecture will allow improving the spike filtering at the trigger level by exploiting shower shape variables currently used offline. Fig. 6 shows the spike rejection factor achievable when the “Swiss-cross” variable can be defined starting from the single crystal information. This algorithm compares the energy deposited in the most energetic crystal (C_1) with the sum of the energies of the four crystals that share one side with C_1 . Efficiencies close to the target level of performance can be attained. The plot also shows that the performance of the Swiss-cross algorithm degrades at high integrated luminosity due to the increase of the APD noise. Cooling the APDs as described in section III will reduce the noise due to the dark current; this will bring the spike killing performance after 3000 fb⁻¹ to the level corresponding to the 1000 fb⁻¹ curves in Fig 6.

Fig. 6. Improved efficiency/rejection performance achievable when the single crystal information is used to reject spike via the “Swiss cross” algorithm described in the text. The plot is computed for spike and $Z \rightarrow ee$ samples, a mean pileup of 140, for L1 candidates with an E_T threshold of 15 GeV and for two different integrated luminosity scenarios.

Further suppression of spikes can be achieved by measuring the time of the signals. Spike signals are generally faster than EM shower signals since they do not have scintillation component. Timing is already used in the CMS offline reconstruction to reject spikes. The modification of the pulse shaping proposed for the new VFE will allow the implementation this algorithm online.

B. Out-of-time pileup mitigation

In the high-pileup environment of the HL-LHC the pulse shape of ECAL channels will be distorted by pileup events from previous bunch crossings (out-of-time pileup). Shortening the signal shaping time by upgrading the VFE will help to mitigate the out-of-time pileup effect.

V. PRECISION TIMING MEASUREMENT CAPABILITY

Precision time measurements are becoming more and more important for calorimeters which have to operate in hadron collider at high luminosity. The main reason is that they allow the subtraction of energy that enters the electron and photon clusters due to pileup events. Moreover, in CMS they could improve the estimation of the production vertex location in di-photon events. In the ECAL barrel this capability can be included in the design of the new Front End electronics or by adding a dedicated timing detector in front of the existing one. R&D projects to develop precise timing measurement devices in the framework of calorimetry for future HEP experiment are ongoing. CMS is building on these works, to determine if practical and cost-effective solutions exist for a dedicated timing measurement detector.

VI. CONCLUSIONS

The HL-LHC environment poses severe requirements to the CMS detector and trigger system. The high radiation damage is not problematic for the ECAL Barrel crystals, even in the highest η region. However, the energy resolution will be degraded by the increase of the APD noise. To reduce this effect the possibility to lower the ECAL operating temperature is considered. Moreover, an upgrade of the ECAL barrel electronics is necessary to cope with the HL-LHC CMS L1 trigger requirement. The new proposed architecture will allow single crystal readout at 40MHz. All buffers and triggering will be moved off detector and the full ECAL granularity will be available for the L1 trigger. Notably, this will improve the filter of anomalous signals. Upgrading the VFE will allow shorter signal shaping time to mitigate pileup and noise. With the planned upgrades the CMS ECAL Barrel will continue functioning well during the extreme conditions of the HL-LHC.

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