The Compact Muon Solenoid Experiment
Conference Report

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

02 October 2017 (v2, 10 October 2017)

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

Arash Jofrehei for the CMS Collaboration

Abstract

The Compact Muon Solenoid Experiment (CMS) is operating at the Large Hadron Collider (LHC) 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 CMS ECAL crystal calorimeter upgrade and present results from the 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 collisions. Precision timing can be exploited to reduce the effect of the pile-up. We report on the timing resolution studies performed with test-beams. We discuss the new readout and trigger electronics, which must be upgraded due to the increased trigger and latency requirements at the HL-LHC.

Presented at *SCINT2017 14th International Conference on Scintillating Materials and their Applications*

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

Arash Jofrehei, Institute for Research in Fundamental Sciences, Sharif University of Technology

On behalf of CMS collaboration

Presented at SCINT2017: 14th International Conference on Scintillating Materials and their Applications

Abstract—The Compact Muon Solenoid Experiment (CMS) is operating at the Large Hadron Collider (LHC) 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 CMS ECAL crystal calorimeter upgrade and present results from the 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 collisions. Precision timing can be exploited to reduce the effect of the pile-up. We report on the timing resolution studies performed with test-beams. We discuss the new readout and trigger electronics, which must be upgraded due to the increased trigger and latency requirements at the HL-LHC.

Index Terms— Compact Muon Solenoid, electromagnetic calorimeter, High-Luminosity Large Hadron Collider, upgrade

I. INTRODUCTION

THE CMS electromagnetic calorimeter (ECAL) is made of homogeneous lead tungstate crystals. It is compact, hermetic within the pseudorapidity region $|\eta| < 3$, radiation tolerant, and fine grained ($\Delta\eta \times \Delta\phi = 0.0174 \times 0.0174$) [1-3]. The ECAL played a crucial role in discovery of the Higgs boson especially in the di-photon decay channel for which an invariant mass resolution of around 1% was achieved. During the next phase of LHC, namely HL-LHC, much higher luminosity will be provided ($5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ instantaneous, 250 fb^{-1} integrated per year and 3000 fb^{-1} in total). Having six times more data enables us to precisely investigate many interesting processes like di-Higgs production which will shed light on the vacuum stability of universe. It also facilitates many other beyond standard model analyses. The cost would be six times more radiation damage and up to five times more pile-up. Therefore, ECAL must undergo an upgrade to mitigate these effects and maintain the same performance as phase 1 [4].

II. LONGEVITY OF CRYSTALS AND APDS

A. Lead-tungstate Crystal Longevity

The effect of radiation on lead-tungstate crystals has been analyzed [5]. Even though the main scintillation process is not affected by radiation, electromagnetic and hadronic damages cause transparency loss in the crystals. Defects from gamma radiation are temporary and anneal in room temperature. Transparency loss due to electromagnetic radiation reaches an equilibrium which depends on annealing and dose rate. The effect on transparency is continuously measured using a light injection monitoring system [6].

Hadrons can cause permanent transparency loss in the crystals by melting small volumes and creating fission tracks [7-9]. This effect occurs when hadrons above tens of MeV

Fig. 1. Simulated relative response of end-cap crystals as a function of pseudorapidity and for different integrated luminosities. The ECAL end-cap is planned to be fully replaced by high granularity calorimeter (HGCal)

interact with heavy nucleons in the crystal.

Longitudinal uniformity of light collection has been achieved by depolishing one of the crystal faces [10]. Due to permanent transparency loss, light is more collected when emitting point is close to photodetectors. This nonuniformity increases the constant term of energy resolution. Moreover, transparency loss decreases the overall light collection and signal to noise ratio which increases the stochastic and noise term of energy resolution respectively.

Hadron damage is much higher in the end-caps so they will be replaced by high granularity calorimeter (HGCAL). In the barrel, the transparency loss is less than 50% and tolerable. Fig. 1 illustrates the simulated foreseen transparency loss in the end-cap region as a function of integrated luminosity.

B. APD Longevity

The APDs are tolerant of high levels of gamma radiation, so the quantum efficiency of their surface will remain the same during HL-LHC [11]. However, APDs will suffer from hadron induced bulk damage leading to an increase in dark current. The electronic noise depends on the square root of this dark current. Without any intervention, the noise will increase by a factor of ten during HL-LHC. Since the bulk dark current strongly depends on temperature, the plan is to lower the temperature from 18°C to 9°C. Fig. 2 shows the reduction in dark current by lowering the temperature.

Fig. 2. APD dark current as a function of integrated luminosity in different temperatures.

III. ECAL BARREL ELECTRONICS UPGRADE

The main motivation for barrel electronics upgrade for HL-LHC is the increase of CMS Level 1 trigger rate from 150 kHz to 750 kHz and the latency from 6.4 μ s to 12.5 μ s. Both front-end and back-end electronics must be upgraded to cope with these conditions. As mentioned in the previous section, the APD noise will also increase. Furthermore, due to the increase

in luminosity, the number of hadron interactions with the APD bulk (spike) will increase. This results in an electromagnetic-shower-like but narrower signal compared to typical crystal scintillation. Currently, they are rejected utilizing geometrical cuts known as Swiss Cross which compares the amplitude in central crystal with four neighboring crystals [4]. This method is not sufficient in HL-LHC conditions but will be utilized independently and in parallel to the new method.

Fig. 3 schematically depicts the proposed upgrade. Barrel crystals, APDs and passive motherboards will be untouched during this upgrade. However, the very-front-end (VFE), front-end (FE), and off-detector electronics will be replaced to address the issues mentioned above.

The main solution is reducing the shaping time of the signals. As previously mentioned, the APD dark current depends on the square root of shaping time. Moreover, out-of-time pileup reduces with shaping time. Efficient discrimination between spikes and scintillation signals as well as precise measurement of arrival time will be achieved by employing a shorter shaping time.

Signals from APDs will be amplified by a dual-gain Trans-Impedance Amplifier (TIA) that gives a voltage proportional to the APD current. It has a dynamic range of 50 MeV to 2 TeV and is followed by two analog-to-digital converters (ADC) to digitize the signal with each gain to 12 bits (13 bits in total). The sampling rate will be raised from 40 MHz to 160 MHz. Amplification and high-rate sampling mitigates the increasing noise due to crystal transparency loss and APD dark current.

New radiation tolerant optical links enable us to transfer data off detector an order of magnitude faster (lpGBT and Versatile Link plus). Each FE card will send data from five VFEs (25 channels) off detector through these links with a bandwidth of up to 10 Gb/s per link. The clock distribution will also move off detector by these links. The required trigger rate and latency will be achieved by having the trigger primitives off detector.

Single channel triggering, higher sampling rate, and shorter shaping time will ensure better spike rejection.

Fig. 3. Layout of the upgrade ECAL barrel electronics architecture. Crystals, APDs, and passive motherboard will be kept. VFE and FE cards will be replaced and they will be connected to off-detector electronics through new fast links.

IV. PRECISION TIMING

Reducing the shaping time results in a faster rise time. Together with the higher sampling rate, they allow precise measurement of time-of-flight from vertices and thus precise vertex locating. In high pileup condition, this would be crucial in achieving efficient primary vertex discrimination comparable to that of LHC (about 80%). According to Fig. 4, 30 ps time resolution provides the required 1 cm vertex position precision. It can be achieved for 20 GeV showers at the start of HL-LHC and 60 GeV showers at the end of HL-LHC. Moreover, precise measurement of vertex position leads to precise measurement of angle between di-photons in Higgs studies, enhancing the mass resolution.

Fig. 4. Vertex positioning resolution as a function of time resolution. To sustain the same efficiency in vertex discrimination, vertex resolution of 1 cm corresponding to time resolution of 30 ps is required.

Fig. 5 depicts the measured energy resolution from 2016 test beam data as a function of normalized amplitude (amplitude over baseline noise rms) for different sampling rates and phases. For 80 MHz, time resolution depends on sampling phase which in principle is random. The difference between time resolution obtained from 160 MHz and 5GHz sampling rates is negligible.

Fig. 5. Amplitude resolution as a function of normalized amplitude (amplitude over baseline noise rms)

V. CONCLUSION

In order to maintain the same performance during HL-LHC, an upgrade for the CMS ECAL is required. Radiation damage in end-caps is intolerable so they will be fully replaced by a new sampling calorimeter known as HGCal. The Barrel ECAL electronics will be upgraded to cope with upcoming issues including dark current, spikes, and high pileup.

REFERENCES

- [1] CMS Collaboration, “The CMS experiment at the CERN LHC”, JINST **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [2] CMS Collaboration, “The CMS electromagnetic calorimeter project: Technical Design Report”. Technical Design Report CMS. CERN, Geneva, 1997.
- [3] CMS Collaboration, P. Bloch, R. Brown, P. Lecoq, and H. Rykaczewski, “Changes to CMS ECAL electronics: addendum to the Technical Design Report”. Technical Design Report CMS. CERN, Geneva, 2002.
- [4] CMS Collaboration, “Technical Proposal for the Phase-II Upgrade of the CMS Detector”, Technical Report CERN-LHCC-2015-010. LHCC-P-008. CMS-TDR-15-02, Geneva, June 2015.
- [5] CMS Collaboration, “Radiation hardness qualification of PbWO(4) scintillation crystals for the CMS Electromagnetic Calorimeter”, JINST **5** (2010) P03010, doi:10.1088/1748-0221/5/03/P03010, arXiv:0912.4300.
- [6] M. Anfreville et al., “Laser monitoring system for the CMS lead tungstate crystal calorimeter”, Nucl.Instrum.Meth. **A594** (2008) 292, doi:10.1016/j.nima.2008.01.104.
- [7] M. Huhtinen et al., “High-energy proton induced damage in PbWO-4 calorimeter crystals”, Nucl. Instrum. Meth. **A545** (2005) 63–87, doi:10.1016/j.nima.2005.01.304.
- [8] G. Dissertori et al., “A Visualization of the damage in Lead Tungstate calorimeter crystals after exposure to high-energy hadrons”, Nucl. Instrum. Meth. **A684** (2012) 57–62, doi:10.1016/j.nima.2012.04.069, arXiv:1202.0403.
- [9] P. Lecomte, D. Luckey, F. Nessi-Tedaldi, and F. Pauss, “High-energy proton induced damage study of scintillation light output from PbWO4 calorimeter crystals”, Nucl. Instrum. Meth. **A564** (2006) 164–168.
- [10] E. Auffray et al., “Crystal conditioning for high-energy physics detectors”, Nucl. Instrum. Meth. **A486** (2002) 22–34, doi:10.1016/S0168-9002(02)00670-8.
- [11] D. Bailleux et al., “Hamamatsu APD for CMS ECAL: Quality insurance”, Nucl. Instrum. Meth. **A518** (2004) 622–625, doi:10.1016/j.nima.2003.11.102.