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Precision Crystal Calorimetry at High Energy and High Luminosity CMS ECAL Performance at 13 TeV and Upgrade Test Beam studies

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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. The instantaneous luminosity during this LHC Run II is expected to exceed $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in routine operation. In this talk we present detailed performance results from the 2016 data (LHC). We review the design and R and D studies for the CMS ECAL crystal calorimeter upgrade and present first test beam results. In the harsh radiation environment, the increasing data rates and the extreme level of pile-up events, up to 200 simultaneous proton-proton collisions. We present test beam results on hadron irradiated PbWO₃ crystals and the status of the new readout and trigger electronics R and D. The pile-up mitigation may be substantially improved.

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Precision Crystal Calorimetry at High Energy and High Luminosity: CMS ECAL Performance at 13 TeV and Upgrade Test Beam Studies

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Abstract—The Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) is currently operating with proton-proton collisions at 13 TeV center-of-mass energy and at a bunch spacing of 25 ns. Achieving and maintaining excellent energy resolution for electrons and photons is of primary importance for the CMS physics program for Standard Model measurements and beyond Standard Model searches. In this paper we review the current performance of the electromagnetic calorimeter (ECAL) of CMS during the LHC Run II period, highlighting the improvements with respect to the previous period of data-taking.

The running conditions in 2016 provide a preview of the challenges that will be faced during the high luminosity phase of LHC (HL-LHC). This phase will impose stringent performance requirements on radiation hardness and pileup resilience that will require an upgrade of the current ECAL detector. We review the design and R&D studies for the CMS ECAL crystal calorimeter upgrade, focusing mostly on the upgrade of the central (barrel) part of the detector.

A prototype of the new detector (a matrix of the same scintillating crystals used in ECAL) equipped with new readout electronics, has been built and tested with high-energy electron beams to study the performance of the upgraded ECAL. The encouraging results of these first tests are reported here.

I. INTRODUCTION

PHOTONS and electrons in CMS are revealed using an homogeneous scintillating crystal calorimeter. The CMS ECAL consists of lead tungstate (PbWO_4) crystal arranged in a cylindrical structure around the interaction point. In the region of the detector, termed the barrel ($|\eta| < 1.48$), crystals are read out by Avalanche Photo-Diodes (APDs) while in the two endcaps (EE), Vacuum Photo-Triodes (VPTs) are used [1].

The purpose of ECAL is to measure with extreme precision the energy of photons and electrons, from hundreds of MeV up to the TeV scale.

II. ECAL CURRENT PERFORMANCE

Good ECAL energy resolution is crucial for many physics analyses of paramount importance for the CMS physics program. The excellent ECAL resolution achieved to date played a key role in the discovery of the Higgs boson through the $H \rightarrow \gamma\gamma$ decay channel and in the measurement of its couplings to other particles. Moreover, it is fundamental in many searches for physics beyond the Standard Model (BSM) such as high-mass resonances or final states with energetic photons or electrons.

The performance of ECAL must be robust to increases in LHC luminosity and pileup (PU - the number of concurrent interactions per colliding LHC bunch). The current period of data taking, LHC Run II, is characterised by an instantaneous luminosity of 1.0 to $1.5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ and an average PU of up to 50. These values are approximately a factor of two larger than those experienced in Run I, and exceed the design parameters of the LHC. New techniques and technologies have been developed to maintain the energy resolution and trigger performance at higher PU [2]. A more efficient electromagnetic trigger algorithm and a new method for pulse shape reconstruction, which effectively suppress contributions from out-of-time pileup events, have been developed. As a result, the excellent performance of the ECAL achieved during Run I has been maintained: the photon energy resolution is between 1 and 3% in the barrel region and better than 4.5% in the endcaps. This allowed to improve the precision on Higgs measurements and to set stringent constraints on many BSM models.

The LHC program foresees a high-luminosity phase (HL-LHC) starting from 2026. Under these conditions the PU will rise substantially to become a major challenge for LHC experiments. The performance degradation due to higher particle fluences will lead to an upgrade of the current ECAL detector.

III. ECAL UPGRADE

The proposed operating scenario for HL-LHC is to provide collisions with an instantaneous luminosity of $5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ and to deliver 250fb^{-1} of data per year for a further 10 years of operation, accumulating a total dataset of about 3000fb^{-1} . The expected pileup level is a factor of five larger than the current Run II values, and unprecedented levels of radiation will be reached in the ECAL region (at $|\eta| = 2.6$, ionising radiation, up to 30 Gy/h, and hadron fluences up to $2 \times 10^{14} \text{cm}^{-2}$).

A substantial upgrade of the full CMS detector is required, to maintain performance during the HL-LHC phase [3]. Different strategies are foreseen for EB and EE, since in the EE region the radiation dose is roughly two orders of magnitude bigger with respect to EB. The endcaps will be therefore completely replaced by an high-granularity silicon-based detector, while the EB will remain, since the lead tungstate crystals and APD will remain performant at HL-LHC, but a full upgrade of the readout electronics is required.

Fig. 1. Schematic representation of CMS ECAL readout electronics.

This paper focuses on the design and testing of the upgraded readout electronics for EB.

A. ECAL barrel electronics upgrade

The basic readout unit of EB detector is a “trigger tower (TT)”, i.e. a matrix of 25 crystals readout by APDs. The APDs are connected, through a passive connector (motherboard), to the very front-end (VFE) electronics which contains pulse amplification, shaping and digitization functions. Each VFE has 5 channels, and 5 VFE are needed for each TT. Amplified and shaped signals from the VFE are passed to the front-end (FE) card where the trigger primitives are formed and where trigger and data signals are transmitted to the off-detector electronics via high-speed optical links. This readout scheme is sketched in Figure 1. The crystals, APDs and trigger towers are organised into supermodule units, each corresponding to 1700 crystals. The ECAL barrel is composed of 36 such supermodule units, for a total of 61200 crystals.

The main motivation for the upgrade of EB is to match the increased Level-1 trigger requirements for HL-LHC. These requirements, which envisage a maximum Level-1 trigger rate of 750 kHz and a trigger latency of about 12.5 μ s, are needed to maintain the current triggering thresholds at HL-LHC. Since there is insufficient bandwidth and buffering in the current EB readout to satisfy these requirements, it will be necessary to completely replace the VFE, FE and off-detector electronics.

The opportunity will be taken to mitigate several radiation and pileup induced effects that affect ECAL performance: mitigate the increase in APD noise, improve the rejection of anomalous APD signals, and improve the timing resolution of the electronics.

The principal concern for the APDs at HL-LHC is hadron damage, since hadron can create defects in the silicon bulk that will cause an increase in dark current and thus electronic noise. To compensate for this effect an upgrade of the cooling system is foreseen, since the dark current is strongly dependent on temperature. The plan is to reduce the cooling temperature down to 10 or 8°C (currently ECAL is operated at 18°C) reducing the dark current by a factor of two, and the electronic noise by a factor of $\sqrt{2}$.

In ECAL, the Level-1 trigger algorithm is affected by “spike” events. A spike is an anomalous isolated signal, not due to an electromagnetic shower but to particles (mainly hadrons) striking the APDs and occasionally interacting causing anomalous signals through direct ionization of the silicon. The rate of these events will increase dramatically at HL-LHC and the current rejection algorithm will lose efficiency. The plan to mitigate this effect is to include the single crystal energy measurement (instead of the sum over a trigger tower) in the trigger algorithm and to design a VFE with fast shaping, able to tag anomalous signals directly from the APD signal.

CMS studies have shown that a precise timing measurement of high energy photons (~ 30 ps resolution for photons with energies of $O(10)$ GeV) can significantly improve pileup mitigation and resolution of the primary vertex determination at HL-LHC intensities [7]. It is therefore highly desirable to design the pulse shaping and digitization in the upgraded EB VFE to provide such precise timing measurement capabilities.

IV. EB UPGRADE BEAM TEST

A. Test setup and goals

In order to test the performance of the upgraded electronics readout, a matrix of 30 $PbWO_4$ crystals has been built and tested with high energy electron and pion beams (between 20 and 200 GeV) in the H4 beam line at CERN SPS. A photograph of the $PbWO_4$ crystals inside a cooled copper block can be seen in Figure 2.

The matrix has been equipped with the first prototypes of the VFE boards, based on the Transimpedance Amplifier (TIA) architecture. The aims of this beam test, which took place in Summer 2016, were:

- 1 The detailed study of APD pulse shapes, for both scintillation and spike events.
- 2 The measurement of the temperature dependence of the pulse shape.
- 3 The determination of intrinsic timing performance of $PbWO_4$ crystals.

B. Results

1) *Pulse shape studies:* In order to study in detail the electronics response, the signal output has been sampled using a high-frequency digitizer, operating at 5GS/s. This feature allowed a detailed study of the crystal response to be made as

Fig. 2. CMS prototype crystal matrix for upgrade studies.

a function of beam energy (to check the electronics stability) and crystal temperature.

The APD pulse shape variation with temperature is an important parameter for HL-LHC performance simulations. The pileup mitigation strategies for HL-LHC use a template fit to subtract the out-of-time pileup and therefore require a good knowledge of the pulse shapes of individual crystals.

Several electron runs have been taken on the same crystals lowering the temperature from 18 to 6 °C. The average pulse shapes acquired at different temperatures can be seen in Figure 3.

Fig. 3. Average pulse shapes for electron beams impinging on the central crystal of the prototype matrix. Pulse shapes acquired at different temperature are shown in different colors.

2) *Spike rejection*: Spike signals in the APDs have been induced using high energy hadron beams. Figure 4 shows a comparison of APD pulse shapes induced by spike and scintillation signals. The TIA architecture applies minimal shaping to the APD pulse and the characteristic difference

between the pulse shapes of spike and scintillation-induced signals can be clearly seen. Further simulation studies will be performed, using these measured pulse shapes, to quantify the spike rejection power of the TIA design in HL-LHC conditions.

Fig. 4. Comparison of APD pulse shape for spike and scintillation events. The pulse shape for spike (scintillation) events is shown in red (blue).

3) *Timing performance*: The timing performance of the new electronics has been evaluated for a single crystal at the centre of the experimental matrix. The timing resolution, measured with high energy electrons, is obtained by comparing the time of the APD pulse at the rear face of the crystal (t_{APD}) with a reference measurement made at the front face (t_{REF}). The time resolution is defined as the width of the distribution of ($t_{APD} - t_{REF}$), measured event-by-event.

The quantity t_{APD} is extracted using a template fit to the acquired pulse shape. Since the signal is acquired at high sampling frequency, different sampling frequencies can be emulated and the corresponding timing performance compared.

The reference time (t_{REF}) is measured using a Micro-Channel plate (MCP) sensor placed in front of the matrix. This is a fast detector able to measure the time-of-flight of particles with an excellent resolution of about 20 ps.

Figure 5 shows the timing resolution plotted as a function of the pulse amplitude divided by the level of electronic noise (A/σ). Different colors and markers correspond to different sampling frequencies ranging from 5 GS/s to 80 MS/s. The blue line is a fit to the 160MS/s experimental points, which is the baseline sampling frequency of the TIA architecture. From the results, it can be seen that:

- 1 No significant resolution degradation is observed when passing from high sampling frequency to 160MS/s
- 2 A 30 ps resolution is achievable at $A/\sigma \sim 250$, which corresponds to a 25 GeV photon at HL-LHC start, and a 60 GeV photon at the end of HL-LHC data taking.

For the 80MS/s sampling frequency two different sampling phases have been used: top (sampling close to the pulse peak) and edge (sampling on the pulse rising edge). It can be seen from the plot that the performance with 80 MS/s sampling is strongly dependent on the sampling phase.

Fig. 5. Timing resolution as a function of normalized amplitude for different sampling frequencies. See text for details.

C. Conclusions

The CMS electromagnetic calorimeter has performed well during LHC Run II, during which time the intensity of the LHC beams has increased to beyond the original design values. It has yielded precise energy measurements of electrons and photons that have played a leading role in many analyses crucial to the CMS physics program.

For the future High Luminosity phase of LHC, an upgrade of the detector will be needed to maintain the same performance in an environment with unprecedented levels of pileup and radiation. A first prototype of the upgraded detector has been built and tested with high energy electron beams at the CERN SPS beam line. This prototype of 30 crystals has been equipped with a first version of the upgraded VFE boards. Preliminary results of this beam tests are encouraging. They demonstrate good performance on many of the key features for the upgraded detector (stability in energy measurement, spike and scintillation separation, timing performance).

Further tests are envisaged in the next several years. The test matrix will be equipped with evolved prototypes of the VFE and FE readout boards and the performance of the upgraded detector in HL-LHC conditions will be extrapolated from the results of these tests.

REFERENCES

- [1] CMS Collaboration, *CMS, the Compact Muon Solenoid: Technical proposal*, CERN-LHCC-94-38
- [2] CMS Collaboration, *CMS ECAL first results with 2016 data*, CMS-DP-2016-031, Jun 2016
- [3] CMS Collaboration, *Technical Proposal for the Phase-II Upgrade of the CMS Detector*, CERN-LHCC-2015-010, Jun 2015
- [4] CMS Collaboration, *The CMS electromagnetic calorimeter project: Technical Design Report*, CERN, Geneva, Technical Design Report CMS, 1997

- [5] CMS Collaboration, *Energy calibration and resolution of the CMS electromagnetic calorimeter in pp collisions at $\sqrt{s} = 7 \text{ TeV}$* , J. Instrum, CMS-EGM-11-001. CERN-PH-EP-2013-097, 8, P09009. 51 p, Jun 2013, arXiv:1306.2016
- [6] CMS Collaboration, *Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at $\sqrt{s} = 8 \text{ TeV}$* , J. Instrum, CMS-EGM-14-001. CERN-PH-EP-2015-006, 10m P08010. 59 p, Feb 2015, arXiv:1502.02702
- [7] Daniele del Re, *Timing performance of the CMS ECAL and prospects for the future*, Journal of Physics: Conference Series, 587, 1, 012003, <http://stacks.iop.org/1742-6596/587/i=1/a=012003>, 2015