The Compact Muon Solenoid Experiment

Conference Report

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The CMS High Granularity Calorimeter for High Luminosity LHC

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Abstract

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The CMS High Granularity Calorimeter for High Luminosity LHC

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Abstract

The CMS experiment at CERN will undergo significant improvements during the Phase-II Upgrade to operate with a 10-fold increase in luminosity and the associated event pileup of the High Luminosity LHC (HL-LHC). The forward calorimetry will be exposed to very high radiation levels and the CMS collaboration is designing a new calorimeter, the High Granularity Calorimeter (CE), to replace the existing endcap calorimeters. It will have higher transverse and longitudinal segmentation for both electromagnetic (CE-E) and hadronic (CE-H) sections to facilitate particle-flow reconstruction. The fine structure of showers can be measured and used to enhance particle identification, whilst still achieving good energy resolution. The CE-E, and a large fraction of CE-H, will be based on hexagonal silicon sensors produced from 8-inch wafers, each with several hundreds of individual cells of 0.5 - 1 cm² cell size. The remainder of the CE-H will be based on highly-segmented scintillators read out with SiPMs. An overview of the CE project presented in this paper is focused on the silicon sensors covering motivation, engineering design, expected performance and the current status of prototypes, from lab measurements to beam tests.

Keywords: LHC, CMS, upgrade, silicon, calorimeter

1. Motivation

Due to begin operation in 2026, the HL-LHC will achieve instantaneous proton-proton luminosities of $5\text{--}7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, corresponding to a peak of 140–200 pp interactions per 25 ns bunch crossing, or *pileup*. It is expected that 3000–4500 fb⁻¹ will be collected within a ten-year run period, yielding an HL-LHC dataset approximately one order of magnitude larger than the projected final LHC dataset. With this data, CMS will conduct precision measurements of the Higgs couplings, searches for rare processes predicted by extensions of the standard model (SM), and studies of rare SM processes, among other programs.

Significant upgrades to the CMS detector [1] are necessary to exploit the increased instantaneous and integrated luminosity to achieve HL-LHC physics goals. In particular, the identification of Higgs particles produced in vector boson fusion (VBF) and the measurement of the WW scattering cross section place specific demands on the performance of the endcap calorimeter covering $1.5 < |\eta| < 3.0$, as these processes both have by two jets in the final state separated by a large rapidity gap. The endcap calorimeter is also essential for the missing transverse energy (ME_T) reconstruction, compulsory in searches for dark matter particles, among many other analyses.

One of the design goals of the CMS Phase 2 upgrades is to maintain similar performance to the current detector with 200 pileup interactions instead of 50. Achieving this goal requires a complete replacement of the current endcap calorimeter system, among other detector upgrades, driven mainly by a radiation-induced loss of transparency of the lead tungstate (PbWO₄)

scintillating crystals of the electromagnetic section [1]. This, along with confusion from multiple pileup energy deposits in a single crystal, leads to an unacceptable worsening of the prompt, unconverted photon energy resolution in the endcap from ~3% to as high as 24% depending on $|\eta|$ [1]. Therefore, CMS is designing and prototyping a replacement endcap calorimeter [2] with large longitudinal and transverse readout granularity. Through a suitable choice of active materials along with the high channel density, the High Granularity Calorimeter (CE) is intended to reliably identify and measure jets, photons, electrons, taus, and ME_T in a high-pileup environment until the end of the HL-LHC run period.

2. Detector design

2.1. Overall design

The longitudinal cross section of one half of one endcap of the CE design is shown in Figure 1. The CE is a 52-layer sampling calorimeter with 28 layers constituting a front electromagnetic section (CE-E) of 25 electromagnetic radiation lengths (X_0) and 1.3 hadronic interaction lengths (λ_I) thickness and 24 layers composing a rear hadronic section (CE-H) of 8.5 λ_I thickness. Copper, tungsten, and lead are used as absorber materials in the CE-E, while stainless steel is used in the CE-H. Detector planes equipped with either silicon sensors or scintillator tiles with silicon photomultiplier (SiPM) readout are used. The silicon sensors will account for ~55% of the total active area, which is 1100 m². The silicon is divided into ~6 million channels with an area of either ~0.5 or ~1 cm². The CE-H design foresees ~400,000 scintillator+SiPM channels.

The total ionizing dose absorbed by the CE active materials after the full HL-LHC run period is expected to be between

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Figure 1: Longitudinal cross section of one half of one endcap of the proposed CE design. Reprinted from Ref. [2].

10^1 and 10^6 Gy [2] depending on $|\eta|$ and depth. Within this harsh radiation environment, sensitivity to the energy deposit of a single minimum ionizing particle (MIP) during the complete HL-LHC run period is required for calibration. Silicon sensors will be placed in the CE wherever the predicted signal-to-noise (S/N) ratio for single MIP in a scintillator+SiPM channel would be less than 5 after 3000 fb^{-1} of integrated luminosity. In this scheme, the minimum MIP S/N predicted in the silicon channels after 3000 fb^{-1} is between 2.2 and 4.7 [2]. The entire calorimeter will be operated at -30°C to reduce the silicon sensor and SiPM leakage currents after irradiation. The S/N values are quoted for this temperature.

The remainder of these proceedings will focus on the design and prototyping of the silicon sensors used in the CE-E and front layers of the CE-H.

2.2. Silicon sensor design

After extensive prototyping with Hamamatsu Photonics K.K. (HPK), Infineon, and Novati/Nhanced, p-type silicon has been chosen as the sensor substrate material based on considerations of performance and availability at HPK, the selected vendor. Sensors are fabricated on 8" wafers and are hexagonally shaped to utilize approximately 70% of the wafer area, leading to cost savings over a rectilinear shape. There are three sensor variants: 300- and 200- μm active thickness with 192 standard pads and 120- μm active thickness with 432 standard pads. The thinnest sensors are deployed in the regions of highest expected neutron fluence where the collected charge of the thicker sensors would be too low. The 300- and 200- μm sensors are processed on float zone (FZ) silicon that is physically thinned. In contrast, the

Figure 2: Diagram of the 192- (left) and 432- (right) pad sensor layouts. The diamond symmetry axes are shown in yellow and sensor boundaries in a black line. Contiguous cells of the same color represent trigger cell groupings. Calibration cells are omitted for clarity. Reprinted from Ref. [2].

120- μm -active-thickness sensors come from an epitaxial layer of 300 μm physical thickness.

The interior sensor pads are hexagonal with area $1.18(0.52) \text{ cm}^2$ for the 192(432)-pad sensors, while the border pads are of slightly different shapes to give straight sensor borders. In addition to the standard pads, 6(12) calibration pads with smaller area (hence smaller noise) are added to each of the 192(432)-pad sensors to ensure high MIP S/N after 3000 fb^{-1} integrated luminosity. A cartoon of the sensor layouts is given in Figure 2. The geometry of the arrangement leads to a threefold diamond symmetry that reduces the complexity of the module readout PCB and permits a straightforward grouping of trigger cells.

3. Silicon sensor prototyping

This paper focuses on sensor prototyping with HPK, which has proceeded in four phases.

2011-2014. CMS Phase 2 tracker R&D, which included a survey of process types (epitaxial vs. deep-diffused FZ vs. magnetic Czochralski), doping polarities (n-on-p vs. p-on-n), sensor thicknesses (320, 200, and 120 μm), and proton and neutron irradiation campaigns [3]. The key conclusions of relevance to the CE design concern the evolution of full depletion voltage with equivalent neutron fluence and the noise performance of p-on-n sensors after irradiation. First, since the full depletion voltage grows with fluence and sensor thickness and over-depletion is necessary for maximum charge collection, sensors thinner than 300 μm must be employed in the highest fluence regions so that over-depleted operation is permissible within a practical power and cooling budget. Second, it was found that p-on-n sensors displayed large non-Gaussian tails in the noise distribution after irradiation, leading to an early preference for n-on-p sensors [4].

2015. Neutron irradiation campaign with CE test structures, which explored 50-, 100-, 120-, 200-, and 300- μm sensor thicknesses at fluences of $\sim 0.4 - 20 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. As shown in Figure 3, it was found that above $\sim 6 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$, 100- μm epitaxial n-on-p sensors at 300 V bias collect more signal charge than 120- μm FZ n-on-p sensors at 600 V bias. This finding led to the decision to use epitaxial n-on-p sensors (of

Figure 3: Charge collection vs. neutron fluence for deep-diffused FZ 320- μm sensors (measurements below $10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$), deep-diffused FZ 200- μm sensors (measurements between $1 - 4 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$), deep-diffused FZ 120- μm sensors (measurements above $6 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$), epitaxial 100- μm sensors (measurements between $6 - 10 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$), and epitaxial 50- μm sensors (measurements above $9 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$). The vertical position of the horizontal double-arrow lines gives the charge collection before irradiation for the indicated sensor type. Reprinted from Ref. [2].

thickness 120 μm) in regions of the CE expected to receive over $2 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$ ($\sim 10\%$ of the total active area).

2016-2017. Full sensors produced on 6" wafers, a well-established process, in 128- and 256-cell variants and 300 (FZ), 200 (deep-diffused FZ), and 120 (deep-diffused FZ) μm thicknesses. Excellent performance was observed across 200 prototypes, with breakdown voltages typically above 1 kV, per-pad leakage current before irradiation of order 1 nA at 1 kV (far below a specification of $\leq 100 \text{ nA}$ per cell, $\leq 20 \mu\text{A}$ per sensor at 800 V and 20°C), and good homogeneity within sensors. A neutron irradiation campaign of these sensors has recently begun with exposures between $1.5 - 7.5 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. The measured leakage currents agree well with the Hamburg model [5] prediction and the sensors have not shown any anomalous behavior after irradiation thus far, despite an increase of per-pad current from $\sim 1 \text{ nA}$ (before irradiation) to a few μA (after irradiation). Figure 4 shows the leakage current per pad for a 128-pad 320- μm 6" sensor at 1 kV and -20°C after exposure to $1.5 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. As expected, the leakage current scales with pad area. The few- μA current gradient across the sensor is due to a known gradient in the reactor flux. Following these successful results, it was decided to port the development to an 8" production line. The larger size of the sensors minimizes the number of modules to be produced and reduces the cost.

2017 onwards. Full sensors produced on 8" wafers with final geometry (192+6 and 432+12 pads), thicknesses (300, 200, and 120 μm physical and active thickness), and processing (epitaxial for the 120- μm thickness, FZ for the rest). The 432-channel 120- μm sensors are planned but have not yet been delivered. Identification of pads with early breakdown generally agrees between HPK and lab measurements after reception. The first

Figure 4: Leakage current per pad for a 128-pad 320- μm 6" sensor at 1 kV and -20°C after exposure to $1.5 \times 10^{15} \text{ n}_{\text{eq}} \text{ cm}^{-2}$. Figure courtesy of M. Valenta.

sensors were etched with a small mask that was stepped over the area of the sensor. Sensors with the nominal full-wafer lithography were delivered in fall 2018 and show promising performance.

4. Performance

The performance of a CE-E prototype equipped with 6" sensors in different sampling configurations has been demonstrated in test beams at Fermilab and CERN in 2016. In the Fermilab test beam, there were 16 active layers interspersed with absorber for a total depth of $15 X_0$. In the CERN test beam, eight active layers were interspersed with absorber in two different configurations: active layers covering $6-15 X_0$, and active layers covering $5-27 X_0$. A MIP calibration was reliably extracted for all working pads and electrons were reconstructed with beam energies between 4 and 250 GeV/c. The GEANT4 [6] predicted and measured electron energy resolution as a function of energy was compared, indicating a good initial understanding of the detector. In addition, the resolution for time tagging the core of showers, where the energy deposited in a single pad is greater than the equivalent of 30 MIPs, was found to be better than 25 ps. More details of the 2016 test beam measurements can be found in Ref. [7].

A more comprehensive experiment in 2018 utilized three different depth configurations optimized either for electromagnetic or hadronic showers. The configuration optimized for electromagnetic showers consisted of a 28-layer CE-E (one silicon module per layer), followed by a 12-layer silicon CE-H (nine layers with seven modules per layer followed by three single-module layers). A 40-mm thick stainless steel absorber was placed between each layer. Behind the silicon layers was a 39-layer scintillator+SiPM hadronic calorimeter prototype provided by the CALICE collaboration [8].

Figure 5: Reconstructed energy deposits in a single silicon sensor pad for two MIP selection algorithms (black and red histograms, with the red histogram representing a tighter selection than the black). The pad equivalent S/N is approximately 3. The red curve shows a Landau fit to the red histogram to extract the most probable value of the conversion factor between measured ADC counts and energy deposited by a single MIP.

Figure 5 shows some preliminary results of the reconstruction of MIP energy deposits in a single pad resulting in an equivalent S/N of 3. This measurement, taken with special low gain electronics settings, demonstrates that calibration with MIPs should be possible late in the HL-LHC run period even after irradiation has significantly reduced the S/N of each pad. Most data were taken with settings for which the silicon pad S/N was well above five. Figure 6 shows the predicted and measured electron energy resolution as a function of energy.

5. Conclusions and outlook

The CE silicon sensor R&D already performed has demonstrated that most of the specifications are achievable. The remaining R&D, including a pre-series campaign, is expected to come to a close by the start of 2021, at which point production will begin in earnest. Sensor production should end by 2023, with the full CE detector assembled and ready for commissioning by 2025. The CE will play a critical role in HL-LHC physics due to its utility in particle flow reconstruction. With a careful deployment of active materials incorporated into its design, the CE detector should perform reliably up to an integrated luminosity of 3000 fb^{-1} . A product of many years of R&D, the CE will be a first of its kind in collider physics.

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Figure 6: Predicted (red circles) and measured (black triangles) electron energy resolution as a function of energy for the 2018 test beam.

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