The Compact Muon Solenoid Experiment

Conference Report

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Status of the CMS High Granularity Calorimeter

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Abstract

Calorimetry in high-energy physics is rapidly evolving, with new specifications (e.g. higher energies, enormous particle densities) and a wide variety of technologies being employed, both for signal creation and detection. Advances in large-area highly-segmented detectors based on, for example, silicon and scintillators, are providing possibilities for high-granularity calorimetry, providing unprecedented levels of information from particle showers. This talk focuses on one example of high-granularity calorimetry The CMS HGCAL, being designed to replace the existing endcap calorimeters for the HL-LHC era. It is a sampling calorimeter, featuring unprecedented transverse and longitudinal readout segmentation for both electromagnetic (CE-E) and hadronic (CE-H) compartments. This will facilitate particle-flow calorimetry, where the fine structure of showers can be measured and used to enhance pileup rejection and particle identification, whilst still achieving good energy resolution. The CE-E and a large fraction of CE-H will use silicon as active detector material the sensors will be of hexagonal shape, maximizing the available 8-inch circular wafer area. The lower-radiation environment will be instrumented with scintillator tiles with on-tile SiPM readout. This concept borrows heavily from designs produced by the CALICE collaboration - calorimetry for linear colliders - but the challenges of such a detector at a hadron collider are considerably larger than at the linear colliders. In addition to the hardware aspects, the reconstruction of signals - both online for triggering and offline - is a quantum leap from existing detectors. We present the reasoning and ideas behind the HGCAL, its current status including design and expected performance, and the challenges ahead.

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HGCAL is a sampling calorimeter, featuring unprecedented transverse and longitudinal readout segmentation for both electromagnetic (CE-E) and hadronic (CE-H) compartments. This will facilitate particle-flow calorimetry, where the fine structure of showers can be measured and used to enhance pileup rejection and particle identification, whilst still achieving good energy resolution. The CE-E and a large fraction of CE-H will use silicon as active detector material: the sensors will be of hexagonal shape, maximizing the available 8-inch circular wafer area. The lower-radiation environment will be instrumented with scintillator tiles with on-tile SiPM readout. This concept borrows heavily from designs produced by the CALICE collaboration, but the challenges of such a detector at a hadron collider are considerably larger than at the linear colliders. In addition to the hardware aspects, the reconstruction of signals - both online for triggering and offline - is a quantum leap from existing detectors.

We present the reasoning and ideas behind the HGCAL, its current status including design and prototype performance.

Index Terms—Electromagnetic calorimeter, Hadron calorimeter, calorimeter upgrade

I. INTRODUCTION

The Compact Muon Solenoid (CMS) [1] is a general-purpose detector designed to run at the highest luminosity provided by the CERN Large Hadron Collider (LHC). The CMS detector calorimeter has been designed to detect cleanly the diverse signatures of new physics through the measurement of jets, electrons and photons and by measuring missing transverse energy flow. The CMS experiment has a 3.8 T superconducting solenoidal magnet of length 13 m and inner diameter 5.9 m. The magnet determines many of the features of the CMS calorimeters because the barrel and end-cap calorimeters are located inside the coil.

The HL-LHC operational phase is scheduled to commence in the last quarter of 2026. It is planned to level the instantaneous luminosity at $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with the goal of integrating some 3000 fb^{-1} by the mid-2030s. The corresponding mean number of collisions (pileup) per bunch crossing will be 140. However, the LHC has the ability to deliver 50 % higher values for both the instantaneous and integrated luminosities. The existing forward calorimeters, the PbWO₄-based electromagnetic calorimeter and the plastic scintillator

based hadron calorimeter, were designed for an integrated luminosity of 500 fb^{-1} . The performance degradation much beyond this integrated luminosity leads to an unacceptable loss of physics performance. To withstand the radiation level and to maintain the excellent performance of its detector, the CMS collaboration will replace its endcap calorimeters. The key parameters for this new calorimeter are its capability to keep good performance even after the expected HL-LHC luminosity, a good timing resolution for pileup mitigation and a tracking capability for the application of particle flow techniques. Among several options, the CMS collaboration chose the High Granularity Calorimeter, HGCAL [2].

In addition to detailed studies of the Higgs boson and SM processes, the searches for physics beyond the SM in the HL-LHC physics program will also include reactions initiated by vector boson fusion (VBF) and those involving boosted objects giving rise to narrow (e.g. from taus) or merged jets (e.g. from hadronic decays of the W and Z bosons). A goal of the HL-LHC running, in an environment of high event pileup, is to trigger cleanly on and reconstruct the narrow VBF jets, as well as merged jets, without placing significant requirements on the rest of the event content. This should further open the domain of physics initiated by WW, WZ, or ZZ fusion.

II. DESCRIPTION OF THE HIGH GRANULARITY CALORIMETER

The High Granularity Calorimeter Endcap (CE) is a sampling calorimeter with silicon and plastic scintillators in its active parts. Figure 1 shows a schematic view of the CE. The electromagnetic compartment (CE-E) will use Cu/CuW/Pb as main absorber and hexagonal silicon sensors as active material. The silicon sensors will also be used in the innermost region of the hadronic section (CE-H) where the radiation is expected to be very high. For the outermost region of the CE-H, plastic scintillator tiles read out by on-tile SiPM will be used. The hadronic calorimeter will use steel as absorber. The full calorimeter will be situated in a single cold volume at -30°C . This calorimeter design provides the high transverse and longitudinal granularity needed for particle flow reconstruction algorithms [3].

The HGCAL group is considering 8'' silicon hexagonal sensors, with the latter being the baseline. Different depletion thicknesses of the sensors will be used, depending on the radiation field: $300 \mu\text{m}$ at the lowest radiation region, $200 \mu\text{m}$ at the medium region, and $120 \mu\text{m}$ at the highest region. Although thinner sensors have lower signal-to-noise (S/N) initially, after severe radiation damage their S/N is higher than the equivalent thicker sensor. The sensors are segmented into hexagonal cells with an area of about 1 cm^2 for the two

Fig. 1. Oblique (top) and cross-sectional (bottom) schematic views of the HGCal.

thickest sensor types and 0.5 cm^2 for the thinnest. This smaller cell size again helps improve the S/N ratio due to the lower capacitance and hence noise. In addition, each sensor has several smaller calibration cells, which have even smaller noise contributions from cell capacitance. Therefore, it is expected to keep sensitivity to minimum ionizing particles (MIP) in at least these cells even after 3000 fb^{-1} . The transition between scintillator and silicon and the tile granularity are under study, the present baseline being cells of a few cm^2 . Again, MIP sensitivity is required in the scintillator part even after 3000 fb^{-1} .

The CE-E will comprise 28 silicon and absorber layers for a total thickness of about 34 cm and $26 X_0$ (radiation lengths). Silicon sensors will be glued to gold-plated polyimide foils, in turn glued to dense copper-tungsten baseplates. A PCB hosting the front-end ASICs will then be glued on top of the silicon. This glued assembly is called a module. The signals from the silicon will be routed to the ASICs via wirebonds through holes in the PCB. Modules will be attached to both sides of copper plates, which provide additional absorber material and also contain thin pipes for CO_2 flow, to cool the detector to -30°C to mitigate the effects of radiation damage to the silicon. Motherboard PCBs will connect to the modules, containing data-concentrator ASICs as well as optical links. Lead absorbers, sandwiched between thin steel plates, are then attached on either side to form cassettes. The cassettes are the major detector subassembly of the HGCal, which are subsequently assembled into full disks in the CE-E or inserted

between absorber layers to form full disks of detectors in the CE-H. In the electromagnetic section, the absorber layers are part of the cassette and the CE-E consists of the stack of cassettes, supported by a full-disk back plate and an inner cone at the $|\eta| = 3$ boundary. In the hadronic section, the absorbers and cassettes are independent of each other. Figure 2 shows a Silicon sensor glued to a baseplate and PCB containing front-end electronics. Figure 3 shows the drawing of a CE-E cassette.

Fig. 2. A Silicon sensor glued to baseplate and PCB containing front-end electronics.

Fig. 3. Schematic view of a CE-E cassette.

The CE-H will be composed of 24 layers reaching a total thickness of about 1.5 m , corresponding to about 9λ (interaction lengths). This calorimeter will be separated into two sampling sections, with 12 layers each, using steel absorber thicknesses of 35 mm and 68 mm respectively. Unlike the CE-E in which the absorber plates are part of the cassettes, the CE-H active layers will be inserted between full disks of steel. As shown in Fig. 1 (bottom), the first layers contain only silicon modules, whilst the layers are mixtures of silicon at the innermost regions and scintillator + SiPM in the outer regions.

In order to cope with the HL-LHC conditions and provide the necessary performance of the calorimeter, the front-end ASICs have strict requirements. The first is to have a very large dynamic range, to be sensitive to the single MIPs (for calibration purposes) and to showers from TeV particles. The concept is to use traditional one-gain stages for small/medium

signals, complemented by a Time-over-Threshold (ToT) circuit for large signals. The ToT dynamic range extends the measurement up to 10 pC and its bin size (2.5 fC) corresponds to less than 4% of the charge at the switch between ADC and ToT. The front-end electronics must be radiation tolerant, up to 200 MRads and have a time of arrival (TOA) precision of better than 50 ps to mitigate event pileup. The power budget for the analog part of the front-end must be around 10 mW per channel in order not to exceed a total power budget of about 200 kW for the HGCAL.

An existing ASIC, the CALICE Skiroc2 has been used for first proof-of-concept tests of HGCAL modules [4] and a newer version was developed afterwards [5].

III. PHYSICS PERFORMANCE

One of the key aspects of the HGCAL detector is the possibility of performing highly granular imaging of particle showers in a five-dimensional space: the magnitude and timing of energy deposits are measured with three cartesian coordinates.

This granularity plays a key role for the event reconstruction in the challenging environment of the HL-LHC, especially in the high occupancy forward region of $1.54 < |\eta| < 3$ where the calorimeter will be located. For example, the Molière radius of electromagnetic shower containment in the dense CE-E part is of the order of 3 cm, whereas the cell size does not exceed 1.3 cm. The large number of longitudinal sampling layers facilitates the exploitation of the differences in the longitudinal shower development for various physics objects, such as electrons or photons and jets originating from VBF or pileup processes. Figure 4 shows the distributions of the layer number at which the cumulative longitudinal energy exceeds 10% of the total energy in a cluster for true electron clusters with and without pileup to clusters from QCD multijet showers (top) and the comparison of the relative isolation for pileup jets and jets from VBF production (bottom).

Together with the other CMS detectors such as the tracker and muon systems, the HGCAL will enable Particle Flow reconstruction to be performed with unprecedented flexibility. The reconstruction with HGCAL offers a great opportunity for novel tracking, clustering and imaging techniques using algorithmic and machine learning approaches.

IV. BEAM TESTS

Several beam tests have been performed over the last three years in order to explore the feasibility of the novel detector design of HGCAL as well as to evaluate the physics performance in prototypes [6]. These beam tests also serve to verify and optimize the physics models used for Monte Carlo simulations of this kind of sampling calorimeter with silicon and scintillator active layers. Such simulations are a key ingredient to fine-tuning the detector design in terms of mechanics, readout and trigger electronics. In addition, beam tests enable the technological prototyping of the silicon detector modules as well as the validation of fundamental architecture choices of the front-end chip: the time-over-threshold and time-of-arrival measurements.

Fig. 4. The distributions of the layer number at which the cumulative longitudinal energy exceeds 10 % of the total energy in a cluster for true electron clusters with and without pileup to clusters from QCD multijet showers (top) and the comparison of the relative isolation for pileup jets and jets from VBF production (bottom).

The hexagonal modules tested in 2016 were equipped with the Skiroc2 ASIC. A hanging-file structure was adopted to place these modules flexibly. It allows for the exploration of different sampling configurations. At FNAL, the system consisted of 16 sampling layers with a total depth of $15.3 X_0$. This configuration was tested with electrons in the energy range from 4 GeV to 32 GeV. Non-interacting protons were used to calibrate the system. At CERN, two different setups were investigated. Both of them comprised eight sampling layers. The first configuration had the modules placed between $6 X_0$ and $15 X_0$, whereas the second one covered a longitudinal depth from $5 X_0$ to $27 X_0$. Furthermore, a series of tests to demonstrate the intrinsic timing capabilities of the silicon sensors were performed at FNAL and at CERN. Irradiated diodes of varying thicknesses along with unirradiated full sensors were tested. A dedicated fast digitizer was installed to retrieve the pulse shape arising from signals in the silicon due to incident electrons on upstream absorbers.

One of the main goals of the 2016 campaign was the validation of the detector simulation using the data taken with the prototypes. Overall, an agreement with the simulated results using the FTFP_BERT_EMM Geant4 physics list at few percent level is found in terms of electron induced shower shapes, depths and energy resolutions.

Figure 5 summarises the intrinsic timing precision of an unirradiated full sensor. As an estimate of that precision, the time difference between pairs of neighbouring cells on the sensor was computed for different incident electron energies. The timing precision is displayed as a function of the effective signal-to-noise ratio, which is defined as

$$(S/N)_{eff} = \frac{(S/N)_{ref}(S/N)_n}{\sqrt{(S/N)_{ref}^2 + (S/N)_n^2}} \quad (1)$$

where ref refers to the reference diode, compared against diode n. It is shown that the intrinsic timing resolution does not depend significantly on the incident particle's energy at a given signal-to-noise ratio. A precision of better than 20 ps was achieved for effective signal-to-noise ratios larger than 100, compatible with the precision measured with single diodes.

Fig. 5. Resolution on the time difference between neighbouring hexagonal cells of a 6'' 300 μm thick p-on-n hexagonal silicon sensor, as a function of the effective signal to noise ratio.

In 2017, the setup has been extended by a hadronic section, which consisted of steel as absorber. The tested modules were equipped with the Skiroc2-CMS ASIC. Dedicated readout boards have been designed and fabricated. Multiple modules were connected to one readout board through HDMI cables. A dedicated synchronisation board provided a common clock to the readout chips and distributed the trigger signal. Data were taken at CERN SPS in July and October 2017. A few sampling layers were used for the main test in July. In order to mimick the scintillator-based hadronic part, the modified 5 interaction length version of CALICE AHCAL prototype was placed downstream of the silicon modules and was read out in parallel.

Three test beam campaigns were performed in 2018. The first took place in March at the DESY beam facility and served to study the response of single silicon modules to low energy electrons using precise tracking with a beam telescope

providing up to 10 μm precision on the impact position. In June and October, a major setup comprising 28 single-module layers of the ECAL part was tested at the CERN SPS beam facility. The modules were arranged in double-sided cassettes with active cooling similar to the foreseen detector design. Data were taken with beams of muons, electrons and pions in a wide energy range from 10 to 150 GeV. In October, CE-E prototype with all 28 layers, CE-H 62 Si modules (12 planes) followed by 39 planes ($72 \times 72 \text{ cm}^2$) of CALICE scintillator SiPM-on-tile prototype were tested. Timing capability for all cells were deployed for the first time. Figure 6 shows a picture depicting the test beam setup.

Fig. 6. A picture depicting 2018 setup.

Figure 7 shows the MIP signal distribution from the online DQM and Fig. 8 shows the 100 GeV electron occupancy plots for all 28 layers, where the last three layers are noisy. And finally, an event display of an 80 GeV electron is shown in Fig. 9. The analysis of the 2018 data is ongoing.

Fig. 7. MIP signal distribution from online DQM.

Fig. 8. 100 GeV electron occupancy plots for all 28 layers (with the last three layers being noisy).

Fig. 9. A sample event display of 80 GeV electron shower.

V. CONCLUSIONS

The CMS high Granularity Calorimeter Upgrade is taking up momentum after the approval of the TDR. Several versions of prototypes were successfully constructed and tested since the start of the project. The overall project is highly ambitious and the schedule is aggressive. The technology is largely based on silicon tracking and the Linear Collider calorimetry experience. Several CALICE groups are actively contributing. High granularity calorimeters such as HGCAL will open a new chapter in the calorimetry literature. This is an exciting time for detector and dedicated software techniques development.

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