PROCEEDINGS OF SCIENCE

The CMS HGCAL detector for HL-LHC upgrade

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The High Luminosity LHC (HL-LHC) will integrate 10 times more luminosity than the LHC, posing significant challenges for radiation tolerance and event pileup on detectors, especially for forward calorimetry, and hallmarks the issue for future colliders. As part of its HL-LHC upgrade program, the CMS collaboration is designing a High Granularity Calorimeter to replace the existing endcap calorimeters. It features unprecedented transverse and longitudinal segmentation for both electromagnetic (ECAL) and hadronic (HCAL) 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 ECAL and a large fraction of HCAL will be based on hexagonal silicon sensors of 0.5 - 1 cm^2 cell size, with the remainder of the HCAL based on highly-segmented scintillators with SiPM readout. The intrinsic high-precision timing capabilities of the silicon sensors will add an extra dimension to event reconstruction, especially in terms of pileup rejection. An overview of the HGCAL project is presented, covering motivation, engineering design, readout and trigger concepts, and performance (simulated and from beam tests).

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1. Introduction

The High Luminosity phase of the HL-LHC, expected to start in 2026, will integrate 10 times more luminosity than the LHC. This increase of luminosity is a challenge for detector radiation tolerance and for the mitigation of the extreme pileup where up to 200 collisions per bunch crossing will be expected. To withstand the radiation level and to maintain the excellent performance of its detector, the CMS collaboration [1] will replace its calorimeter endcaps. The key parameters for this new calorimeter are its capability to keep good performance even after the expected HL-LHC luminosity (3000 fb^{-1}), 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 [2].

2. The High Granularity Calorimeter Endap

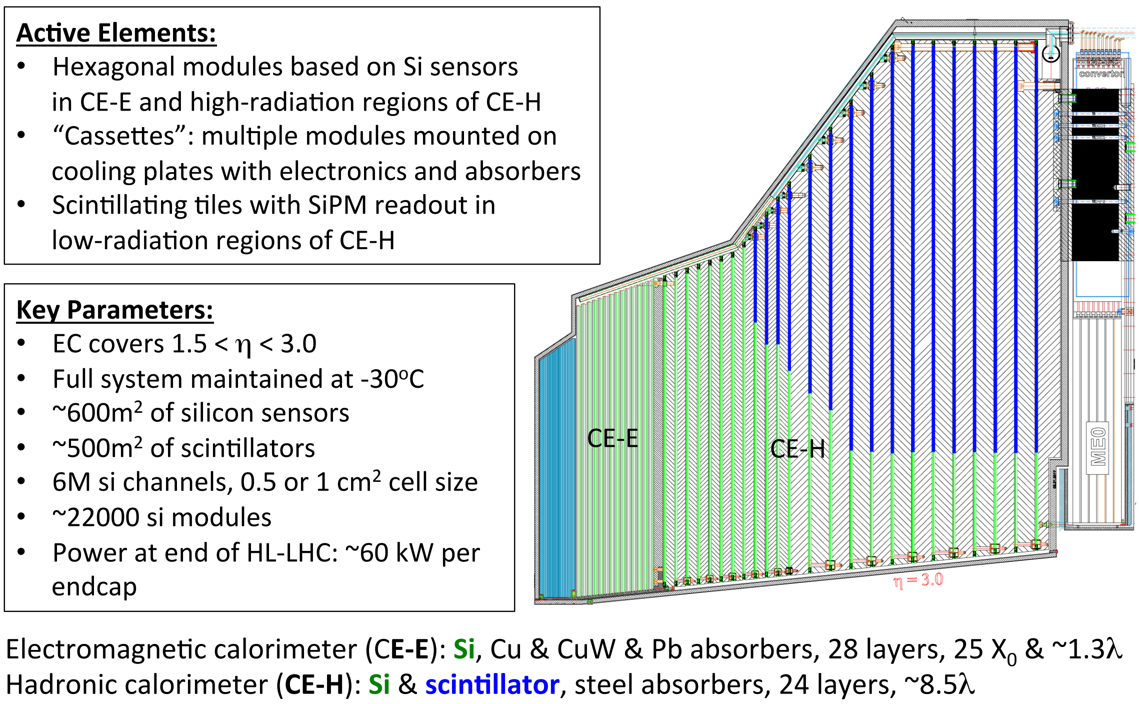

Figure 1: Schematic view and its key parameters, of the design of the CMS high granularity Encap Calorimter (CE).

The High Granularity Calorimeter Endap (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 lead 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 (up to 10^{16} neq/cm^2). For the outermost region of the CE-H, plastic scintillator tiles readout by on-tile SiPM will be used. The hadronic calorimeter will use steel as absorber. The full calorimeter will be situated in the same cold volume at

-30°C. This calorimeter design provides the high transverse and longitudinal granularity needed for particle flow reconstruction algorithms.

2.1 Active elements

The HGCAL group is considering 6" or 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 μm at the lowest radiation region, 200 μm at the medium region, and 120 μm 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 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}.

In the lowest radiation region of the CE-H, plastic scintillator tiles readout by on-tile SiPM will be used. 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}.

2.2 Mechanical design

The CE-E will comprise 28 silicon and absorber layers for a total thickness of about 30 cm and 26 X_0. 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 a 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". A schematic view of a CE-E cassette is shown in figure 2.

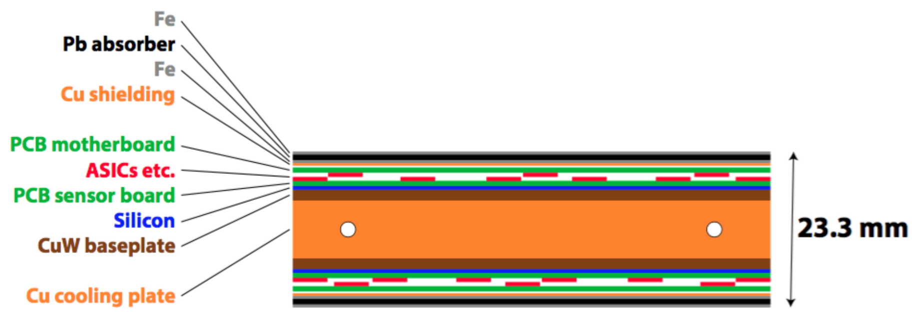

Figure 2: Schematic view of a CE-E cassette

The CE-H will be composed of 24 layers reaching a total thickness of about 1.5 m, corresponding to about 8.5 λ_I. 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 figure 1 the first layers contain only silicon modules, whilst the later layers are mixtures of silicon at the innermost regions and scintillator + SiPM in the outer regions.

2.3 Readout electronics

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 form TeV particles. The concept is to use traditional high and low-gain stages for small/medium signals, complemented by a Time-over-Threshold (ToT) circuit for large signals. The front-end electronics must be radiation tolerant, up to 150 MRads [2] 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 120 kW for the HGCAL. An existing ASIC, the CALICE SKIROC2 [3] has been used for first proof-of-concept tests of HGCAL modules (see section sec.beamtest and evolved to the SKIROC2_CMS [4], including ToA and ToT features. This has been used for 2017 beam tests. A first "HGROC" has been submitted for fabrication, in 130 nm radiation-tolerent CMOS technology.

3. Validation with prototypes in beam tests

To validate the HGCAL concept and verify the simulation of this detector, the HGCAL group has performed beam tests at FNAL and CERN in 2016 [5]. An electromagnetic calorimeter prototype has been constructed with up to 16 layers for the FNAL test and 8 for the CERN test. Each layer was composed of one hexagonal module using a 6" p-in-n silicon sensor from HPK[1]. The physical silicon thickness was 320 μm, deep-depleted to an active thickness of 200 μm. The sensors are segmented into hexagonal cells of about 1 cm^2. In addition, the sensors have two calibration cells with an area of about 1/7th of the area of the full cells. The modules included two PCBs: the first was glued and wire-bonded to the sensor, with signals routed to inline connectors. The second plugged into these connectors and hosted two 64-channel dual-gain SKIROC2 ASICs incorporating 12-bit ADCs for digital readout. For the FNAL tests, the prototype had 16 silicon-module layers with a total depth of 15.3 X_0. Beams of electrons up to 32 GeV were used for energy resolution measurements etc., with 120 GeV protons being used for calibration purposes. For the CERN tests, two 8-layer configurations were tested, with total depths of 15 and 27 X_0 respectively[2]. Electrons with energies between 20 and 250 GeV were used, as well as pions and muons for calibration.

Figure 3 (left) shows example event displays of electron showers recorded with the FNAL and the CERN prototypes. Figure 3 (right) shows the energy distribution obtained in a typical channel for a pion run. The left peak corresponds to the pedestal distribution[3] and the right to the MIP

[1] Hamamatsu Photonics, Hamamatsu, Japan

[2] We focus here on the CERN setup 2, with 27 X_0

[3] The pedestal and the common mode noise have been already subtracted from the raw data.

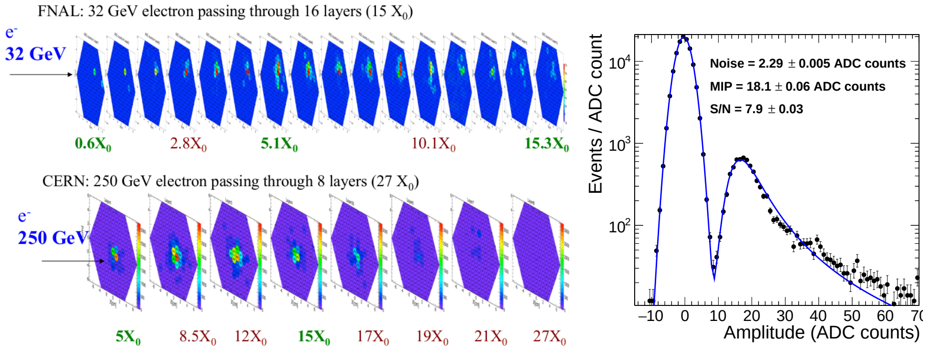

Figure 3: Left: event displays of a 32 GeV electron shower in the 16-layer prototype at FNAL (top) and a 250 GeV electron shower in the 8-layer 27 X_0 prototype at CERN (bottom). Right: distribution of the amplitude (ADC counts) of a typical channel in the first layer of the CERN prototype for runs with a pion beam.

signal. The S/N was measured to be around 7.5 for most of the channels and around 10 for the calibration cells.

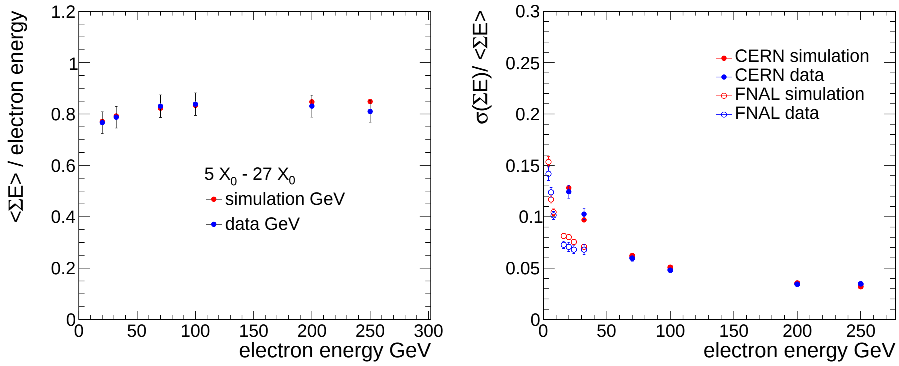

Figure 4: Linearity (left) and relative energy resolution (right) as a function of the beam energy for both data (blue) and simulation (red).

The HGCAL prototype has been simulated using the GEANT4 framework [6]. The upstream materials and all the elements of the prototype were taken into account in the simulation. Figure 4 shows the linearity and relative energy resolution as functions of the beam energy for both data and simulation. The linearity is defined as the ratio between reconstructed energy and the beam energy. The simulation overestimates the visible energy by about 15% on the full energy range, and is downscaled in figure 4. A good agreement between data and simulation is found for the relative energy resolution for both tests, giving confidence for the simulation of the final 28-layer CE-E. The 16-layer thinner calorimeter performs better for low energies than the thicker 8-layer configuration. Electron shower topology was also studied and shows an excellent agreement with the simulation [5].

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Conclusion

The CMS collaboration has embarked upon the construction of a new imaging calorimeter to cope with the challenges of the HL-LHC. The basic design has been validated and a technical design report is being written. Beam test campaigns occured in 2016 to validate the HGCAL concept and the simulation of such a detector. New prototype modules, using the SKIROC2_CMS chip, are being constructed and tested in beams at CERN. This will allow the study of important features (e.g. TOT, TOA) for the final CMS HCGAL project.

References

[1] The CMS Collaboration : *The CMS experiment at the CERN LHC*, Journal of Intrumentation, vol. 3, 2008.

[2] D. Contardo, M. Klute, J. Mans, L. Silvestris, J. Butler : *Technical Proposal for the Phase-II Upgrade of the CMS Detector*, CERN-LHCC-2015-010. LHCC-P-008. CMS-TDR-15-02.

[3] M. Bouchel *et al.* : *Skiroc : a Front-end Chip to Read Out the Imaging Silicon-Tungsten Calorimeter for ILC* , IEEE NSS-MIC Conference Record 2007, vol. 3.

[4] J. Borg, S. Callier, D. Coko, F. Dulucq, C. de La Taille, L. Raux, T. Sculac and D. Thienpont : *SKIROC2_CMS an ASIC for testing CMS HGCAL*, Journal of Intrumentation, vol. 12, 2017.

[5] S. Jain : *Construction and first beam-tests of silicon-tungsten prototype modules for the CMS High Granularity Calorimeter for HL-LHC*, Journal of Intrumentation, vol. 12, 2017.

[6] S. Agostinelli *et al.* : *GEANT4 a simulation toolkit*, Nucl.Instrum.Meth. A506 (2003) 250-303.

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