THE CMS HGCAL DETECTOR FOR HL-LHC UPGRADE

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ABSTRACT

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 LHC (HL-LHC), expected to start its operation in about ten years, will integrate 10 times more luminosity than the LHC, with the aim of pushing forward the demanding physics program of Phase II [1]. The high radiation and high pileup expected are major challenges for the current detectors, which will be upgraded to maintain excellent performance even in the harsh HL-LHC environment. As part of the HL-LHC upgrade program, the CMS collaboration will replace the existing forward calorimeters with a High Granularity Calorimeter [2], providing a unique fine grain in view of a multi-dimensional shower reconstruction. This is a fundamental upgrade for the whole detector given the important role of the forward calorimeter for physics in Phase II, it will also be crucial to complement the tracker upgrade with extended coverage in the forward region and a reduced material budget.

2 The High Granularity Calorimeter

In the mechanical design the HGCAL consists of a sampling calorimeter with silicon and scintillators as active material, including both the electromagnetic (EE) and the hadronic (FH+BH) sections [4]. A schematic view is given in Figure 1. Silicon is the main active material, it is used in the electromagnetic and innermost regions of the hadronic section, where the radiation is expected to be higher (up to $10^{16}$ n/cm$^2$). It is transversely segmented into hexagon cells of about 1 cm$^2$ surface, for a total of over 6 million channels. Plastic scintillator tiles are used in the outermost regions of FH and BH.

In the electromagnetic part, to accommodate 28 sampling layers in about 30 cm, silicon sensors are mounted on either side of a copper plate, based on the stack illustrated in Figure 2 for a total of 14 copper support plates inter-spaced by lead absorbers. The thickness of the EE part amounts to about 25$X_0$ and about 1$\lambda$. The hadronic part extends for about 1.5 m in depth and comprises 12 sampling layers in each of the FH and BH sections with stainless steel as absorber. The thickness of the hadronic part corresponds to about 3.5$\lambda$ and 5.7$\lambda$ for the FH and BH respectively, for a total of about 9$\lambda$ for the 24 layers.

![Figure 1: Schematic view of the High Granularity Calorimeter design.](image)

*To reflect the design decision and the integration in the CMS detector nomenclature, the HGCAL is most recently referred to as CE, the electromagnetic section (EE) is designated CE-E, and the hadronic section (FH and BH) is CE-H.*
3 Reconstruction at the HL-LHC

The calorimeter design, with fine granularity both lateral and longitudinal, is ideally suited for particle flow reconstruction [3], to enhance the pattern recognition in the high congestion typical of the events at the HL-LHC. Within the particle flow, the tracks reconstructed in the tracker are matched to the electromagnetic and hadronic showers individually reconstructed and identified in the calorimeter, where the high granularity is exploited to help in the separation of adjacent and almost overlapping particles. Since the HGCAL is effectively an imaging calorimeter, a 3D imaging-clustering, inspired by the article in [4], is being developed to provide efficient reconstruction, resolving individual particles in the 140/200 pileup environment of the HL-LHC. The algorithm currently proceeds in 2 steps, to first identify 2d-clusters on each layer, based on the energy-density of the cells, and then gathering into multi-clusters all the 2d-clusters found aligned along the shower axis over consecutive layers. The algorithm can be extended to more than two dimensions, to fully exploit the 5D potential of the calorimeter (energy, x- y- z-position, time).

4 Beam tests of the EE prototypes

Since the technical proposal (TP) [2], submitted at the end of 2015 with a basic design of the detector, a lot of progress has been made in the design of the mechanics and an extensive prototyping phase has started. In 2016, the first prototypes of the EE silicon hexagonal modules were tested on the beam in campaigns organized both at FNAL and CERN, with the aim to give a proof of concept of the proposed design and compare the measured performance with a detailed simulation.

4.1 The detector prototypes

The prototypes used for the beam tests made use of active layers and absorbers built in accordance to the TP design. A support system consisting of an hanging file structure was used to insert active and absorber layers so to obtain a sampling calorimeter prototype. The silicon sensors were made from 6” wafers, of 200μm depleted region, manufactured by HPK† and cut into hexagonal shape. A picture of a silicon sensor used is visible in Figure 3. The active modules were assembled as a glued stack of hexagonal components, as illustrated in Figure 4. The full module was then

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screwed to a copper plate properly shaped for insertion in the hanging file system. In Figure 5 a picture of the fully instrumented module is shown together with a sampling prototype tested at CERN. By exploiting the flexibility of the hanging file design, several sampling configurations were tested, despite the limited number of available elements: at FNAL, a 16 layer calorimeter, sampling the shower from $0.6 X_0$ to $15.3 X_0$, while at CERN two different configurations of 8 layers each, to measure the core ($6$ to $15 X_0$) and the tail of the shower ($5$ to $27 X_0$).

The thickness of these sensors is $320 \mu m$ with a depleted thickness of $200 \mu m$. The cells on the sensor, except those on the edges, are hexagonal with an area of $\sim 1 \times 1 cm^2$. There are two cells on the sensor known as calibration pads, that have an area of about 1/9th of the area of the full hexagonal cell. These cells facilitate MIP calibration after extreme irradiation, when the S/N of a standard cell may be too small to detect single MIPs efficiently. Since noise is proportional to the area of the cell (due to the cell capacitance), it will still be possible to see MIP signals in these calibration pads even at the end of HL-LHC operation.

![Figure 3: A 6" silicon sensor with 128 cells used in the 2016 beam tests.](image)

### 4.2 Response to MIP and electron showers

To calibrate the response between the cells, the modules were exposed to a beam of 125 GeV pions and 120 GeV protons, at CERN and FNAL respectively. In Figure 6 the event display of a single minimum-ionizing-particle passing through a stack of 8 layers is shown, together with the typical spectrum of the energy deposition of a MIP. By comparing the most probable value obtained for the MIP energy deposition to the noise, a $S/N \simeq 7$ is measured which is in good agreement with the expectation.

The response of the modules to electromagnetic showers was measured by exposing the prototypes to an electron beam in the energy range $[20-250]$ GeV and $[4-20]$ GeV, at CERN and FNAL respectively. In Figure 7 the shower evolution of a 250 GeV electron is shown in the 8 layers setup, when sampling the shower from $\sim 5 X_0$ to $\sim 27 X_0$. In the same figure the total energy reconstructed over each layer is plotted as a function of the depth in the shower, for all the energy points tested at CERN and it is compared to the expectation from simulation. For the energy reconstruction, a raw calibration to account for the energy lost in the absorber material is applied. As it can be noted, the shower initiated within the first $5 X_0$ is not sampled with this specific configuration tested at CERN, while it was measured in the complementary configuration with 16 layers tested at FNAL.

### 4.3 Results

Data measured at the beam test were compared to a dedicated simulation, where the geometry of the beam line and the detector components were carefully described and the analysis procedure and calibration were applied consistently on the two datasets. Shower shapes variables, such as the transverse shower profiles and the fraction of energy measured in the first layer, were compared between data and simulation. The good agreement found is an indication of the reliability of the showering model used in the simulation as well as
Figure 4: Module assembly for the test beam prototype.

Figure 5: (left) Picture of a full module assembled and mounted on a copper support plate. The full DAQ chain made of cables that carry data, control and low voltage along with the high voltage connections are also visible. (right) Six copper plates with 8 silicon sensors mounted (2 copper plates are double sided) and fully instrumented are inserted in the hanging file system. Hanging layers of lead absorbers are also visible.
of the accurate description of the upstream material. As a representative result of the analysis, in Figure 8, the relative energy resolution measured is shown as a function of the beam energy for both data and simulation, showing a good agreement between the two. Results from the test at FNAL and those obtained at CERN are displayed on the same canvas to emphasize the different sampling regimes of the two setups. The limit in the longitudinal sampling clearly limits the possible electron energy resolution achievable, which is here found at the level of few percents at the highest energies, whereas it is expected to be close to 1% at 300 GeV for the final calorimeter, where a finer sampling (∼1 X₀) will be provided.

5 Conclusions

The High Granularity Calorimeter for the HL-LHC is a very ambitious project, with an unprecedented granularity level it offers an high potential in the reconstruction to exploit the combined information of time, position and pulse-height to disentangle the very complex events that we will see at the HL-LHC. With the Technical Design Report targeted by the end of 2017, it is a critical moment for the detector design, with a main review taking place. The beam test campaign of 2016, to validate the proposed design for the EE silicon modules and provide a basic validation of the simulation was a fundamental step towards the consolidation of the design and the validation of the reconstruction algorithms. The aim of the 2017 campaign is to test
Figure 8: Relative energy resolution measured as a function of the electron energy in data and simulation, for tests at FNAL and CERN.

an extended prototype including electromagnetic and hadronic sampling layers, to measure the response to hadronic showers. Tests and data analysis are ongoing at the time of writing this proceeding.

References

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