HGCAL: A High-Granularity Calorimeter for the Endcaps of CMS at HL-LHC

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Abstract. Calorimetry at the High Luminosity LHC (HL-LHC) faces two enormous challenges, particularly in the forward direction: radiation tolerance and unprecedented in-time event pileup. To meet these challenges, the CMS experiment has decided to construct a High Granularity Calorimeter (HGCAL), featuring a previously unrealized transverse and longitudinal segmentation, for both electromagnetic and hadronic compartments. This will facilitate particle-flow-type calorimetry, where the fine structure of showers can be measured and used to enhance particle identification, energy resolution and pileup rejection. The majority of the HGCAL will be based on robust and cost-effective hexagonal silicon sensors with about 1cm$^2$ or 0.5cm$^2$ hexagonal cell size, with the final 5 interaction lengths of the hadronic compartment being based on highly segmented plastic scintillator with on-scintillator SiPM readout. We present an overview of the HGCAL project, including the motivation, engineering design, readout concept and simulated performance.

1. Introduction

The discovery in 2012 of the Higgs boson by the ATLAS and CMS experiments at the LHC [1, 2] is a major breakthrough in the understanding of the fundamental interactions. The measurements of its properties are compatible, within large uncertainties, with the ones expected by the standard model (SM) predictions. However unrevealing the true nature of the electroweak symmetry breaking will require additional measurements: percent level precision on the couplings to fundamental fields, observation of rare decays ($H \rightarrow \mu\mu$, $H \rightarrow Z\gamma$, ...), di-Higgs production and constraints on the self-coupling, forbidden decays (e.g. $H \rightarrow e\mu$), unitarization of the scattering amplitudes of longitudinally polarized vector bosons, ... In addition, if new particles are found during the Phase-I data taking period of the LHC, aiming at accumulating 300 fb$^{-1}$ by 2023, their properties will have to be determined precisely to disentangle between various models beyond SM. This physics program, in addition to precision studies in top or heavy flavour physics, provides a powerful demand on high luminosity.

The goal of the so-called Phase-II of the LHC machine is thus to accumulate 3000 fb$^{-1}$ after ten years of data taking, starting after the Long Shut-down 3 (LS3) following the end of Phase-I. The proposed operating scenario is to level the instantaneous luminosity at $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$, with potential peak value at $2 \times 10^{35}$ cm$^{-2}$s$^{-1}$. Under these conditions, the additional interactions per bunch crossing, referred to as pile-up (PU) become a tremendous challenge for the experiments with a foreseen average of 140, possibly 200, per beam crossing. Moreover, the particles emerging from the collisions and the radioactivity they induce in the material of the detectors and the on-board electronics will cause significant damage. For instance,
it has been shown with FLUKA simulations that the endcap electromagnetic (resp. hadron) calorimeter will have to sustain up to 1.5 MGy (resp. 30 kGy) of integrated dose and a fluence of $10^{16}$ $n/cm^2$. The ageing and radiations studies [3] have demonstrated the need to replace the entire calorimetric system in the endcaps during LS3.

2. HGCAL Design Overview

The new system has to be radiation-tolerant and has capability to cope with the very high PU, especially at the trigger level, where one has to preserve low thresholds for the Higgs physics while exploring the TeV scale. To address these challenges, CMS proposes the replacement of the endcap calorimeters with a new high-granularity sampling calorimeter, covering the range $1.5 < \eta < 3.0$, referred as HGCAL. His concept is inherited from ILC/CALICE concepts for 3D measurement of shower topologies, adding as well very fast timing capabilities. Its electromagnetic section (EE) consists of 28 layers of tungsten and copper plates interleaved with silicon sensors as active material, for a total of 26 radiation lengths ($X_0$) and 1.5 interaction length ($\lambda$). The hadronic part (FH) has 12 layers of brass and copper plates interleaved with silicon sensors for a total of about 3.5 $\lambda$. HGCAL will be cooled down to -30 °C via evaporating CO2 system to mitigate leakage current in silicon sensors due to radiation damage. HGCAL will be complemented by a brass-plastic scintillator backing-hadron calorimeter (BH) adding 5 $\lambda$ to ensure the full containment of showers. The overall structure can be seen in Fig. 1. Only a few key aspects are described in the following.

2.1. Sensors, Modules, Cassettes and Mechanics

Active elements in HGCAL are 8 inches (or pairs of 6 inches) hexagonal 320 $\mu$m-thick silicon sensors. Size of cells varies from 1.05cm$^2$ to 0.53cm$^2$ and Si active depletion thickness from 300 to 100 $\mu$m as the expected neutron fluence increases in order to maintain the ability to see minimum ionizing particle signal (MIP) with a decent signal-to-noise ratio. It is foreseen to read about six millions channels.

Sensors are mounted on printed circuit boards (PCB), with front-end chip bonded to it, and glued on the other face to a copper-tungsten baseplate to form a module (Fig. 3). The connection to the sensors cells will be made with wire-bonding through suitable holes in the PCB.
Modules will be mounted on a 6mm-thick copper plate with embedded stainless steel pipes for cooling, thus making a 30° wedge “cassette” (Fig. 4). Services and power will be routed in a 2mm air-gap. Cassettes in EE (resp. FH) are double-sided (resp. single-sided).

Cassettes are finally inserted into the mechanical structures. The overall mechanical design of the EE is derived from the prototypes for the ILD [4], although adapted to the CMS needs. It is a carbon-fibre alveolar structure with embedded tungsten plates made from twelve 30° sectors. The geometry is designed so that the radial sector boundaries can be arranged to occur in three different orientations, each rotated by 10° with respect to the others, to mitigate the degradation of performance due to dead areas (Fig. 2). The overall mechanical structure of the FH follows the one of the current CMS endcap hadron calorimeter, with bolted plates of brass, machined to host the cassettes.

2.2. Front-End Electronics

One of the most challenging aspect of this project is the front-end chip as large dynamic range (up to 10 pC, corresponding to about 3000 MIP in 300 μm sensors) is needed together with low noise and low power (about 10 mW per channel).

The baseline architecture consists of a pre-amplifier and shaper DC-coupled to the sensors and a time-over-threshold (ToT) measurement with a TDC for digitization of large signals, while a standard charge readout with a 10-bits ADC for pulses below 100 fC. The timing precision per cell is expected to be 50 ps.

Developments on various aspects of this chip are on-going. The production of a test-chip, SKIROC2_CMS, derived from SKIROC2 [5], was launched in January 2016 and is currently under tests. It includes some of the features specifics to HGCAL: 20ns shaping time, sampling at 40 MHz, p-on-n and n-on-p readout options, ADC and ToT, ... These functionalities will be tested in test beams foreseen in Fall 2016 at CERN. In the mean time, test vehicles on specific blocks are launched (various flavour of pre-amplifiers, shapes, discriminators...). A first iteration of the full chip is expected by Spring 2017.

2.3. Expected Performance

The expected performance of HGCAL were first evaluated with a standalone GEANT4 simulation, benchmarked against CALICE published test-beam results. Figure 5 shows the electron energy resolution as a function of the electron energy for various active thickness of the silicon sensors. The stochastic term ranges from 20 to 24 % but the constant term is targeted to be low (1 %).
The Figure 6 shows the energy containment of electromagnetic showers as a function of the EE layer number. Although it is shown the Molire radius ($R_M$) is 28mm, one can notice that the shower radius is much smaller than $R_M$ in the first layers. Thus, longitudinal segmentation together with high granularity give additional power handles for particle identification or energy reconstruction. It is possible to exploit the difference in the start of shower between electrons and hadrons, restore projectivity, make 3-dimensional fit of shower profile, subtract PU layer-by-layer...

The HGCAL geometry was implemented into a fully detailed simulation of CMS, including the new Phase-II tracker. It was demonstrated that similar or better performance than Phase-I configuration with 50 PU could be achieved with Phase-II simulations with 140 PU. Note that not all the capabilities of HGCAL were exploited, e.g. timing, thus leaving room for future improvements.

![Figure 5. Energy resolution as a function of energy from a standalone simulation of incident electrons on HGCAL, for different thickness of silicon sensors.](image1)

![Figure 6. Radii $\rho$ of the energy deposited in an individual silicon layer by a shower, layer by layer.](image2)

3. Conclusion and Perspective

The High-Granularity calorimeter is on the critical path towards physics discoveries and measurement in the High Luminosity Phase of the LHC. It has all ingredients to sustain the high radiation field, deal with the high rates of particles and mitigate pile-up interactions. However, major and exciting challenges must be faced for the next decade in all areas: engineering, including the routing of thousands of power and signal cables in the very constraint space of the existing detector, front-end electronics and trigger capabilities, software and computing.

HGCAL is now in R&D phase. Much progress has been done since the release of the Technical Proposal. First prototypes are being tested with electron and proton beams. A Technical Design Report is foreseen in late 2017. It will include key technical choices and improved design. The construction should start in 2020 in order to be ready for an installation during LS3.

References

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