High Granularity Calorimeter for the CMS Endcap at HL-LHC

Roger Rusack for the CMS Collaboration

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 an unprecedented transverse and longitudinal segmentation in a collider detector, both for electromagnetic and hadronic compartments. This will enable the optimal utilization of the Particle Flow Algorithms, with which 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 $1\text{cm}^2$ or $0.5\text{cm}^2$ hexagonal cell size, with the final interaction length of the hadronic compartment being based on highly segmented plastic scintillator with SiPM readout. Here, we present an overview of the HGCAL project, including the motivation, engineering design, readout/trigger concept and simulated performance.

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

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On behalf of the CMS Collaboration

Abstract—Calorimetry at the High Luminosity LHC faces many technical challenges. In the forward direction the levels of radiation and the unprecedented in-time event pileup make detector design and operation particularly difficult. To meet these challenges, the CMS experiment has decided to construct a sampling calorimeter with silicon as the primary active medium. This calorimeter – the High Granularity Calorimeter – will have an unprecedented degree transverse and longitudinal segmentation for a collider detector, both for electromagnetic and hadronic compartments. In this paper we discuss the motivation for this choice of calorimeter and its design.

Index Terms—Large Hadron Collider, silicon calorimetry, HL-LHC, CMS.

I. INTRODUCTION

Currently the two endcap calorimeters of the Compact Muon Solenoid (CMS) detector have an electromagnetic calorimeter made with Lead Tungstate crystals and a brass-scintillator hadronic sampling calorimeter. Their placement in the CMS detector is shown in Fig. 1. When the current period of operations of the Large Hadron Collider (LHC) is complete, CERN plans to upgrade the LHC to the High-Luminosity LHC (HL-LHC) with a design luminosity of \(5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}\). Over the operational lifetime of the HL-LHC, expected to be about 10 years, it is anticipated that the total integrated luminosity will be 3,000 \(\text{fb}^{-1}\) or more. The endcap calorimeters were designed to operate for a total integrated luminosity of 500 \(\text{fb}^{-1}\) expected during the operation of the LHC. With the increased luminosity that will be available at the HL-LHC, the fluence of neutrons and ionizing radiation will exceed the design specifications of the current endcap calorimeters.

The CMS collaboration will replace the endcap calorimeters with a High Granularity Calorimeter (HGCAL) that will cover the same pseudo-rapidity (\(\eta\)) regions, \(1.47 < |\eta| < 3.0\) [1]. The HGCAL will be a sampling calorimeter equipped with pixelated silicon sensors in the regions where the radiation levels are highest, and plastic scintillator readout with silicon photomultipliers (SiPMs) in regions where doses will be less than about 50 kGy. Figure 2 shows the expected neutron fluences in the region of the detector at the end of operations of the HL-LHC. The highest neutron fluence will be \(\sim 10^{16} \text{n/cm}^2\) at the location of the electromagnetic shower maximum, close to the beam pipe, where the integrated radiation dose will be 1.5 MGY (150 Mrads). At locations deeper into the calorimeter and further away from the beam pipe the neutron fluence and integrated radiation dose will be less.

The new calorimeters will be required to identify and measure photons, electrons and isolated jets produced at the interaction point (IP) in the center of CMS in the presence of a very large background produced from collisions occurring in the same beam bunch crossing, known as ‘pile up’.

In this paper the design of the detector proposed in the CMS Phase II Upgrade Technical Proposal [1] – the baseline design – will be described. However, as we are continuously optimizing the detector design to achieve the best possible performance at the lowest cost, parts of the original design...
will certainly change. In addition to describing the ‘baseline’ design, possible alternative options will be discussed.

II. MECHANICAL DESIGN

One of the principle design considerations of HGCAL is the selection of a material that can withstand the very high dose and neutron fluence. Our choice of silicon as the main detection medium is based on the experience obtained in operation of silicon trackers at the LHC and elsewhere, and the results obtained from many years of development that silicon sensors have undergone, in particular by the RD50 collaboration. Additionally the improvements in silicon processing technology have led to a significant reduction in cost per unit area, making a large scale calorimeter based on silicon feasible. Nevertheless, to keep costs to a minimum, we have elected to use scintillator as the active medium, where the radiation levels permit.

The HGCAL will be divided into three components, as shown in Fig. 3. The first component, closest to the interaction point (IP) where the beams collide, will be the electromagnetic section (EE). In the baseline design there will be a 28-layer silicon-tungsten sampling calorimeter with a depth of 25 X₀ and an interaction length (λ) of 1.5 λ. Moving away from the IP there will be a 3.5 λ sampling calorimeter (FH), also with silicon as the active medium and stainless-steel as the absorber. This is followed by the backing calorimeter (BH), which will be a scintillator-stainless steel sampling calorimeter that provides the last 5 λ of the ∼10 λ calorimeter. Operation of the EE and FH calorimeters will be at -30°C in order to keep the dark current, and hence the signal-to-noise low after irradiation. In the baseline design the BH will be maintained at room temperature.

A. Modules

The silicon sensors are made from 6” – or possibly 8” wafers – with one sensor per wafer. They are hexagonal in order to maximize the active detector area that can be obtained from a single wafer. The sensors are subdivided into hexagonal pads with areas of 1 or 0.5 cm². Figure 4 shows a 6” silicon sensor. The subdivision into hexagonal pads can be seen on the right-hand side of the image. The sensors are assembled into modules. The construction of a module made from two 6” sensors is shown in Fig. 5. Each module consists of a copper-tungsten (25% - 75%) plate, two sensors (one if we use 8” wafers), and a readout board, where the front-end electronics ASICs are placed. Data are transmitted from the board using Twin-Ax cables for the areas where the radiation levels are highest; optical fibers are used for regions elsewhere in the detector.

The function of the copper-tungsten plate is threefold: it supplies the mechanical rigidity to the module; it provides a thermal pathway to the copper plate, and it is part of the calorimeter absorber. It has a coefficient of thermal expansion (CTE) of ∼7 × 10⁻⁶ °C⁻¹, which is close to that of silicon ∼3 × 10⁻⁶ °C⁻¹, by using a dynamical mounting the silicon can be protected against shrinkage of the copper plate (CTE = ∼16 × 10⁻⁶ °C⁻¹) as it cools from room temperature to -30°C.

The silicon sensors will have an active thickness of 300, 200 or 120 µm, determined by the neutron fluence expected...
where they are located. The cell sizes are adjusted to limit the cell capacitance 60 pF. Table I shows the regions of the EE and FH where the different active thicknesses are used, together with the maximum neutron fluence expected after 3000 fb\(^{-1}\), the cell sizes, and the expected signal-to-noise ratio for a minimum-ionizing particle signal, MIP, before and after 3000 fb\(^{-1}\). The regions are specified by the radius, \(R\), measured from the beam axis.

### B. Cassettes

The modules are mounted with pins and screws onto copper plates to form a ‘cassette’, where each cassette is a 30° wedge-shaped section, and a detector layer is made up of twelve cassettes. Cooling of the modules to -30°C is achieved by circulating bi-phase CO\(_2\) in a pipe embedded in the copper plate. Calculations and a prototype have shown that the heat generated by the electronics and silicon, which is expected to be at most \(\sim 300\) W, for a single cassette, can be achieved with a CO\(_2\) flow rate of 3 grms of CO\(_2\) per minute through a cassette.

In the baseline design the mechanical assembly of the absorber and the cassettes of EE follows the method pioneered by the CALICE collaboration [2]. Tungsten plates are assembled in a carbon-fiber structure with slots between the plates to accept the cassettes. The radiation length of the tungsten plate between the cassette is matched to the radiation length of the two W/Cu plates in the modules. Going from the IP, there are 14 tungsten plates interleaved with 14 cassettes, to give a sampling electromagnetic calorimeter with 28 silicon planes separated by 0.9 radiation lengths (\(X\)) of material. The total thickness of the calorimeter is 25 \(X\) and and \(\sim 1.5\) \(\lambda\).

The FH calorimeter is immediately behind the EE. It is constructed with a stainless steel absorber, also with 30° slots, that accept the FH cassettes. It has twelve sampling layers with 5 cm (0.3 \(\lambda\)) thick absorber plates between them. Behind the FH is the backing calorimeter, BH, which is made up of 9 cm stainless-steel plates (0.5 \(\lambda\)) and eleven layers of scintillator.

The construction of BH will be similar to the design of the endcap hadron calorimeter currently installed in CMS [3]. It will be constructed with 5 \(\lambda\) of stainless-steel absorber formed in 9 cm-thick plates interleaved with scintillator as the active material. The light signal will be collected from the planes using wavelength-shifting (WLS) fibers. Eleven planes of scintillator will be used, with each plane divided into

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**TABLE I**

Silicon Sensor Arrangement: Thickness of the Active Silicon Layers in the EE and FH, Cell Size and \(S/N\) for a MIP Before and After an Integrated Luminosity of 3000 fb\(^{-1}\).

<table>
<thead>
<tr>
<th>Thickness</th>
<th>300(\mu)m</th>
<th>200(\mu)m</th>
<th>100(\mu)m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum dose (Mrad)</td>
<td>3</td>
<td>20</td>
<td>100</td>
</tr>
<tr>
<td>Maximum n fluence (cm(^{-2}))</td>
<td>(6 \times 10^{14})</td>
<td>(2.5 \times 10^{15})</td>
<td>(1 \times 10^{16})</td>
</tr>
<tr>
<td>EE region</td>
<td>(R &gt; 120)cm</td>
<td>(120 &gt; R &gt; 75)cm</td>
<td>(R &lt; 75)cm</td>
</tr>
<tr>
<td>FH region</td>
<td>(R &gt; 100)cm</td>
<td>(100 &gt; R &gt; 60)cm</td>
<td>(R &lt; 60)cm</td>
</tr>
<tr>
<td>Si wafer area (m(^2))</td>
<td>290</td>
<td>203</td>
<td>96</td>
</tr>
<tr>
<td>Cell size (cm(^2))</td>
<td>1.05</td>
<td>1.05</td>
<td>0.53</td>
</tr>
<tr>
<td>Cell capacitance (pF)</td>
<td>40</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Initial (S/N) for MIP</td>
<td>19.9</td>
<td>11.2</td>
<td>5.6</td>
</tr>
<tr>
<td>(S/N) after 3000 fb(^{-1})</td>
<td>8.7</td>
<td>3.8</td>
<td>2.3</td>
</tr>
</tbody>
</table>

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20° sections and offset alternately in depth to allow mechanical connections between the layers.

In BH the radiation doses range from approximately 50 kGy to below 10 Gy (see Fig. 7). In the low dose regions, as in the current calorimeter, a sigma-shaped arrangement of the WLS will be used, while in the higher-dose regions the towers will be structured as set of narrow tiles, each read out with a single WLS fiber along the length. This increases the radiation tolerance of the detector because it shortens the average light path between the energy deposition in the scintillator and the WLS fiber.

![Radiation doses levels in HGCAL. Plastic scintillator will be used throughout, but at the highest level doses](image)

The collaboration is considering several modifications to the baseline as the design optimization proceeds. A new design of the EE is under development where, instead of tungsten encased in carbon-fiber, we would dispense with the alveolar structure and use planes of lead encased in stainless steel. Spacers would be placed between the planes to provide the mechanical support required. We are also investigating for the BH the possibility of using the approach pioneered by the CALICE collaboration where scintillator tiles are readout directly by Silicon Photomultipliers (SiPMs) [4], [5]. BH would be operated at -30 °C, the same temperature as EE and FH, greatly simplifying the thermal shielding, but adding to the overall cooling power required. In this design each detector element would be readout separately. This would allow the development of hadron showers to be tracked throughout the calorimeter, which would greatly benefit the reconstruction of complex events. Furthermore, it would be possible to equip the detector plane with scintillator in the low fluence regions and to use silicon where the dose levels are too high to effectively operate SiPMs.

### III. READOUT ELECTRONICS

In HGCAL there are approximately six million readout channels, thus a premium is placed on minimizing the power consumption of the front end electronics. The requirements of the front-end electronics can be summarized as:

- Large dynamic range 0.4 fC to 10 pC (15 bits),
- Noise < 2000 e− for MIP detection in all sensors after 3000 fb-1,
- Compensation for the dark current in the silicon cells,
- Low power ≤ 10 mW/channel,
- Timing information ≤ 50 ps accuracy,
- System on chip (digitization, processing), high speed readout (>Gb/s), large buffers to accommodate 12.5 μs of latency during the Level 1 trigger selection.
- High radiation tolerance (1.50 MGy, 10¹⁶ n/cm²)

The baseline design of the front-end electronics uses a preamplifier and shaper DC-coupled to the sensors, and a time-over-threshold (ToT) measurement with a TDC for digitization of large signals. The ToT front-end, shown in Fig. [8] has fast shaping with a peaking time of 15 ns, after the first shaping stage and 20 ns after the second stage. The gain is around 25 mV/fC and is linear up to 100 fC, which approximately corresponds to the largest signal at shower maximum in a 5 GeV electromagnetic shower in a 300μm active thickness sensor. A 10-bit ADC is used for measurement of signals <~ 100 fC, while large-magnitude signals (>~ 80 fC) are digitized with the ToT comparator, using the differential signal after the second shaper, starting and stopping a TDC. A schematic circuit diagram of the system is shown in Fig. 8. The ASICs will be fabricated using the 130 nm TSMC CMOS process. The total power requirements of the ToT system, including both the digital and analogue parts is estimated to be ~8 mW/channel if a TDC with 100 ps step size is used. A further 2 mW/channel needs to be added to this to account for additional digital elements to deal with the readout, such as data compression and a pipeline, bringing the total front-end power budget to ~10 mW/channel.

### IV. DETECTOR PROTOTYPE TESTS

In 2016 a series of prototype tests were conducted with beams at the Fermilab Test Beam Facility (FTBF) and at CERN. At the FTBF a sixteen layer 15 X₀ detector was operated with electron beams with energies between 4 and 32 GeV and 120 GeV protons [6]. The silicon sensors used in these tests had an active thickness of 200 μm. For these tests the modules were made with two printed circuit boards (PCBs) with the same hexagonal shape as the sensor and a connector between them. The first PCB, which had only passive components, was glued to the silicon sensor, and electrical connections made with wire bonds through holes in the board. The second board, equipped with the readout electronics, was connected to the first board with two multipin electrical connectors. The readout electronics was the SKIROC2 ASIC [7], developed for the CALICE collaboration, by the OMEGA group.

An assembled module is shown in Fig. 9 and an assembly of eight modules at the FTBF is shown in Fig. 10.

The data were readout through a custom readout chain designed to be scaleable, using commercially available components mounted on custom PCBs [8]. In the DAQ each sensor module was connected to a data collection FPGA, where data were collected during a beam spill and stored. Between the beam spills the data were transferred to an AVNET ZedBoard that communicated, via Ethernet, to a control PC.

²http://zedboard.org
The calibration of the detector cells was performed with protons at the FTBF and with high-energy pions and muons at CERN. Figure 11 shows the ‘mip’ signal from a beam of 120 GeV protons. Figure 13 shows a 32 GeV electron in the sixteen layer stack at the FTBF, while Fig. 14 shows a 250 GeV electron event taken at the CERN H2 beamline.

In Fig. 12 the response of the 16-layer, 15 X₀ calorimeter is shown for different beam energies. The signals observed were compared with a detailed GEANT4 Monte Carlo simulation and the agreement between the two can be seen.

V. Next Steps

The collaboration will continue the optimization process, revising the design in preparation for the Technical Design Report (TDR) which will be submitted to the CERN management in late 2017. We are planning a detailed beam test with a complete 28-layer EE and a 12-layer FH prototype in 2017, which will provide results necessary for the TDR. Construction of the final detector will start in 2019 and will a planned
Fig. 12. The response of the 16-layer, 15 X_0 calorimeter with different electron energies. A comparison with the predicted response from a GEANT4 simulations is shown. Errors shown are the errors on the mean value.

Fig. 13. A 32 GeV electron event in the calorimeter stack. The shower development can be clearly seen in the detector.

Fig. 14. A 250 GeV electron event in the calorimeter stack at the CERN H2 test beam.

VI. CONCLUSIONS

The CMS collaboration is proposing to construct for operations at the HL-LHC a calorimeter for the forward region of the detector that will have silicon pad detectors as the sensitive medium. The pad size will be 1 or 0.5 cm^2 to make a total of six million channels. This unprecedented level of granularity will allow for the recognition of electrons, photons and isolated jets in the high pile-up environment of the HL-LHC. The design of the calorimeter is evolving as we strive to optimize the performance of the detector, while minimizing costs.

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