An overview of the CMS High Granularity Calorimeter, and the engineering challenges in its construction

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Abstract. The CMS Collaboration is preparing to replace its current endcap calorimeters for the HL-LHC era with a high-granularity calorimeter (HGCAL), featuring a previously unrealized transverse and longitudinal segmentation, with 5D information (space-time-energy) read out. This design, an overview of which is presented in this article, uses silicon sensors for the electromagnetic section and high-irradiation regions (with fluences above 10^{14}neq/cm^2) of the hadronic section, while in the low-irradiation regions of the hadronic section plastic scintillator tiles with on-tile silicon photomultipliers are used. The active layers include copper cooling plates embedded with thin pipes carrying two-phase CO_2 coolant, front-end electronics and electrical/optical services. The scale and density of the calorimeter poses many engineering challenges, including: the design and production of stainless steel absorber plates to very high tolerances from 600 tonnes of raw material; the development of the CO_2 cooling system to maintain each 220-tonne endcap at -35°C with electronics dissipating up to 130kW; the need to cantilever the calorimeters from the existing CMS endcap disks, using titanium supports; the production of a thin but strong inner cylinder to take the full weight while minimising impact on physics performance; and the integration of on-detector services in a restricted height of only a few millimetres.

1 Introduction

Calorimetry at CERN's High-Luminosity LHC (HL-LHC) faces two enormous challenges, particularly in the forward direction: radiation tolerance and unprecedented in-time event pileup. Therefore, the CMS Collaboration is preparing to replace its current endcap calorimeters for the HL-LHC era with a high-granularity calorimeter (HGCAL), featuring a previously unrealized transverse and longitudinal segmentation, with 5D information (space-time-energy) read out.

This article presents an overview of the HGCAL detector, followed by selected examples of the engineering challenges faced so far in its design and construction, as presented at CALOR2024. We share the ideas behind HGCAL, the current status of the project, and the lessons that have been learnt while creating this first calorimeter of its type at a hadron collider.

Details of the electronics front-end and back-end, and physics reconstruction were presented in separate talks at the conference.

2 HGCAL detector overview

2.1 Physics case

The HL-LHC aims to perform detailed studies of the Higgs boson and standard model (SM) processes. With the HL-LHC, CMS will face ten times higher integrated luminosity (3000fb^{-1}) than in the LHC, fluences of up to $1.5\times10^{16}n_{eq}/cm^2$, mean collisions per bunch crossing (pileup) as high as 200, and an integrated dose in the endcap calorimeters of 2MGy. Under these conditions, the calorimeters will need to trigger cleanly on and reconstruct narrow vector boson fusion (VBF) jets, as well as merged jets for physics beyond the SM.

The existing $PbWO_4$-based CMS electromagnetic calorimeter (EE) and the plastic scintillator-based hadron calorimeter (HE) were designed for an integrated luminosity of 500fb^{-1}, their performance much above this level will degrade and lead to unacceptable physics performance.

To meet the requirements of operation in the HL-LHC, two HGCAL detectors are currently being constructed. They will replace the EE and HE, and provide a highly granular detector, with elevated radiation-tolerance and efficient data readout. HGCAL will be installed in LHC Long Shutdown 3 (LS3). [1]

2.2 Geometry

HGCAL must fit into the same envelope as the existing EE and HE, with some adjustments to cater for new detectors such as a new layer of muon chambers (ME0) behind HGCAL and an endcap timing layer (ETL) in front. Each HGCAL, shown in ***Fig. 1***, is 5.4 m in diameter and 2.2m long. The electromagnetic part (CE-E) is designed with fine longitudinal resolution, and thin absorber layers of lead (ranging from 3.4mm to 8.3mm) and CuW plus copper (a 1.4mm module baseplate and

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6.2mm cooling plate respectively) between the active layers. The hadronic part (CE-H) has stainless-steel plates of 41.5mm and 60.7mm thickness, plus the 6mm copper cooling plate, acting as absorber material between sensor layers. The total area of active sensors, distributed over 47 layers, is ~960m^2 over both endcaps.

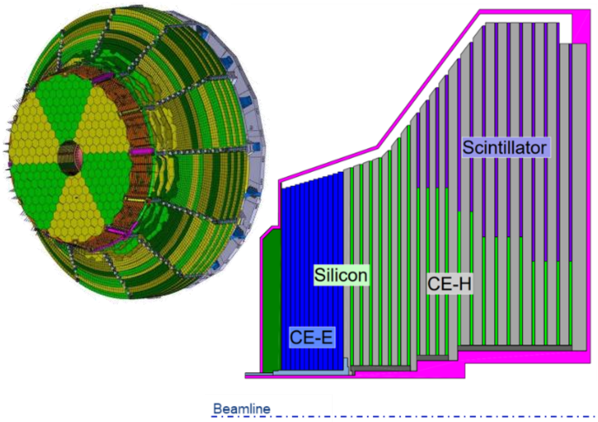

Fig. 1. HGCAL overview and cross-section (axisymmetric)

2.3 Sensors

The HGCAL detector design uses 26,000 silicon sensors for the electromagnetic section and high-irradiation regions of the hadronic section (with fluences above 10^{14}neq/cm^2), while in the low-irradiation regions of the hadronic section 280,000 plastic scintillator tiles with on-tile silicon photomultipliers are used.

The hexagonal silicon modules, as seen in ***Fig. 2***, have a shape chosen to optimise circular silicon wafer usage. They are composed of a glued stack of baseplate, silicon sensor and readout PCB called a hexaboard. Electrical connections between hexaboards and sensors are made via wire-bonding. A range of partial modules is created to fill tiling gaps. High density modules (HD) – with 444 x 0.5cm^2 hexagonal cells – are used in high fluence regions, low density modules (LD) – with 198 x 1.2cm^2 cells – elsewhere.

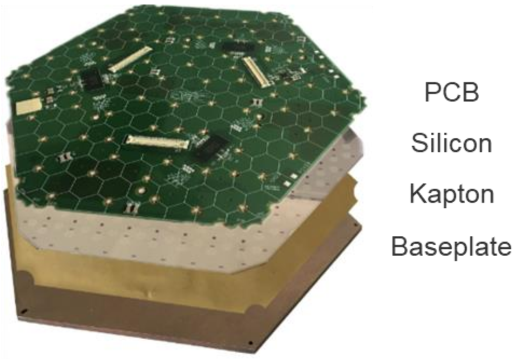

Fig. 2. Silicon LD module, exploded view [2]

The scintillator tiles come in two varieties: cast polyvinyl toluene (PVT) and injection-moulded polystyrene (PS) tiles of 4-30cm^2, comprising 70% and 30% of production respectively. These are wrapped in reflective foil. Injection-moulded scintillators have a reduced light yield by a factor of about two [3], but have a lower price so are used where irradiation levels are lower, and a smaller signal-to-noise ratio is acceptable. The tiles are read-out by silicon photomultipliers (SiPM) and mounted on a PCB which is called a tileboard, shown in ***Fig. 3***.

Fig. 3. Tileboard with wrapped tiles on top of SiPMs

2.4 Cassettes

Modules and tileboards are mounted onto copper cooling plates, forming assemblies called cassettes. The cassettes are instrumented with electronics including motherboards, concentrators, and DCDC converters, in addition to services and connectors. These all must fit in a 5.9mm gap above the modules. The cooling plate is embedded with thin pipes carrying two-phase CO_2 coolant to allow operation at -35°C.

Electromagnetic section CE-E cassettes span 60° and have between 94 and 106 modules per cassette. These are divided across the two sides of the cooling plate with the sensor layer nearest the interaction point used for triggering. The hadronic section CE-H cassettes are 30°, single-sided and exist in two types: all-silicon – with up to 38 modules; and mixed (scintillator and silicon sensor) with 6-15 tileboards and 8-26 modules.

3 HGCAL engineering challenges

The scale and complexity of the calorimeter poses many engineering challenges across a range of fields, including electronics, mechanical, and thermal aspects. Examples from these last two areas are described in the following subsections.

3.1 Detector support structure

To support the 220-tonne detector entails a trade-off between adding enough material to safely hold the detector, while not adding too much that it reduces physics performance. 18 discrete supports connect HGCAL onto the CMS endcap, bridging the gap where ME0 chambers are installed, while leaving access to those same chambers for maintenance. Most of the weight is directed to robust wedge-shaped stainless-steel supports at the 3 and 9 o'clock positions. These supports are split along a horizontal plane with a sliding interface to allow for the 2.5mm radial thermal contraction of the detector rear disc as it is cooled.

The four titanium supports above and below these are articulated to avoid shear load, aiming to keep the support structure load paths determinant. The remaining intermediate supports principally bear the moment load and are also made of titanium with a double I shape which flexes to allow for the thermal contraction. These have now been produced at KIT in Karlsruhe, as shown in ***Fig. 4***.

Fig. 4. Articulated (left) and intermediate (right) supports

The detector self-weight (absorbers, cassettes and CE-E) is supported through machined stainless-steel cylindrical supports at the inner radius of the CE-H, and M36 tie rods with super-bolts at the outer periphery. The Al-alloy CE-E support cylinder holds the CE-E cassettes and lead absorber plates via a series of pins which locate into precisely machined slots.

3.2 Stainless steel absorbers

In the CE-H, there are 40 stainless steel absorber plates, each weighing up to 13.5 tonnes. The key challenges here are the large size with only 0.5mm thickness tolerance, 1.0mm flatness tolerance and 0.1-0.2mm positional tolerance for alignment of mating components such as cassettes. Each plate is split into three to fit into standard material dimensions. 600 tonnes of raw material rectangular plates are first waterjet cut before machining to the final shape.

Milling of these plates releases internal stress with each cutting operation, which can result in significant bending if not correctly addressed. Each plate is therefore flipped multiple times during machining. Full machining takes place on a 16m vertical lathe and 12m 4-axis milling machine and takes 3-4 weeks per disc. Production of these plates is well under way at the Pakistan Atomic Energy Commission (PAEC), see ***Fig. 5***.

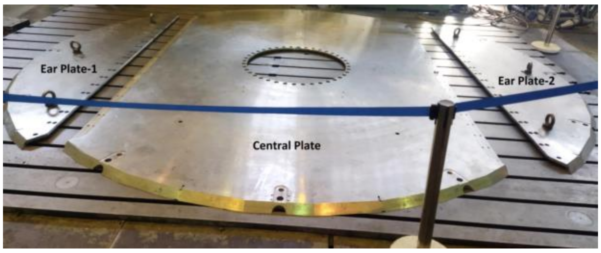

Fig. 5. CE-H absorber disc in three parts

As this material will be installed inside the CMS solenoid, it will experience a magnetic field of 3.8T. To reduce the forces on the endcaps, the magnetic permeability (μ) of the stainless steel needs to be carefully controlled. This required sourcing an SS304L alloy with tight tolerances on chemical composition to keep μ within an acceptable range. The actual plates have been measured with a mean μ of 1.017, which corresponds to an axial force of 31.5 tonnes acting on the CMS endcaps, well below the 100-tonne design limit.

3.3 Cassette cooling plates

The copper cooling plates – each about 6mm thick and up to 70kg – support, cool and align the modules and tileboards.

Each plate is precisely machined within 0.2mm tolerance, starting with the outer profile and overall plate surfacing, then adding hundreds of features such as plain and threaded holes, pockets and cooling pipe grooves. To avoid over-constraining the plates, which will shrink thermally and undergo multidirectional loading during assembly and after rotation, stainless-steel mounting hardware is then added to locally strengthen the softer copper.

Stainless steel cooling pipes are bent by automatic bending machine, then soldered into the grooves, having first been plated with nickel then copper to improve wettability. Ensuring good thermal contact and avoiding bowing of the plates during soldering requires a heated table and careful manipulation. Custom vacuum handling tooling has been developed at LLR in Paris to move the plates.

Several prototype plates have been produced to date, see ***Fig. 6***, allowing soldering process to be refined and cassette integration to be optimised.

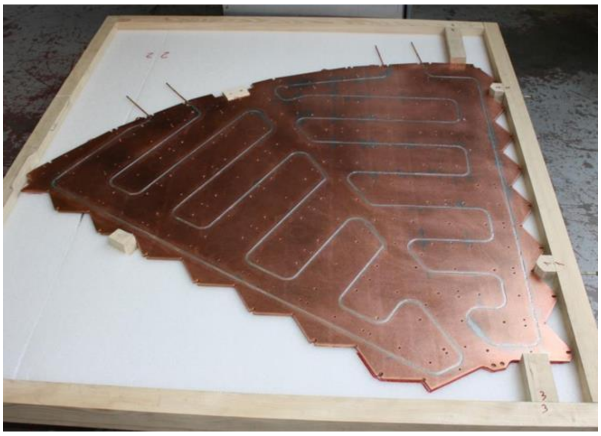

Fig. 6. CE-E copper cooling plate prototype

3.4 Detector handling

The CE-H mechanical structure will be machined and assembled first in Pakistan for testing. It will then be disassembled, shipped to CERN, and reassembled for the final detector construction. Handling the detector is extremely challenging due to the large weight with limited area for supports. In addition, the detector will be assembled lying on its back (axis vertical) before being rotated 90° into its final orientation. A steel cradle has been designed which will hold the detector during rotation and transport, and which is compatible also with the removal of the existing endcap calorimeters. It will be fastened by screws to the HGCAL back flange and will then clamp around the quasi-cylindrical region of CE-H absorbers using hydraulic pistons.

During LS3, the detector in its transportation cradle will be lowered carefully down the 100m deep CMS shafts to the floor of the cavern by specialist cranes before being manoeuvred into its final position using air pads and a stacking riser system.

3.5 Cooling

To reliably operate silicon sensors after irradiation, and to keep low the electronics noise that results from the increased leakage current and decreased charge collection efficiency after irradiation, and to keep the radiation-induced SiPM electronics noise sufficiently low, HGCAL will be operated at -35°C using CO_2 (R744) coolant. The coolant will remove from the detector the approximately 130kW of electrical power and environmental heat leak. Another benefit of using two-phase coolant is that, as long as the pressure losses in the internal cassette pipework are kept low enough and the vapour quality does not exceed the dry-out limit, the temperature of the coolant remains constant within a couple of degrees Celsius throughout the sensor region. This uniformity reduces thermal stresses on mechanical components and PCBs and ensures good cooling to all the electronics and sensors wherever they are positioned in a cassette.

The CO_2 is delivered to HGCAL from the CMS cooling plants to the endcap distribution manifolds via flexible coaxial, vacuum-jacketed transfer lines through moving cable chains. These lines need to operate for around 100 lifetime open/close cycles and have required careful testing to ensure the vacuum jackets are mechanically robust enough while sizing the process pipes correctly to keep fluid pressure drops within acceptable limits.

24 connections are made for each detector to the external transfer lines. Inside the detector, CO_2 passes through custom 2.5m-long manifolds. These have been the target of manufacturing optimisation: reducing the number of welds by machining single pieces to replace welded assemblies, and by making custom fittings. This has saved ~2500 welds per endcap compared to the original design which had more than 5000 welds.

3.6 Thermal insulation

HGCAL is surrounded by an insulating layer called the thermal screen. This stops condensation and ice formation inside the detector by creating a sealed volume and maintaining a low humidity environment through dry gas flushing. Due to the 20-30mm thickness and complex geometry, passive insulation was not sufficient, and vacuum insulation not versatile enough, to prevent below ambient temperatures on its own outer surface. Cold surfaces and condensation could negatively impact surrounding detector systems, so the thermal screen panels are heated to +20°C by polyimide heating foils with copper traces.

The key challenges here have included the complex detector shape – driven by pre-existing envelopes – and sealing around the many penetrations such as mechanical supports and services. In addition to insulating the detector internals and maintaining their outer surface temperature, the panels need to protect the detector from potential minor impacts, be of low density to minimise particle interaction and be tolerant to radiation and the CMS magnetic field.

These constraints have led to a general design of panels with a bonded composite sandwich construction of carbon fibre reinforced polymer (CFRP), aramid honeycomb, and aluminium alloy. G-11 epoxy-fibreglass stiffeners are used within the panel interconnection structure, while other parts of the thermal screen – with fewer structural requirements or less irradiation – use silica aerogel or EPDM closed-cell foam as insulation while keeping the aluminium alloy outer shell design for sealing.

3.7 Services

HGCAL will have a huge number of services to integrate across the two detectors:

- Over 44,000 individual wires inside the cassettes, with tens of thousands of optical and electrical connectors.
- More than 10,800 cables inside the two detectors (not including those in the cassettes), covering 20km in total.
- Circa 4,600 cables outside the detector connecting to power supplies and readout racks, totalling 150km.
- Dozens of pipes for cooling, dry gas, fire detection, and tray water-cooling.

Fitting these services in has posed a significant challenge, the first of which was shrinking the detector absorber to leave enough space outside it to route pipes and cables while remaining inside the overall envelope.

Services outside of the detector will also need to fit in the space left by removing HE and EE services. With the new CO_2 transfer lines taking up a large proportion of the fixed cable trays, HGCAL's low voltage and bias voltage cables will run outside of the existing trays across the top of muon chambers. This will present more challenges during CMS operation as the HGCAL cables will need to be disconnected and folded back if access is required for muon chamber maintenance, but there was no practical alternative.

One key observation from this exercise has been that mock-ups and prototyping continue to be vital tools in the design process.

4 Summary

HGCAL will be the first large-scale calorimeter with silicon and SiPM-on-tile technologies providing unprecedented granularity and time resolution.

Designs are now becoming reality – production is in progress on almost all components from modules to mechanics. A huge project-wide effort has enabled us to address numerous engineering challenges.

Assembly of detector structures, comprising cassettes and mechanics, is starting this year with installation of the first endcap planned for LS3.

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