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Status and plans for the CMS High-Granularity Calorimeter upgrade project

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The CMS Collaboration is preparing to build replacement endcap calorimeters for the high-luminosity LHC (HL-LHC) era. The new high-granularity calorimeter (HGCAL) is, as the name implies, a highly-granular sampling calorimeter with approximately six million silicon sensor channels (~1.1 cm^2 or 0.5 cm^2 cells) and about four hundred thousand channels of scintillator tiles read out with on-tile silicon photomultipliers. The calorimeter is designed to operate in the harsh radiation environment at the HL-LHC, where the average number of interactions per bunch crossing is expected to exceed 140. Besides measuring energy and position of the energy deposits, the electronics is also designed to measure the time of particles' arrival with a precision on the order of 50 ps. In this talk, the reasoning and ideas behind the HGCAL, the current status of the project, the many lessons learnt so far, in particular from beam tests, and the challenges ahead will be presented.

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1. The High-Luminosity LHC and the CMS High-Granularity Calorimeter

The high-luminosity upgrade of the LHC [1], currently planned to commence in 2025, will bring very harsh pileup and radiation conditions, in which the experiments need to operate. Up to 200 simultaneous proton-proton collisions are expected and the neutron fluence will be at the level of 2.3×10^{16} n_{eq}/cm^2. The CMS experiment [2] in its current configuration will need to be upgraded, and the current endcap calorimeters will be replaced by the High-Granularity Endcap Calorimeter (HGCAL) [3].

1.1 HGCAL design choices

For the design of the HGCAL, a sampling calorimeter design with timing capabilities has been chosen. For the electromagnetic part of the calorimeter (CE-E) and in regions of highest radiation of the hadronic calorimeter part (CE-H), silicon sensors are employed. Scintillating tiles with on-tile silicon-photomultiplier readout are used elsewhere. A summary of the calorimeter specifications is shown in Table 1.

Table 1: Summary of the specifications of the CMS HGCAL.

Active material (both endcaps)	Silicon	Scintillators
Area	~620 m^2	~370 m^2
No. of modules	~27000	~4000
Channel size	~0.5–1 cm^2	4–30 cm^2
No. of channels	~6 million	~240.000
Operation temperature	−30 °C	−30 °C
Passive material (per endcap)	**CE-E**	**CE-H (Si) + CE-H (scintillator)**
Absorber	Pb, CuW, Cu	Stainless steel, Cu
Depth	27.7 X_0	10.0 λ_{int}
Layers	26	7 + 14
Weight	~230 t	

1.2 Silicon modules and cassettes

The silicon modules [4] are a sandwich consisting of a printed circuit board (PCB), the silicon sensor, a gold-on-kapton layer for bias voltage distribution and a baseplate for structural rigidity and cooling. Wire-bonding is used to connect the PCB with the silicon sensor. CuW baseplates act as part of the absorber for the CE-E. These modules are mounted back-to-back including the Pb absorber on self-supporting cassettes. For the CE-H absorbers, PCB baseplates provide a good compromise between thermal properties and cost.

2. Performance in beam tests

The new technology developed for the HGCAL is being tested on the bench and in high-energy beams. The last beam test took place in October 2018 at the CERN H2 beam line. Six-inch prototype silicon sensors [4] were used (while the final sensors will be eight inch). The overall detector setup

PoS(EPS-HEP2021)846

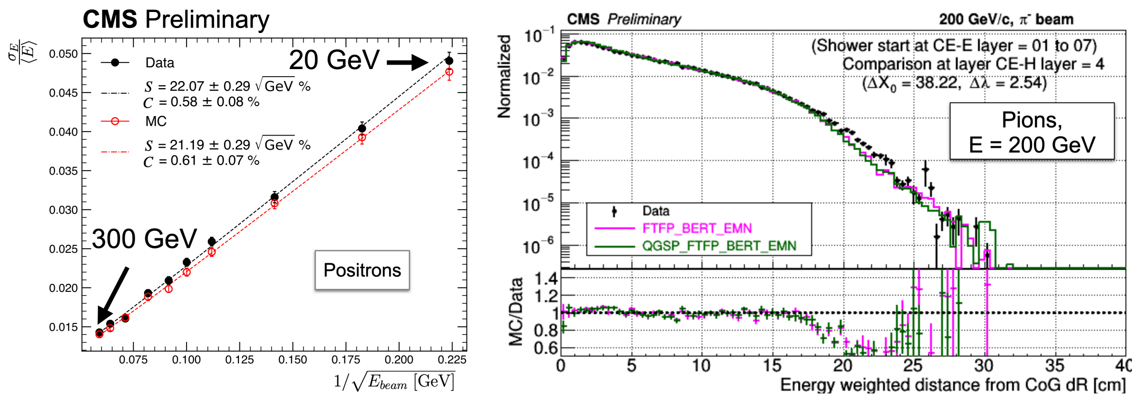

Figure 1: Left: the positron energy resolution as a function of $1/\sqrt{\mathrm{E_{beam}}}$. Right: energy-weighted distance of reconstructed particle hits from the centre-of-gravity in Cartesian coordinates for pion beams of 200 GeV, where the shower starts in the first seven layers of the CE-E and the values are shown in layer 4 of the CE-H. The data are compared to simulation using two different physics lists.

was close to the final design: the electromagnetic calorimeter consisted of 28 sampling layers with Cu/CuW/Pb absorbers corresponding to 28 X_0 or 1.5 λ_{int}. The silicon-sensor part of the hadronic calorimeter consisted of twelve sampling layers with steel absorbers (3.5 λ_{int}). For the scintillator part, a SiPM-on-tile scintillator-steel hadronic calorimeter (AHCAL) [5] was used. The AHCAL consists of 39 layers with steel absorbers (4 λ_{int}).

Different kinds of particles (e^+, π^+, μ^+) with energies between 20 and 300 GeV were directed at the detector [6]. The analysis of the data demonstrates good agreement with simulation. The energy resolution for positrons is shown in Fig. 1 (left). Similarly good agreement is found for pions. An example of the shower shapes for pions is presented in Fig. 1 (right).

3. Module mass-production

For the silicon part of the detector, a total of 27,000 modules of different shapes and sizes will need to be produced. Therefore, their production in the so-called Module Assembly Centres (MACs) is automated where possible. A total of six MACs will be used, of which five are already fully equipped and on track to be qualified for assembly this year. The development of tooling and the preparation for large-scale production is progressing well. Tooling is already completed for low-density full modules and will soon also be available for high-density full modules. The design of gantry tooling for partial modules is also ramping up this year.

4. Event reconstruction and triggering

Further important active areas of the development are event reconstruction and triggering. The HGCAL is effectively an “imaging” calorimeter. It allows for the precise energy and time measurement of particle showers in a fine three-dimensional (3D) spatial grid. At the same time, objects from MIP to TeV-particle will have to be reconstructed. Therefore, different reconstruction approaches being pursued: an iterative clustering approach [7], aiming to reconstruct individual particles step-by-step, and a novel approach based entirely on machine-learning techniques, which aims to reconstruct all particles in one step. Both approaches are challenging due to the high amount of pileup, the resulting combinatorics and the constrained computing budget.

The HGCAL will also contribute to the L1 trigger. Here, the huge data rate needs to be reduced from ~300 TB/s to about 4 TB/s within microseconds while performing 3D clustering.

5. Summary and outlook

The CMS high-granularity calorimeter is a very ambitious detector project that is now converging in time for the high-luminosity upgrade of the LHC. The detector is equipped with silicon sensors in regions of high radiation and scintillators with silicon photomultipliers elsewhere. The performance of the calorimeter has been confirmed in large-scale beam tests. Work is ongoing towards a fully-engineered design for module production start in 2022. Event reconstruction and triggering are also important areas of development.

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PoS(EPS-HEP2021)846