Status and Overview of the CMS HGCAL

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On behalf of the CMS Collaboration
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Radiation Challenge

- After the HL-LHC upgrade, the CMS end-cap will operate in an unprecedented radiation environment
  - Fluences of up to $10^{16}$ neq/cm$^2$ and doses of up to 1.5 MGy

- Will need very radiation hard detector material and readout
  - Strong dependency on $|\eta|$ and $|Z|$ suggest that design can vary with exact location

![Diagram of expected hadron fluences](image1.png)

![Diagram of expected total dose](image2.png)
CMS uses particle flow algorithms to improve on jet energy resolution

- reconstruct every particle in a jet
- For each particle use the detector with best energy/momentum measurement
- High granularity is key for correct assignment of energy deposits to tracks

“Typical” jet:
- ~62% charged particles (mainly hadrons)
- ~27% photons
- ~10% neutral hadrons
- ~1% neutrinos
Pileup Suppression with Timing

- Plots show cells with $E > \sim 3.5$ MIPs, projected to the front face of the endcap calorimeter
- Concept: identify high-energy clusters, then make timing cut to retain hits of interest
- Design HGCAL to obtain a $\sim 30$ps timing measurement for multi-MIP energy deposits

VBF ($H \rightarrow \gamma\gamma$) event with one photon and one VBF jet in the same quadrant,

![](image)
# Technology Choices

- Dissipated power $\sim 250 \text{ kW}$
- Removed with two-phase CO2 cooling operated at $-35 \text{ C}$
- Geometry slightly adjusted since the TDR release

<table>
<thead>
<tr>
<th>Both Endcaps</th>
<th>Silicon</th>
<th>Scintillator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>~620 m²</td>
<td>~370 m²</td>
</tr>
<tr>
<td>Channel Size</td>
<td>0.5 - 1.2 cm²</td>
<td>4 - 30 cm²</td>
</tr>
<tr>
<td># Channels</td>
<td>~6 M</td>
<td>~240 k</td>
</tr>
<tr>
<td># Modules</td>
<td>~27000</td>
<td>~4000</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Per Endcap</th>
<th>CE-E</th>
<th>CE-H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber</td>
<td>Pb, CuW, Cu</td>
<td>Stainless steel, Cu</td>
</tr>
<tr>
<td>Depth</td>
<td>27.7 $X_0$</td>
<td>10 $\lambda$</td>
</tr>
<tr>
<td>Layers</td>
<td>26</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>Weight</td>
<td>23 t</td>
<td>205 t</td>
</tr>
</tbody>
</table>

- Both Endcaps
  - Silicon
  - Scintillator

- Per Endcap
  - CE-E
  - CE-H

- Scintillator
- Silicon
- CE-E
- CE-H

- Weight: 23 t, 205 t
- Depth: 27.7 $X_0$, 10 $\lambda$
- Layers: 26, 7, 14
Lateral Structure, Cassettes

- Silicon and scintillator modules assembled into cassettes
- Supported and cooled by copper cooling plate
- Data from modules collected by motherboards
- Cassettes house all services and DC2DC converters
Cooling Performance

- A mockup cassette has been fabricated to verify cooling performance.
- With CO2 temperature at -35°C and expected heatload of 270W, silicon sensors were maintained at -30°C.
The weight of a single endcap is estimated to be 230 tonnes. This poses serious challenges on the detector support system design. To meet these challenges a variety of supports with a different key features will be used.

**CE-E support:**
Forged aluminium support machined from a single solid piece of metal

**CE-H support:**
Stainless steel support assembly designed to take the weight of the Hadronic cassettes and stainless steel absorbers

**Sliding wedges:**
Stainless steel supports designed to take the total detector weight. Sliding feature will allow to cope with a thermal contraction as one end of the wedges will be at -35°C while the other end will be at 18°C

Machining of absorber starts this year
Silicon Sensor Design

- Design has been finalized in 2021
- Hexagonal shape to maximize usage of circular wafers
- 8” wafers to lower cost wrt 6”
  - Established new production line with Hamamatsu
- Planar, DC-coupled, p-type sensors
  - more radiation hard than n-type
- Thin sensors collect more charge at high fluence
  - Publication

LD: ~200 cells of 1.2cm$^2$
300um & 200um thickness

HD: ~450 cells of 0.5cm$^2$
120um active thickness
Radiation-Hardness Qualification

• In 2020/21 irradiated 40 sensors with neutrons up to $10^{16}$neq/cm$^2$ at Rhode Island Nuclear Science Center, US
• Most sensors met specs and identified the best production process (publication soon)
• Ordered ~300 pre-series sensors
  • Practice QA/QC and cassette prototyping

Probe card system for full-wafer IV+CV tests

RINSC 8-inch irradiation slot
Multi-Geometry Sensor Design

- To save on the number of masks and all the associated tooling, we designed multi-geometry sensors (MGS).
- All dicing lines have been collected on a single design and each of the resulting islands have been protected by an individual guard ring.
- Prototype testing on-going, ordering pre-series soon.
Silicon Modules

- Glued stack of baseplate, sensor and readout hexaboard
- Baseplates are made of CuW in CE-E, PCB in CE-H
- Relative alignment within ~50um achieved with gantry based automated assembly
- Electrical connections are done with wire-bonds

* In CE-H, PCB baseplate with laminated Kapton™

Automated module assembly with gantry

- Signal bonds
- Shield bonds
- Backside HV bonds
Scintillators

- Economical solution for low radiation areas
- 240k cast or molded tiles, 4-30cm²
- Individually wrapped by machines
- Read-out by SiPMs (2, 4, 9mm²) assembled on PCBs
- Successfully operated tileboards in beam tests

See Ted Kolberg’s talk for details

CALICE AHCAL SiPM-on-tile prototype

Injection molded tile

Tile wrapping machine

Tileboard prototype with irradiated SiPMs
• **HGCROC:**
  - Low noise (<2500e) and high dynamic range (0.2fC-10pC)
  - 10bit ADC below ~50fC, 12bit ToT above
  - Timing information (ToA) down to 25ps
  - Less than 20mW per channel and radiation hard

See Nadja Strobbe’s talk for on-detector electronics and Louis Portales’ talk on L1 trigger
Offline Reconstruction

- Exploring multiple reconstruction concepts:
  - Iterative reconstruction based on trackster reconstruction (TICL)
  - End-to-end Machine-Learning based approaches (ML4Reco)
- The Iterative CLustering workflow
  - merge hits to 2D Layer Clusters (LC)
  - link clusters to tracksters
  - Reconstruct clearly identifiable objects first, then continue with remaining objects

Simulation of 140 pileup events in CMS
First large-scale test of more than 90 HGCAL modules in October 2018 data-taking at CERN. The setup was exposed to $e^+$ & $\pi$ beam of energies ranging from 20 to 300 GeV and 200 GeV $\mu$ beams.

**CE-E:** Hanging file structure
- Double sided cassettes
- $\text{Pb/CuW/Cu absorber}$
- $\sim 26 \, X_0$, $1.4 \, \lambda_{\text{int}}$

**CE-H:** Hanging file structure
- $\text{Steel/Cu abs.}$
- $\sim 3.4 \, \lambda_{\text{int}}$

**CALICE AHCAL:**
- $\text{Scintillator/SiPM}$
- $\text{Steel absorber}$
- 39 layers, 14k channels
- $\sim 4.4 \, \lambda_{\text{int}}$
Construction and commissioning of CMS CE prototype silicon modules

The DAQ system of the 12,000 channel CMS high granularity calorimeter prototype

Response of a CMS HGCAL silicon-pad electromagnetic calorimeter prototype to 20-300 GeV positrons

Performance of CMS High Granularity Calorimeter prototype to charged pion beams of 20-300 GeV (coming soon)

Timing performance (coming soon)

Time evolution of EM shower, ~1ns
Test Beam Results for Positrons

- Stochastic term is 22%
- Constant term of 0.6%
- Linearity within 3%
- Good agreement between data and simulation, also for angular resolution

**Energy Resolution**

\[
\frac{\sigma_E}{\langle E \rangle} = \frac{S}{\sqrt{E_{\text{beam}}}} \oplus C
\]

- Data
- MC

**Angular Resolution**

- Data
- MC (CE-E and DWC)
- MC (CE-E intrinsic)

**Linearity**

- Data lin. regression
- MC lin. regression
- \(E_{\text{beam}}\) uncertainty
Summary and Outlook

- HGCAL will be the first large scale calorimeter with Si and SiPM-on-tile technologies providing unprecedented granularity and time resolution.
- Beam tests confirm expected performance.
- Several key components approach end of prototyping phase:
  - Sensors, SiPMs, HGCROC.
- Timeline:
  - EDR in late 2022.
  - Mass-production to start in 2023 (sensors, scintillator tiles, electronics).
  - Module assembly to start beginning of 2024.
  - Cassette assembly to start beginning of 2025.
  - Cassette assembly finished late summer 2026.
  - First endcap ready for lowering March 2027.
  - Second endcap ready for lowering July 2027.