Status and Plans for the CMS High Granularity Calorimeter Upgrade Project

on behalf of the CMS collaboration
Thorben Quast (CERN)
The medium-term future at CERN: High Luminosity LHC

Experimental testing via high-energy particle collisions: **Large Hadron Collider (LHC)** @ CERN.

- LHC consolidations
- low $\beta^*$ quadrupoles
- Run 1 (7-8 TeV)
- Run 2 (13 TeV)
- Run 3 (13-14 TeV)
- 14 TeV
- HL-LHC
- ~30 fb$^{-1}$
- ~300 fb$^{-1}$
- ~3000 fb$^{-1}$

LHC upgrade to ~5x design luminosity = HL-LHC

**cf. Detector challenges from HL-LHC to FCC**, Werner Riegler
HL-LHC necessitates upgrades to the CMS detector

<table>
<thead>
<tr>
<th>Experimental challenges</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>General mitigation strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>• inst. luminosity</td>
<td>$2 \times 10^{34}$ s$^{-1}$ cm$^{-2}$</td>
<td>up to $7.5 \times 10^{34}$ s$^{-1}$ cm$^{-2}$</td>
<td>• improved trigger &amp; computing</td>
</tr>
<tr>
<td>• detector irradiation</td>
<td>O($10^{14}$ neq/cm$^2$)</td>
<td>&gt;O($10^{15}$ neq/cm$^2$)</td>
<td>• radiation-tolerant sensors &amp; electronics</td>
</tr>
<tr>
<td>• pile-up interactions</td>
<td>O(40)</td>
<td>140-200</td>
<td>• timing and increased granularity</td>
</tr>
</tbody>
</table>

**Compact Muon Solenoid (CMS)**

**HL-LHC Upgrades**

- **Tracker:**
  - Radiation tolerant,
  - high granularity,
  - less materials, tracks in hardware trigger (L1),
  - coverage up to $|\eta| = 3.8$

- **Barrel Calorimeter:**
  - New BE/FE electronics,
  - ECAL: lower temp.,
  - HCAL: partially new scintillator

- **Muon system:**
  - New electronics
  - GEM/RPC coverage in $1.5 < |\eta| < 2.4$,
  - investigate muon tagging at higher $\eta$

- **other:**
  - HLT up to 7.5kHz
  - MIP timing detector

To be replaced for HL-LHC

**Endcap Calorimeters:**

$1.5 < |\eta| < 3.0$

cf. **CMS Phase-2 Inner Tracker Upgrade**, Sudhir Malik

cf. **...**
High granularity for particle flow

Real need to improve *jet energy resolution* for the next generation of calorimeters @ HL-LHC

CMS follows the *particle flow* paradigm:
- Accurate reconstruction of *each particle within a jet*.
- For each individual particle in a jet, use detector with best energy/momentum resolution.
- Assignment of energy deposits to tracks: *granularity in the energy measurement*.
- *Granularity* is more important than energy resolution.

*cf. Highly Granular Calorimeters for Particle Flow, Katja Krüger*
New calorimeter endcap: High-Granularity Calorimeter (HGCAL)

HGCAL = Sampling calorimeter

- Hexagonal silicon sensor based modules in CE-E and high radiation regions of CE-H.
- Scintillating tiles with on-tile SiPM readout in low-radiation regions of the CE-H.

<table>
<thead>
<tr>
<th>Both endcaps</th>
<th>Silicon</th>
<th>Scintillators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>~620m²</td>
<td>~370m²</td>
</tr>
<tr>
<td>#Modules</td>
<td>~27000</td>
<td>~4000</td>
</tr>
<tr>
<td>Channel size</td>
<td>0.5 - 1 cm²</td>
<td>4-30 cm²</td>
</tr>
<tr>
<td>#Channels</td>
<td>~6 M</td>
<td>~240k</td>
</tr>
<tr>
<td>Op. temp.</td>
<td>-30 °C</td>
<td>-30 °C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Per endcap</th>
<th>CE-E</th>
<th>CE-H (Si)</th>
<th>CE-H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber</td>
<td>Pb, CuW, Cu</td>
<td>Stainless steel, Cu</td>
<td></td>
</tr>
<tr>
<td>Depth</td>
<td>27.7 $X_0$</td>
<td>10.0 $\lambda$</td>
<td></td>
</tr>
<tr>
<td>Layers</td>
<td>26</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td>Weight</td>
<td>~230 t / endcap</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

cf. The CMS High Granularity Calorimeter
Scintillator/ SiPM Tileboards, Mathias Reinecke
620m² of 8” silicon sensors: Radiation-tolerant and fast signals

- **8” hexagonal geometry**: most efficient use of Si area.
- **Bulk**: p-type, found to be more irradiation-tolerant than n-type.
- **Sensor thickness and cell size vary** with radiation levels:
  - 120, 200, 300 μm thickness.
  - 0.5 and 1cm² cell size.
- **Minimising degradation**
  - Operation at -30° C: Reduce increasing bulk leakage current.
  - Increasing the bias voltage up to -800V to reduce signal loss.
Electrical characterisation of silicon sensors is crucial

**Important:** leakage current = power dissipation, capacitance ~ noise

★ **Switching and probe-card setup**
- Contact all cells via pogo-pin card, all pads biased while one is tested.
- Switch between channels using switching card.
- **Temperature control of the sensor**, important after irradiation to \(O(e^{-14} - e^{-16})\) neq/cm².

---

![Probe- and switch card](image)

8'' prototype sensor

---

O(\(\mu\)A) per cell
At -35°C and after \(6.5e14\) neq/cm²

\[d=300\mu m\]

~500V depletion voltage
After \(6.5e14\) neq/cm²

\[d=300\mu m\]

Depletion voltage estimate [V]

\[I_{\text{pad}, \text{scaled}} = 30\mu \text{C} \times 0.6\]

Values for \(U = 800.0\) V

---

As expected: Leakage current ~ fluence

- \(I_{\text{leak}}(U_{\text{dep}}) \times 10^{-2} \text{ A/cm}^2\)
- \(I_{\text{leak}}(U_{\text{dep}}) \times 10^{-2} \text{ A/cm}^2\)
- \(I_{\text{leak}}(U_{\text{dep}}) \times 10^{-2} \text{ A/cm}^2\)
- \(I_{\text{leak}}(U_{\text{dep}}) \times 10^{-2} \text{ A/cm}^2\)

Leakage current ~ fluence

- \(I_{\text{leak}}(U_{\text{dep}}) \times 10^{-2} \text{ A/cm}^2\)
- \(I_{\text{leak}}(U_{\text{dep}}) \times 10^{-2} \text{ A/cm}^2\)
- \(I_{\text{leak}}(U_{\text{dep}}) \times 10^{-2} \text{ A/cm}^2\)

Irradiation fluence \([1E14\) neq/cm²]\)
Silicon modules

Sandwich of **PCB**, **sensor**, **biasing/insulation layer** and **baseplate** for rigidity/cooling.

- Wire-bonding from PCB onto the silicon.
- CE-E: CuW baseplates act as absorbers.
- CE-H: PCB baseplates (good thermal properties and cheaper).

5D calorimetry FE electronics requirements:
- **Low noise** (<2500e) and **high dynamic range** (0.2fC -10pC).
- Timing information to **tens of picoseconds**.
Demonstrated in test beam: HGCAL = Imaging calorimeter

μ (200 GeV) vs. π (250 GeV), 1 = 0.99993

Dπ vs. π, 2 = 0.99998

Dπ vs. π, 3 = 0.99984

➡ pion-like

Hit energy scale:
- 0.5 MIP
- 5 MIP
- 500 MIP
- 50 MIP

cf. Performance of CMS high granularity calorimeter prototypes in testbeam experiments, Clemens Lange (poster)
Demonstrated in test beam: Timing resolutions down to ~70ps

Resolve time evolution of real particle showers!

Run 980 event 3920: positron (39 hits in FH) after 7.09 ns
Electronics are challenging

**HGCAL FE electronics requirements:**

- **Low noise** (<2500e) and **high dynamic range** (0.2fC - 10pC).
- **Timing information** to **tens of picoseconds**.
- **Radiation tolerant**.
- **<20mW** per channel (cooling limitation).
- **Zero-suppression** of data to transmit to DAQ.
- Computation of **trigger sums** for L1 trigger.

---

**System overview**

- **10 Gb/s links**
- **On** detector
- **Off** detector
- **V3 HGCROC** ASIC both for silicon and SiPMs
- **ECON** as concentrator ASIC

---

**cf. HGCROC: the front-end readout ASIC for the CMS High Granularity Calorimeter, Damien Thienpont**

**cf. Electronics and Triggering Challenges for the CMS High-Granularity Calorimeter, Matthew Noy**
HGCAL trigger = 3D clustering

On-detector: 1.5μs

Off-detector: 3.5μs

Energy sums (compressed)

~300 TB/s

50 TB/s

Trigger cells

60 TB/s

3D clusters

4 TB/s

120° sector

Stage 1

Trigger cells

Stage 2

3D clusters

120 degree sector 12 boards, 1 crate

120 degree region 9 boards, 1 crate

120 degree sector 12 boards, 1 crate

120 degree region 9 boards, 1 crate

120 degree sector 12 boards, 1 crate

120 degree region 9 boards, 1 crate

Central L1T

Tracker

Calorimeter

Muon

Electronics and Triggering Challenges for the CMS High-Granularity Calorimeter, Matthew Noy
Sophisticated offline reconstruction = **The Iterative CLustering**

**Goal:** 1) merge hits to 2D clusters, 2) to clusters aligned as tracks

**Iterative strategy:** Reconstruct “easy stuff” first and work with what is left

- **Rechits** → **2D Clusters** → **Tracks** → **TrkEm**
- **Masked LC** → **Global** → **EM**
- **Masked LC** → **Tracks** → **TrkHAD**
- **Masked LC** → **Global** → **HAD**

**Current TICL highlights**

- Modular framework, written in C++.
- Works well with single EM particles, validated with test beam.
- Pattern recognition for hadronic shower to be optimised.
- Competitive to end-to-end machine learning approaches.
- TICL reconstruction on tt+200PU = O(100ms) on CPU, only ~5% of CMS phase 2 reconstruction budget.

**Pattern recognition** based on cellular automaton, e.g. doublet-search.

---

Thorben Quast | TIPP 2021, 26 May 2021
**Silicon modules and cassettes**

**Silicon modules**
Sandwich of **PCB**, **sensor**, **biasing/insulation layer** and **baseplate** for rigidity/cooling.
- Wire-bonding from PCB onto the silicon.
- CE-E: CuW baseplates act as absorbers.
- CE-H: PCB baseplates (good thermal properties and cheaper).

**CE-E cassettes**
Self-supporting sandwich structures (with absorbers).
- Modules placed on both sides of Cu cooling plate and closed with Pb plates.

---

**Diagram 1:**
- **Silicon module:** Sandwich of PCB, sensor, biasing/insulation layer, and baseplate.
- **CE-E cassette:** Self-supporting sandwich structures with absorbers.
- **CE-H cassette:** PCB baseplates (good thermal properties and cheaper).

---

**Diagram 2:**
- **Silicon module components:**
  - PCB
  - Sensor
  - Biasing/insulation layer
  - Baseplate
- **CE-E cassette components:**
  - Pb absorber
  - Motherboard
  - ASICs
  - Module PCB
  - Silicon
  - CuW baseplate
  - Cu cooling plate
  - CuW baseplate
- **CE-H cassette components:**
  - Pb absorber
  - Motherboard
  - ASICs
  - Module PCB
  - Silicon
  - CuW baseplate
  - Cu cooling plate
  - CuW baseplate

---

**Diagram 3:**
- **Silicon module:** Sandwich of PCB, sensor, biasing/insulation layer, and baseplate.
- **CE-E cassette:** Self-supporting sandwich structures with absorbers.
- **CE-H cassette:** PCB baseplates (good thermal properties and cheaper).

---

**Diagram 4:**
- **Silicon module components:**
  - PCB
  - Sensor
  - Biasing/insulation layer
  - Baseplate
- **CE-E cassette components:**
  - Pb absorber
  - Motherboard
  - ASICs
  - Module PCB
  - Silicon
  - CuW baseplate
  - Cu cooling plate
  - CuW baseplate
- **CE-H cassette components:**
  - Pb absorber
  - Motherboard
  - ASICs
  - Module PCB
  - Silicon
  - CuW baseplate
  - Cu cooling plate
  - CuW baseplate

---

**Diagram 5:**
- **Silicon module:** Sandwich of PCB, sensor, biasing/insulation layer, and baseplate.
- **CE-E cassette:** Self-supporting sandwich structures with absorbers.
- **CE-H cassette:** PCB baseplates (good thermal properties and cheaper).
Towards mass production of silicon modules around the world

### 27k silicon modules to be produced

<table>
<thead>
<tr>
<th>Module Type</th>
<th>300 µm</th>
<th>200 µm</th>
<th>120 µm</th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full</td>
<td>8820</td>
<td>7740</td>
<td>4356</td>
<td>20916</td>
</tr>
<tr>
<td>Five</td>
<td>1158</td>
<td>144</td>
<td>0</td>
<td>1302</td>
</tr>
<tr>
<td>Choptwo</td>
<td>0</td>
<td>0</td>
<td>312</td>
<td>312</td>
</tr>
<tr>
<td>Semi</td>
<td>450</td>
<td>0</td>
<td>312</td>
<td>762</td>
</tr>
<tr>
<td>Half</td>
<td>1386</td>
<td>156</td>
<td>84</td>
<td>1626</td>
</tr>
<tr>
<td>Full+Three</td>
<td>1092</td>
<td>0</td>
<td>0</td>
<td>1092</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td>13998</td>
<td>8040</td>
<td>5064</td>
<td>27102</td>
</tr>
</tbody>
</table>

### Modules have different shapes

- Half
- Five
- Semi
- Choptwo
- Full + Three

### Modules assembled by automatic gantries

6" prototype modules assembled by automatic gantry at UCSB.

### Tooling development and preparation for large scale production:

- **Tooling** for low density full modules **ready**, soon also for high density full module.
- Design of gantry tooling for **partial modules ramping up** this year.

### Module Assembly Centers (MACs) preparation is well advanced

- All 6 sites progressing on qualification of various module production steps.
- **5 sites fully equipped** and on track to be qualified for assembly in 2021.

### Production plan

- 10 modules/day per MAC with 6 MACs.
- Could achieve up to 24 modules / day per MAC.
Prototyping of services and passive absorber plates advancing

- **Mockup structures** to study installation steps and on-detector services locations.
- Procurement process of **600 tons of stainless steel** started.
- Achieved **1 mm flatness** for CE-H steel absorber plates.
- Lead sandwich absorber development challenging due to relative weakness and low workability.

---

**Steel absorber plate prototypes for the CE-H**

- 66 mm absorbers
  - ~220 cm
- 35 mm absorbers
  - ~200 cm

**CE-E lead sandwich absorber plate prototype**

**HGCAL detector services mockup**
Recent re-optimisation of longitudinal sampling

- Mobile-phone-size front-end embedded in industrial-size absorbers.
  - Absorber tolerances add up to ~height needed by front-end.

- Absorber plates must be ordered soon.

  ➡ Adapt to realistic absorber tolerances while preserving overall nuclear/radiation depths.

<table>
<thead>
<tr>
<th></th>
<th>Dec 2018</th>
<th>New: Scenario 13</th>
</tr>
</thead>
<tbody>
<tr>
<td># layers in CE-E, sampling layout</td>
<td>28, uniform</td>
<td>26; last four thickened</td>
</tr>
<tr>
<td># layers in CE-H (all Si)</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td># layers in CE-H (mixed)</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>CE-H: thickness of thin/ thick absorbers</td>
<td>35.0mm / 66.0 mm</td>
<td>41.5 mm / 60.7 mm</td>
</tr>
<tr>
<td>Depth of CE-E</td>
<td>25.4 $X_0$</td>
<td>27.7 $X_0$</td>
</tr>
<tr>
<td>Total depth</td>
<td>9.85 $\lambda$</td>
<td>9.97 $\lambda$</td>
</tr>
</tbody>
</table>

Calorimetric performance impaired only minimally.

- Number of layers reduced to minimise overall risk with minimal impact of performance.

- Currently, the focus is on:
  - Finalisation of design, prototyping towards final systems.
  - Market surveys, orders.
  - Pre-productions, qualification of final components.

- Next major step: **Engineering Design Review due at the end of this year**

- Production starting in 2022.
**HGCAL: where highly granular calorimetry comes to life at the energy frontier**

- Silicon as sensitive material in high radiation region, scintillator+SiPMs elsewhere.
- 3D energy & time measurement of particle showers.

**Moving towards fully-engineered design in 2021**

- e.g. silicon sensors close to being qualified.
- e.g. preparation for mass production of active modules. Prototyping of passive absorber plates.
- e.g. recent optimisation of longitudinal sampling to relax mechanical tolerances for metal plates and for air gaps.
CMS endcap calorimeter upgrade proposal

An all-new ‘imaging’ calorimeter with unprecedented readout granularity that offers robustness and good performance through the full HL-LHC operational lifetime.

**Requirements**

- **Radiation tolerance**
  fully preserving the energy resolution after 3000 fb$^{-1}$

- **Dense calorimeter**
  preserve lateral compactness of showers

- **Fine lateral granularity**
  two shower separation + observation of narrow jets, minimise pileup contributions in energy & timing measurements

- **Fine longitudinal granularity**
  fine sampling of the shower: good energy resolution, pattern recognition, pile-up discrimination, …

- **Precision time measurement**
  high energy showers for pile-up rejection, primary vertex identification

- **Contribute to L1 (Hardware) trigger**

---

Thorben Quast | TIPP 2021, 26 May 2021
~370m² of scintillator for regions of lower radiation

- **Cheaper** than silicon.

- Rely on experience from CALICE and past CMS HCAL upgrade.

- Radiation hardness of scintillators & Si-PMs well understood.
- Overall **S/N for MIP** remains > 5 after 3000 fb⁻¹.

**SiPM-on-tile design**
- 240k SiPMs integrated into the PCB, need to be cooled.
- Light **readout** directly on detector.
- More compact and cost-effective.

**Ongoing R&D**
- e.g. validate interplay SiPM - ROC.
- e.g. tile geometry and wrapping optimisation.
- …

**S/N > 5 after 3000fb⁻¹**

>50% scintillator signal after 3000fb⁻¹

**Radiation hardness of scintillators & Si-PMs well understood.**

**Overall S/N for MIP** remains > 5 after 3000 fb⁻¹.

**SiPM-on-tile design**
- 240k SiPMs integrated into the PCB, need to be cooled.
- Light readout directly on detector.
- More compact and cost-effective.

**Ongoing R&D**
- e.g. validate interplay SiPM - ROC.
- e.g. tile geometry and wrapping optimisation.
- …

**S/N > 5 after 3000fb⁻¹**

>50% scintillator signal after 3000fb⁻¹

**Radiation hardness of scintillators & Si-PMs well understood.**

**Overall S/N for MIP** remains > 5 after 3000 fb⁻¹.

**SiPM-on-tile design**
- 240k SiPMs integrated into the PCB, need to be cooled.
- Light readout directly on detector.
- More compact and cost-effective.

**Ongoing R&D**
- e.g. validate interplay SiPM - ROC.
- e.g. tile geometry and wrapping optimisation.
- …
Arrangement of active modules

Silicon-only layer (in CE-E) showing “cassettes” and different sensor thicknesses.

Mixed layer (in CE-H) with silicon at high $\eta$ and scintillator+SiPM at low $\eta$.

Inner/Outer coverage:
Best coverage by O(10) variants of hexagonal modules.
**Tileboards**

- Holds SiPMs, HGROCs, LEDs, …
- Complex layout.
- **Good**: alive and sending data.
- Ongoing R&D: tile-board characterisation (electronically, thermo-mechanically).

**Technical challenges**

- High-speed data transfer.
- Cooling of SiPMs through PCB.
- Thermo-mechanical rigidity +/- 40 °C.
- Radiation hardness.

---

Arranging scintillator tiles in $r$-$\phi$ grid with constant azimuthal angle: 4 - 32 cm$^2$ area / tile
Longitudinal structure and lateral coverage

Longitudinal sampling

50 layers for total depth of ~9.8 λ

- CE-E: 28 fine samplings for 25 $X_0 / 1.3 \lambda$
- CE-H (1): 12 samplings in the first ~3.5 λ
- CE-H (2): 10 samplings in the last ~5 λ

Main constraint: fit into existing detector endcap —> limited space.
- e.g. air gap in CE-E: limited space, very difficult for electrical components and connectors.
1. Assembling CE-E: self-supporting cassettes are assembled horizontally.

2. CE-H is assembled in two steps: absorber material, followed by insertion of cassettes.

3. Attach CE-E to CE-H, then rotate whole CE to vertical.

4. Lowering into cavern.
Principle of the timing measurements in test beam
October 2018 run 517 - event 30:
250 GeV π^-