Overview of Latest Developments in the CMS HGCAL Upgrade Project

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On behalf of the CMS collaboration

IPRD 2019

October 15th, 2019
High Luminosity LHC

- **Two major challenges** for detectors:
  - **Unprecedented radiation levels**
    - Fluences of up to $\sim 10^{16} \text{n}_{\text{eq}}/\text{cm}^2$ (Doses of up to $\sim 2 \text{ MGy}$)
    - Requires
      - Radiation hard detector material and readout
  - **High Pile-up**
    - Up to $\sim 140-200$ interactions per bunch crossing
    - Mitigated with
      - High granularity
      - Precise timing

- **75% design luminosity**
- **Design luminosity**
- **HS-LHC** ~ 5 times higher than design instantaneous luminosity

- **$\sim 10x$ more integrated luminosity (~ $3000 \text{ fb}^{-1}$)**
CMS HL-LHC Upgrades

- CMS will be going through major upgrades!

- **New Tracker**

- **New Endcap Calorimeters**
  
  Current calorimeter is designed for integrated luminosity of maximal 500 fb$^{-1}$

- **Muon Systems**

- **Trigger/HLT/DAQ**

- **Barrel ECAL/HCAL**

- **MIP Precision Timing Detector**

- **CMS Detector**
CMS High Granularity Calorimeter

- CMS electromagnetic and hadronic endcaps will be replaced
CMS High Granularity Calorimeter

- CMS electromagnetic and hadronic endcaps will be replaced

HGCAL is a 5-D imaging calorimeter (energy, x, y, z, t)
High Granularity Calorimeter Active Elements

- **Silicon** detectors are
  - Radiation tolerant enough
  - Fast enough to mitigate pile-ups
  - Can be finely segmented to allow high granularity

- **Active elements of High Granularity Calorimeter:**
  - **Silicon** in high radiation area (600 m²)
  - **Scintillator** in lower radiation area (400 m²) *(To reduce cost)*

Fluences of up to $10^{16}$ n_{eq}/cm²
Doses of up to 2 MGY

Strong dependence on $|\eta|$ and $|z|$
Overall High Granularity Calorimeter Design

- HGCAL: A sampling Calorimeter:
  - **Very high granularity**
  - 6 million Silicon channels
  - 240 thousand Scintillator channels
  - Weight per endcap: ~ 215 tonnes!
  - Total longitudinal thickness: 9.8λ
  - Electromagnetic longitudinal thickness: 25X₀

Electromagnetic section (CE-E)
- 14x2 Layers
- 8 Layers
- 14 Layers

Hadronic section (CE-H)

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Silicon Sensors

- 8 inch wafers
- Hexagonal sensor geometry
- Planar p-type DC-coupled sensor pads
- Active thickness: 300 μm, 200 μm, 120 μm
  - Advantage of deploying thinner sensors in the higher fluence regions
    - More tolerant to large neutron fluences
  - Reduced cell size in thinner sensors
    - Keeping the capacitance reasonable

- 300/200 μm: 192 cells
- 120 μm: 432 cells
Silicon Modules

Hexaboard
Silicon sensor
Kapton sheet
Base plate

8 inch HGCAL Silicon module assembly set-up
(At one of the 6 module assembly centers worldwide)

8 inch HGCAL Silicon module
Plastic Scintillators and Scintillator Tile-Boards

- SiPM-on-tile technology like in the CALICE AHCAL
- Scintillator cell sizes:
  - $\sim 2 \times 2 - 5.6 \times 5.6 \text{ cm}^2$
- Tile board size: $\sim 40 \times 40 \text{ cm}^2$

CALICE $3 \times 3 \text{ cm}^2$ scintillator tiles mounted on a PCB that holds one SiPM per tile

HGCal Scintillator tiles mount on tile-boards

- Tile-board prototypes and tile assembly center preparations are in progress
Cassettes

- Modules are installed on **Copper plates** with embedded tubing (both CE-E and CE-H)
  - *Coolant: two phase CO$_2$*
    - *High latent heat of vaporization*

- **Cassettes:** Units of installations at CMS (between absorber layers)
  - CE-E: Double-sided
  - CE-H: Single-sided

![Diagram of a 60° CE-E cassette and Two 30° CE-H mixed cassette](image)
First Thermo-Mechanical Mock-up

- First thermo-mechanical mock-up was designed and fabricated
- Largest all-Silicon CE-H cassette
- Verified the dynamic mounting scheme
- Verified the Silicon module and cassette cooling performance
  - Applied 270 W heat load
  - Successfully maintained:
    - CO₂: -35 ºC
    - Silicon: -30 ºC

Number of RTDs

- CuW
- PCB

Measured Silicon temperature

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Cassette Prototypes

- Design verification is in progress through various cassette and assembly prototypes

- First electromagnetic copper plate prototypes

- First mixed hadronic cassette

- First all silicon hadronic cassette to verify the readout chain

First electromagnetic copper plate prototypes

First mixed hadronic cassette

One layer assembly prototype
Read-out Chain

• The front-end electronics
  • Measures and digitizes the charge
    • 10bit ADC (0.2fC - 100fC)
    • 12bit TDC (50fC to 10pC)
  • Provides a high precision measurement of the time of arrival of the pulses
    • 10bit TDC with 25ps bins
  • Transmits the digitized data to the back-end electronics

• Similar front-end electronics for the readout of the SiPMs
Expected Performance

- **High granularity and compact design:**
  - Narrow showers
  - Good particle separation
  - Pile-up rejection within the first layers

- Significant Silicon coverage:
  - High-precision timing capabilities
    - Time resolution: \( \sim 25 \text{ ps} \)
      (for an energy deposit equivalent to \( \sim 50 \text{ fC} \))

\[ E_{\text{photons}} = 80 \text{GeV} \]
\( \rho_T = 14.4 \text{GeV} \)
\( \eta = 2.4 \)
Beam Tests

- Various test beam studies at Fermilab and CERN during 2016-2018
- Various configurations were explored
  - Measure the performance and compare with a detailed simulation
  - Validate the HGCAL design
Achieved energy resolution: below ~1% for highest energies

Achieved position resolution: below ~1mm

Achieved time resolution: ~70 ps
(for channels close to shower maximum with provisional electronics)

More information: Matteo Bonanomi’s poster!
“BEAM TESTS OF CMS HIGH GRANULARITY CALORIMETER PROTOTYPES AT CERN”
Summary

• Detector design faces two major challenges at HL-LHC:
  • Unprecedented radiation dose
  • High pile-up

• To address these challenges at the CMS endcap calorimeters:
  • The endcaps will be placed with the HGCAL, a high granularity 5-D imaging calorimeter
    • 600 m² of Silicon coverage
  • The expected performance of HGCAL is demonstrated
    • Mitigates the pile-up well, providing cleaner signals
    • Mitigates the high radiation HL-LHC environment

• Currently going through intensive phase of prototyping
• Preparations for production are going well at the assembly centers

**HGCAL will play a major role in maintaining the overall CMS Physics performance throughout the full HL-LHC period**
Back-up
Challenges at HL-LHC

- **Two major challenges** for detectors:
  - **High Pile-up challenge**
    - Mitigated with
      - High granularity
      - Precise timing
  - **Unprecedented radiation dose challenge**
    - Requires
      - Radiation hard detector material and readout

Simulated and reconstructed vertices with pileup 200

- Beam-spot RMS: \( \Delta z \sim 5 \) cm
- Beam-spot RMS: \( \Delta t \sim 150 \) ps

Dose, 3000 fb\(^{-1}\)
Overall High Granularity Calorimeter Design

- **HGCal**: A sampling calorimeter:
  - **Electromagnetic section (CE-E)**
    - Active element: Silicon
    - 14 x 2 layers
    - Absorber: Lead, Copper-Tungsten, Copper
  - **Hadronic section (CE-H)**
    - Active elements:
      - Silicon
      - Layers 1-8
      - Silicon & Scintillator
      - Layers 9-22
      - Absorber: Stainless Steel
  - Very high granularity
    - 6 million Silicon channels
    - 240 thousand Scintillator channels
  - Weight: ~ 215 tonnes per endcap!
  - Total longitudinal thickness: 9.8\(\lambda\)
  - Electromagnetic longitudinal thickness: 25\(X_0\)
300 μm, 200 μm and 120 μm Sensors

<table>
<thead>
<tr>
<th>Thickness [μm]</th>
<th>Expected dose range</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>1E14-5E14</td>
</tr>
<tr>
<td>200</td>
<td>5E14-2.5E15</td>
</tr>
<tr>
<td>120</td>
<td>2.5E15-1E16</td>
</tr>
</tbody>
</table>

Outer radius

Inner radius

Limit between 300 μm and 200 μm sensors

Limit between 200 μm and 120 μm sensors
Silicon Sensors Key Technical Specifications

- **Sensor breakdown voltage** $V_{\text{break}} > 800\text{V}$, $I_{\text{800}} < 2.5 \times I_{\text{600}}$
- **Current @600V (at 20°C):** ≤ 100 µA integrated over the sensor and guard rings
- **Current @600V $I_{\text{600}}$ (at 20°C):** ≤ 100 nA/pad

- **Allowed number of bad pads:**
  - ≤ 8 for full-sized sensors
  - ≤ 4 for half and semi
  - ≤ 6 for choptwo and five types
  - ≤ 2 for chopfour and three types
  - Not more than two adjacent bad pads

Corresponds to roughly 2%-4%

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>300 µm</th>
<th>200 µm</th>
<th>120 µm</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>(F) Full</td>
<td>11400</td>
<td>9096</td>
<td>3840</td>
<td>24336</td>
</tr>
<tr>
<td>(a) Half</td>
<td>1404</td>
<td>144</td>
<td>108</td>
<td>1656</td>
</tr>
<tr>
<td>(b) Five</td>
<td>990</td>
<td>144</td>
<td>48</td>
<td>1182</td>
</tr>
<tr>
<td>(c) Three</td>
<td>1290</td>
<td>0</td>
<td>0</td>
<td>1290</td>
</tr>
<tr>
<td>(d) Semi</td>
<td>720</td>
<td>0</td>
<td>0</td>
<td>720</td>
</tr>
<tr>
<td>(d-) Semi(-)</td>
<td>0</td>
<td>0</td>
<td>336</td>
<td>336</td>
</tr>
<tr>
<td>(g-) Choptwo(-)</td>
<td>0</td>
<td>0</td>
<td>336</td>
<td>336</td>
</tr>
</tbody>
</table>
Trigger Cells

Schematic illustration of the three-fold diamond configuration of sensor cells on hexagonal 8” silicon wafers, showing the groupings of sensor cells that get summed to form trigger cells, for the large, 1.18 cm$^2$, sensor cells (left), and for the small, 0.52 cm$^2$, cells (right).
Silicon Sensor Characterization

- Various efforts on *characterizing* Silicon wafers and test structures at different temperatures

  - **Measuring:**
    - Leakage currents
    - Interpad resistance
    - Charge collection
    - Depletion voltage
      (Two techniques:
       - 7 needle
       - full hexa-board)

- **Studying irradiation effects**
  - Neutrons
  - Protons
  - Electrons

Automated Probe Station at Fermilab

Cold chuck control

Laser
Wire-bonding Notches

- 12 notches for guard ring bonds
  - Stepped design to keep bond wires below PCB surface for protection
  - Moved closer to mouse bite to be less likely to be touched during handling
- 6 notches in PCB for bonding to shield in Kapton or PCB baseplate
  - Also close to mouse bite, opposite side from baseplate notch
- 6 notches in baseplate (at mouse bites) for backside bias bonds
  - Adding bond pad on an inner step on underside of PCB
Module Assembly and Testing

Automated gantry assembly

Wirebonder

Signal bonds at stepped holes

Optical inspection microscope

OGP

Test stand

Guard ring bonds at edge
Thermo-mechanical Mock-up Cooling Plate

- FEA calculations have been made for a heat load of 270W
  - Expected at end of life
- 6.8 meter long tube, 3/16” OD, 0.03” wall thickness
- 3.3 g/sec CO2 flow (35% vapor quality)
- Pressure drop = 0.8bar
- Outlet temp = -35C (inlet -33C)
- Maximum temperature of copper plate is below -32C
- Cooling plate has been fabricated at Fermilab
Thermo-mechanical Mock-up Hexaboard

- Mockup of 432 channel module board
  - Designed to *apply heat loads* and *measure temperature of the silicon*

12 heaters mocking 12 read-out chips

8 RTDs in contact with Silicon

ADS124S0x chip for heater control and temp measurements

High bandwidth connectors
  - 2mm high rigid
Simulated Temperature Distribution of Silicon

Base Plate Material: CuW 20/80

Delta T (°C)
wrt to cooling plate

Base Plate Material: PCB

Delta T (°C)
wrt to cooling plate

Unit: °C

Carbon Fiber  CuW    PCB

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Assembly and Installation

Stacking of CE-E cassettes

Assembly of CE-H absorber structure

CE-H cassette insertion

Rotation of the entire HGCal to vertical position

Lowering of one HGCal into the experimental cavern and connection onto YE1
Scintillator Tile-boards Read-out Chain

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Shower Development

- Event displays of the energy seen in each cell of consecutive silicon layers due to electron-induced electromagnetic showers.

**Fermilab**
- 16 layers
- 32 GeV electron
- 1 $X_0$  5 $X_0$  10 $X_0$  15 $X_0$

**Cern**
- 8 layers
- 250 GeV electron
- 5 $X_0$  15 $X_0$  21 $X_0$  27 $X_0$