The CMS High Granularity Calorimeter for High Luminosity LHC

Rachel Yohay (Florida State University)
On behalf of the CMS Collaboration
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Outline

- Motivation
- Detector design
- Silicon sensor prototyping
- Performance
- Conclusions and outlook
The focus of this talk

- Motivation
- Detector design
- Silicon sensor prototyping
- Performance
- Conclusions and outlook
Motivation
The Compact Muon Solenoid (CMS) detector

**CMS DETECTOR**
- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

**STEEL RETURN YOKE**
- 12,500 tonnes

**SILICON TRACKERS**
- Pixel (100x150 μm): ~16m² ~66M channels
- Microstrips (80x180 μm): ~200m² ~9.6M channels

**SUPERCONDUCTING SOLENOID**
- Niobium titanium coil carrying ~18,000A

**MUON CHAMBERS**
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

**PRESHOWER**
- Silicon strips ~16m² ~137,000 channels

**FORWARD CALORIMETER**
- Steel + Quartz fibres ~2,000 Channels

**CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)**
- ~76,000 scintillating PbWO₄ crystals

**HADRONDON CALORIMETER (HCAL)**
- Brass + Plastic scintillator ~7,000 channels

Endcap calorimeter
- $1.5 < \eta < 3.0$

High luminosity physics and the endcap

Physics goals of the High Luminosity LHC (HL-LHC) make specific performance demands of the endcap calorimeter:

- Measurement of vector boson fusion (VBF) Higgs production and WW scattering, processes identified by two characteristic forward jets
- Searches for rare heavy particles associated with supersymmetry (SUSY) and other Standard Model (SM) extensions
  - Extend electron, photon, tau, and jet reconstruction to the endcaps to better exploit the dataset
  - Improved missing transverse energy (M_{ET}) reconstruction
- CMS upgrade philosophy: equal or better performance under HL-LHC conditions
Complete overhaul required

- PbWO$_4$ crystal transmission loss due to radiation damage
- Worsening energy resolution due to increased pileup
Detector design
**High Granularity Calorimeter (CE)**

**Active Elements:**
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- “Cassettes”: multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H

**Key Parameters:**
- CE covers $1.5 < \eta < 3.0$
- ~215 tonnes per endcap
- Full system maintained at -30°C
- ~600m² of silicon sensors
- ~500m² of scintillators
- 6M si channels, 0.5 or 1 cm² cell size
- ~27000 si modules
- Power at end of HL-LHC: ~110 kW per endcap

Electromagnetic calorimeter (CE-E): Si, Cu & CuW & Pb absorbers, 28 layers, 25 $X_0$ & ~1.3$\lambda$

Hadronic calorimeter (CE-H): Si & scintillator, steel absorbers, 24 layers, ~8.5$\lambda$
High Granularity Calorimeter (CE)

Active Elements:
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassei9es": multiple modules mounted on cooling plates with electronics and absorbers
- Scin6llating cells with SiPM readout in low-radiation regions of CE-H

Key Parameters:
- CE covers $1.5 < \eta < 3.0$
- ~215 tonnages per endcap
- Full system maintained at -30°C
- ~600m$^2$ of silicon sensors
- ~500m$^2$ of scintillators
- 6M Si channels, 0.5 or 1 cm$^2$ cell size
- ~27000 Si modules
- Power at end of HL-LHC: ~110 kW per endcap

Electromagnetic calorimeter (CE-E): Si, Cu & CuW & Pb absorbers, 28 layers, 25 $X_0$ & ~1.3$\lambda$
Hadronic calorimeter (CE-H): Si & scintillator, steel absorbers, 24 layers, ~8.5$\lambda$
Design in a nutshell

Particle flow (PF) calorimeter, optimized for PU rejection and jet energy resolution (JER)

- PU rejection required by high HL-LHC instantaneous luminosity
- JER improved with respect to cone-based reconstruction
  - Good position resolution from fine longitudinal and transverse granularity to associate calorimeter segments to charged hadron tracks
  - High resolution tracking information used to estimate the energy of charged jet candidates
  - Low resolution calorimeter information “only” used to estimate the energy of neutrals

Typical jet is composed of:
- 62% charged particles
- 27% photons
- 10% neutral hadrons
- 1% neutrinos
Design in a nutshell

- Per-channel calibration with minimum-ionizing particles (MIPs) throughout HL-LHC lifetime imposes requirements on radiation tolerance
- Dictates choice of active materials
- Dictates geometry
Silicon sensor design

- n-on-p sensors for superior radiation hardness
- Cost optimization
  - Hexagonal sensors from 8” wafers
  - Thickness decreases as expected fluence increases
- Cell sizes (~ capacitance ~ noise) set by MIP signal-to-noise (S/N) requirement at end of life
- Threefold diamond symmetry permits easy grouping of trigger cells and association to readout chips
- Fractional variants to cover inner and outer boundaries

<table>
<thead>
<tr>
<th>Active thickness (μm)</th>
<th>Cell size (cm²)</th>
<th>Cell capacitance (pF)</th>
<th>Expected fluence range (×10¹⁵ neq/cm²)</th>
<th>Initial MIP S/N</th>
<th>Smallest MIP S/N after 3000 fb⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>1.18</td>
<td>45</td>
<td>0.1-0.5</td>
<td>11</td>
<td>4.7</td>
</tr>
<tr>
<td>200</td>
<td>1.18</td>
<td>65</td>
<td>0.5-2.5</td>
<td>6</td>
<td>2.3</td>
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<tr>
<td>120</td>
<td>0.52</td>
<td>50</td>
<td>2-7</td>
<td>4.5</td>
<td>2.2</td>
</tr>
</tbody>
</table>

192-channel sensor

432-channel sensor

CE-E layer 9
Silicon sensor design

- 300- and 200-μm sensors in physically thinned float zone (FZ) silicon
- 120-μm sensors in epitaxial high-resistivity silicon layer on lower resistivity substrate (“epi”)
- “Mouse bites” for module mounting
- Dedicated small (low-capacitance ~ low-noise) calibration cells
- Common and individual p-stops under consideration

Common p-stop

Individual p-stop

192-channel wafer layout with calibration cells
Silicon sensor prototyping
Prototyping timeline

CMS Phase 2 Tracker R&D: Hamamatsu
- FZ (200- and 320-µm) vs. epi (120-µm)
- n-on-p vs. p-on-n
- Proton (23 MeV and 24 GeV) and reactor neutron irradiation campaigns

8” hexagonal n-on-p sensors: Hamamatsu
- FZ (300- and 200-µm) and epi (120-µm)
- 192 channels (current module design)
- Common vs. individual p-stop
- Stepper and full-wafer lithography

6” hexagonal sensors: Hamamatsu
- FZ (300-µm) and deep-diffused float zone (ddFZ) (200- and 120-µm)
- n-on-p vs. p-on-n
- 128- and 256-channel variants
- Common vs. individual p-stop
- Reactor neutron irradiation campaign


CE R&D: Hamamatsu
- Test structures on Phase 2 tracker wafers
- Reactor neutron irradiation campaign

2011 JINST 6 (2011) P10010
Lessons learned: tracker R&D

• Thin (≤300 μm) sensors required in regions of highest fluence

• Over-depleted operation necessary for maximum charge collection

• Reduced full depletion voltage ⇒ reduced leakage current ⇒ reduced power dissipation

• n-on-p sensors have better noise performance after irradiation than p-on-n

Before irradiation

After irradiation

200 μm p-on-n pedestal-subtracted noise
Lessons learned: CE R&D

• Difference in charge collection between p-on-n and n-on-p sensors small above $10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$

• Above $\sim 6 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$, 100-μm epi n-on-p sensors (300 V bias) collect more signal charge than 120-μm ddFZ n-on-p sensors (600 V bias)

• Diode noise measurements agree with Hamburg model (linear dependence of current/volume on fluence)
Lessons learned: Hamamatsu 6”

- Excellent sensor performance across 200 prototypes
- Homogeneous leakage current across sensor area
- Per-cell leakage current at 1000 V before irradiation of order 1 nA (spec is ≤100 nA per cell, ≤20 μA per sensor at 800 V and 20°C)
- Breakdown voltage typically >1 kV
- Hamamatsu established as a reliable vendor
- Leakage current measurements in agreement with those supplied by Hamamatsu
- Decision made to develop 8” sensors
- Development of switch + probe card system for fast sensor characterization

### Per-cell leakage current at 1 kV bias for one 128-channel sensor

<table>
<thead>
<tr>
<th>Cell leakage current (nA)</th>
<th>Values for U = 1000.0 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>1.4</td>
<td>1.4</td>
</tr>
<tr>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>2.0</td>
<td>2.0</td>
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<tr>
<td>2.3</td>
<td>2.3</td>
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<tr>
<td>2.6</td>
<td>2.6</td>
</tr>
<tr>
<td>2.9</td>
<td>2.9</td>
</tr>
<tr>
<td>3.2</td>
<td>3.2</td>
</tr>
</tbody>
</table>

### Leakage current measured with switch + probe card setup (23/200 sensors)

- $I_{\text{max}}$ @ 1000V
- $I_{\text{mean}}$ @ 1000V
- $I_{\text{median}}$ @ 1000V
- $I_{\text{min}}$ @ 1000V

```
<table>
<thead>
<tr>
<th>sensor number</th>
<th>$I_{\text{max}}$ @ 1000V</th>
<th>$I_{\text{mean}}$ @ 1000V</th>
<th>$I_{\text{median}}$ @ 1000V</th>
<th>$I_{\text{min}}$ @ 1000V</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0</td>
<td>0.5</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>5</td>
<td>1.5</td>
<td>1.0</td>
<td>0.8</td>
<td>0.5</td>
</tr>
<tr>
<td>10</td>
<td>2.0</td>
<td>1.5</td>
<td>1.3</td>
<td>1.0</td>
</tr>
<tr>
<td>15</td>
<td>2.5</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>20</td>
<td>3.0</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>
```
Lessons learned: Hamamatsu 6"

- Sensors exposed to $1.5 \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2$
- Performance after neutron irradiation in line with expectations
  - Leakage current scales with cell area
  - Dependence of leakage current per unit volume on fluence agrees with Hamburg model expectation
- Noise measurements needed to confirm non-Gaussian tails in p-on-n sensors
Lessons learned: Hamamatsu 8”

- Stepper sensors considered an 8” proof of principle for investing in full-wafer lithography
- Commissioning of different measurement techniques for quality control
  - Sensor geometry and DC coupling precludes an integrated biasing circuit with a single grounded contact point for IV and CV testing ⇒ multiple cells need to be biased simultaneously to replicate operating conditions
  - “Seven-needle” measurement as reference
  - Probe card with pogo pin contacts for fast characterization
Lessons learned: Hamamatsu 8"

- Excellent sensor quality as for 6” sensors
- Good agreement with Hamamatsu leakage current measurements
- Per-cell capacitances in line with TDR expectation

### Per-cell IV curves for prototype 192-channel sensor (300 μm, individual p-stop)

- **Hamamatsu 7-needle**
- **CERN probe card**

#### Table: Design vs. Measured Capacitance

<table>
<thead>
<tr>
<th>Cell area (cm²)</th>
<th>Sensor thickness (μm)</th>
<th>Design capacitance (pF)</th>
<th>Measured capacitance (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.18</td>
<td>200</td>
<td>65</td>
<td>69-71</td>
</tr>
<tr>
<td>1.18</td>
<td>300</td>
<td>45</td>
<td>49-50</td>
</tr>
</tbody>
</table>

- **OF**
- **Cells with high current or breakdown**
Performance
Test beam: 2016

- 6” modules with different depth configurations
- First demonstrations of:
  - MIP calibration
  - Shower reconstruction
  - Time tagging core of showers
    - Resolution on time difference between neighboring cells of a sensor ~25 ps at an effective S/N of 100
    - Good timing precision can be achieved for high energy deposits found in the core of electromagnetic and hadronic showers
Test beam: 2018

- 6” modules with readout PCB, readout chip, and absorber closer to design spec
- 28-layer CE-E + 12-layer CE-H for 94 silicon modules total (+ 39 scintillator layers behind CE-H)
- Preliminary results with basic reconstruction (currently being improved) indicate:
  - MIP signal visible even for low S/N
  - Excellent description of the energy resolution and linearity with simulation

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Agreement for longitudinal and transverse shower profiles (still some tuning of Geant4 model description needed)

- Long. profile wiggles due to back-scattering from CuW
- Good linearity in energy response up until 300 GeV
- Data/MC energy scale difference only 4%
- Data and MC resolution agree with TDR expectation
  - MC momentum spread ~1%

MIP calibration possible with HGC-only tracking – agreement with DWC-selection

- Reliable MIP reconstruction even in Low Gain (S/N ~ 3, cf. S/N ~ 7 in HG)
- All types of cells and sensors calibrated:
  - 7531 channels (63%), 363 chips (97%)

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Reconstructed HighGain [ADC]

- Module 78, chip 2, channel 42
  - MPV: 44.8 ADC / MIP

Reconstructed LowGain [ADC]

- Module 78, chip 2, channel 42
  - MPV: 5.31 ADC / MIP

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28-layer CE-E setup from June + 12-layer CE-H-Si setup (total: 94 modules)

- 3 configurations (full CE-E vs full CE-H)
- Bias, current and environmental control, active water cooling (same as in June)
- Delay Wire Chambers, threshold Cherenkov counters, MCP-PMTs for timing reference
- CALICE AHCAL as scintillator CE-H
- Trigger: 2x scintillators in front of CE-E + 1x additional (veto) behind CE-H-Si

Beams: μ and e, π up to 300 GeV

➡ Large-scale test of O(100) HGCAL modules

More than 6 million events recorded!
Conclusions and outlook

- R&D converging on an optimized, constructible design
- CE expected to play a critical role in delivering HL-LHC physics
  - PF calorimeter able to accurately reconstruct electrons, photons, taus, and jets in extremely high pileup
  - Careful deployment of active materials to ensure adequate performance after 3000 fb^{-1}
- CE a first of its kind in collider physics!
Backup
Non-Gaussian noise

- High electric fields between adjacent cells can create avalanche multiplication of thermally generated charge carriers
- Effect worst in p-on-n sensors with large interpad gaps (CE TCAD simulation)
Hamburg model

Current increase caused by irradiation

\[ \Delta I = \alpha \Phi_{eq} V \]

Temperature scaling

\[ \frac{I(T_2)}{I(T_1)} = \left( \frac{T_2}{T_1} \right)^2 \exp \left( -\frac{E_{eff}}{2k_B} \left[ \frac{1}{T_2} - \frac{1}{T_1} \right] \right) \]

1. Calculate current expected after irradiation
2. Scale to measurement temperature (-20 degC) and operation temperature (-30 degC)

- Parameters:
  - \( V \) = sensor or cell volume
  - \( \Phi_{eq} \) = Fluence per cm² equivalent to 1 MeV neutrons
  - \( \alpha = 5e-17 \) A/cm
  - \( k_B = 8.61733e-5 \) eV/K
  - \( T_{reference} = 293.15 \) K (20 degC)
  - \( T_{measurement} = 253.15 \) K (-20 degC)
  - \( T_{operation} = 243.15 \) K (-30 degC)
## Irradiated samples

<table>
<thead>
<tr>
<th>Fluence ($n_{eq}/cm^2$)</th>
<th>$1.5 \times 10^{14}$</th>
<th>$5 \times 10^{14}$</th>
<th>$7.5 \times 10^{14}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. sensors (300 μm p-on-n)</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>No. sensors (320 μm n-on-p common p-stop)</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>No. sensors (320 μm n-on-p individual p-stop)</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>
Switch card circuit

External Instruments

- HV
- LCR
- A

Sensor
- Probe Card
- Switch Card

.. up to 512 ..

.. switches ..

.. pogo pins ..

40k 10k 60n
1u
10M

MUX

CERN-LHCC-2017-023
Timing resolution

\[(S/N)_{\text{eff}} = \frac{(S/N)_{\text{ref}}(S/N)_n}{\sqrt{(S/N)^2_{\text{ref}} + (S/N)^2_n}}\]

\[\sigma(t_{\text{ref}} - t_i) = \sqrt{\left(\frac{A}{\sqrt{(S/N)}}\right)^2 + \left(\frac{B}{S/N}\right)^2 + C^2}\]