Overview of the Phase-II CMS Calorimetry Upgrade

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On behalf of the CMS Collaboration
The exploitation of the full potential of the LHC is the highest priority of the Energy Frontier in both Europe and US.

### LHC / HL-LHC Plan

<table>
<thead>
<tr>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>HL-LHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 TeV</td>
<td>8 TeV</td>
<td>13-14 TeV</td>
<td>14 TeV</td>
</tr>
<tr>
<td>30 fb⁻¹</td>
<td>150 fb⁻¹</td>
<td>300 fb⁻¹</td>
<td>3000 fb⁻¹</td>
</tr>
</tbody>
</table>

**LHC approved running to deliver 300 fb⁻¹ by 2023**

**Phase II at L = 5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}**

**3000 fb⁻¹ over 10 years**

**major upgrades required on the LHC (replace more than 1.2 km)**

**Experiments will undergo a series of detector and trigger upgrades**

- to cope with radiation damage and high pileup (140 PU events)
- to maintain or enhance the current physics performance

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Phase-II Upgrade of the CMS Calorimetry
**Trigger / HLT /DAQ**
- Track information at L1 trigger
- L1-trigger – 12.5 μs latency / 750 kHz output
- HLT output 7.5 kHz

**Muons**
- Replace DT & CSC FE+BE electronics
- Complete RPC coverage in 1.5<\(\eta<2.4\) (new GEM/RPC technology)
- Muon-tagging in 2.4<\(\eta<3\)

**New Calorimeter EndCaps**
- Radiation tolerant - high granularity
- 5D capability
- Coverage up to \(\eta \sim 3\)

**Barrel ECAL**
- Replace FE electronics

**New Tracker**
- Rad. tolerant – low material
- High granularity – 40MHz selective readout (\(P_T > 2\) GeV) for L1 trig.
- Extend coverage to \(\eta = 3.8\)

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Phase-II Upgrade of the CMS Calorimetry
The Radiation and Pile-Up Challenge

Inner tracker will be subject to influences as high as $10^{16} \text{n}_{\text{eq}}/\text{cm}^2$

- Si sensors are active material for the bulk of the upgrade of the endcap calorimeters

Operation at $L = 5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ leads to $\langle PU \rangle = 140$ interactions per beam crossing

- need DAQ upgrade to overcome increased bandwidth and event size
  - L1 latency increased from 3.4 $\mu$s to 12.5 $\mu$s

- need sufficient reduction of trigger rates
  - introduce tracker information at L1 level

- reconstruction relies on “Particle Flow”
  - increase tracker and end-cap granularity

Absorbed dose in the CMS cavern after 3000 $\text{fb}^{-1}$

Need to maintain the performance up to 200 interactions/beam crossing

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Phase-II Upgrade of the CMS Calorimetry
CMS Electromagnetic Calorimeter

Homogeneous, hermetic, compact, fine-grain crystal calorimeter

- Lead tungstate (PbWO$_4$) as scintillating crystals
  - 61200 in EB, 7324x2 in EE
  - APDs/VPTs as photodetectors

PbWO$_4$ crystal properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_0$</td>
<td>0.89 cm</td>
</tr>
<tr>
<td>$R_M$</td>
<td>2.19 cm</td>
</tr>
<tr>
<td>Front face (EB)</td>
<td>2.2×2.2 cm$^2$</td>
</tr>
<tr>
<td>Rare face (EB)</td>
<td>2.6×2.6 cm$^2$</td>
</tr>
<tr>
<td>Length (EB)</td>
<td>23 cm (25.8X$_0$)</td>
</tr>
<tr>
<td>Face (EE)</td>
<td>2.86×2.86 cm$^2$</td>
</tr>
<tr>
<td>Length (EE)</td>
<td>22 cm (24.7X$_0$)</td>
</tr>
</tbody>
</table>

1%-5% energy resolution for e/γ from Z/H
**e/γ Energy Reconstruction**

- **e/γ energy is reconstructed by the sum over all crystals in the supercluster (SC)**
- **Dynamic clustering algorithm:**
  - EM showers spread in several crystals (crystal size $\sim R_M$)
  - Basic clusters are extended in $\phi$ direction to form SC and hence recover further energy spread due to magnetic field (conversion of photons/bremsstrahlung from electrons)

Low brem electrons

$$R_9 = \frac{E_{3x3}}{E_{SC}} \geq 0.94$$

Single electron energy resolutions are measured by relating them to di-electron mass resolution of $Z\rightarrow ee$ events
Crystal transparency changes under radiation damage

- recovers partially through self-annealing during shutdowns

A laser monitoring (LM) system cycles continuously over the ECAL to follow each crystal’s evolution under the irradiation and recovery periods

EB LM system will be upgraded due to radiation damage of light distribution system and PN diods
Main effect at HL-LHC due to hadron irradiation

\[ \frac{\sigma_E}{E} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C \]

Radiation damage affects all three terms:

- **Stochastic:** crystal light yielding components
- **Noise:** amplified by the light output loss
- **Constant:** non-uniformity of the light collection

**EB** crystals will perform well during HL-LHC

- \( \leq 50\% \) transparency loss
- APDs continue to perform well but will have increased noise

**EE** crystals will suffer large transparency losses

- must be replaced in LS3 by HGCAL

**Phase-II Upgrade:**

*EB upgrade + EE complete replacement*
Everything before motherboard remain unchanged

- **APD:** colder operation (from 18°C to 8°C)
- **VFE:** optimize shaping & sampling, improve **timing**
  → reduce impact of noise, PU, spikes
- **FE:** read data from all crystals
  → increase trigger latency and reject spikes

→ ECAL granularity available at L1 trigger (improved by x25)

Intrinsic **timing** resolution of PbWO₄+APD is ≤ 30 ps

→ recover vertex finding eff. to 75% (versus 80% in low PU)

New VFE is designed with 30 ps precision for high energy signals
VFE serves 5 crystals
- Analog ASIC: CATIA
  - 35 MHz trans-impedance amplifier
- Digital ASIC: LiTE-DTU
  - 12-bit, 160 MHz ADC, Data Transmission Unit

FE serves 5 VFEs
- fast optical links using LpGBT
- clock distribution

Low Voltage Regulator (LVR)
- rad-hard cards based on the FEAST DC-DC converter

Barrel Calorimeter Processor (BCP)
- FPGA-based
- L1 primitive formation and readout cards
- pulse reconstruction
- spike rejection
- receive and distribute LHC clock to FE
Phase II upgrade will allow us to maintain energy resolution for measuring electrons and photons at the similar level of current Run II.
Objectives for High Granularity

CMS Generic:
- replace the forward calorimeter by a radiation hard detector capable of withstanding at HL-LHC luminosities

HGCAL Specific:
- highly granular “5D” (x, y, z, E, t) sampling calorimeter inspired by CALICE (ILC), adapted to HL-LHC rates
- exploit topology of deposits and shower tracking capabilities in a particle flow
- mitigate PU through precision timing

Forward physics specific:
- VBF H, search for DM, invisible H decays, SUSY searches, VBS and unitarity

Interactions are spread over space and time 100-200 ps

Disentangle overlapping vertices with precise timing
Key resolution: 10-30ps
General Layout

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

Hadronic (CE-H)
- Si & Sci, steel absorbers
- 22 layers, $8.5\lambda$
Radiation tolerance of sensors and electronics

- proven to levels corresponding to $1.5 \times 3000 \text{ fb}^{-1}$
- 6 million Silicon channels
  - $620m^2$ 3xCMS Tracker
  - 0.5 and 1 cm$^2$ cell sizes
- Mixed layers in hadronic part
  - 240k scint. channels
  - 400m$^2$ plastic scintillator
  - on-tile SiPM
- Operate at $-30^\circ\text{C}$
  - with CO$_2$ cooling
  - mitigate Si leakage current
Hexagonal Si sensors:

- 8” wafers (HPK)
- Cell capacitance of $\approx 65$ pF

Modules and motherboards on cooling plates assembled in cassettes of $60(30)^{\circ}$ sectors for CE-E(CE-H)

Three Si sensors thicknesses according to expected radiation dose:

- Higher pseudo-rapidity $\rightarrow$ thinner sensors
- $120 \mu m$, $200 \mu m$ & $300 \mu m$ active thickness

Scintillating tiles in low radiation regions (mixed Si-Sci cassettes) with SiPM-on-tile
HGCAL Module using 2x8” wafers mounted on both sides of active cooling Cu plate

Two PCBs for each sensor layer

- the sensor is glued unto W/Cu baseplate covered with Au/Kapton foil
- the readout PCB is glued unto the sensor
- wire bonds through holes in the PCB connect readout board to sensor cells
Precision timing is a great challenge for the electronics system:

- Very strict requirements on the timing performance of all components, starting from the sensor to the clock distribution.
- Challenging front-end ASIC HGCROC is key to overall timing performance.
- Clock distribution system is expected to contribute ≤15 ps jitter.

Front-end chip requirements:

- large dynamic range: 0.2 fC–10 pC
- low noise: $\leq 2500$ e$^-$/ENC (0.4 fC)
- low power budget: $\leq 20$ mW/ch
  (limited by cooling power)
- radiation hardness: $\geq 2$ MGy, $10^{16}$\,n$_{eq}$/cm$^2$
- precise timing: 25 ps binning

HGCROC features a ToA based on constant-threshold discriminator and a 3 stage TDC

Skiroc2CMS designed for testbeam and HGCROCV2 is in production

Reach 50 ps constant term withing Skiroc2CMS specifications in test beam

- increased noise environment in the test beam (noise term worse)
- combining channels improves shower timing $\propto \sqrt{N_{hits}}$
High granularity and narrow shower size

- good particle separation and PF
- PU rejection within the first layers

Good energy resolution

- stochastic term of 24% (300 µm)
- constant term of 0.8%
Pileup mitigation through localisation of vertex of interest profits from multiple measurements

- per cell $\Delta t = 50$ ps
- cluster resolution: $\leq 20$ ps
- for energy $\geq 10$ GeV

Besides dedicated electronics for precision clock synchronisation between cells the system is very demanding on precision time calibration.

Reconstruction of vertex space-time from two objects, i.e. 2 photons

- assume 30 ps time resolution per object
- worse scenario is a small rapidity gap
- degenerate triangulation
Conclusions

The challenging conditions of the HL-LHC will require dedicated upgrade project of the CMS calorimetry

- full refurbishment of ECAL barrel electronics during LS3
- complete replacement of the CMS endcap calorimeter by ambitious a High Granularity Calorimeter for the HL-LHC

ECAL barrel upgrade is needed to maintain the performance

- operate cooler to mitigate increased APD noise
- new VFE & FE to cope with increased noise, pileup, spikes
- upgraded off-detector readout to cope with higher output bandwidth from FE

The HGCAL brings a change in paradigm for calorimetry-tracking detector technologies of the future

- it allows to cope with the high radiation damage and harsh PU conditions at HL-LHC with a “5D“ reconstruction approach: position, energy, time
- it is a great opportunity for CMS and the Physics at HL-LHC with possibly a major impact for VBF-like processes, jet tagging and high multiplicity events