CMS ECAL monitoring and its upgrade for High-Luminosity LHC

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The 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

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ECAL: the main component of CMS to detect and precisely measure the energies of electrons and photons.

Goal: excellent diphoton mass resolution (∼1%), needed for H→γγ observation.
Two crystal producers: BTCP (Russia) and SIC (China)

**Barrel:**
- 36 Supermodules (18 per half barrel);
- 61200 crystals;
- Total crystal mass 67.4t;
- Avalanche PhotoDiode readout;
- Coverage: $|\eta| < 1.48$, $\sim 26X_0$.

**Endcaps:**
- 4 Dees (2 per endcap);
- 14648 crystals;
- Total crystal mass 22.9t;
- Vacuum PhotoTriode readout;
- Coverage: $1.48 < |\eta| < 3$, $\sim 25X_0$.

**Endcap Preshower:**
- Pb ($2X_0$, $1X_0$)/Si;
- 4 Dees (2 per endcap);
- 4300 Si strips;
- 1.8 mm x 63 mm;
- Coverage: $1.65 < |\eta| < 2.6$. 
Lead tungstate crystals (PbWO\(_4\))

Barrel crystal, tapered 34 types, \(\sim 2.6 \times 2.6 \, \text{cm}^2\) at rear

Endcap crystal, tapered 1 type, 3x3 \(\text{cm}^2\) at rear

Emission spectrum (blue) and transmission curve (red)

Reasons for choice:

- Homogeneous medium;
- High density 8.28 g/cm\(^3\);
- Short radiation length \(X_0 = 0.89\) cm;
- Small Moliere radius \(R_M = 2.19\) cm;
- Fast light emission \(\sim 80\%\) in 25 ns;
- Emission peak 425 nm;
- Reasonable radiation resistance to very high doses.

Challenges:

- LY temperature dependence -2.2%/°C;
- Stabilise to \(\leq 0.1°\)C;
- Irradiation affects crystal transparency;
- Need precise light monitoring system;
- Low light yield (1.3% NaI);
- Need photodetectors with gain in magnetic field.
Absorbed dose after 10 years

Radiation dose at the EM shower max for $L=10^{34}$ cm$^{-2}$s$^{-1}$:
- 0.3 Gy/h in EB;
- 6.5 Gy/h at $\eta=2.6$.

Evolution of transmission due to irradiation

Ionizing radiation damage:
- It recovers at room temperature.

Hadron damage:
- No recovery at room temperature;
- Shift of transmission band edge;
- Will dominate at HL-LHC.
History of PN Diodes laser amplitude measurement in 2018

- 2 lasers are used: 447 nm (main laser) and green;
- Laser light injection in each crystal every \( \sim 40 \) minutes;
- Very stable PN-diodes used as reference system;
- ECAL signals compared event by event to PN reference;
- Redundancy allows to detect faulty PNs (at least one working in each module).
The response change observed in the ECAL channels is up to 13% in the barrel and it reaches up to 62% at $\eta \sim 2.5$;

The response change is up to 96% in the region closest to the beam pipe;

The recovery of the crystal response during the periods without collisions is visible;

Corrections obtained and applied promptly ($\sim 48$ h). Expected precision is 0.2%;

These measurements are used to correct the physics data.
Performance of LM system

Energy-scale corrections and checks using physics (E/p for W,Z; $\pi^0$ mass)

- Residual corrections after laser $\sim$ few % for a whole year
- No dependence on instantaneous luminosity

E/p (2018)

Laser corrections in $\pi^0$ invariant mass (2017)
High-luminosity LHC Accelerator upgrade in LS3 to provide $10 \times$ larger dataset for physics focus on new physics searches, Higgs coupling and precision SM measurements:
- Luminosity – $7.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$;
- Peak pileup – 200;
- Delivered luminosity – 320 fb$^{-1}$ per year;
- Total integrated luminosity – 3000-4000 fb$^{-1}$ in 2026-2038.

Luminosity and radiation well beyond detector design

Phase II upgrade will allow us to maintain energy resolution for measuring electrons and photons at the similar level of current RunII
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

- **ECAL barrel** crystals expected to loose < 50% of transparency
  - APDs continue to perform well but will have increased noise
  - Upgrade of electronics for the trigger and precise e/γ

- **Endcap calorimeters** replaced by HGCal (mostly Si)

**Phase-II Upgrade:**
**EB upgrade + EE complete replacement**

**Known and possible problems of ECAL LM system:**
- PN diodes tested at \(5 \times 10^{13} \text{ n/cm}^2\), 2 kGy (\(\sim 500 \text{ fb}^{-1}\))
  - Only 0.7% Q.E. loss but few already show strange behaviour
  - Increase redundancy of PN diodes \((\times 2)\)
- Fibers darkening with radiation
  - Essential to keep the injected light measurement inside the detector (PN diodes)
- Electronics not compatible with readout scheme for HL-LHC
Everything before motherboard remain unchanged

- **APD**: colder operation (from $18^\circ C$ to $8^\circ C$)
- **VFE**: optimize shaping and 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)

**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
The CMS electromagnetic calorimeter has efficiently operated during LHC Run I and Run II;

Laser monitoring system was used to control the changes in transparency of each crystal with high precision;

This system permitted to have stable calorimeter parameters under LHC radiation conditions;

The excellent ECAL performance was crucial for the Higgs boson discovery made by CMS and remains very important for precision measurements and for searches of new physics, as well;

Planned upgrade for high-luminosity LHC to ensure good performance for another 10-15 years.
BACKUP
ECAL photodetectors

Barrel: Avalanche PhotoDiodes (APD)
- Two 5×5 mm² APDs/crystal, ∼4.5 p.e./MeV
- Gain 50
- QE ∼75% at 420 nm
- Temperature dependence 1/G ∆G/∆T = -2.4%/°C
- High-Voltage dependence 1/G ∆G/∆V = 3.1%/V
- Need to stabilize HV at 30 mV
- Measured HV fluctuation: ∼30 mV

Endcaps: Vacuum photo-triodes (VPT, Research Institute "Electron Russia")
- More radiation resistant than Si diodes
- UV glass window
- Active area ∼280 mm²/crystal, ∼4.5 p.e./MeV
- Gain 8-10 (B=4 T)
- Q.E. ∼20% at 420 nm
- Gain spread among VPTs ∼25%
- Need intercalibration
Monitoring System
Measuring deposited energy

Candidate $H \rightarrow \gamma\gamma$ event