CMS ECAL upgrade for precision timing and energy measurements at the High-Luminosity LHC

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On behalf of the CMS Collaboration

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ECAL is a homogeneous, high-granularity calorimeter.
Lead tungstate (PbWO$_4$) crystals
(~61k EB, ~14k EE)

In the central barrel:
- 2x2x23 cm size
- $X_0 = 0.89$ cm
- $r_M = 2.19$ cm
- $\rho = 8.28$ g/cm$^3$
- $t_{75\%} = 25$ ns
- APD photosensors
Excellent energy resolution

Electrons from $Z \to ee$ decays

Good time resolution

Time difference of the two most energetic crystals of an ECAL cluster
ECAL has a crucial role in the CMS physics program

H → γγ

- γγ mass resolution < 1%
- γ energy scale well known (< 0.1% level)

After contributing to the Higgs boson discovery in 2012, ECAL continues to be vital for Higgs precision measurements and for a vast number of searches for rare Standard Model or beyond SM phenomena
CMS and ECAL at HL-LHC (after 2026)

HL-LHC: enrich the LHC physics program (Higgs couplings at % level, HH, searches for NP)

### Machine conditions

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<th>HL-LHC (ultimate)</th>
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Vertex location, possible with a time resolution < 30 ps, will be essential
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Expected 10-fold increase in total integrated luminosity

High radiation dose

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EB up to $\sim$50 kGy
EE up to $\sim$10$^3$ kGy
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Radiation-induced leakage current in the APD would make APD noise the dominant term in energy resolution at HL-LHC, in the current configuration.

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Machine conditions

- EB up to $\sim$50 kGy
- EE up to $\sim$10$^3$ kGy
Crystal transparency

- Has been measured regularly during data taking in Run1-Run2, and accounted for in specific corrections (see Chia-Ming Kuo’s talk tomorrow)

- Is affected by radiation damage:
  - EM damage recoverable at room temperature
  - Hadron-induced damage (dominant at HL-LHC) not recoverable

Expected signal loss in EB ($0 \leq |\eta| < 1.5$) from 55% to 70% at 3000 fb$^{-1}$

✅ Crystals in EB will still perform well

☐ EE will be fully replaced by HGCAL, a high granularity calorimeter, silicon and scintillator-based (a few HGCAL talks during the conference)
- Limit radiation-induced APD noise in EB (proportional to $\sqrt{I_{\text{dark}}}$)

Operation temperature reduced $18^\circ\text{C} \rightarrow 9^\circ\text{C}$. This will also enhance the light yield by ~20%

Limit radiation-induced APD noise in EB (proportional to $\sqrt{I_{dark}}$)

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Complete redesign of EB electronics from the APD up

- Cope with increased CMS-wide L1 trigger latency (4.5 µs → 12.5 µs) and rates (100 kHz → 750 kHz)
- Upgrade trigger capabilities

L1 trigger logic moved off-detector and evaluated by powerful and flexible FPGA processors

- Improve time resolution (30 ps at 50 GeV) → better primary vertex ID
- Improve discrimination between scintillation light from EM showers and direct hits in the APD (“spikes”)

Faster analog electronics and sampling frequency increased to 160 MHz

ECAL electronics upgrade

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 to stream all crystals data off detector at 40 MHz using lpGBT; clock distribution

LVR
Rad-hard voltage regulator cards based on the FEAST DC-DC converter

Off-Detector
Barrel Calorimeter Processor (BCP)
- FPGA-based
- L1 primitive formation and readout cards
- Pulse reconstruction
- Spike rejection
- Receive and distribute LHC clock to FE
CAlorimeter Trans-Impedance Amplifier

- 130 nm CMOS
- 35 MHz bandwidth (imposed by APD/kapton impedance)
- 2 gain (x1 and x10) to cover a dynamic range from 50 MeV to 2 TeV
- Test pulse injection

Faster response allows better separation between scintillation and spikes
CAlorimeter Trans-Impedance Amplifier

V0 and V1 tested in lab and test-beam showed excellent performance in terms of noise and linearity.

Energy resolution matching Legacy electronics

Time resolution < 30 ps for E > 50 GeV, matching the target for HL-LHC
Lisbon-Torino ECAL Data Transmission Unit

- Digital ASIC in 65 nm CMOS technology
- 2x 12 bit, 160 MHz ADC
- Data Transmission Unit implements baseline subtraction, gain selection, serialization and data compression logic
- PLL block from lpGBT
- TID tolerance up to 100 kGy
- SEU-protected control logic
Lisbon-Torino ECAL Data Transmission Unit

Compression algorithm
Based on a simplified Huffman encoding

12 + 1 bits words at 160 MHz → \(2.08\ \text{Gb/s}\) bandwidth occupancy

…but lpGBT e-link rate is \(1.28\ \text{Gb/s}\)

Compression algorithm reduces occupancy down to \(1.08\ \text{Gb/s}\)

Hit energy spectrum falls very rapidly → noise or low energy signals make most of the transmitted samples. The compression algorithm uses 6 bits to encode signals of up to 2.5 GeV of energy, and 12 (+1) bits for more energetic signals, while keeping latency < 350 ns
### Front-End

- Initialization and control of all VFE components
- eLink serial interface to ADC, clock and i²C interface
- Precise clock distribution to all VFE cards
- Streaming of the digitized data generated by the VFE to the back-end electronics
- 4 uplinks at 10.24 Gb/s (data links)
- 1 downlink at 2.56 Gb/s (control link)

DISCLAIMER: no lpGBT-based connection here! Coming in the next prototype
**Off-Detector and Trigger**

Barrel Calorimeter Processor

- FPGA-based, ATCA blade form factor
- Common for ECAL and HCAL
- Trigger primitive formation
- Clock distribution
- Detector control
- Data readout
- Decompression

Streaming samples off-detector

- Better granularity: L1 trigger primitives at crystal level (currently 5x5 matrix)
- Power and flexibility thanks to FPGA: anomalous signal rejection, PU subtraction etc.
A “vertical test” of the upgrade electronics is foreseen at the end of 2020, with most up-to-date versions of the boards. Then...

During LS3 (2024-2026) we will refurbish ECAL.

All the crystals will be translated outside CMS (using “enfourneurs”) and the new readout electronics will be installed.
Conclusions

The CMS ECAL has been of paramount importance for the CMS scientific program and has performed well during LHC Run1 and Run2

- Due to strong increase of radiation levels and reduction of crystal transparency, ECAL Endcaps will have to be replaced by a new kind of detector at HL-LHC

✓ ECAL Barrel crystals will still perform well, but their readout electronics from the APD up will be upgraded to:

- Improve L1 trigger capabilities/flexibility
- Allow better anomalous signal rejection
- Withstand increased radiation at HL-LHC
- Cope with increased pile up, improving time resolution (< 30 ps at 50 GeV)

- Such targets will be achieved by:

  - Lowering operational temperature (18° → 9°)
  - Using a faster readout electronics and increasing the sampling rate
  - Streaming all data and forming trigger primitives off-detector
Spikes or “anomalous” signals

Spikes are signals generated by hadron interaction within the APD volume

“Anomalous” in terms of energy release wrt EM showers, but not in terms of frequency

If not suppressed, they would dominate the L1 trigger rate at HL-LHC