Status of the CMS ECAL phase 2 upgrade for high precision timing and energy measurements

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Excellent energy resolution maintained throughout entire LHC Run1 & Run2
- laser monitoring system allowing to track crystal transparency variation at 0.1%
- in-situ calibration at crystal level <1% ($\pi^0/\eta, Z \rightarrow ee, W \rightarrow ev$)

Total ~75k PbWO$_4$ crystals ($r_M=2.19$ cm, $X_0=0.89$ cm)

Photosensors:
- Barrel (EB): Avalanche Photo Diode (APD)
- Endcap (EE): Vacuum Photo Triode (VPT)
ECAL performing as expected:
Excellent $\gamma\gamma$ mass resolution (<1%)

Higgs discovery with $H \rightarrow \gamma\gamma$ in 2012

Prominent ECAL role in all CMS physics program. E.g. Higgs mass:
- $\gamma$ energy scale well known (<0.1% level).
- Enables Higgs mass to be measured with ~0.1% systematic error (CMS HIG-19-004)
The HL-LHC Challenge (>2026)

HL-LHC (>2026): exploit the LHC full potential!
- Higgs couplings (at % level), access Higgs self-coupling (HH)
- Precise SM measurements and search for new physics

Challenging experimental conditions

<table>
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<tr>
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<th>LHC</th>
<th>HL-LHC baseline</th>
<th>HL-LHC ultimate*</th>
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<tbody>
<tr>
<td>$\mathcal{L}_{\text{inst}} (\text{cm}^{-2}\text{s}^{-1})$</td>
<td>$2 \times 10^{34}$</td>
<td>$5 \times 10^{34}$</td>
<td>$7.5 \times 10^{34}$</td>
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<tr>
<td>PU ($n_{\text{vtx}}$)</td>
<td>40-60</td>
<td>140</td>
<td>200</td>
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x 10 total luminosity (>3000 fb$^{-1}$)
High radiation doses

EB up to ~50 KGy

EE up to ~$10^3$ KGy

x 5-7 inst. luminosity (>5E34 cm$^{-2}$s$^{-1}$)
High pile-up (>150)

Precision timing (~30ps) can help vertex location

CMS ECAL designed for 300 fb$^{-1}$@ 1E34 cm$^{-2}$s$^{-1}$: upgrade is required
Crystal signal loss vs $\eta$ vs lumi

@3000 fb$^{-1}$: expected LO loss in ECAL barrel from 55% to 70% ($|\eta| \rightarrow 1.5$)

Crystal replacement NOT needed in ECAL Barrel

ECAL Endcap needs to be fully replaced → High Granularity Calorimeter

APD dark current at $\eta=1.45$ vs lumi

APD increased dark current (higher noise)

Decrease operating temperature $18^\circ$C → $9^\circ$C

→ APD dark current reduced by 50%
→ LO increased by 18%
**ECAL ELECTRONICS @ HL-LHC**

**Faster front-end electronics**
- Improve timing resolution (H→γγ vertex identification at high pile-up)
- Improve discrimination between scintillation and direct hits in the APD ("spikes")

**New off-detector electronics**
- Cope with increased CMS-wide L1 rate (100 kHz → 750 KHz) and latency (3.4 μs → 12.5 μs)
- Improve trigger flexibility: stream all crystal data off-detector
**Upgraded Readout Scheme**

**VFE board (serves 5 crystals)**
- New faster preamplifier: Trans-impedance amplifier (TIA), CATIA ASIC
  - bandwidth 35 MHz (x2)
  - 2 gains (x1 and x10) dynamic range from 50 MeV to 2 TeV
- New ADC: Lite-DTU ASIC
  - 12 bit @ 160 MS/s (x4 sampling rate), data transmission with compression

**FE (serves 5 VFEs)**
- Fast optical links to stream all crystal data off-detector @ 40 MHz using LpGBT
- VFE clock distribution using LpGBT eClock

**Off-detector: Barrel Calorimeter Processor (BCP)**
FPGA based
- Pulse reconstruction
- Zero suppression
- Spike rejection
- L1 trigger primitives
- Receive & distribute LHC clock to FE
CATIA

CAlorimeter Trans-Impedance Amplifier
- bandwidth 35 MHz (imposed by APD/kapton impedance)
- TSMC 130nm CMOS
- 2 gains (x1-x10), test pulse, ADC calibration

Two prototypes (V0 & V1) already tested in lab and in test beam
- performance as expected for noise and linearity
- preliminary radiation hardness tests encouraging

Last iteration v2: foreseen in 2020

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Much improved separation between scintillation/spikes

Noise within 10% from simulation
**Test Beam 2018 Results**

Test beam 2018@ CERN: 5x5 matrix, prototype VFE with CATIA, commercial ADC @ 160 MHz

Energy resolution matching current performance

- **ECAL Test Beam 2018**
  - ECAL 3x3 matrix
  - $N / \sigma_N + S / \sigma_S + C$
  - $N = 0.51$ (fixed)
  - $S = (2.9 \pm 0.6) \times 10^{-2}$
  - $C = (3.7 \pm 0.4) \times 10^{-3}$

Time resolution <30ps for $E>50$ GeV matching ECAL HL-LHC target

- **Time resolution (ps)**
  - $N / \sigma_N + C$
  - $N = 10.7 \pm 0.4$ ns
  - $C = 20.0 \pm 0.7$ ps

**Equivalent energy at HL-LHC start (GeV)**

- **Single channel, 160 MS/s**
LiTE-DTU

Digital ASIC in 65nm CMOS
- 2 x 12bit 160MS/s ADC: commercial IP block
- Data Transmission Unit (DTU): baseline subtraction, gain selection, serialisation and lossless data compression
- PLL from LpGBT
- TID tolerance up to 100 KGy, SEU protected logic

LiTE-DTU v1 currently under test. Checking:
- ADC noise/linearity
- PLL and clock distribution
- selection and compression algorithms validation
- radiation hardness

Foreseen also a combined test with CATIA v1
FE CARD

Streaming VFE digitised data off-detector
Precise clock distribution to VFE
Initialisation and control of VFE

- 4 uplinks @ 10.24 Gb/s
- 1 uplink @ 2.56 GB/s
- eLink serial interface to ADC
- i^2C interface

v1 prototype
- 5 Gb/s links (using GBTx)
- 1 VTRx + 2 VTTx VL modules

Next steps:
- v2: 10 Gb/s links
- v3: fine tuning and bug fixes
Off-Detector & Trigger

**Barrel Calorimeter Processor**
- Control & data readout, decompression, clock distribution, trigger primitives formation, common for ECAL and HCAL
- FPGA based, ATCA blade form factor

Streaming all samples off-detector. Allows:
- Granularity at crystal level for L1 trigger primitives (instead of 5x5 matrix)
- Large flexibility for developing pulse reconstruction/selection algorithms: PU subtraction, anomalous signal rejection, ...

BCP in numbers: 9 ATCA crates, 108 ATCA blades, 216 FPGAs, 3060 optical links to FE

Discrimination using digital filter on crystal samples for scintillation/spike
**SUMMARY**

HL-LHC exciting physics opportunities but also significant experimental challenges: high radiation dose and >5 increase in detector occupancy

CMS ECAL Barrel will be upgraded bringing improved readout/trigger flexibility, maintaining excellent energy resolution and improve timing resolution (~30ps @ 50 GeV)

- keep crystals and photosensors, lowering operating temperature from 18 °C → 9 °C
- new readout chain:
  - faster front-end
  - higher sampling rate
  - stream all data off-detector, trigger primitives formation off-detector
Several ingredients determine the time resolution of an electromagnetic shower in a homogeneous crystal calorimeter:

- **Intrinsic EM shower fluctuations**
  - longitudinal shower fluctuations
  - optical transit time spread: scintillation rise/decay time, light propagation

- **Photodetector + electronics**
  - photodetector: rise time, transit time
  - noise: dark current, electronic noise

- **DAQ**
  - clock distribution
CURRENT ECAL TIMING PERFORMANCE

Test beam (2008)
- 2 crystals in the same EM shower: **20 ps constant term**

In-situ (Run1)
- 2 crystals in the same EM shower & same readout unit: **70 ps constant term**,
degradation due to time calibration stability
- 2 crystals in different showers from Z→ee: **150 ps constant term**, additional
degradation from clock distribution
Photon timing (<30ps) allows to determine di-photon interaction vertex position (and time)

Vertex currently determined using recoiling tracks properties. Efficiency ~80% with current pile-up LHC conditions, will become 30% @ PU200

ECAL+track precision timing allows to ~ keep current vertex efficiency @ PU200