The CMS ECAL Upgrade for Precision Crystal Calorimetry and Timing at the HL-LHC

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on behalf of the CMS Collaboration.

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HL-LHC and CMS upgrades

- **HL-LHC goal**: \( \times 10 \) integrated luminosity delivered to the experiments (ATLAS, CMS):

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<th>( \text{PU} , (n_{\text{vtxs}}) )</th>
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  - Greater tracker (\( |\eta| = 4 \)) and muon spectrometer (\( |\eta| = 2.8 \)) acceptances.
  - Higher first level trigger (L1) rate: \( 100 \text{kHz} \rightarrow 750 \text{kHz} \).
  - Tracking information at L1.
  - Detector upgrades to cope with larger radiation levels and higher pile-up.
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CMS calorimeters at HL-LHC

- **Endcaps**: complete replacement of current calorimeters to cope with expected radiation flux.
  - High granularity, silicon based, sampling calorimeter (HGCAL).
- **Barrel**:
  - **ECAL**: retain crystals+APD $\rightarrow$ upgraded readout electronics.
  - **HCAL**: Brass/plastic scintillator + SiPM.

**Test with irradiated crystals in H4:**

$$1 - L_{\text{loss}} = e^{-\mu_{\text{ind}} L}$$

Barrel crystals will retain 30-50% of the light output after 3000 fb$^{-1}$.

**Limited degradation of energy resolution.**
ECAL APD performance

- ECAL barrel photo-sensors will continue to operate during HL-LHC:
  - Increase in APD leakage current due to radiation damage → APD noise will dominate HL-LHC energy resolution.

  - Mitigation:
    - Lower ECAL operation temperature $6 - 9^\circ C$ (now $18^\circ C$).
    - Shorter pre-amplifier shaping time (reduce PU impact, better S/N).
ECAL trigger

- **Improved Level-1 trigger capabilities needed at HL-LHC:**
  - Larger trigger rates (x 7.5) and trigger latency (12.5 µs) mandatory to exploit increased luminosity and implement Level-1 track-trigger.

- **Improved rejection of ECAL APD anomalous signals required.**
  - “Spike” from direct hadron ionization in APD volume.
    - Large isolated signals.
    - Faster signal than scintillation.
  - Will dominate L1 trigger at HL-LHC if unsuppressed.
ECAL upgrade key aspects

- **Replace off-detector electronics:**
  - To cope with higher output bandwidth from FE and upgraded CMS L1 trigger.

- **Replace on-detector electronics** (VFE and FE):
  - New amplifier + ADC running at 160MHz.
    - Spike rejection, pileup and noise mitigation.
    - Precise time measurement.

- **Run Colder:**
  - mitigrate increase in radiation induced APD noise.

The upgrade will allow to exploit the full potential of the CMS ECAL during HL-LHC.
TDR design choices

- **Pre-amplifier:** Trans Impedance Amplifier (TIA) architecture:
  - matches the requirements for noise, pileup mitigation and CMS-wide effort for hermetic precision timing.
- **ADC designed chosen:** 12 bit, 160MHz sampling frequency.
  - Custom chip designed by external company + data compression system.
  - 2 TeV dynamic range, two gain ranges (G1, G10) with 50, 500 MeV LSB.
- **FE card design:**
  - Fast optical links to stream crystal data off-detector through CERN lpGBT/VL+ chip.
- **Off-detector electronics (OD):**
  - FPGA based. Will provide single crystal information to L1 trigger (750 kHz, 12.5 µs latency).
Beam configuration at the CERN SPS North Area

- Series of tests performed at the H4/H2 beam lines:
  - **H4**: very pure electron beam $\Delta p/p = 0.5\%$ with $20 < p < 250$ GeV.
  - Beam time in H2 exploited to collect sample of APD direct hadronic ionization signals using pion beam.

Slot originally assigned to CMS-HCAL. Shared with CMS-iTK

- Excellent support from SPS team (in particular N. Charitonidis and B. Rae) allowed us to take high quality data efficiently.

**Trigger only selection.** $e^-_{\text{beam in H4.}}$

**EM-shower shape with $e^-_{\text{beam in H4.}}$.**

**Pion beam in H2**

$\pi$ (120 GeV), crystal matrix, 160 MHz

Beam energy cutoff all seeds

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Test beam setup infrastructure

- On the H4 line setup hosted in the CMS-ECAL air-conditioned experimental area (18 °C).
- **Remote controlled cooling unit and movable table easily operated through DAQ GUI** (also for different setups: CMS-MTD, AIDA2020, ...).
- **Trigger counters and reference detectors installed just upstream of R&D setup.**

→ Plastic fiber hodoscopes for position measurement.
→ A pair of **Micro channel plates devices** (1.2 cm diameter, thickness < 1X₀) provide a **precise reference time**. MCP signals sampled by a DRS4 chip (CAEN V1742 board, 5 GS/s) [1].

[Diagram of beam setup with labels: HODO 1 2, MCP 1 2, CRYSTAL (5 x 5 MATRIX), APD, custom-made FE, custom-made ADC, VFE ADAPTER, BEAM, DIGITIZER, VFE commercial ADC, HODO 1 2, MCP 1 2, CRYSTAL (5 x 5 MATRIX)].

Custom DAQ, see Giacomo’s talk
One ECAL tower reproduced in R&D box:

- Same noise condition of CMS can be achieved with HL-LHC prototypes.
- Cooling available: 9 - 18 °C.
- Bare APDs also installed to study direct ionization signals.
Reference time reconstruction

- DRS4 ([2]) and ECAL readout synchronized by reading out the ECAL clock with the same DRS4 chip used for the MCPs.
- Dedicated DRS4 calibration to achieve best time resolution with the MCPs:
  - ADC calibration.
  - Cell-to-cell time delay calibration.

**MCP and ECAL sync**

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**MCP time performance**

![Amplitude vs Time Graph]

![MCP time resolution Graph]

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Impact of ADC sampling frequency

- Setup: PbWO$_4$ + APD + discrete component TIA + DRS4 readout. **Noise different from real detector.**
- Different ADC sampling frequency emulated offline by sampling the 5 GS/s signal from the DRS4:
  - Results prove that 160 MHz sampling is optimal to achieve the best time resolution.
  - Lower sampling frequencies performance depends on relative phase between APD signal and ADC clock.

![Graph showing resolution as a function of normalized amplitude](image)
First results with ASIC prototype

- One ECAL tower (25 channels) equipped with first prototype of HL-LHC ASIC amplification chip and 160 MHz commercial ADC.
- Electron beam, 25-250 GeV energy range. Setup kept at 18 °C.
- Preliminary results:
  - Energy resolution performance matches LHC legacy electronics.
  - Excellent time resolution, $\sigma_t < 40$ ps:
    - $E_{EM-shower} > 30$ GeV (HL-LHC start).
    - $E_{EM-shower} > 75$ GeV (HL-LHC end).

\[ \begin{align*}
\text{Normalized amplitude (A/} &\text{E)} \times 10 \text{\%} \\
\text{Time resolution (ps)} &\times 10 \text{\%} \\
\text{Time resolution (ps)} &\times 10 \text{\%}
\end{align*} \]

\[ \begin{align*}
C = (3.7 \pm 0.4) \times 10^3 \\
S = (2.9 \pm 0.6) \times 10^{-2}
\end{align*} \]

\[ \begin{align*}
N = 0.51 \text{ (fixed)} \\
N = 10.7 \pm 0.4 \text{ ns} \\
C = 20.0 \pm 0.7 \text{ ps}
\end{align*} \]
ECAL upgrade impact on trigger

- Spike suppression target: 1kHz @ L1 trigger ($E_T > 5$ GeV).

Phase-I (CMS in-situ)

Phase-II ($\pi/e$ TBs)

Example of signal shape discriminant (TDR simulation)
Plans for test beams in Run 3

- **Test with spare supermodule:**
  - Test full HL-LHC electronics chain: VFE + FE + DAQ.

- **CMS-ECAL area in H4 upgrade LS2:**
  - Supermodule support table refurbishment.
  - Room and SM cooling upgrade to run at 9 °C.
  - Tracking telescope and reference detectors upgrade.

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Spare SM (1700 channels)

SM support table

Tracking and triggering

Beam
Summary

- HL-LHC demands a general upgrade of the CMS detector in order to provide required performance:
  - The CMS ECAL barrel electronics will be upgraded:
    - Mitigate noise and pile-up impact.
    - Improve trigger capabilities.
    - Add precise time information to the event reconstruction.
  - Series of test with electron and pions beams performed during Run 2:
    - TBs have been crucial to test new electronics design.
  - New electronics maintains excellent energy resolution and provides signal shape analysis and precise time reconstruction capabilities.