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

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On behalf of the CMS collaboration

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The CMS ECAL

- **at LHC:**
  - Results and performance during RunI and RunII.

- **at HL-LHC:**
  - Detector challenges.
    - Trigger.
    - Pile-up and noise mitigation.
  - Upgrade design and goals.
  - Prospects for the upgraded detector.
The CMS ECAL

- CMS main features are the compact design and the high (3.8 T) magnetic field.

- The CMS ECAL is an homogeneous crystal scintillator (PbWO$_4$), the design was driven by volume constrains and energy performance requirements.

- ECAL has been a key component for the observation of the Higgs boson.
  → Excellent resolution and electron/photon ID crucial for Higgs analysis.
HL-LHC and CMS upgrades

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

<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>$\mathcal{L}_{\text{inst}}$ (cm$^{-2}$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 ($n_{\text{vtxs}}$)</td>
<td>40-60</td>
<td>140</td>
<td>200</td>
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*unexpected at the time of original ECAL TDR.

- **CMS upgrade**
  - Larger tracker ($|\eta| = 4$) and muon spectrometer ($|\eta| = 2.8$) acceptances.
  - Larger first level trigger (L1) rate: 100kHz $\rightarrow$ 750kHz.
  - Tracking information at L1.
  - Detector upgrades to cope with larger radiation levels and higher pile-up.
CMS calorimeters at HL-LHC

- **Endcaps**: complete replacement of current calorimeters to cope with expected radiation flux.
  - Radiation tolerant high granularity, silicon based, sampling calorimeter (HGCAL).
- **Barrel**: same technology → upgraded readout electronics.
  - **ECAL**: PbWO$_4$ + APD.
  - **HCAL**: Brass/plastic scintillator + SiPM.

Barrel crystals will retain 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 and trigger latencies 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 pre-amplifier + ADC running at 160MHz.
    - Spike rejection, pileup and noise mitigation.
    - Precise time measurement.

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

The upgrade is needed to retain the excellent CMS ECAL performance.

Simone Pigazzini | 25.05.2018
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.
  - 2 TeV dynamic range (two gain ranges, G1 and G10) with 10 MeV LSB.
- **ADC designed chosen**: 12 bit, 160MHz sampling frequency.
  - Custom chip designed by external company + data compression system.
- **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).
VFE and FE R&D progress

→ **VFE prototype (TIA)** tested in recent test beams:
  → Noise performance matches expectation for HL-LHC.

→ **FE demonstrator equipped with GBT chips**:
  → Data streaming tested with legacy VFE and trigger boards.
Detector refurbishment

- **Replacement of all detector services** during CERN LS3:
  - LV/HV lines, cooling pipes, readout and control links.
  - Improve insulation of water cooling pipes coupled to new cooling system.
    - **Will allow to cool the detector to** 9° C. Lower temperatures will require further upgrades of the cooling system.
ECAL upgrade impact on trigger

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

- **Shower shape discrimination**: sensitive to noise and PU.

- Even with single crystal granularity the method used during Phase-I does not provide enough spike suppression.

![Graphs showing spike and shower shape discrimination](image-url)
ECAL upgrade impact on trigger

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

- **Shape discrimination** essential to achieve desired suppression level.
  - Requires faster pre-amp and higher sampling frequency.

![Graphs and diagrams showing spike suppression and shape discrimination](image-url)
ECAL upgrade impact on physics analysis

- **CMS physics program** at HL-LHC includes:
  - Precise measurement of the Higgs properties (e.g. self-coupling).
  - Search for BSM in exotic channels.

ECAL energy resolution.

ECAL time resolution.

+ hermetic precision timing.
Summary

- CMS ECAL performance has been key to the Higgs discovery/characterization during LHC RunI/II.

- Upgrade needed to maintain great performance throughout HL-LHC:
  - Mitigate noise/pileup increase.
  - Improve trigger capabilities.
  - Add precise time information to the event reconstruction.
  - TDR published last year, prototypes being tested.

- Upgraded detector will again impact key aspect of the CMS physics program.
Additional material
Scintillation signal vs temperature.

- No significant shape changes with crystal temperature observed in TB (TIA prototype + 5GHz ADC).