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The Upgrade of the CMS Electromagnetic Calorimeter for the High-Luminosity LHC

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The High Luminosity upgrade of the LHC (HL-LHC) at CERN will provide, starting in 2030, unprecedented instantaneous and integrated luminosities of around $5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and $3000\,\mathrm{fb}^{-1}$, respectively. The expected average of 140 to 200 collisions per bunch-crossing (pileup) represents a severe challenge for the detectors. While the endcap part of the calorimeters will be replaced by a new detector, the ECAL barrel's lead tungstate crystals and photodetectors are expected to sustain the new conditions.
The Very Front End electronics will be equipped with two already produced custom ASICs per crystal: a dual gain trans-impedance amplifier and an ASIC providing two 160 MHz ADC channels, gain selection, and data compression. The noise increase in the photodetectors, due to radiation-induced dark current, will be mitigated by reducing the ECAL operating temperature from 18 to 9 °C. The trigger primitive formation will be moved off-detector and performed by powerful and flexible FPGA processors. The upgrade of the ECAL electronics will allow maintaining the excellent energy resolution of the detector and, in addition, will greatly improve the time resolution of electrons and photons for energies above 50 GeV, down to a few tens of picoseconds.
The final design of the full ECAL barrel readout chain and the status of the individual component R&D will be presented and results from recent test beam campaigns at the CERN SPS, using electron beams with energies of up to 250 GeV, will be summarised. In particular, we will present measurements of the energy and timing resolution performance of the latest HL-LHC ECAL readout electronics prototypes.

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1. Introduction

The Compact Muon Solenoid (CMS) experiment [1][2] is a general-purpose detector at the CERN Large Hadron Collider (LHC), designed to explore a wide range of fundamental physics processes. A key component of CMS is its electromagnetic calorimeter (ECAL), which provides high-resolution measurements of electrons and photons. The ECAL is composed of 75848 lead tungstate (PWO) scintillating crystals arranged in a barrel (EB) and two endcap (EE) sections. The EB consists of 61200 crystals grouped into 2448 readout units (RU).

With the upcoming High-Luminosity LHC (HL-LHC) upgrade [3], scheduled to begin collisions in 2030, the instantaneous luminosity will increase by a factor of five with respect to the original LHC baseline design, reaching approximately $5 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$. This will lead to harsher operating conditions: increased radiation levels and a rise in the average number of proton-proton interactions per bunch crossing (pile-up) from about 60 to up to 200.

These conditions pose significant challenges for the EB. Firstly, the existing avalanche photodiodes (APDs) and crystals will not be replaced, but their performance will decline with accumulated dose. In particular the APD leakage current increases with radiation, while the crystals loses transparency. Secondly, the higher pile-up increases also the anomalous signals caused by direct ionization in the APDs, called spikes. These spikes resemble scintillation signals produced by high energy particles but differ slightly in their time profile. Discriminating between the two is crucial to preserving energy resolution and event reconstruction quality.

Due to these factors, a major upgrade of the ECAL system [4] is required to ensure robust performance at the HL-LHC. The EEs will be replaced entirely by a new High-Granularity Calorimeter (HGCAL), while the EB will keep its scintillating crystals and photodetectors but replace its readout electronics with a new and faster one.

2. Overview of the ECAL Barrel Upgrade

The EB upgrade is designed to preserve the detector's excellent energy resolution and extend its capabilities to provide precise timing information, which is essential for event reconstruction in the dense environment of the High-Luminosity LHC (HL-LHC).

Radiation damage mitigation To mitigate the radiation-induced effects on the existing crystals and APDs, the operating temperature of the EB will be reduced from 18 °C to 9 °C. This choice decreases the APD leakage current while simultaneously enhancing the crystal light yield. The light monitoring system, that will be as well upgraded, will continue to track transparency variations and correct for them in reconstruction.

Faster front-end electronics To cope with the HL-LHC increased pile-up, a completely new front-end chain has been developed. The signal from each APD pair will be amplified by a new ASIC, the CATIA (Calorimeter Trans-Impedance Amplifier) [5], designed to preserve the fast component of the PWO scintillation light, resulting in a signal developing to its max in about 15 ns compared to the 50 ns of the current system. The shaped signal is then digitized by the LiTE-DTU (Lisbon–Turin ECAL Data Transmission Unit) ASIC [6] at 160 MS/s. The higher sampling frequency, compared to the 40 MS/s in use in Phase-1 is a key improvement to be able to improve the time resolution and enables the online rejection of the spikes.

Back-end and trigger requirements The on-detector adopts a fully trigger-less architecture: all digitized samples are continuously transmitted off-detector, in contrast with the current system that provides trigger primitives at front-end level. The data are received by the new Barrel Calorimeter Processor (BCP) [7], a high-throughput ATCA board. This redesign is required to meet the upgraded Level-1 trigger (L1) specifications, which increase the maximum trigger rate from 100 kHz to 750 kHz and the latency from 4 µs to 12.5 µs.

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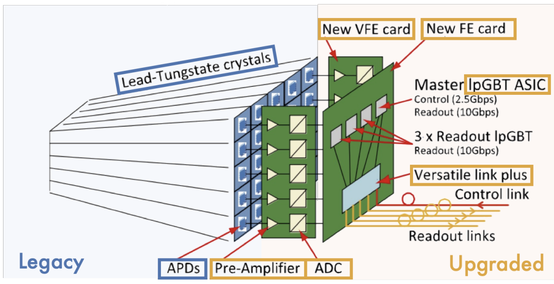

Figure 1: The Phase-2 EB 5x5 matrix readout unit (RU): the components highlighted in orange on the right are a new Phase-2 design; crystals and APDs are kept from Phase-1

Target improvement and impact on physics performance The improved readout speed and timing precision (target resolution better than 30 ps for 50 GeV photons or electrons) will greatly reduce the impact of out-of-time pile-up. Precise timing enables the association of energy deposits to their correct interaction vertex and contributes to particle-flow reconstruction and timing-based pile-up mitigation across the CMS. Maintaining an energy resolution of $\sigma_E/E < 1\%$ for high-energy electrons and photons ensures that the ECAL continues to play a leading role in precision measurements (such as the Higgs boson decay to two photons) and in searches for new phenomena producing high-energy electromagnetic objects.

3. The Upgraded Readout Electronics

On-detector PCBs The RU, shown in Fig. 1, integrates a fully redesigned set of on-detector electronics boards. Each RU is read out by five Very-Front-End (VFE) cards. Each VFE hosts five channels, consisting of a CATIA and a LiTE-DTU ASIC pair. The VFE boards interface on one side with the APDs and on the other with a Front-End (FE) card that serves as data concentrator for the RU. The FE includes four lpGBT [8] transceivers for bidirectional data, clock, and control links. Optical transmission to the counting room is handled by the radiation-tolerant VTRx+ [9] ASICs developed at CERN.

Power distribution is provided by a dedicated Low-Voltage Regulator (LVR) card using CERN DC-DC converters [10]. In total, the upgraded EB will comprise about 12240 VFE cards, 2448 FE cards, and an equal number of LVRs.

Front-end ASICs The CATIA, designed in TSMC 130 nm features two parallel gain paths (×1 and ×10) to cover energies up to roughly 2 TeV. The spectral response has a -3 db point around 35 MHz and it is optimised for the fastest components of the scintillation signal. CATIA can also supply programmable voltage levels for the calibration of the ADCs, and is equipped with test pulse injector circuits, and temperature sensors. The LiTE-DTU, designed in TSMC 65 nm technology, digitizes the analogue signal using two time-interleaved 12-bit 160 MS/s ADCs. The optimal gain is selected later by a look-ahead algorithm. The data is then losslessly compressed to fit the available bandwidth of 1.28 Gbps with a simplified Huffman encoding, then transmitted to the next stage (of the lpGBT for the FE card). The LiTE-DTU also features a PLL block that is the same used in the lpGBT design.

Back-end electronics and data processing Off-detector, the new Barrel Calorimeter Processor (BCP) was designed to meet the new central trigger requirements and to interface with the new RU. The new boards receive, deserialise, decompress and align the data from the FE. Moreover, they will be able to perform online spike vs signal discrimination and per-crystal trigger primitive formation. This architecture fully replaces the previous tower-based trigger logic.

4. System Validation with Beam Test Data

To validate the performance of the upgraded EB readout chain and assess compliance with the Phase-2 physics requirements, an extensive beam-test campaign was conducted at the CERN SPS H4 beam line in 2023. The setup reproduced realistic detector conditions using pre-production components of the whole new readout chain, enabling measurements of energy and time resolution with electron beams in the 20–250 GeV range.

Experimental setup A total of nine RUs, each equipped with the new front-end electronics, and read out by two BCPs were installed in a spare ECAL supermodule. This module was operated in the most recent test beam at the CERN SPS. (Fig. 2). Auxiliary instrumentation included: a micro-channel plate (MCP) providing a precise reference timing signal, a pair of hodoscopes for beam-position monitoring and impact-point reconstruction.

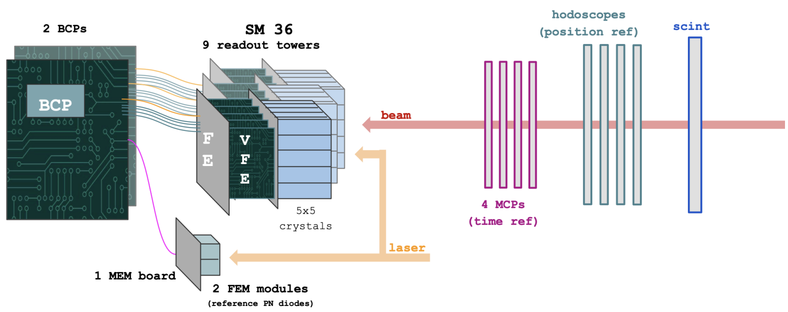

Figure 2: Configuration of the 2023 test-beam setup at the CERN SPS H4 line. Nine readout units equipped with Phase-2 electronics were instrumented and read out through two BCPs, plus the laser monitoring system.

Energy and time resolution The energy response was reconstructed from the digitized samples of each crystal using an optimized pulse-shape template fit. The energy resolution follows the usual parametrization described in Fig. 3. The measured resolution is fully compatible with the target performance of the present ECAL: $\sigma_E/E < 1\,\% forE > 50$ GeV. The constant term was found to be below 0.5%.

The time resolution was evaluated using events where the beam was centred on the boundary between neighbouring crystals. The relative timing between the two channels, $\sigma(t_1 - t_2)/\sqrt{2}$, was studied as a function of the effective signal-to-noise ratio A_{eff}/σ_n. The dependence can be described by the equation in Fig. 3. A constant term of C = (28.1 ± 0.5), ps was measured, corresponding to an expected single-channel resolution of about 40 ps for 50 GeV electrons (Fig. 3). This is compatible with the HL-LHC timing requirement for effective pile-up mitigation.

5. Status and outlook

All components of the upgraded ECAL Barrel readout chain have reached an advanced stage of production and validation. The CATIA and the LiTE-DTU have been fully produced and almost completely tested. A large fraction of the qualified chips has already been shipped in their final versions for assembly on VFE cards.

A first batch of about 500 production VFE cards, equipped with the final ASIC versions, was successfully tested and mounted on an ECAL spare supermodule. The LVR design has been finalized and is ready for mass production. The FE cards are also in production, while the BCP back-end card has been received in its new and final version (BCPv3) and is currently undergoing laboratory tests. Previous beam tests were performed using the earlier prototype (BCPv1).

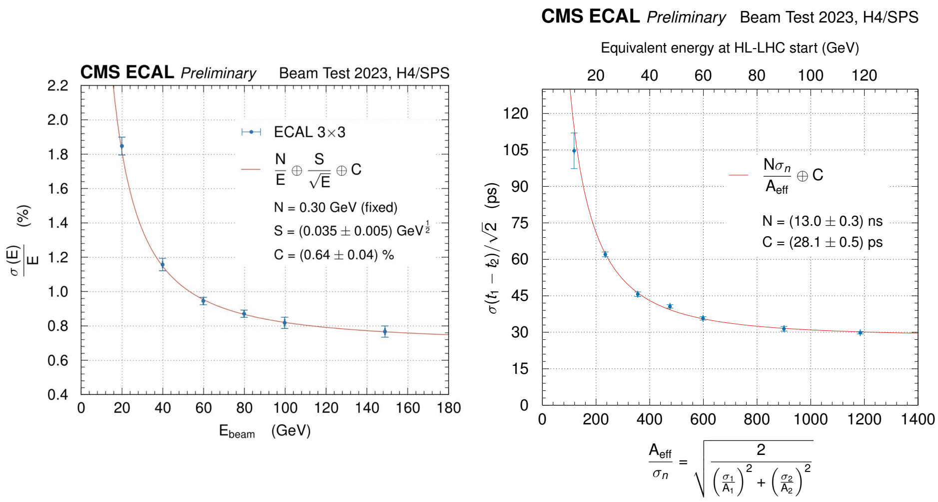

Figure 3: *Left*: energy-resolution performance measured at the 2023 beam test. In the parametrised Energy resolution curve: N is the noise term, S the stochastic term, and C the constant term. The fitted parameters are consistent with the target $\sigma_E/E < 1\%$. above 50 GeV. *Right*: relative time-resolution performance measured at the 2023 test beam. The constant term is below 30 ps.

A new test beam campaign started in late October 2025 at CERN SPS, with 18 RU equipped and 3 BCPs taking data simultaneously. Its data will be analysed to asses the final performance of the newly-developed readout system.

6. Conclusion

The CMS EB upgrade has reached an advanced stage of implementation. The new readout architecture, based on fast, radiation-tolerant front-end ASICs and trigger-less data flow, has been validated through extensive laboratory and beam tests. The achieved energy and timing resolutions meet the HL-LHC performance targets, ensuring that the detector will maintain its precision for electrons and photons in the challenging high-luminosity environment.

With the ASIC production completed and the first large-scale integration tests successfully performed, the system is on track for full deployment during Long Shutdown 3, preparing the ECAL to deliver high-quality data throughout the HL-LHC.

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