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Upgrade of the CMS Electromagnetic Calorimeter for High-Luminosity LHC

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Abstract: The CMS Electromagnetic Calorimeter (ECAL) is a homogeneous $PbWO_4$-based detector. The upcoming High-Luminosity upgrade of the CERN LHC will provide detectors with unprecedented instantaneous luminosity, entailing an increase of the average number of proton-proton collisions per bunch crossing up to a value of 200. To cope with such busy environment and with the trigger latency and rate, the ECAL readout and trigger electronics system will be replaced. The front-end electronics will deploy custom ASICs optimised for precise timing, improved signal discrimination, lossless data compression, and fast transmission. Off-detector FPGA processor boards will form trigger primitives and perform basic signal reconstruction. The upgraded system has been validated over several test beam campaigns. In terms of physics performance, it will match the outstanding energy resolution of the current ECAL detector, while significantly enhancing the time resolution of electrons and photons above 50 GeV.

Keywords: Digital electronic circuits; Front-end electronics for detector readout; Performance of High Energy Physics Detectors; Radiation-hard electronics

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Contents

1 Introduction

The Electromagnetic Calorimeter (ECAL) [1] of the CMS (Compact Muon Solenoid) experiment [2, 3], operating at the CERN Large Hadron Collider (LHC), is a homogeneous calorimeter consisting of an array of over 75848 scintillating lead tungstate ($PbWO_4$) crystals, arranged in a barrel (61200 crystals) and two endcaps (7324 crystals each). The scintillation light produced by the passage and showering of electrons and photons is read out by avalanche photodiodes (APD) in the barrel, and vacuum phototriodes in the endcaps. The small Molière radius (2.19 cm) and short radiation length (0.89 cm) of the ECAL crystals allow the electromagnetic showers to be contained in a compact volume and to be reconstructed with high space resolution. The lead tungstate is a fast scintillator: in a typical ECAL crystal, 80% of the light is emitted within 25 ns, which matches the time spacing between bunch crosses at the LHC. Signals are sampled at 40 MHz and digitised in a set of 10 consecutive amplitude measurements, and dedicated energy reconstruction algorithms are in place to mitigate the contribution of detector noise or simultaneous interactions per bunch crossing (pileup) to the measured energy.

The current LHC operations will last until 2026. By then, the entirety of the data delivered by the collider will amount to about 450 fb^{-1}. As the LHC transitions into the High-Luminosity phase (HL-LHC), the ECAL faces new challenges. The HL-LHC is expected to achieve an instantaneous luminosity up to 7.5× higher than the original design value of 10^{34} cm^{-2} s^{-1}, which will drastically increase event rate and exposure to radiation. An average pileup of 140–200 will be typical at the HL-LHC, compared to a maximum of about 65 during the typical ongoing operations.

The radiation damage to the crystals of the endcaps will be unsustainable beyond 500 fb^{-1}, which calls for a full replacement of the system by a novel calorimeter. The ECAL barrel, instead, will be upgraded [4] to cope with the high-radiation and busy collision environment, maintain the current energy resolution, and provide precise timing to contribute to the CMS 4D vertex reconstruction.

The ECAL barrel crystals will be kept in the upgraded detector, as they are expected to have retained 30–50% of their initial light output at the end of the HL-LHC (3000 fb^{-1}). The readout electronics will be replaced: the on-detector electronics will feature custom pre-amplifiers and analog-to-digital converters (ADC) with improved signal discrimination and higher rate sampling. The off-detector electronics will cope with the higher output bandwidth of the upgraded CMS Level-1 (L1) trigger. In addition, lowering the operational temperature from 18 to 9°C will help mitigate the radiation-induced electronic noise of the APDs.

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2 The ECAL upgraded system

The upgraded L1 trigger system will operate at 750 kHz with 12.5 μs latency, a 7.5× increase in rate and 3.3× in latency compared to the current system. The upgraded ECAL readout system must cope with the L1 trigger needs, ensuring fast, high-granularity data transmission. A driving motivation for the upgrade is the need to reject signals from direct ionization of the avalanche photodiodes (APDs) by hadrons, which would otherwise saturate the L1 trigger bandwidth. The layout of the upgraded system is outlined in figure 1.

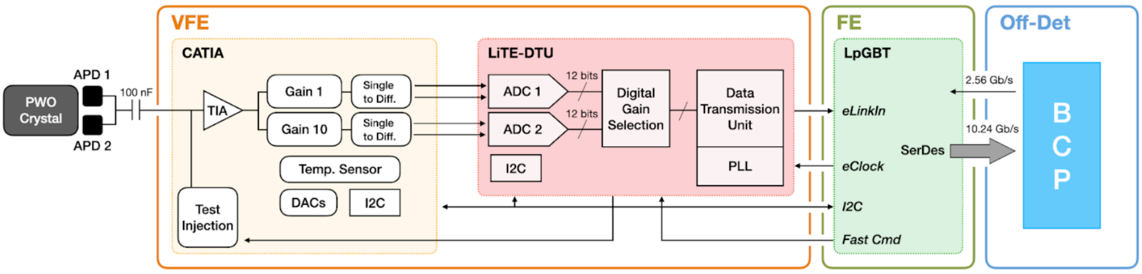

Figure 1. Schematic layout of the upgraded readout electronics.

The Very Front End (VFE) board hosts two custom ASICs: the CATIA (Calorimeter TIA) and the LiTE-DTU (Lisboa-Torino ECAL Data Transmission Unit). The CATIA ASIC is a fast, dual-gain trans-impedance amplifier with dynamic range up to 2 TeV and 35 MHz bandwidth. The minimal pulse shaping contributes to precise timing and improved signal discrimination. The CATIA is complemented by the LiTE-DTU, a high-performance analog-to-digital converter operating with 160 MHz sampling rate and 12-bit resolution. A key feature of the LiTE-DTU is the lossless data compression, which reduces the output rate from 2.08 Gb/s to 1.08 Gb/s.

The Front End (FE) board implements lpGBT transceivers, featuring fast, radiation-hard optical links. Single-channel data will be transmitted to the trigger, rather than in 5×5 channels sums as in the current system, which will drastically enhance the discrimination against direct APD ionization signals.

The data is transmitted off-detector with 10.24 GB/s rate. The BCP (Barrel Calorimeter Processor) board, a FPGA-based aggregator, performs decompression and basic signal reconstruction, and prepares pre-processed data for the L1 trigger.

3 The performance measured on beam

The upgraded system is being validated for data integrity and physics performance in test beam campaigns at the H4 beamline branching from the CERN Super Proton Synchrotron (SPS). The H4 beamline provides pure electron beams with $\Delta p/p = 0.5\%$ over the range $20 < p < 250$ GeV. The 2021 campaign was carried out using a 5×5 crystals readout unit equipped with VFE board prototypes. For the 2023 campaign, 9 readout units of a spare ECAL supermodule, for a total of 225 crystals, were equipped with close-to-final prototypes of the full upgraded readout chain. The latter setup also included the upgraded readout of the laser that monitors the light output of the crystals under radiation.

Several physics performance benchmarks guide the design of the upgraded ECAL. The excellent energy resolution achieved by the current system, within 1% for the typical energy of the products of the Higgs boson, must be maintained. While the current system achieves a timing resolution of a

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few hundreds of ps, precise timing will be a crucial addition to the ECAL capabilities. The target for the upgraded system is to reduce it to 30 ps for electromagnetic showers above 50 GeV. This improvement is expected to enhance the H$\rightarrow \gamma\gamma$ vertex reconstruction efficiency by 10%, so that the diphoton mass resolution is not degraded by large pileup.

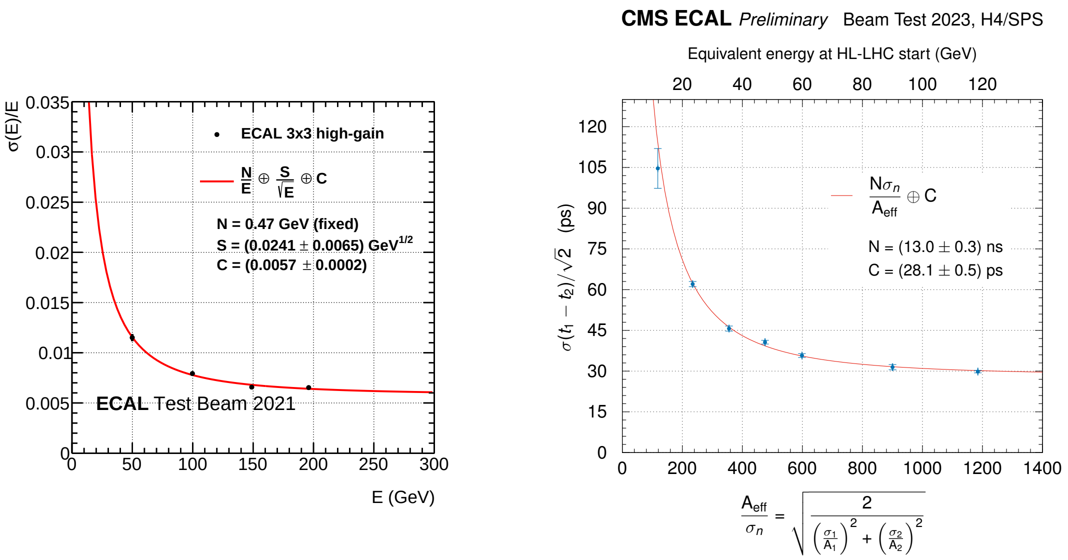

Figure 2. Performance of the ECAL upgraded electronics measured with 2021 and 2023 test beam data. On the left, energy resolution as a function of the beam energy. On the right, time resolution as a function of the effective signal amplitude normalised by the electronic noise.

Results from the analysis of the 2021 and 2023 test beam data are shown in figure 2. The energy resolution $\sigma(E)/E$ is computed over a 3×3 crystals matrix and is parametrised as a function of the energy of the incoming electron beam. The measurements are fitted using the functional form

$$\sigma(\mathrm{E})/\mathrm{E} = \frac{\mathrm{N}}{\mathrm{E}} \oplus \frac{\mathrm{S}}{\sqrt{\mathrm{E}}} \oplus \mathrm{C}$$

where N is the noise term, S is the stochastic term and C is the constant term. The noise is fixed to the measured weighted sum of the average baseline RMS across channels. The constant term, representing the asymptotic energy resolution, is well below 1%, matching the design target.

The timing resolution is extracted from the spread of the signal pulse time in neighbouring channels and is parametrized as a function of the effective amplitude $\mathrm{A_{eff}}$ over the two channels, normalized by the measured noise σ_n. The noise contribution and the constant term are determined by fitting with

$$\frac{\sigma(t_1 - t_2)}{\sqrt{2}} = \frac{\mathrm{N}\sigma_n}{\mathrm{A_{eff}}} \oplus \mathrm{C}.$$

The constant term lies within 30 ps.

These results confirm that the upgraded system has excellent physics performance, meeting the requirements.

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4 Conclusion

The HL-LHC operations will present unprecedented challenges for the CMS detector in terms of data acquisition and both online and offline event reconstruction. Like the other CMS detectors, the ECAL must cope with an extremely busy environment, while ensuring the fast transmission of high-quality data.

The ECAL barrel will be fully refurbished with a new readout system. The upgraded system is designed to maintain the outstanding energy resolution of the legacy system while dramatically improving the timing resolution. Test beam campaigns with close-to-final prototypes have successfully validated the upgraded readout chain, and have shown that the target physics performance is met.

The VFE ASICs are currently in the pre-production phase, while the FE and BCP boards design is being finalized. Further test beam campaigns will test newer iterations of the readout components in preparation for the HL-LHC operations.

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