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On-beam system test of the new readout electronics for the CMS Electromagnetic Calorimeter upgrade

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ABSTRACT: Starting in 2029, the High Luminosity LHC (HL-LHC) at CERN is projected to achieve unparalleled instantaneous luminosity ($7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$) for an integrated luminosities of 4500 fb^{-1} . To cope with the extreme conditions of 200 collisions per bunch crossing (pile-up), both on-detector and off-detector electronics of the CMS Electromagnetic Calorimeter (ECAL) will be upgraded. The new system will incorporate a dual-gain trans-impedance amplifier alongside an Application-Specific Integrated Circuit (ASIC) that includes dual 160 MHz ADC channels and features for gain selection and data compression. The lead tungstate crystals and avalanche photodiodes (APDs) will remain in service due to their proven reliability. To counteract the noise amplification in the APDs, attributed to radiation-induced dark currents, the operational temperature of the ECAL will be reduced from 18°C to roughly 9°C . Preliminary tests of these new electronics have yielded promising results. During tests beams at the CERN H4 beamline using an electron beam, the new electronics met both required energy resolution and linearity and achieved a timing resolution of 30 ps for energies above 50 GeV.

KEYWORDS: Calorimeter methods; Detector design and construction technologies and materials; Radiation-hard detectors

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1 Introduction

The Electromagnetic Calorimeter (ECAL) of the CMS experiment employs lead tungstate ($PbWO_4$) crystals, delivering remarkable energy resolution capabilities under the LHC's high-radiation conditions [1]. Specifically, it has demonstrated a 1% mass resolution for the Higgs boson when decaying via the $\gamma\gamma$ channel [2]. ECAL is a hermetically sealed, compact detector placed around the beam line with a cylindrical symmetry, with its crystals oriented towards the nominal interaction point and is divided into barrel (covering the central region of the cylinder) and endcap segments (the lateral faces of the cylinder). The barrel region comprises 61,200 crystals, organized into 36 supermodules, and utilizes avalanche photodiodes (APDs) for light detection.

The main objective of the High Luminosity LHC (HL-LHC) is to augment the dataset available to the experimental setups for various purposes: the exploration of new physics landscapes, precise measurements of Higgs boson couplings, and high-accuracy verification of Standard Model predictions. Target operational parameters include achieving an instantaneous luminosity up to $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. Such enhanced luminosity will allow to accumulate an integrated luminosity of up to 4500 fb^{-1} over a span of about 12 operational years. Additionally, the HL-LHC aims to have up to 200 simultaneous interactions per bunch crossing, a scenario demanding substantial advancements in detector technology and data acquisition systems. Due to the higher luminosity, there will also be an increased rate of anomalous signals (“spikes”), which are caused by hadrons impacting directly on the APDs.

2 ECAL upgrade

To allow ECAL to cope with the elevated luminosity objectives of LHC's Phase-2, substantial upgrades are imperative. This entails the refurbishment of both the front-end and off-detector electronics in the ECAL Barrel (EB), while the ECAL Endcap will be replaced. The main reason behind the need for EB modifications is the revised Level-1 trigger conditions for Phase-2, specifying a latency of $12.5 \mu\text{s}$, in contrast to the current $4 \mu\text{s}$, and a trigger rate approximating 750 kHz, as opposed to the current 100 kHz [3]. To comply with these augmented specifications, both barrel front-end cards and off-detector electronics will be upgraded.

CMS will add a per-particle temporal information with a precision of 30 ps to refine event reconstruction and help mitigate the high pileup effects. Simulation data indicate that coupling the timing measurements of electrons and photons with that of charged hadrons will allow CMS to make precise measurements in the Standard Model (SM) sector as well as improve the CMS sensitivity to novel physics that extends beyond the SM [4].

Crystals and APD. Radiation effects on lead tungstate crystals have been assessed through empirical investigations. While scintillation mechanics remain invariant, the emergence of scattering color centers compromises crystal transparency [5]. The most pressing concern for the ECAL operation at HL-LHC is the irreversible loss of light transmission due to hadron-induced irradiation. Extensive tests have enabled the parametrization of crystal aging expected under HL-LHC conditions. A small increase in the constant term of energy resolution to roughly 1.5% at high values of η in the barrel is anticipated by the closure of LHC Phase-2, which is within acceptable physics constraints, hence EB crystals will be preserved.

Avalanche Photodiodes (APDs) will remain operational throughout Phase-2. However, an amplification in dark current is inevitable due to bulk silicon damage from hadron exposure. To reduce this effect by a factor ~ 2 [3], the operational temperature for EB will be adjusted from the Phase-1 of 18°C down to 9°C. The existing cooling infrastructure is sufficiently robust to maintain the 9°C setpoint with only minor alterations to the water distribution system.

Electronics upgrade. As part of the electronics upgrade, both the very front-end and front-end cards will be replaced, while retaining the existing mechanical layout of the cooling system and motherboards. These motherboards are situated beneath the cooling structure and distribute both low-voltage and bias-voltage to the electronics and photodetectors, in addition to routing APD signals to the very front-end cards.

The Very Front-End (VFE) within the HL-LHC readout architecture consists of two ASICs: the CATIA [6] and the LiTE-DTU [7]. CATIA serves as a pre-amplifier ASIC, employing a trans-impedance amplifier (TIA) that is designed for minimal noise (less than 80 MeV at HL-LHC start) and shorter pulse shaping (160 MS/s). In particular, the shorter pulse shaping is vital for achieving accurate timing, enhancing the ability to reject spikes and mitigate the dark current increase. It also offers two levels of output gain: $\times 1$ and $\times 10$ to maintain a dynamic range of signals up to 2 TeV. The LiTE-DTU functions as data conversion, compression, and transmission ASIC. It incorporates dual 12-bit ADCs operating at a data conversion rate of 160 MS/s. The ASIC also incorporates lossless data compression and features a look-ahead algorithm that prevents mixing of samples from different gains within the same APD signal timeframe through sample saturation checks. The Front End (FE) incorporates 5 VFE, each containing a CATIA and LiTE DTU chips, and enables streaming of data at full granularity (i.e. single crystal information) to the off-detector electronics at 160 MHz, instead of the actual 40. It dispatches a clock signal to the VFE directly from the lpGBT controller and employs I2C communication via a controller-responder chain. Moreover, it monitors the APD dark current.

The backend electronics consist of a barrel calorimeter processor (BCP) [3] board unifying both trigger and DAQ functionalities while delivering clock and control signals to the FE electronics. Each board handles signals from 600 crystals and employs commercially available FPGAs.

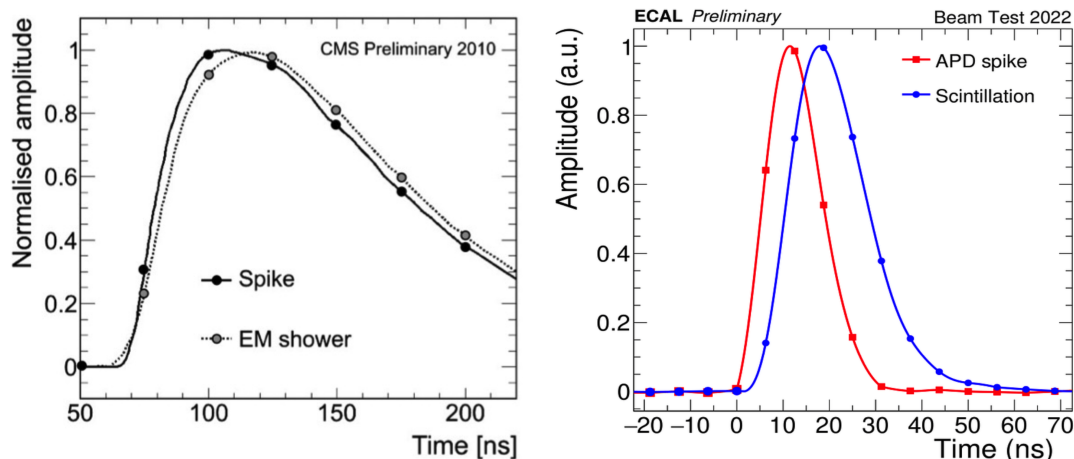


Figure 1. Comparison of the pulse shapes for representative spikes and electromagnetic (EM) showers within the current CMS ECAL (left) and the upgraded ECAL (right) planned for the HL-LHC era. The pulse shapes for the HL-LHC era are measured during the 2022 test beam with the new readout electronics.

Spike rejection. In the HL-LHC environment, the issue of spikes (i.e. large isolated signals caused by hadron interacting directly with APDs) becomes more pressing. Figure 1 (left) compares the pulse shapes of spikes and electromagnetic (EM) showers in the current electronics; both exhibit similar start times and pulse duration, making them challenging to discriminate.

In contrast, the Phase-2 upgrade electronics will enable better discrimination between spikes and EM showers, as shown in figure 1 (right). The spikes have faster rise times and shorter pulse duration compared to EM showers, characteristics that can be exploited only by Phase2 electronic. This feature allows for the suppression of spike signals, which if left unaddressed, would become a dominant contributor to the Level 1 (L1) trigger rate in the HL-LHC.

3 Test beam campaign

Several tests beams were performed in the last years. In the first test beams (2018–2021), the new very front-end cards were tested on the H4 beam line. A more detailed description of the experimental setup is in the next paragraph.

Two additional tests beams (one in November 2022 and one in July 2023) were made using the entire Phase-2 readout chain, from crystal to the backend BCP board. For these tests beams a spare ECAL supermodule was employed, featuring 8 readout towers (consisting of 200 channels) equipped with the newly developed readout electronics. This supermodule was then transported to CERN’s H4 beamline for evaluation with high-energy beams.

Experimental setup. Test beam campaigns were executed at the H4 beam line at CERN’s SPS to evaluate both on-detector and off-detector electronic, using an electron beam with energies from 25 GeV to 250 GeV. It has a dispersion as minimal as $\delta p/p = 0.5\%$ and high purity levels (greater than 95%). The test setup, shown in figure 2, includes two planes of plastic fiber hodoscopes that measure the position of incoming electrons with a precision below 0.2 mm. Dual micro-channel plate (MCP) devices, 1.2 cm in diameter and less than one radiation length in thickness, furnish a time reference with a resolution better than 15 ps. The MCP signals are sampled at 5 Gs/s by a DRS4

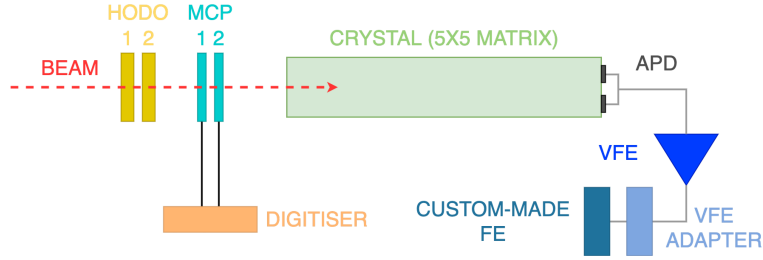


Figure 2. Test beam setups for 2021. In 2018 the VFE was a commercial ADC, while in 2021 the LiTe-DTU was used.

chip on a CAEN V1742 board. An ECAL trigger tower (5×5 crystal matrix) equipped with the first version of HL-LHC electronics, specifically the CATIA v1.2 and LiTe DTU v1 was tested.

Test beam results. Figure 3 (left) illustrates the energy resolution for a 3 × 3 crystal matrix. This measure is made with 2018 test beam data using CATIA v1 and a commercial 160 MHz ADC. The setup was congruent with the one employed in 2021. The results confirm that the energy resolution satisfies the requirements for the High-Luminosity LHC, exhibiting a constant term of less than 0.5%.

Figure 3 (right) shows the time resolution as a function of the energy. The time resolution has two contributors: the single crystal time resolution and the MCP time resolution (σ_{MCP}). The MCP time-resolution contribution is computed on an event-by-event basis. This calculation relies on the amplitude of the MCP signals and a parametrization of their time resolution. Then average value of the σ_{MCP} distribution is removed in quadrature for each data point. The constant term of about 13 ps meets the requirements for the HL-LHC design. A timing resolution of 30 ps for $E > 50$ GeV is shown to be achievable.

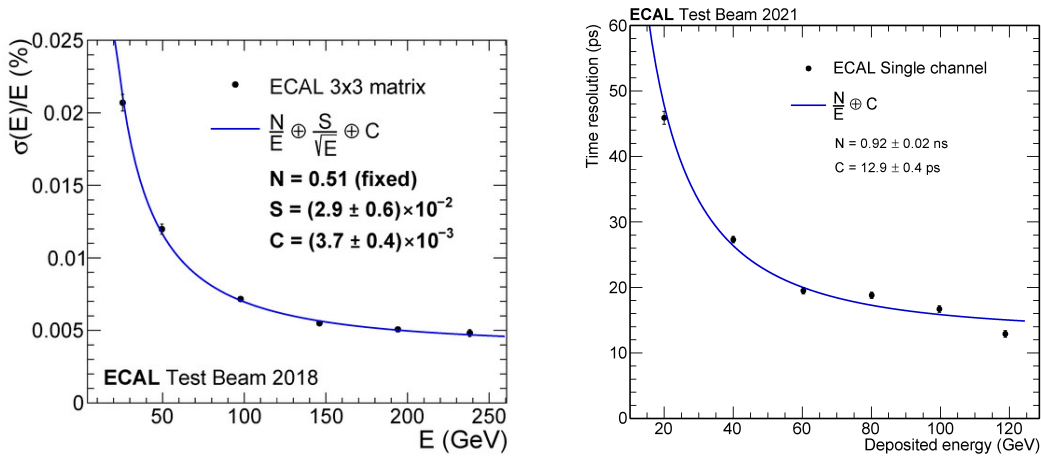


Figure 3. The energy (time) resolution for electrons a function of deposited energy on the left (right), using data collected from the 2018 (2021) test beam.

Figure 4 shows the signal amplitude with respect to the energy of the incoming particle. A deviation from linearity smaller than 0.3% is found, in agreement with Phase2 requirements.

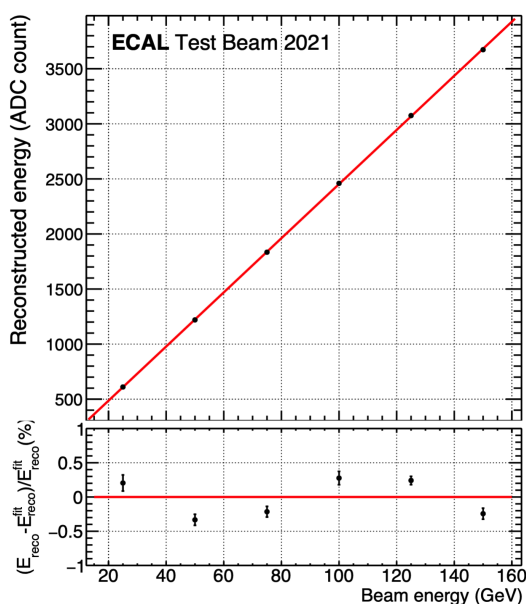


Figure 4. Signal amplitude linearity as a function of energy of the incoming particle using data from 2021 test beam.

4 Conclusion

The ECAL barrel will undergo an upgrade aimed at preserving its operational efficiency during the High-Luminosity phase of LHC. While the crystals and the APDs will remain the same, both the on- and off-detector electronics will be replaced in the ECAL barrel region to maintain the current performance and meet the Phase2 requirements. The objectives are to uphold the highest feasible energy resolution and enhance the system’s capacity to mitigate the pileup, by adding a time resolution of 30 ps, and suppress spikes, by providing a faster pulse shape. Tests of the new very-front end on the H4 beam line have shown that the performance requirements in terms of energy and time resolution are met. Finally tests of the full readout chain on the beam line shows promising results.

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