IL NUOVO CIMENTO **47 C** (2024) 105
DOI 10.1393/ncc/i2024-24105-1

Colloquia: IFAE 2023

Design and performance of the Phase 2 CMS experiment electromagnetic calorimeter readout electronics(*)

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received 13 February 2024

Summary. — The High Luminosity LHC project aims to increase the instantaneous luminosity of the collisions by a factor of 4 compared to the value at which the LHC currently operates. To cope with these new data taking conditions, the central part of the CMS electromagnetic calorimeter will undergo a complete upgrade of both the on-detector electronics and the readout electronics located in the service cavern. Only the lead-tungstate crystals and the avalanche photodiodes are expected to maintain good performance and do not need to be replaced. The results of the 2018 and 2021 test beam campaigns are presented. Electron beams up to 250 GeV were employed to test the Phase 2 electronics mounted on the ECAL crystals in terms of time and energy resolution.

The CMS electromagnetic calorimeter

The CMS electromagnetic calorimeter (ECAL) is a homogeneous calorimeter with a compact design [1]. It is made of 75848 lead-tungstate ($PbWO_4$) scintillating crystals, placed around the beam line, following a cylindrical symmetry and oriented towards the nominal interaction point. The detector is made of two sub-detectors: the Barrel (EB) and the Endcaps (EE). The barrel, covering the central region of the cylinder, is assembled in 36 identical supermodules (SM) each one made of 1700 crystals whose scintillation light is measured by Avalanche Photodiodes (APD). The endcaps are on the lateral faces of the cylinder and consist of 4 D-shaped sectors, 2 on each side, with 3662 crystals each and equipped with Vacuum Phototriodes (VPT) as photodetectors.

The challenge of High Luminosity LHC

In 2029 LHC will start a new data taking phase named High Luminosity LHC (HL-LHC) aiming to deliver a much larger dataset to the LHC physics program. The analyses that would benefit the most of the upgrades are new physics searches, precise measurements of the Higgs boson couplings, including its self-coupling, and precision measurements of Standard Model processes.

(*) IFAE 2023 - "Poster" session

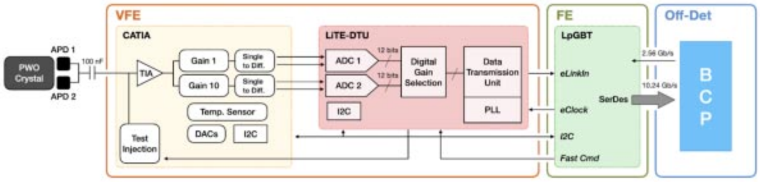

Fig. 1. – A complete scheme of the new Phase-2 readout on- and off-detector electronics.

The new LHC phase targets a peak luminosity of 5×10^{-34} cm^{-2} s^{-1} and an integrated luminosity of 250 fb^{-1} per year, almost twice the LHC-Run2 integrated luminosity. These conditions would correspond to an average of 140-200 interactions per proton-proton collision.

The full upgrade of the EB readout electronics is imperative in order to allow ECAL to cope with the challenges arising from these unprecedented data taking conditions [2]. The $\mathrm{PbWO_4}$ crystals and the APDs will remain operational throughout Phase-2 since their performance is predicted to satisfy the standards required by the CMS physics purposes. A scheme of the Phase-2 ECAL readout system is reported in fig. 1.

Among the primary motivations for the EB calorimeter upgrade is the requirement for the trigger to cope with the trigger latency increasing from the current value of 4 μs to a maximum of 12.5 μs and of the Level-1 trigger rate up to 750 kHz, compared to the current 100 kHz. The Level-1 calorimeter trigger will provide a single-crystal granularity in space to precisely match electromagnetic showers to tracks, thus reducing backgrounds, and keeping the photon trigger transverse energy thresholds down to 25 GeV, hence at the level required for Higgs boson precision studies. A increase of the dark current is inevitable due to silicon bulk damage from hadron exposure. Such an effect is mitigated by lowering the EB operational temperature from the Phase-1 standard of 18 °C down to 9 °C. The Phase-2 Very Front End (VFE) architecture will include two ASICs: the CATIA and the LiTE-DTU [3, 4]. The CATIA serves as pre-amplifier and it is designed for minimal noise and shorter pulse shaping, having 6.25 ns sampling period with respect to the current 25 ns. This enables a more optimal filtering of the APD increased noise and of the out-of-time contribution, through the multifit amplitude reconstruction [5]. Furthermore it allows an almost complete suppression of anomalous signals in the APDs, termed *spikes*, that would saturate the Level-1 trigger [6]. The LiTE-DTU incorporates dual 12-bit ADCs operating at a data conversion rate of 160 MHz, four times the current sampling rate, necessary to match the ECAL timing resolution requirements.

The back-end electronics consists of a barrel calorimeter processor (BCP) board unifying both trigger and DAQ functionalities while delivering clock and control signals to the FE electronics.

Test with electron beams

Between 2018 and 2021, two test beam campaigns were held on the H4 beam line at CERN's SPS (Super Proton Syncrotron) with the aim of testing and characterizing the Phase-2 VFE cards performance. Figure 2 reports a schematic representation of the experimental setup at the H4 site. A 5x5 matrix of $\mathrm{PbWO_4}$ crystals was equipped with the legacy APDs and the upgraded VFE cards and placed on a movable table so to make possible to shoot single crystals with the beam. The SPS is able to deliver a pure and

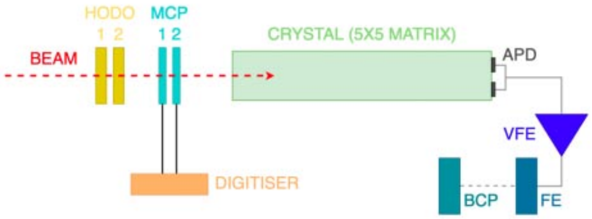

Fig. 2. – Schema of the H4 beam-line: in front of the crystal matrix two hodoscope plates are placed to monitor the beam position on the transversal plane and two Micro Channel Plates (MCPs) to provide an external time reference for the particle arrival.

monochromatic electron beam, with an energy ranging between 25 GeV and 250 GeV and with a momentum spread $\Delta p/p < 0.5\%$.

To maintain the same ECAL energy resolution as in Phase-1, which was crucial to observe the $H \to \gamma\gamma$ decay, the target timing and energy resolution is smaller than 30 ps and 1% respectively, at energies higher than 50 GeV [7]. Such ambitious timing resolution would improve the signal to background ratio by mitigating the extra energy flow from pile up within ECAL clusters.

The 2018 test beam campaign tested CATIA-v1 equipped with commercial 160 MHz ADC. Figure 3 reports the performance in terms of energy and timing resolution of the central 3x3 crystal matrix satisfying the HL-LHC requirements [8]. During 2021 test beam campaign CATIA and the LiTE-DTU-v1.2 were tested. So far the analysis of the test beam data concentrated on the characterisation of a single crystal response. The pulse shapes associated with the particles energy deposits in ECAL are measured using the template-fit method. A template is a quasi-continuous function constructed by combining together many sampled signals. The template-fit consists in adapting the

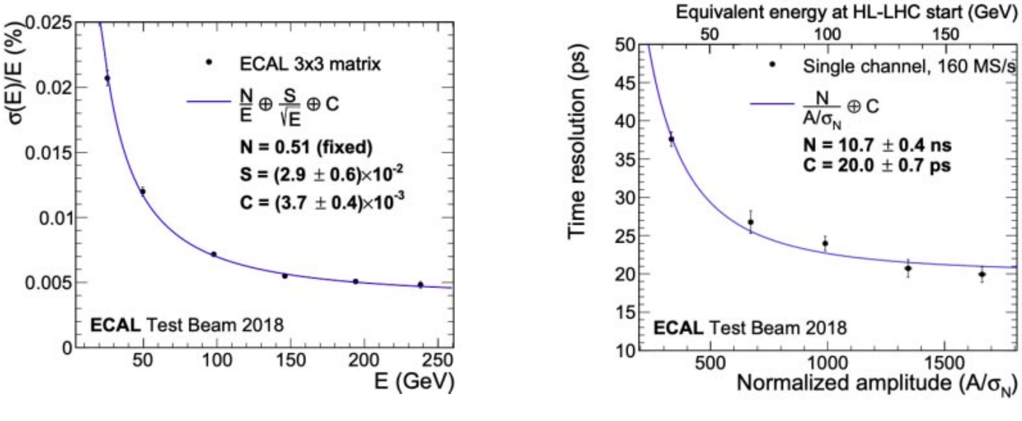

Fig. 3. – 3x3 crystal matrix performance from the 2018 test beam. Left: energy resolution as function of the electron beam energy. The constant term is smaller than 0.5%. Right: timing resolution as function of the signal amplitude normalised to its width (lower x-axis) and of the equivalent energy in the HL-LHC conditions (upper x-axis)

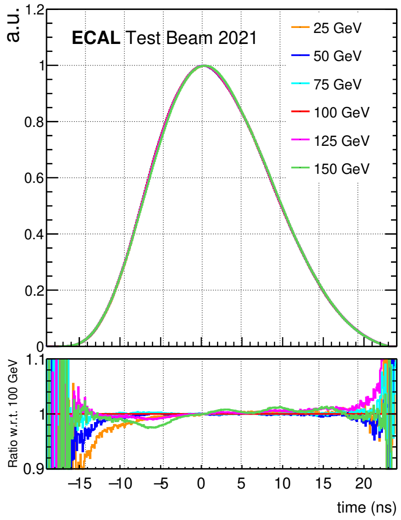

Fig. 4. – Single crystal templates derived for nominal beam energy ranging between 25 and 150 GeV.

template normalisation and peak position to the digitized pulses in order to measure the amplitude and the particle arrival time with good precision. Figure 4 shows that the template shapes exhibit no strong dependence on the beam energy, demonstrating that the template fit introduces no systematic error which is function of the particle energy. The signal amplitude, computed with the template fit, is studied as a function of the beam energy and the observed maximum deviation from linearity is as large as 0.3%,

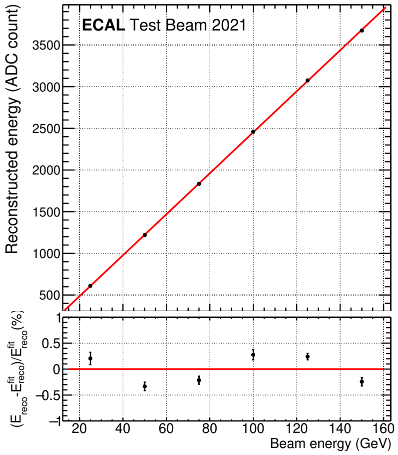

Fig. 5. – Signal amplitude (E_{reco}), in ADC counts, as function of the nominal beam energy from a single crystal of the 5x5 matrix. The lower panel reports the pulls with respect to the linear fit (E_{reco}^{fit}).

in agreement with Phase-2 requirements, as shown in fig. 5. Such deviation is due to the partial misalignment between the crystal and the beam and to the non-fully efficient containment of the electromagnetic shower by a single crystal.

Conclusions

The ECAL barrel upgrade aims at preserving its operational performance during the High-Luminosity phase of LHC. 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 in terms of both energy and timing resolution. The objectives are to uphold the highest feasible energy resolution, enhance the system capacity to mitigate the pileup by achieving a 30 ps time resolution, and suppress spikes with a a faster sampling rate. According to the tests at the H4 beam line, the new electronics meets the performance requirements. The energy and time resolution, the signal amplitude linearity and pulse shape stability as function of the particles energy were tested successfully.

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