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The CMS ECAL barrel upgrade for high precision timing and energy measurements at HL-LHC

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The Electromagnetic Calorimeter (ECAL) of the Compact Muon Solenoid (CMS) experiment will be upgraded for the High-Luminosity phase of the LHC (HL-LHC) to cope with the new, harsher conditions, in terms of luminosity and pileup. The current lead tungstate crystals and avalanche photodiode detectors in the barrel region of the ECAL will remain, while the front-end and off-detector read-out electronics of the calorimeter will be upgraded. The new electronics will have to fulfill the requirements of the upgraded Level 1 hardware trigger system, in terms of increased latency and data bandwidth, in order to preserve detector performance despite the increased instantaneous luminosity. The upgrade will provide single crystal granularity for the hardware trigger and will enable a full read-out of the detector. A crucial characteristic of the new design will be the ability to measure the time of electrons and photons with high precision, of the order of 30 ps for energies above 100 GeV. This excellent time resolution will improve the overall CMS physics performance under the expected pileup conditions. The status of the ongoing R&D activities is presented, together with the latest beam test results with prototypes.

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1. Introduction

The HL-LHC at CERN will provide unprecedented and very challenging conditions. The peak instantaneous luminosity will increase by five to seven times the nominal value of $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with consequent much larger levels of overlapping collisions (pileup), with a maximum expected average of 250-300, and with higher radiation levels than in the LHC. The upgraded HL-LHC parameters will affect the CMS experiment directly in two ways: in order to maintain L1-trigger performance close to what was achieved at the LHC, the CMS L1-trigger rate will have to increase from the present 100 kHz to 750 kHz and the L1-trigger latency will also increase from 3.4 μsec to 12.5 μsec to accommodate a new track-based hardware trigger designed to better suppress the larger pileup. The CMS legacy electromagnetic calorimeter cannot cope with the new requirements; hence upgrades are required, as described in detail in the recent upgrade Technical Design Report [1].

2. The electromagnetic barrel calorimeter at the HL–LHC

The CMS legacy lead-tungstate crystal ECAL was designed to be compact, hermetic, fine grained ($\Delta\eta \times \Delta\phi \simeq 0.0174 \times 0.0174$), low noise and to provide an energy resolution, $\sigma_\mathrm{E}/\mathrm{E}$, of about 1%. All of this with appropriate radiation tolerance [2]. A barrel covers the region $|\eta| < 1.48$ and two endcaps cover the region $1.48 < |\eta| < 3.0$ with a Pb/Si preshower extending to $1.65 < |\eta| < 2.6$. This calorimeter played a pivotal role in the discovery of the Higgs boson in the two-photon decay channel as well as in the initial studies of the boson properties [3, 4, 5]. More is expected from Phase II where the large amount of data should give access to double Higgs boson production and to the measurement of its self-coupling. It is vital to preserve in Phase II the same performance achieved so far, insuring a resolution on the diphoton mass of $\sim 1\%$. The challenges to be confronted are, however, multiple and can be summarized as follows: higher trigger rates and longer latency, increased pileup level, further radiation-induced transparency loss of the crystals, increased dark current in the avalanche photo-diodes (APDs) [6] because of higher radiation with consequent increased noise. The latter three effects impact negatively the energy resolution. Furthermore the higher pileup leads to a substantial reduction of the identification efficiency of the primary vertex (from 80% to 40%) which affects negatively the Higgs boson mass resolution in the diphoton decay channel. Last, but not the least, the higher instantaneous luminosity leads to an increased rate of anomalous high energy ($\geq$ 100 GeV) signals induced by hadrons interacting directly with the APD core (“spikes”), which if left unmitigated would dominate the ECAL L1-trigger.

The barrel crystals are expected to survive well to the end of the HL-LHC, with a transparency loss which will be about 50% of the value at the end of Phase-1, so they need not to be replaced (Fig. 1 (left)). On the other hand, the APD dark current is expected to increase because of the higher integrated luminosity and correspondingly the noise would increase by a factor of ten by the end of the HL-LHC. However the dark current is strongly dependent on the temperature; cooling further down the detector, from $18^\circ C$ to $9^\circ C$, would keep the noise under control (Fig. 1 (right)) without replacing the APDs. The imperative reason for upgrading, hence, is related to the expected CMS higher trigger rates and extended latency. While the geometrical arrangement of crystals into

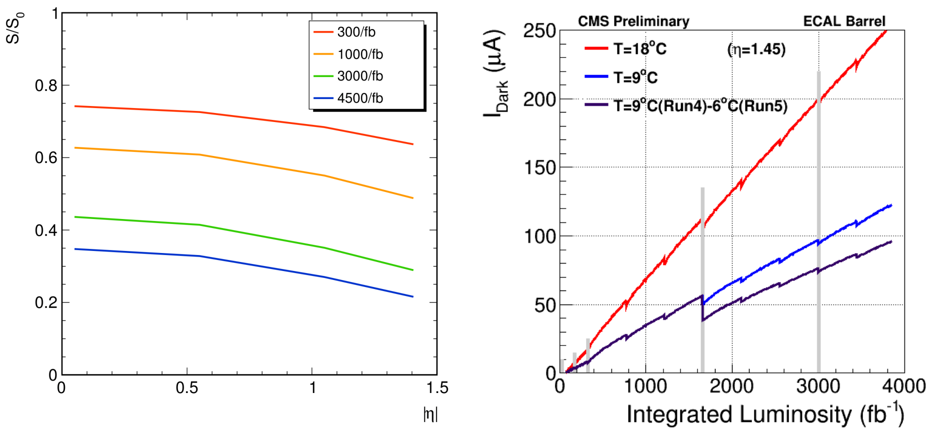

Figure 1: (left) Expected ratio S/S$_0$ of the crystal light output for 50 GeV photon showers (left) with respect to the initial value for the ECAL barrel crystals; expected dark current (right) for APDs operated at two different temperatures (present and future planned) as function of the integrated luminosity.

five-by-five matrices, the APDs, and the motherboards will be left untouched, the overall read-out electronics, very front-end (VFE), front-end (FE) and back-end (BE) will have to be replaced so that the necessary longer data pipelines can be dealt with in the back-end. The trigger primitive formation, which in the legacy ECAL is done in the FE, will also be moved off-detector (Fig. 2).

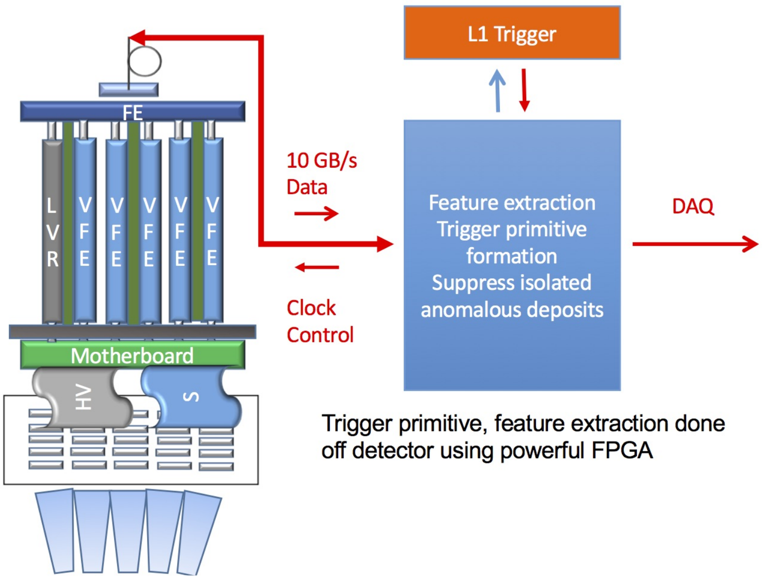

Figure 2: Block diagram for the upgrade of the ECAL barrel electronics.

Given that the VFE and FE have to be redesigned, the opportunity is taken to improve the design by reducing the signal pulse length, increasing the sampling frequency, and introducing data compression to reduce the bandwidth and save on the number of optical links and back-end cards. The need for a shorter pulse is twofold: it is necessary to disentangle online genuine scintillation signals and anomalous spikes and to achieve high timing resolution (target $\leq$ 30ps). As shown in Fig.3 (left) the signal from anomalous spikes is much shorter than the genuine scintillation signal, hence only a shorter pulse lengths from the VFE can disentangle the two. This distinction cannot indeed be done based on the signal shape in the legacy calorimeter where only a coarse topological algorithm is used at L1-trigger. For Phase II an online signal shape analysis, based on a linear discriminant (Fig.3 (right)), can provide online (in the BE) a flag for each channel and suppress it if the signal comes from a spike.

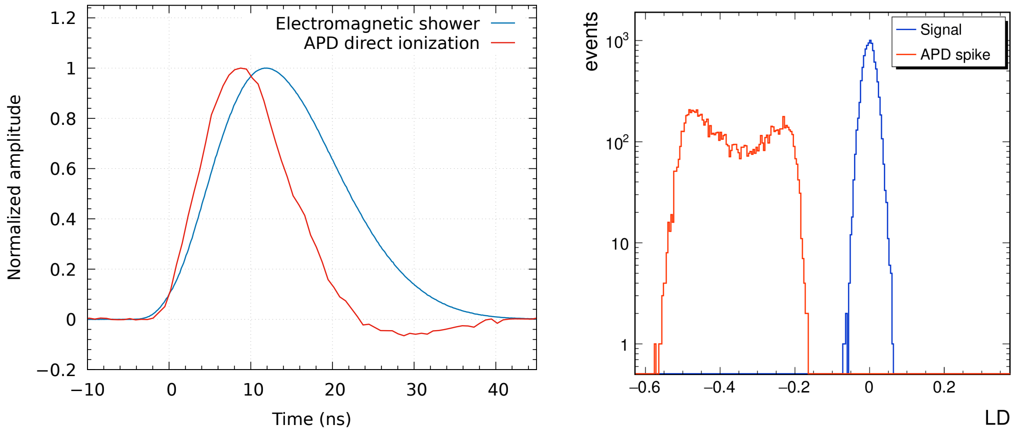

Figure 3: (left) The signal from an anomalous spike (light grey) is narrower than the genuine signal from scintillation (dark grey); (right) Example of signal shape linear discriminant.

Precision time resolution is of huge importance to distinguish between many interaction vertices piling up along the beam axis as shown in the left plot of Fig. 4. The timing information is essential to recover the Higgs boson mass resolution, as shown in the right plot of Fig. 4. Pileup suppression with timing is of interest to CMS in general hence the ECAL barrel is one of the efforts being put in place to reach the goal. The intrinsic time resolution of the crystal-plus-APD system is less than 30 ps; to fully exploit it, the VFE needs to have short pulse length and very precise local clock distribution. The latter is in fact the limiting factor, since any two clocks at the FE must be aligned within 15 ps.

Figure 5 shows the full read-out chain of a single crystal. The VFE will use a trans-impedence amplifier (TIA) with optimized signal pulse length and with a 2 TeV dynamic range, with two gains ($\times$1, $\times$10) respectively with 50, 500 MeV LSB. A dual 12-bit ADC will digitize the signals at a sampling frequency of 160 MHz. A data transmission unit (DTU) will compress data for bandwidth limitation. Data will flow along a single path (i.e. no distinction between data and L1-trigger data) through high-speed, radiation-hard optical links which can sustain a bandwidth of up to 10 Gb/s. This means that data from all individual crystals will be available to be used at L1-trigger level, largely improving the granularity with respect to the legacy calorimeter, where the information going to the L1-trigger is the energy of a 5×5 crystal tower. A back-end barrel calorimeter processor (BCP), housing two powerful FPGAs, will buffer and decompress the incoming data, ship data to the data-acquisition system, apply calibration, process data to form the trigger primitives, perform signal shape analysis to suppress anomalous "spikes". One ECAL barrel tower of crystals

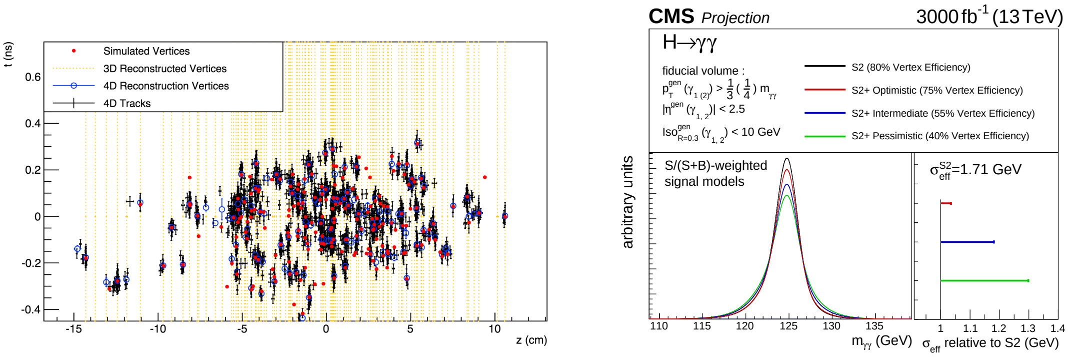

Figure 4: (left) Proton-proton interaction vertices: time versus longitudinal coordinate. The time information is essential to distinguish vertices spread along the beam axis. (right): $H \to \gamma\gamma$ mass resolution under different vertex efficiency scenarios. The 80% efficiency is what has been achieved in Phase-I; 40% efficiency is what is expected for Phase-II if no timing information is provided; the other two cases include different degrees of precision timing.

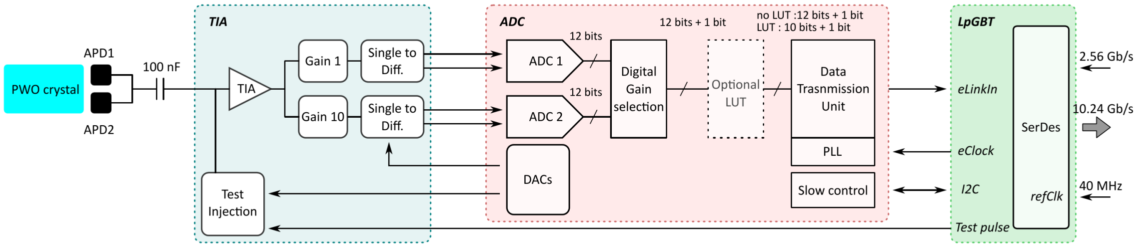

Figure 5: Detailed block diagram picturing the full read-out chain, from the crystal towards the back-end electronics.

equipped with the first TIA prototype, followed (for the time being) by a commercial 160 MHz ADC and an ad-hoc transmission unit card, has been tested in 2018 in a very pure electron beam in the energy range 25 GeV to 250 GeV, at $18^\circ C$. A pion beam has also been used to trigger spikes in the APD and study the TIA response, as already shown in Fig. 3. Figure 6 (left) shows that the result obtained matches the legacy energy resolution: less than 1% for electrons above 100 GeV. The right plot shows the result for the time resolution, which meets the requirements, i.e. less than 30 ps for energies above 50 GeV.

3. Summary

The future HL–LHC phase will impose challenging requirements for the ECAL barrel: a longer data pipeline and larger bandwidth; a more powerful filter at trigger level against anomalous spike signals; mitigation of increased APD noise as well as precision timing for primary vertex determination and pileup energy subtraction. The accomplishment of all these goals will require the design and replacement of the VFE and FE electronics as well as of new powerful off-detector boards for processing high bandwidth and granularity data. Further reduction of the cooling tem-

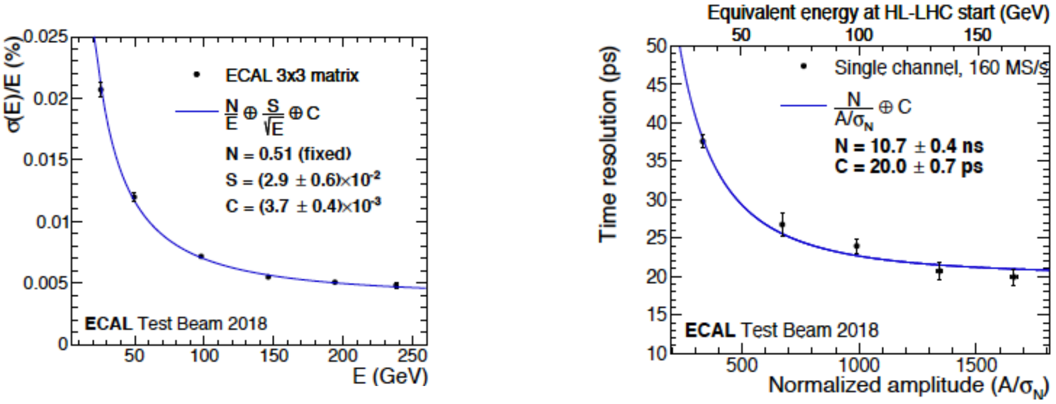

Figure 6: Results from 2018 test beam: 25 crystals equipped with a TIA prototype and commercial ADC. (left) Energy resolution; (right) time resolution. On the x-axis the amplitude is normalized to the noise.

perature will mitigate the increase of the APD noise. The ECAL barrel will hence undergo a full refurbishment and recommissioning during the LHC third long shutdown in the years 2024-2025.

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