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Upgrade of the CMS Barrel Electromagnetic Calorimeter for the LHC Phase-2

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Abstract. The Phase-2 High-Luminosity upgrade of the LHC (HL-LHC) at CERN will provide from 2029 onwards an unprecedented instantaneous and integrated luminosity of around $5 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}$ and $3000\,\text{fb}^{-1}$, respectively. Particular challenges at the HL-LHC are the harsh radiation environment, the increasing data rates, and the extreme level of pileup events, with up to 200 simultaneous proton-proton collisions expected. In the barrel region of the CMS electromagnetic calorimeter (ECAL), the lead tungstate crystals and avalanche photo-diodes (APDs) will continue to function and meet the Phase-2 requirements, while the readout and trigger electronics need to be replaced. The upgraded on-detector readout will use new, faster analog electronics and an increased pulse sampling rate to provide better time resolution, which will improve pileup mitigation and the rejection of large unwanted signals in the APDs, termed spikes. This paper provides an overview of the scope of the ECAL barrel upgrade, describes the current status, and highlights the key results from the latest integration tests.

1 Introduction

The CMS electromagnetic calorimeter (ECAL) consists of 75848 lead tungstate ($PbWO_4$) scintillating crystals, arranged in a barrel (EB) and two endcaps (EEs), and a silicon preshower [1]. It serves a crucial role in the successful CMS physics program with precise energy and time measurements of electromagnetic particles from high-energy collisions of the LHC at CERN [2].

In 2029, the LHC will start its High-Luminosity (HL) Phase-2 era, providing an instantaneous luminosity of $5 \cdot 10^{34}\text{cm}^{-2}\text{s}^{-1}$ with an average of 140-200 simultaneous collisions (pileup) to deliver to the experiments a total integrated luminosity of $3000\,\text{fb}^{-1}$ [3].

ECAL must be upgraded to maintain its current performance until the end of LHC Phase-2 [4]. New trigger requirements must be met, with an increase in the Level-1 trigger rate, from 100 kHz to 750 kHz, latency, from 4 µs to 12.5 µs, and granularity, from 5×5 array to single-crystal information. Moreover, to improve the event reconstruction and the robustness against pileup, CMS will use time information per particle with a 30 ps precision, compared to the current ECAL time resolution of $O(150\,\text{ps})$[5]. As shown by simulations [6], combining the time information for electrons, photons, and charged hadrons will allow CMS to fully exploit the higher luminosity to precisely test the Higgs sector and widen the search for new physics. For example, the ECAL will contribute significantly in the study of the diHiggs production, since one of the most sensitive channels is the one where one Higgs decays into a pair of photons and the other into a $b\bar{b}$ pair [4].

The endcaps of the CMS electromagnetic and hadronic calorimeters will be replaced by the new High Granularity Calorimeter detector [7]. For the ECAL barrel, a new readout electronics have been designed and its block-scheme is reported in Figure 1.

2 Longevity of legacy components

The crystals, their avalanche photo-diodes (APDs), and the motherboards will be retained from the legacy readout. Multiple ageing studies have been conducted to ensure that the performance of these components will remain adequate until the end of the Phase-2 operations.

Radiation damage does not change the crystal scintillation mechanism but reduces the transparency by creating scattering colour centers. The evolution of the light output can be parameterized thanks to data collected at recent beam test campaigns [8]. At the end of LHC Phase-2, the constant term of the ECAL energy resolution, the one dominating at higher energies, is expected to increase to approximately 1-1.5% depending on the pseudorapidity η, compared to $< 0.5\%$ measured before LHC collisions at beam tests with not-irradiated crystals and without material upfront [9]. The ECAL energy resolution will still be compatible with the physics requirements, and the EB crystals will thus be maintained.

The APDs will continue to function until the end of HL-LHC, but hadron irradiation will induce damage in the silicon bulk increasing their dark current. To mitigate this effect, the EB will be operated at 9 °C, compared to the current 18 °C. As shown in Figure 2 for $|\eta| = 1.45$, basically the largest pseudorapidity coverage of EB and thus the most exposed area to irradiation, by running at 9 °C the

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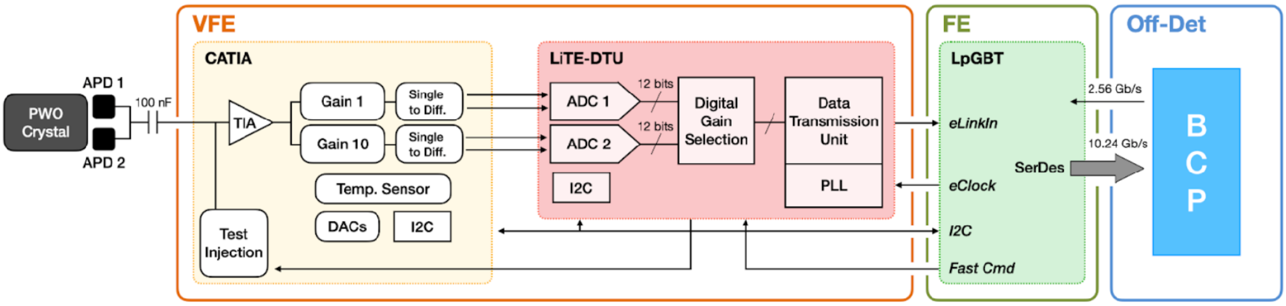

Figure 1. Scheme of the EB upgraded readout electronics for HL-LHC.

dark current will be halved at 3000 fb^{-1}. A similar reduction is expected at $|\eta| = 0$, with a final dark current level of around 70 µA.

The longevity and reliability of the motherboards have been assessed through ageing tests with thermal cycling, which confirmed their operativeness until the end of HL-LHC.

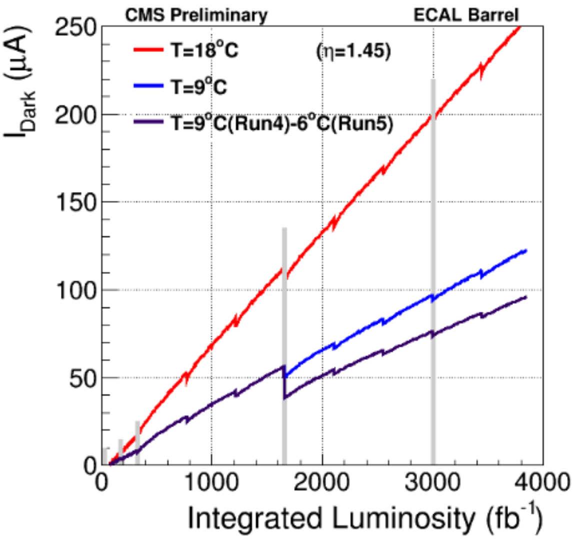

Figure 2. APD dark current evolution at $|\eta| = 1.45$ for the current temperature of 18 °C (red), the HL-LHC temperature of 9 °C (blue) and a mixed scenario with a further decrease to 6 °C (purple) [4]. The last scenario would require more complex operations to the cooling system and is still under evaluation.

3 Front-end ASICs

Two new ASICs have been designed for the Front-end (FE) electronics. The APDs signals from each crystal will be read by the Calorimeter Trans-Impedance Amplifier (CATIA) [10] and the Lisbon Turin ECAL - Data Transmission Unit (Lite-DTU) [11].

The CATIA ASIC is a dual-gain (×1 and ×10) trans-impedance differential amplifier designed in a CMOS 130 nm technology. The APDs signals are converted into a voltage signal in an equivalent energy scale between approximately 100 MeV and 2 TeV, limited on the lower side by the intrinsic noise of the APDs. Extensive studies have been conducted to determine the architecture to replace the charge-sensitive amplifier of the legacy readout in order to mitigate the increasing noise and meet the Phase-2 physics requirements, with the trans-impedance amplifier identified as the best one. The signal shaping is reduced from the current 70 ns to 20 ns, providing better noise filtering. The first CATIA prototypes have been tested with laser light and beam test campaigns with commercial ADCs, successfully showing that the design objectives have been met and that the components are radiation-resistant.

The CATIA signals are digitized by two 12-bit ADCs (ADESTO) sampling at 160 MSs^{-1}, compared to the 40 MSs^{-1} of the legacy readout. The sampling frequency has been decided to optimize the time resolution. The two ADCs are mounted on the LiTE-DTU chip, designed in a radiation tolerant CMOS 65 nm technology. A data control and transmission unit selects then the highest not saturated channel and performs a lossless data compression to reduce the output bandwidth to a single 1.28 Gbit s^{-1} serial link. The extensive tests performed on the ASIC prototypes in the laboratory and beam tests showed fully adequate performance and radiation tolerance.

The design of the ASICs is now completed and the pre-production batch of the final version is currently under evaluation.

4 Front-end boards

The new Very Front-end (VFE) board will house five readout channels, similar to the legacy readout, each composed, for the upgraded readout, of a CATIA and a LiTE-DTU. The VFE board will be connected to the motherboard and will carry the crystal signals, the APDs temperature sensor measurement, and two different power supplies for the two ASICs. A total of 12240 boards are needed to read all the crystals of the EB. A picture of a prototype of the board is shown in Figure 3.

The upgraded FE board will still serve five VFE boards, thus maintaining the legacy 5 × 5 crystal array structure, called readout unit (RU). The RU data will be transmitted by 25 e-links at 1.28 Gbit s^{-1} and they will be handled by four Cern custom gigabit tranceivers (lpGBT) mounted in a single FE board. The information will be sent to the off-detector system via four 10.24 Gbit s^{-1} op-

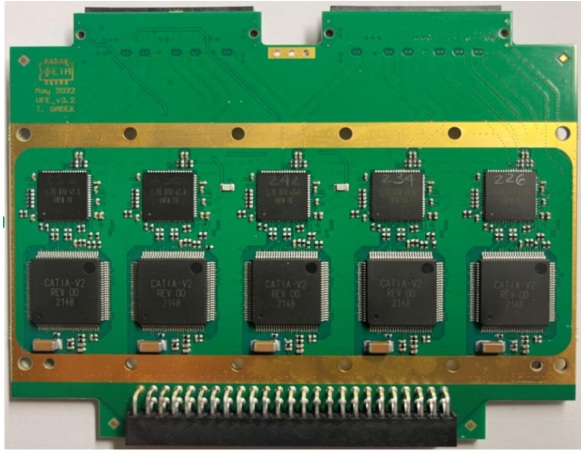

Figure 3. Prototype of the upgraded VFE board housing five CATIA (bottom) and LiTE-DTU (top) ASICs.

tical links. The FE board will also be responsible to distribute the clock and the control signals to the FE ASICs. A total of 2448 boards are required to cover EB.

The new Switch Low Voltage Regulator (SLVR) will distribute the power to the RU. It will house new CERN radiation-hard DC-DC converters developed for LHC experiment to supply the required voltage to the VFE ASICs and the FE board [12]. The power consumption is expected to be halved compared to the legacy readout.

The design of the FE boards is near completion, and the functionalities and radiation-hardness of the prototypes have been successfully tested.

5 Off-detector system

The off-detector electronics consists of the new Barrel Calorimeter Processor (BCP) board. It will be located in the CMS service cavern, thus not requiring a radiation-tolerant design. Each board will handle 600 channels, with a total of 108 units required. The board will also serve the Hadron Calorimeter off-detector readout.

The BCP is a custom-designed Advanced Telecommunications Computing Architecture (ATCA) board embedded with a large Xilinx Virtex Ultrascale Plus VU13P FPGA. It is controlled via a Xilinx ZYNC FPGA mezzanine running Linux.

The board will receive the crystal data, convert the digitized pulse into transverse energy, perform local clustering, form the trigger primitives (TPs), reject the "spikes", and provide the FE with the clock and the control signals.

Spikes are signals generated by hadrons hitting the APDs, which, after ionization, generate a signal that can exceed, in an energy scale, hundreds of GeV and thus mimic interesting signatures. Their rate is proportional to the luminosity. If not rejected, they would saturate the trigger. The spikes are characterized by a faster raising time than the scintillation signal, with this difference being more distinguishable with the faster upgraded electronics.

Each TP contains the position, the transverse energy, and the time measured with a linearized multifit-timing algorithm. A spike flag bit is added using the differences in the pulse shapes and energy topology discrimination.

A prototype board BCP v1, shown in Figure 4, was produced with the Xilinx Kintex Ultrascale KU115 FPGA to develop the firmware and test the interface with the FE and the DAQ. This prototype was deployed in the latest large-scale beam test with a near-to-final version of the FE ASICs. Preliminary results demonstrate that the 30 ps time resolution is achieved for particles with typical energies of the photons from Higgs boson decays.

The firmware and the layout of the BCP final version v2 board are being finalized.

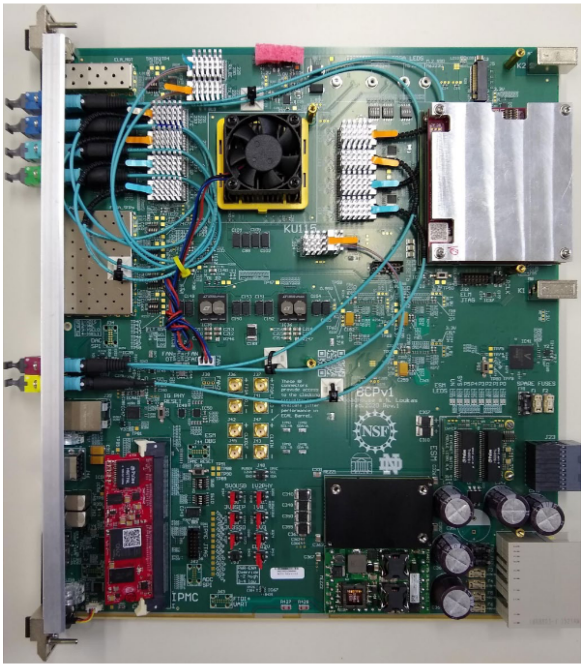

Figure 4. Prototype of the off-detector board BCP v1 equipped with a Xilinx Kintex Ultrascale KU115 FPGA.

6 Laser monitoring system

A laser monitoring system constantly monitors the ECAL crystal transparency changes using PN diodes as a reference. Corrections at the trigger level are uploaded at every LHC fill. The current electronics is not compatible with the HL-LHC conditions and the system must therefore be upgraded.

The number of PN diodes will be doubled to 864 to increase the redundancy. They will be hosted in the HL-Front End Module (FEM) (422 units), and their signal will be pre-amplified by the new MONACAL ASIC built in a CMOS 130 nm technology. The 26 HL - Monitoring Electronics readout Module (MEM) will receive the analog signals from the FEMs, digitize them with the LiTE-DTU sampling at 80 MSs^{-1}, and send the data to the off-detector electronics through standard FE boards. The interface with the trigger and DAQ will be managed by the single new Laser Monitoring Board employing a commercial FPGA.

The first prototypes of the upgraded laser monitoring components are fully operational and compliant with the requirements, while their placement and cabling are being finalized.

7 Enfourneur

During the Long Shut Down 3, the period between the end of Run 3 and the start of HL-LHC, all the 36 supermodules of the EB, weighing about 3 tons each, must be extracted, refurbished with the new electronics and inserted again in less than a year.

Two machines will be used, the Enfourneur E1 and E2, operating one per each CMS side. E1 was designed for the original EB installation. It was upgraded to comply with the current safety norms, but it was necessary to build a new machine to meet the logistic requirements and complete the project in time. The new E2 machine, depicted in Figure 5, will be installed in an area only accessible through narrow shafts and tunnels. The original hydraulic functionality has been replaced by electrically driven controls and motors, improving the safety and simplifying the procedures [13]. Its construction has been completed, and it is now under commission.

Figure 5. ECAL new supermodules extraction and insertion tool Enfourneur E2.

8 Conclusions

The CMS barrel electromagnetic calorimeter will undergo an upgrade for the High-Luminosity Phase-2 of the LHC to meet the trigger requirements, maintain the current energy performance and improve the timing precision. The crystals and APDs will be retained but operated at 9 °C. The on-detector and off-detector electronics has been completely redesigned, also improving the robustness against pileup and spikes. Preliminary tests with a near-to-final version of the upgraded readout components show that the Phase-2 targets are met.

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