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Phase-II Upgrade of the CMS Electromagnetic Calorimeter Detector Control and Safety Systems for the High Luminosity Large Hadron Collider

Raul Jimenez Estupinan for the CMS Collaboration

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PHASE-II UPGRADE OF THE CMS ELECTROMAGNETIC CALORIMETER DETECTOR CONTROL AND SAFETY SYSTEMS FOR THE HIGH LUMINOSITY LARGE HADRON COLLIDER

R. Jiménez Estupiñán†, G. Dissertori, L. Djambazov, N. Härringer, W. Lustermann, K. Stachon,
ETH Zurich, Zürich, Switzerland
L. Cokic*, CERN, Geneva, Switzerland
P. Adzic, D. Jovanovic, M. Mijic, P. Milenovic, University of Belgrade, Serbia
On behalf of the CMS Collaboration

Abstract

The Electromagnetic Calorimeter (ECAL) is a subdetector of the CMS experiment. Composed of a barrel and two endcaps, ECAL uses lead tungstate scintillating crystals to measure the energy of electrons and photons produced in high-energy collisions at the Large Hadron Collider (LHC). The LHC will undergo a major upgrade during the 2026-2029 period to build the High-Luminosity LHC (HL-LHC). The HL-LHC will allow for physics measurements with one order of magnitude larger luminosity during its Phase-2 operation. The higher luminosity implies a dramatic change of the environmental conditions for the detectors, which will also undergo a significant upgrade. The endcaps will be decommissioned and replaced with a new detector. The barrel will be upgraded with new front-end electronics. A Sniffer system will be installed to analyse the airflow from within the detector. New high voltage and water-cooled, radiation tolerant low voltage power supplies are under development. The ECAL barrel safety system will replace the existing one and the precision temperature monitoring system will be redesigned. From the controls point of view, the final barrel calorimeter will practically be a new detector. The large modification of the underlying hardware and software components will have a considerable impact in the architecture of the detector control system (DCS). In this document the upgrade plans and the preliminary design of the ECAL DCS to ensure reliable and efficient operation during the Phase-2 period are summarized.

INTRODUCTION

The control systems of the CMS ECAL detector were designed [1] before the first LHC collisions in 2009. It has been maintained throughout more than 15 years of operation. During this time, multiple components have been updated or replaced by more modern ones to extend the systems lifetime across multiple data-taking periods. However, many of these components will become obsolete by the next long shutdown. Hence, the importance of evaluating and anticipating the necessary hardware and software updates. In addition to this, two major detector partitions will be decommissioned during the next long shutdown: the ECAL endcaps (EE) and the preshowers (ES). The HL-LHC will increase its luminosity by an order of magnitude, entailing an increasing level of radiation in the experimental area. To extend the lifetime of the ECAL crystals, the remaining ECAL barrel calorimeter (EB) will be cooled down from a nominal temperature of 18ºC to 9ºC. The EB supermodules will be extracted to install new front-end electronics, also bringing the opportunity to prepare them from the controls point of view. These modifications, detailed in the Technical Design Report of the CMS Barrel Calorimeters [2], will have a considerable impact on the DCS architecture. The work has been organised in 5 different projects as follows:

1. The ECAL Barrel Safety System.
2. Controls for the low voltage (LV) power.
3. Software for the high voltage (HV) power.
4. The ECAL precision temperature monitoring.
5. The Phase-2 supervisory system.

ECAL BARREL SAFETY SYSTEM

The CMS safety systems consist of multiple interconnected components, designed to detect and mitigate potential hazards within the experiment. They form a network of Programmable Logic Controllers (PLCs), serving as the backbone of the safety infrastructure. The ECAL Safety System (ESS) is one of these components, crucial in providing safety to the ECAL detector. The design of the ESS is being currently revamped to address the requirements of the future EB, after which it will be referred as the "ECAL Barrel Safety System" (EBSS). The EBSS will be responsible for safeguarding the detector by monitoring environmental conditions and interacting with a range of devices through its interlock system. The EBSS will be built strictly with industrial components, using the latest generation of Siemens equipment, and programmed with the CMS PLC software framework. The new design includes several improvements based on the accumulated experience of more than 15 years of operations and will serve as a reference for other detectors' safety system. The most distinctive features of this system are:

- Single Siemens S7-1500 series CPU design with distributed I/O modules on a PROFINET [3] ring, ensuring high reliability and availability.
- Redundant capabilities at the level of the sensors, cable pathways and connectors.

† jraul@phys.ethz.ch
* Previously at the University of Belgrade, Serbia.

- Temperature monitoring with 288 platinum based (PT1000) sensors, across 36 analog input modules.
- Up to 256 digital I/O signals, across 8 high-end digital modules with extensive diagnostic information.

CONTROLS FOR THE LV POWER

A new type of power supply is being developed to provide extra-low-voltage power to the future EB and three more detectors. Engineers from ETH Zürich are leading this development together with W-IE-NE-R Power Electronics [4], a global manufacturer of high-performance power supply systems. The new water-cooled power supplies are modular and compact and will be mounted in a 10-slots chassis. The power density of the racks will increase, as well as the number of units needed to power up the supermodules. With the number of power supplies set to double, the ECAL DCS team will be responsible for designing the racks layout, the underlying network architecture, the interlock system, and various layers of the control software.

Fieldbus control

The power supplies will be installed in the experimental area, in proximity to the detector, and the controls either in the service area or in the surface area. Due to this arrangement, a specific network architecture needs to be designed. We can differentiate two sections: 1) The ethernet network, and 2) the fieldbus network. The fieldbus network will connect the power supplies using Controller Area Network (CAN) buses from the experimental area to the service area. CAN buses will transmit data using a fault-tolerant version of the CAN protocol characterized by a limited number of nodes and a deliberately slow data transmission rate. The network will span across 12 buses over approximately 100m cables, each of them containing the order of 20 nodes. The chassis of the power supply provides a section of the CAN bus, setting the maximum number of nodes per bus (multiples of 10). Buses will be linked to a CAN bus interface sitting in the service area, accessible by any of the control machines over ethernet. A new generation of CAN bus interfaces is currently under evaluation.

Control software

The future EB detector requires 216 of these power supplies. Managing such large network of devices and making it work as single entity requires a robust and scalable software framework. To meet these demands, three software components are needed. Firstly, we need a software to provide access to the CAN bus network, abstraction from the hardware, and a centralised point of information. This component will be a version of the OPC UA [5] server, which is the standard software interface for data exchange in industrial automation. Secondly, the power supplies need to be modelled and integrated into the CERN JCOP framework [6]. A new device definition will be created, featuring the specific characteristics of this power supply. This software will be available to all the users, offering basic functionality to configure the new power supplies. Ultimately, a specific application will be created to control the LV power distribution of the EB. This last component will implement high-level features to operate the LV power of the detector, in combination with the rest of the systems.

SOFTWARE FOR THE HV POWER

A new model of HV power supply is also underway in collaboration with CAEN SpA [7], a leading company in the field of High/Low voltage power supply systems for nuclear and particle physics. The existing EB HV system is composed of 144 modular power supply boards, inserted across 18 different mainframes. The new model will partly replace the existing A1520PE. This new board presents similar features, with larger maximum voltage and current values. Every mainframe will accommodate 8 of these boards of either type, sufficient to provide HV power to two distinct submodules. The plans for the upgrade consist of incrementally install new boards, replacing up to 50% of the existing units by the end of the next long shutdown. One of the prototypes was tested, and the results indicated that the existing SY4527 mainframes are in principle compatible with the new boards. This means that software modifications will be relatively minor. Currently, this project foresees the following activities: 1) Further testing of the prototypes, 2) Software integration into the CERN JCOP framework, and 3) Design and implementation of a high-level application to control the HV system of the future EB.

ECAL PRECISION TEMPERATURE MONITORING

The temperature inside the ECAL must be monitored and kept within 0.05°C around the cooling temperature to maintain the scintillating crystals response and hence the corresponding energy resolution. The ECAL Precision Temperature Monitoring System (PTM) is a high precision and high accurate temperature monitoring system that helps maintain the thermal stability of the detector. The system employs 100K61A negative temperature coefficient (NTC) thermistors and embedded local monitoring boards (ELMB), a general-purpose plug-on I/O electronic component developed at CERN. Its readout units are installed in the experimental area. Sensors are connected using two wires method and the inaccuracies due to the wire resistance are mitigated using complex calibration procedures. During the decommissioning of the EE, numerous thermistors will be removed, while the other 360 will remain in the EB. Every supermodule is equipped with 10 thermistors organised as follows: 4 thermistors at the grid, 4 at the thermal screen, and 2 more at the in-flow and out-flow cooling water pipes. NTC thermistors change their resistance in response to changes in temperature. To improve the accuracy, the existing readout unit uses stable current sources instead of voltage sources, along with multiple other electronic components. These components will become soon obsolete, forcing a replacement of the readout units during the next long shutdown.

As we prepare to replace the system, we will incorporate various improvements to simplify the design and facilitate its maintenance. One of these improvements is the relocation of the readout units. Regardless of the specific type of system, the sensors readout will be moved to the service area, granting us flexibility to access it at any time, whether it's for addressing hardware issues or conducting maintenance tasks. Consequently, the interface cables will be extended about 80 meters, from the detector to the service area. To compensate for the resistance added over a long-distance cable, sensors will connect to the units using a four wires method. Various types of readout units are under consideration. One possibility is to develop a system, using an upgraded version of the monitoring boards (ELMB2). This would require the creation of multiple hardware components, a new mechanical design, and extensive testing and calibration procedures. A second, more straightforward option includes the use of industrial off-the-shelf equipment. This option offers several advantages such as vendors long term support, pre-calibrated systems, and shorter development timelines. The preferred candidate is a data acquisition system from Keithley [8], a manufacturer of high-performance monitoring instruments. Figure 1 compares the Keithley DAQ6510 to an equivalent ELMB2-based system, measuring 125kΩ, 250kΩ and 357kΩ resistors from three identical boards.

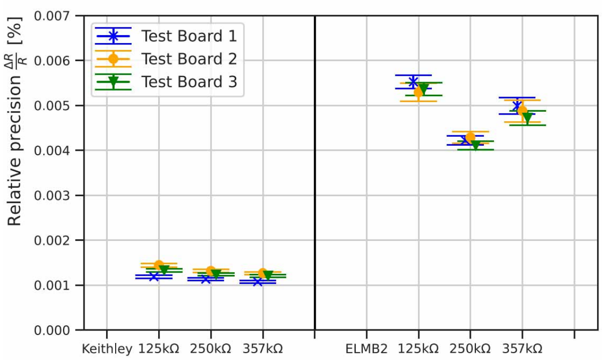

Figure 1: Relative resistance precision comparison.

For the 250kOhm resistor, which is close to the target ECAL temperature of 9°C, we achieved a relative precision performance of 13.00 ± 0.30 ppm. Figure 2 shows the temperatures and precision for one randomly chosen datapoint of the 250kΩ resistor measurements, with error bars indicating the sample standard deviation. We find a per-point temperature precision of T(250kΩ) = 5.82 ± 0.02°C for the Keithley and T(250kΩ) = 5.83 ± 0.07°C for the ELMB2.

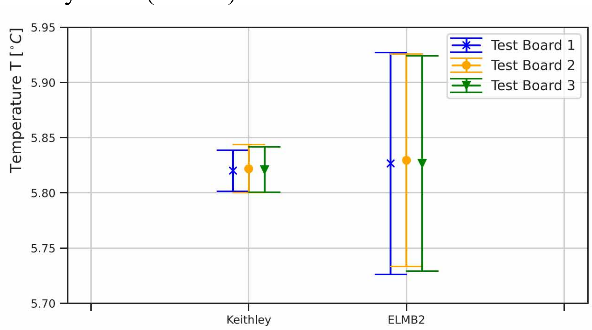

Figure 2: Temperatures for 250kΩ resistor measurements.

In conclusion, the setup with the Keithley DAQ6510 system achieved a higher precision than the ELMB2.While not the primary reason, this improved precision is also a compelling argument in favor of the Keithley devices.

PHASE-2 SUPERVISORY SYSTEM

The decommissioning of the EE and ES, and the upgrade of the EB will translate into major modifications of the supervisory system. The supervisory system, commonly referred to as the "ECAL DCS", is a supervisory control and data acquisition system (SCADA), running on 3 redundant and distributed computing servers. The supervisory system features a modular software architecture, based on the SIMATIC WinCCOA [9] proprietary platform. The software architecture is composed of 68 components, of which 26 are specific ECAL applications. Each component provides functionality for a certain area of the detector. The upcoming hardware modifications requires a thorough revision of this architecture. After an initial analysis, we foresee that 14 software components will be deprecated, 6 will be reutilised, and 6 will be redesigned as the underlying hardware will be different.

The Finite State Machine

The JCOP framework allows us to model the behaviour of the detectors as objects and to create a finite state machine (FSM). The FSM permits to abstract from the hardware, group multiple devices and operate the detector as a single entity. One of the functions of the ECAL FSM is to preserve the consistency across the powering systems. To protect the ECAL electronics, the LV power must be present before powering the HV. This sequence is reversed when powering off the detector. Following this schema, the ECAL FSM implements a set of preventive automatic actions to protect the detector. Information from multiple sources (e.g., power supplies, cooling, or temperatures) is combined to determine whether a certain partition must be powered off. This mechanism permits the early detection of issues before they escalate to the safety system. The automatic actions have a granularity of one supermodule, due to intrinsic limitations imposed by the hardware. The ECAL electronics are grouped in units known as trigger towers (TTs). A supermodule is composed of 68 TTs across 4 modules, which are powered by 34 HV channels and 17 LV channels from 3 different power supplies. Unlike the HV channels, the LV channels cannot be individually controlled. This means that each LV power supply is the smallest controllable entity within the supermodule. In addition to this, the arrangement of LV and HV channels complicates the implementation of a finer granularity. The upcoming version of the LV power supply has 12 independent channels per board. With 6 boards per supermodule, each channel will provide LV power to a single TT. This arrangement will allow us to differentiate 35 independent regions. A proof of concept was developed and tested during the test beam operations in 2023. The prototype implemented groups of 4 TTs, forming what we refer to as "power groups". Thanks to this new feature, a LV channel failure would cause the shutdown of 2 HV channels, as opposed to a complete supermodule. This feature will provide more flexibility in future operations, reduce significantly the area impacted by an automatic action and therefore increase the overall efficiency of the detector.

PHASE-2 UPGRADE ACTIVITES

The ECAL DCS projects are part of a larger scope, which includes major modifications within the detectors and the facility itself. Therefore, our project schedule must be aligned with what it is called the CMS master schedule. The master schedule serves as a global timetable, depicturing important operations during the upgrade. The purpose of the master schedule is to anticipate tasks and to ensure an effective, safe, and timely execution of activities. From this schedule we can differentiate various important periods: the decommissioning of hardware, the refurbishment of ECAL Barrel supermodules, the installation of services in the CMS cavern, and the commissioning of the detector. The master schedule serves as a baseline to organise our schedule, but at the same time it is subject to modifications as we progress. With more than 480 interdependent activities, the scale and complexity of the works constitute a challenge, and the effective managements of the projects become crucial.

The ECAL DCS team is formed by 4 members with diverse profiles and levels of participation. Each member is dedicated to specific domains according to our respective areas of expertise, enhancing the overall quality of the projects. Our projects are subject to certain activities listed in the master schedule and influenced by external factors such as the lead delivery times of components. To help manage this complexity, we have made a retro planning of activities anchoring our projects to one of the most important upgrade milestones, the construction of the ECAL integration stand. Operations in the ECAL integration stand will start in autumn 2026, when the systems must be ready to support the operation of up to one-fourth of the detector. The construction of the integration stand is set to start a year before the refurbishment, leaving approximately two years for projects development. This planning will help us ensure that resources are effectively allocated, while prioritizing tasks to meet the project's objectives. In Fig. 3, we can find an overview of the preliminary project schedule.

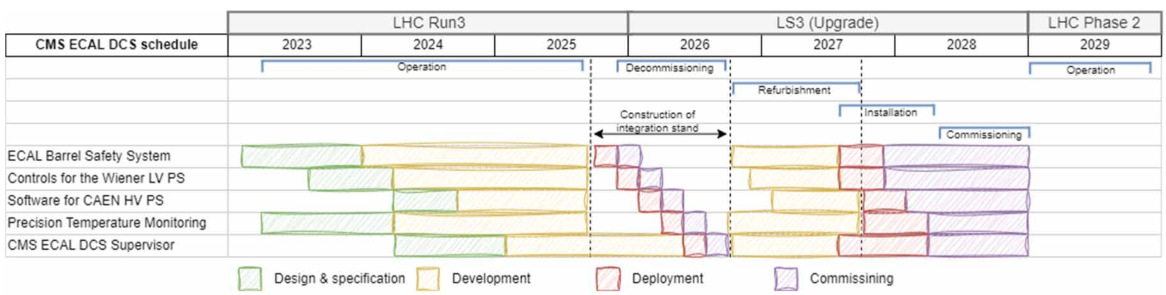

Figure 3: Overview of the preliminary project schedule for the Phase-2 upgrade.

Decommissioning

A significant amount of hardware will be no longer used or rendered obsolete after the upgrade. Table 1 summarises the expected hardware modifications, expressed in number of units to decommission or install. The ECAL DCS team will participate in the decommissioning of the safety systems, monitoring systems, and other related hardware. A plan has been prepared, including a detailed inventory of the racks, specific hardware properties, and the precise locations of each unit.

Table 1: Forthcoming Hardware Modifications

Area	System	Decom.	Install
EB	LV power supply	108	216
EB	HV power supply	72	72
EE	LV power supply	28	-
EE	HV power supply	4	-
ES	LV power supply	60	-
ES	HV power supply	32	-
EE/EB	CAN applications	2	1
EE/EB	PTM readout unit	2	9
EE/EB/ES	Safety system	3	1
EE/EB/ES	Others	9	-

Refurbishment of the ECAL Barrel

The ECAL supermodules will be extracted one by one, lifted to the surface, transported to the integration area, opened, and prepared to replace the new front-end electronics. After the refurbishment, each supermodule will be tested in the integration area to make sure all modifications are in place and to apply any corrections before its re-insertion.

Installation of services

Another important step is the installation of services in CMS. This period will be used not only to install the necessary equipment in racks but also the required infrastructure, such as the cooling system, interface cables, or the detector safety systems. The installation of this latter system is considered particularly important since it must be operational before any other system.

Commissioning

Following the assembly of the detector and the installation of essential services, the commissioning phase will start. This period will be used for the testing and validation of the entire system's functionality. The systems will be closely monitored, while applying any necessary corrections before starting the next physics operations.

ECAL INTEGRATION STAND

By the end of the next long shutdown, systems will be installed, tested, and commissioned. Before this, there will be a preliminary step, which is the construction of the ECAL integration stand. The integration stand is a location in the CMS surface area where the ECAL supermodules will be prepared for the upgrade. The purpose of the integration stand is to provide an adequate space for the manipulation, execution of the maintenance operations, installation of the new front-end electronics, and the commissioning of individual supermodules. The refurbishment of the supermodules will be done in sequence, with each supermodule moving through a pipeline until it reaches the testing area. The testing area will accommodate up to 9 supermodules simultaneously, providing the necessary flexibility to adapt the pipeline speed to various activities. The commissioning time for each supermodule is estimated to last approximately 4 weeks, in which a series of automated tests will be conducted. To support these activities, the ECAL DCS team will prepare the integration area with a tailored version of the EBSS. The PTM system will monitor up to 9 supermodules. Four different racks will be equipped with 54 LV power supplies, 5 HV mainframes and 36 HV boards. A computer server will install the first version of the supervisory system, connecting to all the hardware to provide monitoring and control during the tests. In summary, the ECAL integration stand will count with a representative part of each Phase-2 subsystem, and it will be the first opportunity to validate its functionality and make all subsystems work together. For that reason, the ECAL integration stand represents one of the most important milestones during the upgrade.

LESSONS LEARNED FOR PHASE-2

The ECAL DCS plays a critical role in ensuring safe and smooth operations. Our systems stand out as very valuable tools for understanding and addressing critical issues within the detector. For more than a decade, the systems have proven to be well designed, well maintained, robust and reliable. The systems have been updated several times, adapting to meet new requirements of the experiment. One of the most effective changes for improving the operations took place during the first years of the COVID-19 pandemic, when the experiment faced a shortage of shifters and operators. The travel restrictions, the lack of shifters in the region and the high reliance on experts posed a significant challenge to support the 24/7 on-call operations. To address this situation, we had to come up with a plan to change both technical and organisational aspects of the operations. The shifts organization changed from a fixed, long-term rotation of personnel to a subscription-based mechanism. This approach allowed participants to decide when and for how long they can engage in the operations. A virtual phone application was adopted, enabling operators to receive calls via the internet without the need for a local phone subscription. This tool facilitated the communication between the operators, the CMS control room, and the rest of the experts. The rules for participation were updated, allowing colleagues to contribute from their base countries. This brought the opportunity to participate from various regions, including Chile, Italy, Switzerland, Spain, or Serbia. The alarm system was thoroughly reviewed with the help of the domain experts, adding web-based instructions with high level of detail about specific issues. These tools empowered operators to respond effectively to alarms with a clear understanding of the problem. As a result, the team counts now with a pool of 15 highly autonomous operators with different levels of commitment, a well-documented alarm system and a significant reduction of expert interventions. These relatively simple, yet very effective modifications will be part of the on-call service strategy for the Phase-2 operations.

CONCLUSION

The ECAL DCS team is responsible for the controls and safety systems of the ECAL detector. Our duties include managing a 24/7 on-call service with 4 experts and 15 operators, maintaining the existing systems, and developing the new ones. To ensure a successful execution of the Phase-2 upgrade projects, we have thoroughly defined their scope, anticipated many important tasks, and prepared a comprehensive planning in alignment with the CMS master schedule. The impact of these developments will extend beyond our detector since they will serve as a reference for other control systems within CMS. The design principles, development guidelines as well as multiple components will be used by other teams. With this foundation, we are confident that our projects will be completed on schedule, preparing the ECAL detector for the Phase-2 physics period and contributing in that way to the success of the CMS experiment.

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