MOVING TONS OF FRAGILE CRYSTALS WITH CARE: THE CMS ECAL ENFOURNEUR2 PROJECT

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Abstract

The CMS experiment at the CERN Large Hadron Collider features a high-precision electromagnetic calorimeter (ECAL) made of 61,200 lead tungstate crystals in its central (barrel) part. The crystals are both heavy and fragile, requiring extreme care during handling. As part of the HL-LHC upgrade, the ECAL barrel front-end electronics will be replaced, requiring the extraction, refurbishment, and re-insertion of all 36 supermodules (SM), each weighing about 3 tons, within a strict schedule of the technical operations inside the CMS cavern during Long Shutdown 3. A specialized machine, the Enfourneur, will be used for SM extraction. To accelerate operations, a second Enfourneur has been developed, replacing hydraulic actuators with electrical motors and controls. The new system manages three movements: rotation to the insertion angle, forward-backward motion, and controlled SM push-pull. Safety of SMs handling is ensured by numerous sensors and an advanced control system. A touchpad interface provides real-time control of SMs positioning with extreme accuracy, thanks to the implementation of electric motors and related controls, and operational safety, offering to the machine operator predefined movements, fine adjustments, and a continuous monitoring of the forces applied by the machine and ongoing deformations on the most critical metallic carpentry structures. This paper details the Enfourneur2 design, commissioning and operational performance after an intensive testing campaign carried out at CERN.

INTRODUCTION

ECAL is the high-precision electromagnetic calorimeter in CMS experiment at CERN [1, 2]. Its barrel is made of 61,200 lead tungstate crystals, distributed in 36 supermodules (SM), each weighing about 3 tons. During Long Shutdown 3 (LS3), the SMs need to be extracted and re-inserted to allow the replacement of the front-end electronic as part of the HL-LHC upgrade.

The handling of the ECAL SMs requires stringent constraints imposed on the design of the extraction and insertion system [1]. The machine that handles the ECAL supermodules (called the Enfourneur) must reach millimetre-level precision in positioning of these multi-ton elements, avoid mechanical stress on the crystals and on the supporting structures, and be compatible with the confined geometry of the CMS cavern. Safety is a primary concern, both for the protection of the ECAL detector elements and for personnel. The system must provide continuous monitoring of applied forces, structural deformations and positions, and include multiple interlocks to prevent operations under unsafe conditions. In addition, reliability and ease of operation are essential, as the extraction and re-installation of the 36 SMs must be performed within a limited time window.

These requirements motivated the production of a second machine (Enfourneur2 or E2), that will help increase the flexibility and reduce the time required by the ECAL SM insertion/extraction activities. The design changes, with respect to the first machine, aim at improving precision, reducing the activity time and ensuring the highest possible level of safety - for people and objects - guaranteed by the certification of the machine in accordance with the latest regulations in force, issued by the manufacturer. E2 design and construction were entirely coordinated by INFN Roma, as a core contribution to the CMS upgrade.

ENFOURNEUR2 DESIGN

Enfourneur2 is a dedicated 20-tons handling machine designed to interface directly with the ECAL barrel SMs (Fig. 1). It will be placed in front of the CMS detector allowing operators to access the internal layer of the ECAL barrel. It consists of four main mechanical subsystems, derived from the geometry of the Enfourneur1 but individually optimized to meet the requirements of the new machine [3]: Bati, Cradle, Cage and Yellow Beam (Fig. 2).

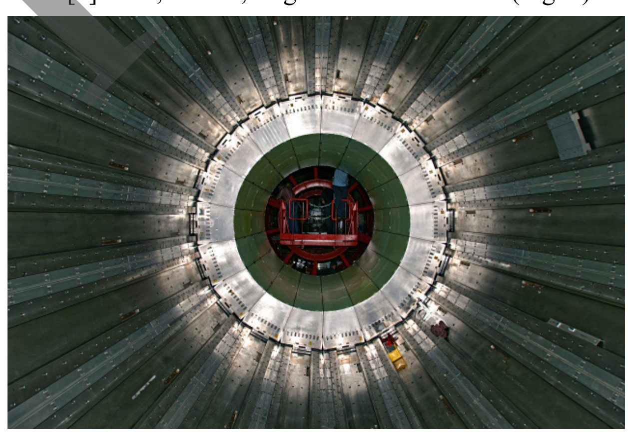

Figure 1: one side along the beam axis of ECAL barrel SMs installed in 2007.

The Bati is the metal carpentry structure that supports the other components during the operations, offers walkways and harnesses connections to allow operators to safely work on the machine, also at height, allows first level of adjustment system to ensure the correct alignment of the machine with respect to CMS, and it provides the lifting points for the machine handling in the CMS cavern. A semi-cylindrical structure called Cradle is connected to the Bati through nuts that slide on planetary screws driven by a pair of electrical motors (Fig. 3). The translation movement of the Cradle allows the system to slide in the CMS experiment and approach the ECAL barrel, with a measured positioning repeatability of less than one millimetre, despite the overall displacement of a mass of nearly 15 tonnes. To reach all the 18 ECAL barrel sectors, the cylindrical structure called Cage is mounted on 4 radial wheels on the Cradle. It is equipped with a rack installed in the central ring (Fig. 2) and it rotates through pinions and two electrical motors on the sides. The Yellow Beam mounted on the Cage is the interface with the CMS detector that connects to the HCAL rails (which represent the physical anchorage of the electromagnetic calorimeter supermodules). The extraction/insertion of the SM is ensured by a pushing/pulling system defined by two planetary screws driven by electrical motors (Fig. 3).

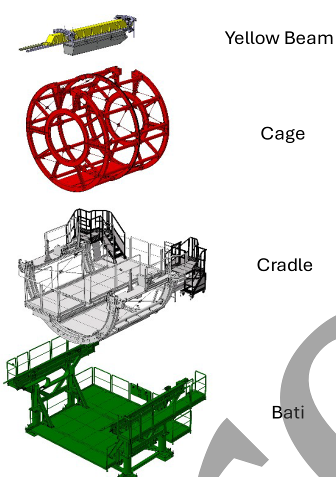

Figure 2: Exploded view of main parts of E2.

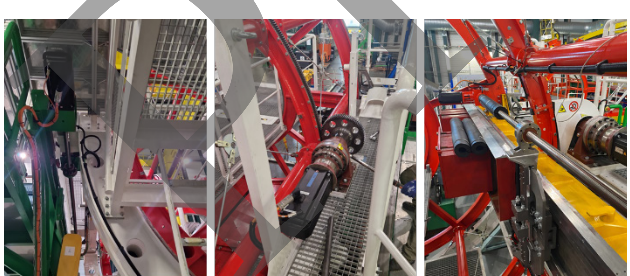

Figure 3: Cradle translation (left), Cage rotation (centre), and SM translation (right) systems.

Each E2 movement is electrically driven and controlled by a dedicated touchpad interface, developed to provide intuitive and precise control of the system (Fig. 4). The operator can select predefined motion sequences for standard operations or perform fine manual adjustments when required.

Figure 4: Touchpad interface – main page (left), translation controls (centre), sensors monitoring (right)

Moreover, Enfourneur2 is equipped with an advanced control system integrating multiple sensors for position, force and structural deformation monitoring. Load cells and displacement sensors provide continuous feedback, enabling real-time supervision of the forces applied and of the stresses on the critical mechanical components. Through this real-time information the operator maintains full situational awareness during the critical phases. In addition, the control logic implements safety interlocks and automatic stops in case of abnormal conditions, ensuring safe operation throughout all handling phases [4]. This approach significantly reduces the risk of operator error and enhances overall operational safety.

COMMISSIONING AND TESTING

Enfourneur2 has been delivered by the manufacturer partially assembled at CERN (Fig. 5), where the assembly has been performed in the surface building of the CMS site, followed by survey checks for relative alignment between the parts.

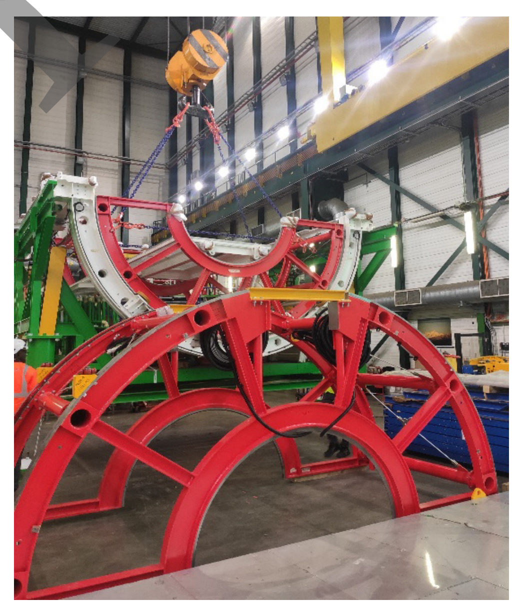

Figure 5: Enfourneur2 arrived at CERN partially assembled.

Prior to deployment in the cavern, an extensive commissioning and testing campaign has been carried out.

The goal has been to simulate full load operations of extraction and insertion scenarios, assessing the mechanical performance of the system, the accuracy and repeatability of relative movements between subcomponents, as well as the overall safety and efficiency of the operations. In parallel it has been possible to train the team of technicians who will operate the machine in real conditions.

A dedicated test setup has been used, to closely reproduce the interfaces between the machine and the actual CMS environment. The test setup (Fig. 6) includes two sliding rails for the Cradle. These are located at the side of the Bati, and they are representative of the Vacuum Tank rails inside the CMS detector, to which E2 will be anchored. The machine will slide on these rails into the detector and approach the ECAL barrel. In addition, two test structures are positioned in front of the machine to represent two of the eighteen possible positions of the HCAL rails where the SM are located. One of the two selected SM position under test is at 90 degrees. This configuration represents the most demanding operational condition, because the Enfourneur motors must cope with the maximum load capacity, due to the maximum momentum defined by the eccentric position of the SM weight.

For the test execution, an ECAL supermodule mock-up has been used. It simulates the same geometry, weight distribution, and mechanical interfaces of a real SM.

Figure 6: E2 during insertion test at 90degrees.

The commissioning process followed an iterative approach. Each critical issue or improvement identified during testing – either on specific hardware components or on the procedure - has been analysed and addressed. Following each modification, the system has been re-tested through a full set of insertion and extraction cycles to validate the effectiveness of the implemented changes and to ensure that no new issues were introduced.

The testing campaign allowed the ECAL group to improve some critical areas of the activity, both acting on some system components, increasing stiffness and reliability, and on the procedure steps, reducing risks on people, schedule and components.

After the extensive testing campaign, Enfourneur2 provides improved precision, high repeatability, enhanced safety and increased operational flexibility. The system is fully integrated into the CMS ECAL upgrade workflow and is expected to play a key role in the successful completion of the ECAL barrel refurbishment.

CONCLUSIONS

The availability of two handling systems - represented by the two Enfourneurs (the first with hydraulic actuation and the second with electric actuation) - for the extraction and insertion of ECAL supermodules during LS3 at CERN allows parallelization of the activities and offers redundancy, contributing to risk mitigation and schedule optimization.

The new machine, Enfourneur2, has been developed to work together and in parallel with Enfourneur1, with each machine focused on one side of the CMS experiment.

Enfourneur2 has arrived at CERN after an intense design and construction time [5] ready to be tested and commissioned, after an acceptance test carried out and passed at the manufacturer's facility. The testing campaign has been carried out simulating the real working conditions for the machine in the CMS cavern.

At the end of the testing campaign the system meets the stringent mechanical, safety and operational requirements imposed by the HL-LHC upgrade.

The system demonstrated stable behaviour, high positioning accuracy, high repeatability and operational reliability. The electric actuation system provides smooth and well-controlled movements, validating the design choices and confirming the readiness of Enfourneur2 for LS3 operations. Thanks to the various improvements implemented during the tests, this machine also reduces the time required to perform the same operations compared to the previous model, while requiring less personnel due to the level of automation achieved.

Following successful commissioning and testing, Enfourneur2 is ready for operational use. It is currently stored at CERN in the CMS surface site, awaiting use during the ECAL upgrade planned for the next technical shutdown.

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