THE CMS ECAL ENFOURNEUR: A GIGANTIC MACHINE WITH A SOFT TOUCH

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Abstract

The electromagnetic calorimeter (ECAL) of the CMS experiment at the LHC is composed of 75848 scintillating lead tungstate crystals arranged in a barrel section and two endcaps. The barrel part is made of 36 Supermodules (2.7 tons each) and is installed inside the CMS magnet. There are 18 SMs on each side of CMS, with each SM containing 1700 crystals. During Long Shutdown 3, all ECAL SMs must be extracted to refurbish the electronics in preparation for HL-LHC. A dedicated machine called the "Enfourneur" is used to extract and re-insert the SMs inside CMS, with a required accuracy of about 1mm. In order to speed up the extraction and insertion process, two Enfourneurs will be employed, operating in parallel on both sides. In view of the purchase of the second Enfourneur, the design has been improved, starting from the feedback of the past operations. The improvements to the new Enfourneur design include: increased space for the operators, optimization of the operations and the controls with the use of electric motors, and an updated alignment system. Handling plans inside the CMS cavern have been defined in order to be compliant with the rest of CMS structures and procedures.

THE FIRST ENFOURNEUR AND ECAL SUPERMODULES

The CMS [1] electromagnetic calorimeter (ECAL) central part is made of 61200 lead tungstate scintillating crystals, equipped with readout electronics. The crystals are arranged in Supermodules (SMs), containing each 1700 crystals. The crystals and the associated electronics are extremely fragile, but very heavy. Therefore a dedicated machine, called "Enfourneur" (French name, literally the "loader") [2] is needed to delicately and precisely position the SMs in CMS. Fig.1 shows the machine during the first installation (in 2007) inside the CMS cavern at P5 (Cessy, France).

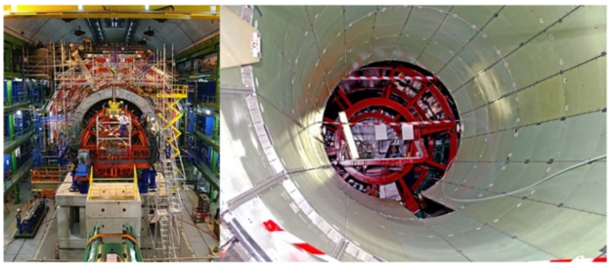

Figure 1: Enfourneur first operations and last Supermodule installation (2007)

The calorimeter geometry and SMs pattern (n.18 per side, conventionally named plus and minus side) is represented on the right of Figure 1.

The previous pictures also show the axis height from the cavern floor (about 9 m), to be aligned with the LHC beam pipe. Each SM is about 3 m long and weights about 2.7 tons. Considering dimensions, mass and position in-height the handling of these Supermodules, which are extremely fragile, plays a critical role.

Figure 2: Original Enfourneur at P5 site (Cessy, France)

The loading of the Supermodule is performed from above, via overhead crane, and a dedicated lifting interface called Yellow Beam, which precisely matches the free slot of the rotating cylindrical structure [2]. The Enfourneur is a large and heavy machine (about 7x6x5 m overall dimensions and a weight of 20 tons), hydraulically actuated and is depicted in Fig.2 in its original condition. It is able to perform 3 motions: main body axial sliding, rotation of the central cage and axial translation (with pushing or pulling force depending on whether it is insertion or removal) of the Supermodule. The machine performed successfully these operations during the first installation, and is represented in its original condition (2017) in Figure 2.

During the third Long Shutdown (LS3), currently foreseen to start in 2025, all ECAL barrel Supermodules must be extracted from CMS to replace their electronics with ones better suited for operations with high intensity beams. In order to accomplish this critical task an upgrade of the existing machine - following feedback from previous operations – and the design and construction of a new one with electrical - instead of hydraulic - actuation and a series of optimized controls to make operations simpler and faster.

The upgrade of the first Enfourneur

The current machine was the starting point of the development of the new one, in order to define the main dimensions and operation features. It has undergone a major overhaul aimed at making it more compliant with current safety standards and more suitable in terms of space available for the operators required to operate it (up to 5 people at the same time). This machine will have to be installed at a height of 8.79 m from the ground, complete with hydraulic pistons, hoses and control unit, as shown in Figure 1. Therefore, the possibility for operators to move from one point to another of the machine to access the various elements simply and quickly is fundamental for correct overall functioning. The work started in 2018; a finite element modelling and analysis - of the whole machine and of the single parts - has been performed to verify the compliance of new structures designed to applicable norms (Eurocode), calculating forces applied on all the screws (all frictional joints with preload applied), stress on the constituting beams and deformation (requested within 1 mm at cage level to not affect alignment procedures). An example of the single platform checks performed and the structural analysis of the overall machine is represented in Figure 3, with the analysis of the rear lower balcony, one of the most critical area of the machine because supporting the hydraulic control unit – point load by about 250 kg – plus 250 kg per square meter distributed load (applied on all walkways of the Enfourneur as requested by norms and CERN HSE division). Per each design change the maximum deformation, the stress in the preloaded bolts and the structure Von Mises stress were calculated and verified to be compliant with limit defined by Eurocode 3 (Fig.3).

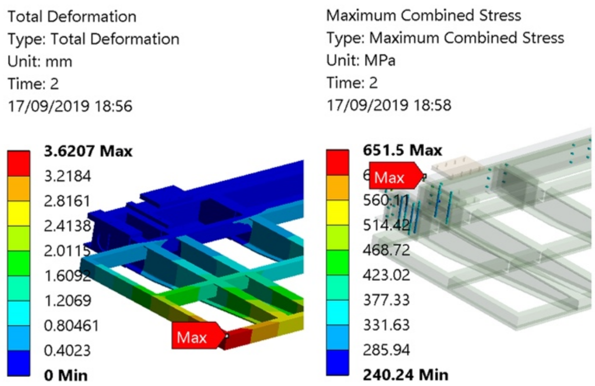

Figure 3: Maximum combined stress calculated on the screws with preload applied on the new rear low balcony (the most critical because supporting also the hydraulic control group)

The objective was rather challenging as these modifications entailed a significant increase in the surface area of the gangways and platforms for the operators, while at the same time having to comply with certain constraints including the total mass of the object (maximum 20 tons per load limit of the overhead cranes involved in the movements) and maintaining the same modularity as the original structure while still guaranteeing the full functionality of the machine. After some iterations and optimizations, the design was frozen and the changes implemented on the existing machine, introducing new platforms, new aluminium stairs (lighter) and new rigid tubing for the hydraulic controls, replacing the previous one made of flexible pipes that caused routing difficulties during the various movements. The machine at the end of upgrade (early 2021) is depicted in Fig.4.

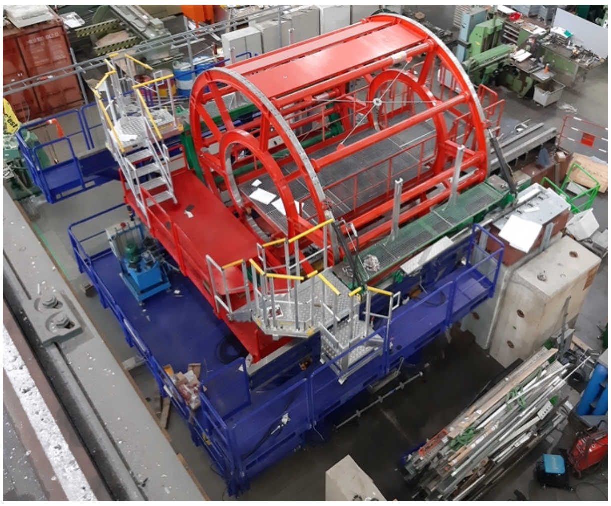

Figure 4: The first Enfourneur upgraded

Installation inside the CMS cavern (UXC)

A dedicated study was needed for the installation inside the cavern on the two opposite sides of the detector (plus side and minus side). The minus side is relatively easy to access thanks to a large shaft equipped with a large-capacity overhead crane (40 tons) to lower the Enfourneur directly into the operation area. The challenge - from an engineering point of view - was the possibility of installation in the plus side. Unlike the first installation, the plus side now can only be reached through a smaller shaft with a reduced capacity crane followed by a tunnel. All this, considering the size and mass of the Enfourneur, made it necessary to carry out a technical and logistic feasibility study aimed at verifying the possibility of disassembling the machine into its main sub-assemblies, moving them individually and transporting them through the mentioned passages (including additional structural calculations necessary due to the introduction of additional lifting points and handling configurations, with different orientation to the operational configuration). The main technical outcomes of the study were implemented in the design of the second Enfourneur. The final configuration of the systems operative on both sides of the detector is represented (CAD) in Figure 5.

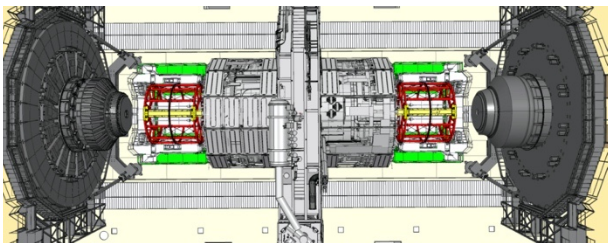

Figure 5: Enfourneurs installed at both sides of CMS

THE NEW ENFOURNEUR

Setting as design constraints the results of the design optimization and installation studies in the CMS cavern carried out on the first machine, the second Enfourneur was designed with the aim of making it more modern, simple, safe and reliable from the point of view of actuation. While maintaining all the necessary predispositions for a possible operation with traditional hydraulic drive (double-acting pistons), it was decided to implement electric motors coupled with planetary ball screws for translations and with a rack and pinion system for rotation. The advantages of this modification are many: dramatic reduction of handling times by moving from a series of manual operations to a single and continuous movement (due to their limited stroke the pistons must be continuously disassembled and reassembled), greater safety related to the leakage of oil from the pipes (with risks related to damage of experimental equipment), and greater accuracy in primary movements. In the following images the new design is represented with new electric and mechanical elements included: in Figure 6 the main body translation synchronous motors are evident on the two side beams on the rear view (darkest parts) while the top view shows the main body translation screws on the two sides, the two redundant asynchronous motors (for safety reason in the event of failure of one of the two) connected to the rack and pinion system devoted to centrale cage rotation (rack aligned with the centre of gravity of the whole machine to avoid secondary moments), and the two synchronous motors devoted to SM pushing (or pulling) inside (or outside) the CMS calorimeter main structure.

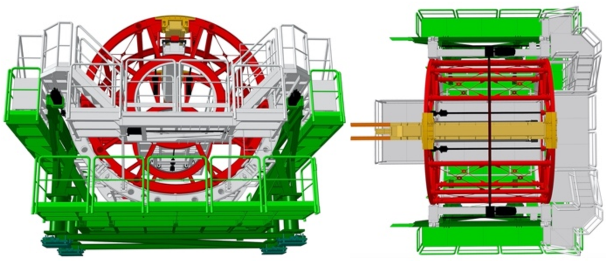

Figure 6: Rear and top view of the new Enfourneur 3D CAD model with electrical motors, translation screws and rack integrated (darkest parts)

The rack presents a removable segment to allow the insertion of the Yellow Beam with Supermodule attached, that will be lowered from the top by cavern crane at the beginning of each insertion operation. This segment will be equipped with dedicated sensors to confirm its proper installation and – in case – to prevent the rotation of the motor in case of lack or wrong installation of the segment itself directly communicating with control software.

All motions control will be possible through a dedicated touch screen panel with a software including predefined positions to be reached by the machine in order to ease and speed up as possible operations, compatibly with acceleration limits defined by Supermodule fragile components and imposed at software level.

The alignment of the machine will be instead mechanical and identical to the previous version, with some pushing screws and sliding parts systems available on the four support pedestals and at guides level, for a proper alignment of the whole machine with the detector main structure. The Supermodule will exploit instead a dedicated tuning system (more fine and accurate) installed on its handling interface - the Yellow Beam - based on leverages and toothed wheels, in order to allow a perfect alignment with the calorimeter guides and a smooth and continuous motion. All guides for mobile parts of the Enfourneur will present a surface coating able to reduce the contact friction factor.

This design was extremely challenging because the main constraints related to the overall mass and the modularity, as required by the technical installation plan, implied an important optimization of the overall structure. Compliance of stress level with Eurocode limits and with deformation limit defined by the correct functionality of the machine (+/- 1 mm at level of the rotating cage) were checked during the design phase, in order also to check the meeting of alignment requirements. Considering some relevant structural changes (in particular on the cage for the addition of the rack), a dedicated finite element analysis has been performed to check these parameters. The design converged to acceptable value after some iterations and an optimization phase.

CONCLUSIONS

The Enfourneur project, aiming to provide two machines working in parallel, has achieved its goals with the improvement of the existing machine (to be completed by 2021) and the definition of the project for the second one (the construction work will start by the first half of 2021). The two machines will be able to operate at both ends of the CMS detector (plus side and minus side), in accordance with available space, handling infrastructure and in total safety with respect to current safety regulations. The second Enfourneur will operate in the more complex side (plus side) exploiting the modularity imposed as a constraint of the project and in a faster and more flexible way thanks to the implementation of the electrical control of the three necessary movements. The first Enfourneur has been fully refurbished and improved making it safer and more comfortable for the staff involved.

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