The Manufacture of Modules for CMS Coil

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***Abstract*— CMS (Compact Muon Solenoid) is a general-purpose detector designed to run at the highest luminosity at the CERN Large Hadron Collider (LHC). Its distinctive features include a 4 T superconducting solenoid, composed of five modules, with a 6 m diameter by 12.5 m long free bore, enclosed inside a 10,000-ton return yoke. The construction of the five modules composing the coil was a very challenging task due to the large dimensions and weight of each module (50 t) and to the severe requirements on tolerances. This paper describes the main technical issues related to the module construction, namely the winding, the vacuum impregnation (requiring 1100 l of epoxy resin for each module), the machining operations (to get the proper tolerances on dimensions), the hydraulic circuit connections and the blank module-to-module mechanical coupling. Despite the limited number of modules, the manufacture was arranged as a series construction in a single large area. This area was subdivided in sectors for winding, impregnation, mounting and machining operations and equipped with the required large tools such as two 100 t cranes, a huge lathe and an autoclave suitable for hosting a single module enclosed in its impregnation mold.**

***Index Terms*— Al stabilized conductors, detector magnets, LHC project, winding.**

I. INTRODUCTION

THE CMS experiment (Compact Muon Solenoid) is a general-purpose, proton-proton detector designed to run at the highest luminosity of the Large Hadron Collider . CMS includes a large superconducting solenoid, able to accommodate the calorimeters, allowing precision measurements of electrons and photons, due to its 4 T magnetic field. The magnetic length is 12.5 m and the free bore is 6 m diameter [1]-[3]. The coil is composed of 5 modules each 2.5 m long and 50 t in weight.

The CMS coil was designed according to general criteria, which are based on the operating conditions of a magnet included in a large detector. The main point is that the magnetic field is static, so no heat dissipation due to ac losses can occur inside the winding, except during charge and discharge, which can be done in a sufficiently long time (order of few hours) to limit the heat dissipation at a very low level. Under this condition, the main role of the cooling system is to keep the coil at the operating temperature removing a limited heat load due to the cryostat heat losses, and the dissipation in the electrical joints and the current leads. The LHe is circulated in pipes (indirect cooling) connected to the mandrels enclosing the coil. The protection against localized disturbances is provided by the thermal stabilization (very pure aluminum) included in the conductor.

Differently from the other detector magnets, in CMS coil there is a considerable hoop stress (130 MPa caused by the high field strength). As discussed in previous papers [3], in order to limit the shear stress level inside the winding; the modules were wound with a new kind of Al-stabilised and reinforced conductor able to withstand a large fraction of the hoop stress.

The construction of a winding using a reinforced conductor has required technological developments for both the conductor and the winding. Although all problems related to the winding were faced and solved through a long preparatory activity and finally assessed with the construction of a module prototype, the construction of the five modules has never been trivial. The paper deals with the main topics related to the modules manufacture, faced as a mini-series construction to minimize the time and to obtain homogeneous components.

II. THE TOOLS

The manufacture of the CMS modules required the construction of several *ad hoc* tools. Some of them required a development activity. In this section the main tools are presented.

- *Winding Line*. This tool has been presented in previous papers [4], [5]. We recall here its main components shown in Fig.1: a) De-spooling unit, able to support the 10 ton spool containing the conductor length of 2.5 km, followed by the straightening unit, for removing the bending deformation; b) Bending unit to bend the conductor at the final radius, c) Sand-blasting unit for preparing the conductor surface, d) Taping unit for insulating the conductor with a glass tape, e) Conductor driving unit, which carries the pre-bent turn from the top to its position in the winding, f) Conductor positioning system, which deposits the conductor inside the winding. The winding lines also includes a pressing system, for axial compactation of the winding and the support structure of the components and all ancillary plants

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Fig. 1. The main main components of the Winding Line: The de-spooling system and the straightening unit (a); the bending unit (b); the sand-blasting unit (c); the taping unit (d); the conductor driving unit (e); finally the conductor positioning system (f).

- *Autoclave*. In principle, the epoxy impregnation under vacuum is not different from that used for other existing large coils. Nevertheless, the amount of resin for each module is quite large (1000 l) and coupled with the huge dimensions and the large weight of the single module pose significant technological challenges; first of all the autoclave. This tool has the role to keep the coil in an atmosphere at pressure of 1 mbar during the impregnation. The coil is heated up to a maximum temperature of 140 ^{o}C, by directly feeding the winding with a current up to 500 A. In order to avoid to generate a magnetic field during this operation, the 4 layers of the module under impregnation are connected non-inductively. Due to the large diameter of the coil (7200 mm when including the cooling pipes), the outer diameter of the autoclave had to be 7620 mm (at the closing flange). This object (an annular chamber 3000 mm in height, composed of two parts) was not transportable and was build directly on site, taking advantage of the presence there of a very large lathe, which is a further important tool, discussed later. Fig. 2 shows the autoclave during the operation of coil mounting inside it (Fig.2. a) and once closed during impregnation. (Fig.2. b)
- *Lathe*. An important aspect related to the CMS coil construction is the manufacture of the thin (50 mm) and large (7000 mm OD) Al-alloy mandrels enclosing the winding. The construction of these mandrels could have been done in a location different from the one used for the modules manufacture. Nevertheless this choice would have entailed so many constraints and difficulties (such as the need to transport the finished mandrels to the winding site, i.e. as a minimum five transportations as complex as the transportation of a single module) that it was decided to construct the mandrel in the same location as the module manufacture. This resulted in large benefits and optimization of the processes, since some tools were used both for mandrels and modules. In particular the large lathe used for machining the mandrels (Fig 3.a) was also used for removing the resin excesses from the inner surface of any finished modules (Fig. 3.b) and for a precise machining of the upper flange as preparatory work for the module-to-module mechanical coupling.

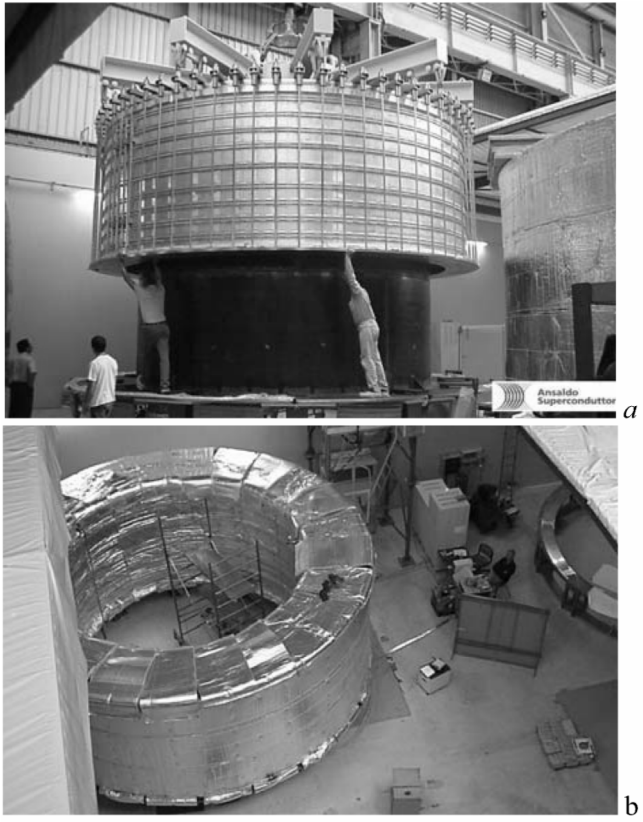

Fig. 2. The autoclave. (a). A module is mounted in the lower/inner part of the autoclave. (b) The autoclave (now closed) during the impregnation

Fig. 3 The large lathe; (a).the machining of the outer surface of a mandrel; (b) the machining of the inner surface of a finite module for removing resin excesses. This latter is a very critical operation since the proximity to the winding (1 mm ground insulation)

III THE MODULE FACTORY

When organizing the manufacture of the CMS coil, it appeared that this task had to be faced as mini-series construction since the coil is made from five almost identical modules. Furthermore, as discussed in the previous section, due to the large dimensions of the objects, in view of an optimization of construction processes, it was decided to manufacture the mandrels and modules in one location: the module factory. The objective was to have a factory where conductor lengths and materials come in and completed modules go out. To this aim a large industrial area (2200 m^2) was identified. This area was already served by 2 cranes, able to lift up to 100 t. The presence of these cranes has been of fundamental importance allowing continuous handling of mandrels and modules.

The area was subdivided in three large sectors (Fig. 4):

- An area (called the *mandrel factory* occupying 40% of the total area) was fully dedicated to mandrel construction. It was equipped with the large lathe (able to machine at a diameter of 8000 mm with high precision) and with a large welding station. The mandrels [6] are composed of bent plates and seamless rings coupled by difficult MIG welds. The welding and the mechanical operations (machining and drilling) were done in a way requiring several shifting of the mandrels between welding station and lathe. In this sector the aluminum alloy plates, the seamless rings and the pipes come in, while the almost finished mandrels go out.
- A smaller area (the *mounting and impregnation area* as large as one third of the total area) was used for the winding preparatory operations (mounting of mandrels on the rotating table), the operations related to the vacuum impregnation (preparation of the coil before the impregnation, cleaning of the coil after the impregnation), the module-to-module preliminary connection and the and finishing the modules (electrical exits, joints, sensor applications and last welding on cooling pipes). In order to perform operations in clean condition, differently from the mandrel factory, this sector was protected both at the sides with temporary walls and at the top with a movable roof.
- A third area (the *winding area*) was prepared to host the winding line. This area was temperature and humidity controlled to guarantee that the winding operation was carried out in controlled way with respect the geometrical tolerances. In fact the aluminum has a thermal expansion of 23 ppm/^{o}C at room temperature, consequently a variation of 10 ^{o}C causes a variation of 1.6 mm of the coil diameter . If the winding line has been set for a given diameter, a temperature variation can cause defects inside the winding.

IV THE SEQUENCE OF OPERATIONS

In this section the operations required for constructing a module of the CMS coil are briefly summarized. The five modules are numbered as they are placed in the coil: CB-2, CB-1, CB0, CB+1 and CB+2. The construction followed the same order to allow performing the assembly at CERN as they are finished, in parallel to the manufacture of the remaining modules.

Setting at 100% the global resources required for the construction of the five modules (in terms of time, number of needed operations, required manpower,..), the construction of a single module takes a fraction ranging from 18% for CB+2 module to 21% for CB-1 (the modules are slightly different when considering the supporting system and the cooling circuit).

The construction of a single module can be subdivided in three main parts: a) The mandrel construction, taking around 45% of resources; b) The winding (22%); c) The impregnation and the module finishing, requiring the remaining 33%. Since the winding process was described in previous papers [4], [5], we will discuss here the mandrel construction, the impregnation and the coil finishing.

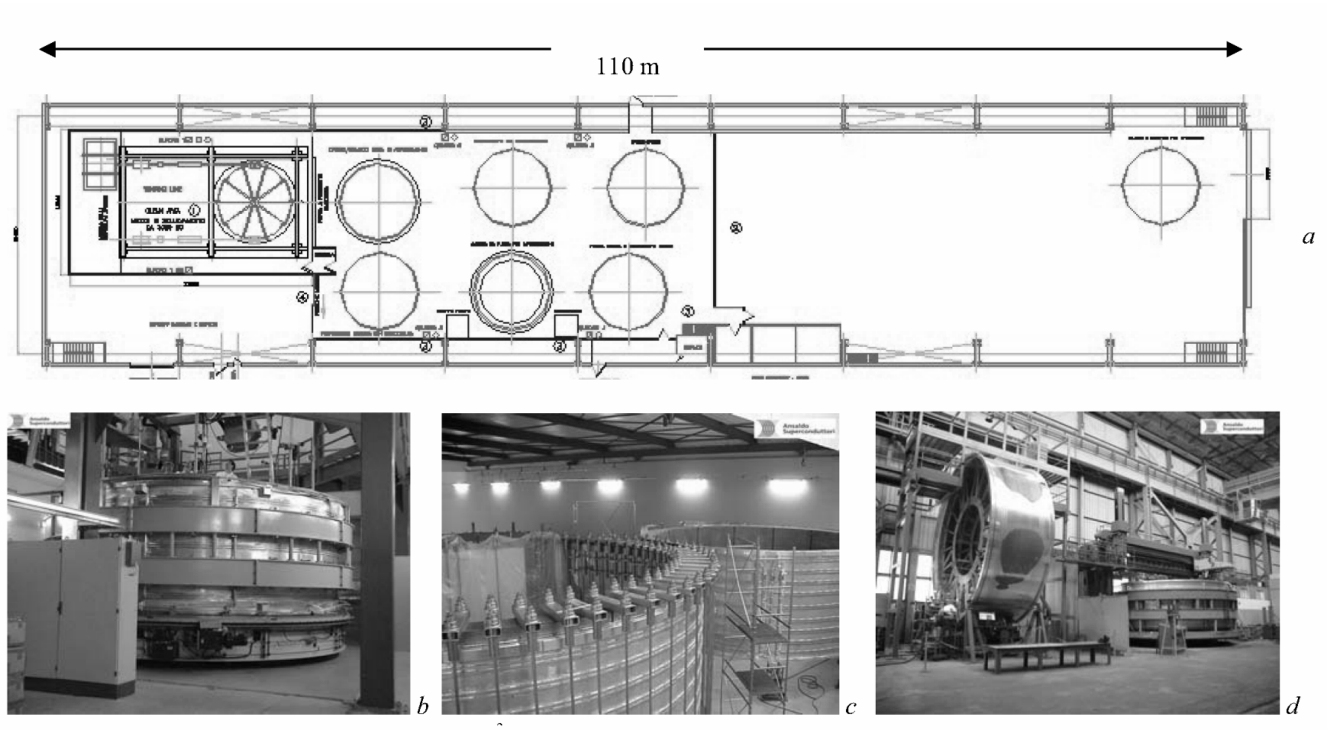

Fig. 4 The map of the CMS factory (a). An area 110 × 22 m^2 is subdivided into three sectors: the winding area (at the right) including the winding line (b), the mounting and impregnation area (in the center), allowing parallel operations on modules (as shown in c) and the mandrel factory allowing two mandrels to be built in parallel.

A. *The Mandrel Construction*

Each mandrel, having an inner diameter of 6.84 m and a length of 2.53 m is composed of three elements: a 50 mm thick shell (obtained as a welded construction starting from 3 plates 75 mm thick further reduced in thickness by machining) and two 130 mm thick end flanges manufactured by ring rolling as seamless rings [6]. The central module (CB0) has thicker end flanges (180 mm) including shoulders for longitudinal tie-rods. The mandrels for CB-1 and CB+1 include the shoulders for radial and vertical rods. The radial shoulders to be welded within the shells have been removed from a specially fabricated seamless ring. The manufacturing methods have been validated by measuring the tensile properties down to cryogenic temperature on samples and welds removed from components constituting the real modules of the mandrels. The tests showed that the yield strength was within specification for all samples

Contrary to the construction of mandrels of former solenoids (e.g. Delphi, Finuda, Babar) no stress relieving heat treatments have been applied to the mandrels, for avoiding a dramatic loss in mechanical properties: the yield strength shall be as high as 209 MPa at 4.2 K. Unfortunately if mechanical stresses are not released, the mandrel is not mechanically stable and the requirement on the circularity (max 1 mm) becomes critical.

In order to overcome this problem and to keep under control the mandrel diameter during the construction, two stiffening structures are involved: an inner large ring is used during welding and outer machining operations, whilst an outer ring is used when the inner wall is machined (see Fig. 4.c). Finally an outer mechanical structure is applied for keeping the mandrel round again during the winding, as shown in Fig. 4.b, where the mandrel with this stiffening ring is mounted on the winding table. At the end of the winding the outer mechanical structure is removed as the rigid winding pack maintains the cylindricity.

B. *Vacuum impregnation and module finishing.*

Before putting the module in the autoclave, the inner surface is covered with thin aluminum plates, forming a liquid tight inner shell. This shell, together with a bottom flange and the outer mandrel, constitutes the impregnation mold to be filled with resin. Great care has been taken to minimize the voids in this vessel, for avoiding excesses of resin in the coil. From this point of view the coupling between the inner shell and the module is critical: in Fig. 5 the inner shell, composed of welded plates pressed against the inner wall of the module, is shown. The coil is axially compacted by 140 steel rods, able to apply a pressure of 2 MPa (see Fig. 4.b or 5.a). To fill each module, 1000 l of resin (Araldit F) are required. This amount includes the spaces around the electrical exits plus 200 l for filling the resin vessel well above the 2.5 m coil height. The total impregnation time is one month according to the following process

a) The module is heated up to 100 °C. In the meantime the pressure is lowered to 1 mbar. The coil remains in this condition for 7 days for allowing a degassing of water trapped inside the winding insulation (fiber-glass)

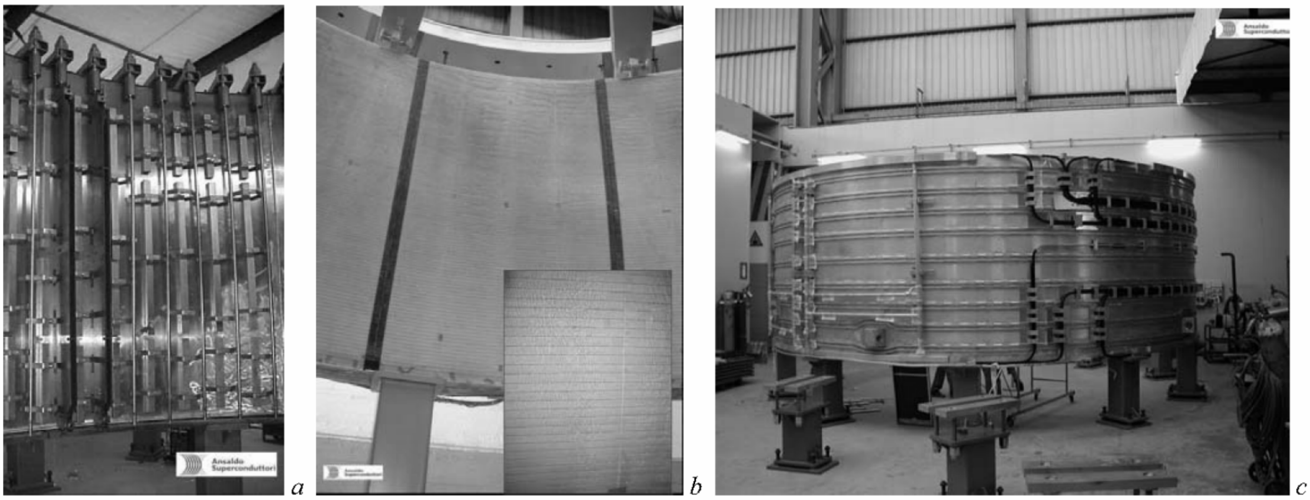

Fig. 5 A module during the last construction stages: a) The module has been enclosed inside the impregnation mold. Part of the mold is the Al alloy thin shell, constructed inside the inner bore and tightly coupled to the inner diameter through a mechanical pressing system. Tie rods are used for axial compactation. b) The coil after the impregnation and cleaning. The transparency of the resin allows viewing the winding details. Some resin excess is removed by machining the inner surface. c) Once the electrical exits are formed and the joints are welded, both are insulated and mechanically fixed to the mandrel

b) The temperature is lowered to 75 °C and the resin impregnation is started slowly filling the module from the bottom. The resin level is checked looking at the resin level in a glass pipe parallel to the module. This indication has only a relative meaning because the resin impregnation proceeds by capillarity effect. Within three days the resin emerges from the coil top (windows are used for inspecting the coil from the top). In a further day, resin is added to achieve a resin level 100 mm above the coil.

c) The temperature is raised to 135 °C for the curing, an operation lasting 5 days.

d) The coil is naturally cooled down to room temperature. This step takes 10 days.

After the impregnation the module is taken away from the autoclave and the impregnation mold is removed (practically in part destroyed) as well as any resin excess. As discussed before, the resin excesses at the inner diameter (resulting from not perfect coupling between module and inner shell of the impregnation mold) are removed by coil machining with the large lathe.

The electrical joints are TIG welded according a qualified procedure and then insulated with fiberglass and impregnated with epoxy.

Once two modules of the series (e.g. CB-2 and CB-1) have been completed, they are mechanically pre-coupled before sending the previous module (CB-2 in the case) to CERN site. The mechanical coupling is made through the bolting of 41 bolts and pins (in Titanium alloy) at the connecting flange. Their relative number depends on the interface: as an example the coupling CB-2 to CB-1 is made by 29 bolts and 12 pins. The distribution depends on the required momentum and shear strength for support during the swiveling at CERN site [7].

QUALITY CONTROLS

All construction stages were done according to procedures previously settled and checked through process and operator qualifications, tests and measurements. Few cases of non-conformities occurred. The main one is related to the coil inner diameter: a lower diameter was accepted (6310 mm –0 +4 mm rather than 6319 –2 +2 mm) to allow for the final ovalness of the modules (from 2.7 to 6 mm) .

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