CMS Coil Design and Assembly

F. Kircher, P. Brédy, D. Campi, P. Fabbricatore, S. Farinon, H. Gerwig, A. Hervé, I.L. Horvath,
B. Levesy, R. Musenich, Y. Pabot, A. Payn and L. Veillet

[1]***Abstract*—The Compact Muon Solenoid (CMS) is one of the general-purpose detectors to be provided for the LHC project at CERN. The design field of the CMS superconducting magnet is 4T, the magnetic length is 12.5 m and the free bore is 6 m. The construction phase of the superconducting coil is now in full progress. Due to the size and characteristics of the coil (4T central field, 2.7 GJ stored energy), its design and the practical realization thereof require solutions with are more than extrapolations of those previously used for superconducting solenoids dedicated to physics experiments. This presentation will summarize the coil design with a particular emphasis on the engineering aspects of its components, and their status. The developments that have been done to validate the solutions that are now finalized, will be reported. Finally, the assembly scenario of the coil, which will be mainly done in a vertical position before swiveling to a horizontal position, will be described.**

***Index Terms*—Detector Magnets, Superconducting Magnets.**

I. INTRODUCTION

THE CMS magnet is a compact and powerful spectrometer one, well matched to the physics potential of the high luminosity collider LHC. This magnet consists of a 4 T central field, 6 m free bore and 12.5 m magnetic length, superconducting solenoid, enclosed in an iron yoke, which is also used for muon detection [1]. These magnetic characteristics make the muon spectrometer both simple in design and powerful in efficiency, with a good momentum resolution.

The geometrical and magnetic characteristics of the solenoid make it the biggest and more powerful superconducting one ever built, with a stored energy of 2.7 GJ. So, simple extrapolation of the biggest solenoids built for the LEP collider, Aleph [2] and Delphi [3] would not achieve the requested parameters. If the main basic concepts
have been used in both kinds of magnets, these concepts have been pushed to farther limits for the CMS case.

Obviously, the confidence in the CMS design and construction is based on a lot of calculations, large pre-industrialization programs for the conductor and the winding, characterization and qualification tests for most of the components and a quality control as developed as possible.

II. GENERAL DESIGN

The general design of the coil was frozen in the beginning of 1999 [4]. This design is based on a 5 module coil. The conductor used is an aluminum-stabilized and mechanically reinforced one. For each module, the winding consists of four layers of conductor, wound inside an external mandrel; each module is epoxy impregnated after winding. The coil is indirectly cooled with two-phase helium at 4.5 K, using a thermosiphon mode. After assembly in vertical position, the coil is swiveled to its horizontal position and attached to the vacuum tank through several sets of titanium tie rods. In case of quench, the external mandrel acts as a quench-back tube and propagates the quench uniformly over the whole coil. An artistic view of the cold mass, i.e the part of the coil at 4.5 K, is shown on Fig 1.

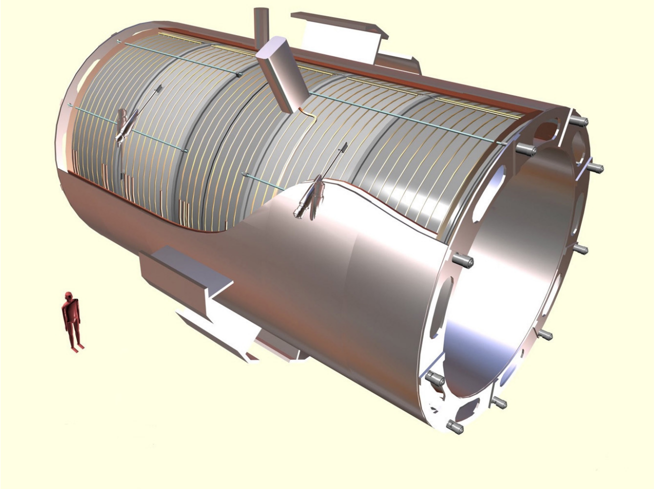

Fig. 1. Artistic view of CMS cold mass

Manuscript received September 24, 2001

F. Kircher (corresponding author, telephone 33 1 69 08 25 88, e-mail : kircher@dapnia.cea.fr), P. Brédy, B. Levesy, A. Payn are with CEA Saclay, DAPNIA/STCM, F 91191 Gif-sur-Yvette, France.

D. Campi, H. Gerwig, A. Hervé, L. Veillet are with CERN, CH-1211, Geneva 23, Switzerland.

P. Fabbricatore, S. Farinon, R. Musenich are with INFN, via Dodecaneso 33, I-16146 Genova, Italy.

I.L. Horvath is with ETH, Swiss Federal Institute of Technology, 8093 Zûrich, Switzerland.

Y. Pabot is with CEA Saclay, DAPNIA/SGPI, F 91191 Gif-sur-Yvette, France.

The main parameters of the coil are listed in Table I.

TABLE I
CMS COIL MAIN PARAMETERS AT 300 K

Magnetic length	12.50 m
Free bore diameter	6.00 m
Coil internal diameter	6.32 m
Coil external diameter	6.85 m
External cylinder thickness	50 mm
Vacuum tank external diameter	7.60 m
Cold mass weight	225 t
Central magnetic field	4.0 T
Maximum field on the conductor	4.6 T
Nominal current	19500 A
Total ampere-turns	42.51 MAt
Winding overall current density	11.0 A/mm^2
Stored energy	2.67 GJ
Self inductance	14.04 H
Fast dump resistance	30 m Ω
Fast dump voltage to ground	± 300 V

III. TECHNICAL DEVELOPMENTS

A. Conductor

The CMS conductor consists of a 32-strand Rutherford cable embedded in a very high purity aluminum (initial RRR at 0 T ~ 3,000) by a co-extrusion process and then reinforced by two aluminum alloy strips welded to its smaller sides using by an electron beam welding technique. The successful production of this conductor is the result of a long development work done in collaboration between several laboratories and various industrial firms.

One of the most important result is that, although the initial current density industrially obtained in the superconducting part of the virgin strand. (J_c ~ 3,200 A/mm^2 at 5 T and 4.2 K) is quite high, the total degradation in J_c for the full process (cabling, co-extrusion, and electron beam welding) is only in the range of 7 ± 1 %.

A more complete description of the conductor components and experimental results is given in [5], [6], [7], [8] and [9] respectively for the full conductor, the strands, the aluminium alloy used for the reinforcement, the electron beam welding process and measurements of critical current on stabilized conductor.

B. Winding

The main challenge of the CMS winding is to accurately pack a large and stiff conductor over four layers, using an internal winding technique. Moreover, although the coil is fully impregnated, the high level of stress in the winding requests a good bonding between the conductors and the epoxy resin. Also, a good bonding between the epoxy and the external mandrel is needed, as this mandrel also acts as a cooling wall between the cooling tubes and the coil.

Concerning the impregnation, accent has been put on the surface treatment of both the conductor and the inner surface of the external cylinder used as mandrel. Sandblasting was chosen for both treatments and shear stress in the range of 35 MPa at room temperature was measured between the conductor and the insulation [11]. This is conformed to the specification.

The work related to the winding line is described in [10]. A short-length model coil was wound in the frame of the pre-industrialization work and now, a prototype module, shorter by a factor of about 4 compared to the final modules, is ready to be wound using the final conductor and winding line.

An other important point for the winding is the electrical junctions. Each layer will be wound from a single length of conductor and the electrical junctions between layers and modules will be done over the outer surface of the mandrel, where the magnetic field is low ($B < 0.5$ T). The junction length is about 2 m. Extrapolation of experimental results obtained on shorter prototypes would give a value of a few 10^{-10} Ω for each junction resistance.

C. External cylinders

The external cylinders are an essential part of the cold mass as they have a multi-purpose function: external mandrel for the winding, cooling wall between the cooling tubes and the coil, mechanical support when the coil is energized and quench back tube in case of fast discharge. The retained material for the realization of these cylinders must have excellent mechanical properties and must be accurately machinable as strict dimension tolerances are imposed for the winding. After various mechanical and welding tests, aluminum alloy 5083-H321 was retained. It is worthwhile to notice the realization of the cylinder: the shell is fabricated by rolling, then welding three 75 mm thick plates, the end flanges are produced as seamless rings and then circumferentially welded to the shell. A full description of the fabrication process and of the properties obtained is given in [12].

D. Internal and proximity cryogenics

The coil is indirectly cooled by saturated helium at 4.5 K through a network of aluminum alloy tubes welded to the external mandrel and supplied with helium in a thermosiphon circulating mode. This thermosiphon process is intrinsically reliable as long as its elements (phase separator and cooling tubes) are properly dimensioned according to the expected thermal losses. In this respect, experimental measurements were performed to confirm the CMS thermosiphon design. Tubes are 14 mm in diameter and about 250 mm spaced from each other. The cooling circuit is redundant for reliability reasons. Considering the modular structure of the coil, this makes the cryogenic circuit quite complex: no less than 17 tubes are passing through the cryogenics chimney for the inlet and outlet thermosiphon circuits, thermal shields and current lead feeding. A second chimney contains the two 20,000 A current leads and is also used for vacuum and instrumentation.

A phase separator cryostat, located on a platform above the coil, is used as the feeding part of the thermosiphon circuit (Fig. 2). There is about 600 l of LHe in the cryogenic circuit in normal operation, about half in the phase separator and half in the cooling tubes.

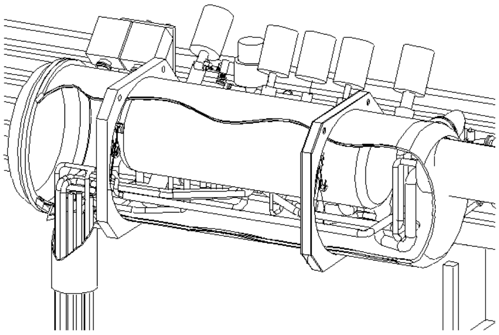

Fig. 2. Phase separator cryostat

The detailed study of this part is almost completed. It is foreseen to partially test the phase separator at low temperature before its final installation.

E. *Thermal shields*

Though not the most critical part of the coil, thermal shields must be carefully designed and realized considering the size of the magnet. Particular attention must be given to the possibility of problems arising because of differential thermal contractions or induced currents. Taking into account thermal, electrical, mechanical and assembly considerations, the final design of the thermal shields consists of 20 panels for each of the internal and external thermal shield. These 20 panels are divided in 5 longitudinal sets of four 90° shells, each panel being typically 6 m wide by 2.5 m long. End panels will also be installed.

A thermal shield panel is of a classical design, using 5 mm thick plates of aluminum alloy 3003 H22, cooled by pipes welded on it (the pipe circuit is doubled for redundancy reasons). The inner thermal shield is supported by the inner vacuum tank through epoxy supports, while the outer thermal shield is supported by the external mandrel. The complete design of the thermal shields and the analysis supporting it are detailed in [14]. Call for tenders, including the realization of at least one mock-up will be launched in the last quarter of 2001.

F. *Suspension system*

The cold mass is supported by tie rods inside the vacuum tank. These tie rods, an essential part of the mechanical structure, must contain both the 225 t weight of the cold mass and the magnetic forces due to the coil misalignment inside the iron yoke (10 mm maximum allowable in all directions). The complete cold mass system consists of three different sets of tie rods, for a grand total of 30 elements [15]. For mechanical and thermal reasons, titanium alloy was chosen as basic material for their realization and two grades were pre-chosen and intensively characterized at 300 K and 4 K: Ti 5Al-2.5 Sn ELI and Ti-6 Al - 4 V ELI. At 4 K, if the titanium Ti-6 Al - 4 V ELI presents higher mechanical properties than titanium Ti 5Al-2.5 Sn ELI, it also presents a lower fracture toughness and some notch sensitivity [16]. The choice for the retained alloy will be done after reception of the offers (October 2001).

An existing test facility has been adapted at Saclay to test all the tie rods in their operational conditions after their production. Several prototypes were already tested in this test facility with successful results (110 % of their nominal load without problem, with one end at 300 K and the other around helium temperature).

G. *Current leads*

The CMS current leads are of a classical design, using a multi-stage copper cable located in a stainless steel conduit and cooled by helium flow (Fig. 3). Due to the presence of a thick iron yoke around the coil, the current leads are particularly long (3.3 m). Their copper section has been dimensioned such that the current leads can operate at full current without cooling for a period of 7 minutes without any damage ; i.e. giving a maximum temperature of the insulation of less than 450 K. This period of 7 minutes at full current is equivalent, for the Joule heating effect, to 5 minutes at full current plus the time needed for a fast discharge of the magnet (time constant ~ 190 sec).

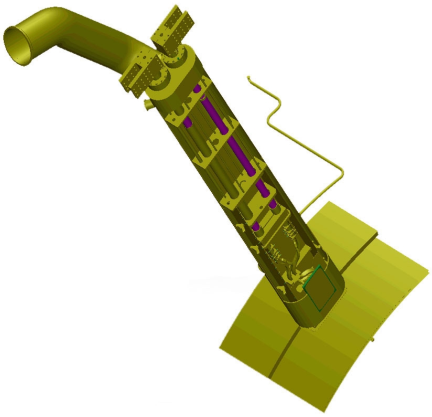

Fig. 3. Current lead design

A large test facility will be adapted at Saclay to test these current leads before their final installation.

IV. ASSEMBLY SCENARIO

It has always been the choice of the CMS collaboration to do the assembly of the CMS magnet (coil + yoke) in a surface hall at CERN, followed by a full cryogenic and electrical test before lowering the magnet in the underground cavern. For practical reasons, most of the cold mass assembly will be done in the vertical position before swiveling to the horizontal position. A dedicated platform, used both for support and swiveling, has been constructed for this purpose.

Brief summary of the assembly scenario:

- before transportation to CERN, each module will be blank assembled to the next one for checking their fit;
- once at CERN, the modules will be loaded in vertical position on the platform, and all the connections (mechanical, electrical, hydraulic) will be done;
- the outer thermal shield will be installed;
- this first unit will be swiveled to the horizontal position, introduced within the outer vacuum tank (which is supported from the barrel yoke central ring) and fixed to it, using part of the tie rods;
- in parallel, the inner thermal shield will be installed over the inner vacuum vessel in the vertical position;
- this second unit will be swiveled to the horizontal position and introduced within the first unit;
- the end plates of the shield and of the vacuum vessel will be mounted, the longitudinal tie rods will be fixed and the vacuum vessel will be closed.

During the assembly, several surveys operations will be performed, with the goal of reaching an assembly accuracy in the range of 10 mm in all directions (extra adjustment will be possible at 4.5 K).

The assembly platform is built and its provisional acceptance was pronounced in August 2001 after a successful static load test (Fig. 4).

Fig. 4. The assembly platform ready for provisional acceptance

This platform will be delivered to CERN in October 2001 and a dynamic load test will be performed in the first quarter of 2002, using the inner vacuum tank and counterweights as load.

V. CONCLUSIONS

The detailed design of the CMS coil is now almost completed and the last main orders will be placed within few months. Numerous calculations, pre-industrialization works and qualifications tests support this design.

A strict control of the components which will be included in the cold mass has been defined and is already in operation. It will be kept in place during the whole construction and assembly phases. Particularly, several crucial elements, as the current leads and the support tie rods will be tested in actual conditions before final assembly.

VI. ACKNOWLEDGMENT

The authors would like to thank all their colleagues from laboratories and industries who have been involved in this work, as well as the CMS Collaboration.

VII. REFERENCES

[1] “The Compact Muon Solenoidal Technical proposal”, CERN/LHC 94-38 (1994).
[2] J.M. Baze et al., “Design, Construction and Tests of the Large Superconducting Solenoid Aleph”, IEEE Trans. Mag., 1998, 2, 1260 - 1263.
[3] R. Apsey et al., “Design of a 5.5 m Diameter Superconducting Solenoid for the DELPHI Particle Physics Experiment at LEP”, IEEE Trans. Mag., 1985, 2, 490-493.
[4] F. Kircher et al., “Status Report on the CMS Superconductiong Solenoid for LHC”, IEEE Trans. Appl. Superconduct., vol 9, 2, 837 – 840.
[5] B. Blau et al., “The CMS Conductor”, IEEE Trans. Appl. Superconduct., submitted for publication.
[6] B. Curé et al., “The Superconducting Strand for the CMS Solenoid Conductor”, IEEE Trans. Appl. Superconduct., submitted for publication.
[7] S. Sequeira Tavares et al., “Aluminium Alloy Production for the Reinforcement of the CMS Conductor”, IEEE Trans. Appl. Superconduct., submitted for publication.
[8] R. Folch et al., “Continuous EB Welding of the Reinforcement of the CMS Conductor”, IEEE Trans. Appl. Superconduct., submitted for publication.
[9] M. Greco, P. Fabbricatore, R. Musenich, “Critical Current Measurements on the CMS Stabilized Conductor”, IEEE Trans. Appl. Superconduct., submitted for publication.
[10] P. Fabbricatore et al., “The Winding Line for the CMS Reinforced Conductor”, IEEE Trans. Appl. Superconduct., submitted for publication.
[11] F. Rondeaux, CEA Saclay, personal communication, 2001.
[12] S. Sgobba et al., “Design Construction and Quality Tests of the Large Al-alloy Mandrels for the CMS Coil”, IEEE Trans. Appl. Superconduct., submitted for publication.
[13] B. Baudouy, “Heat and Mass Transfer in Two-phase He I Thermosiphon Flow”, Adv. In Cryogenic Eng., submitted for publication.
[14] P. Fazilleau, P. Brédy, B. Levesy, “CMS Coil Thermal Shield Final Design and Assembly”, IEEE Trans. Appl. Superconduct., submitted for publication.

[15] B. Levesy, H. Gerwig, F. Kircher, M. Reytier, “Design and Test of the Titanium Alloy Tie Rods for the CMS Coil Suspension System”, IEEE Trans. Appl. Superconduct., submitted for publication.
[16] M. Reytier, F. Kircher, B. Levesy, “Characterization of Titanium Alloys for Cryogenic Applications”, Adv. in Cryogenic Eng., submitted for publication.