Final Design of the CMS Solenoid Cold Mass

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Abstract - **The 4 T, 12.5 m long, 6 m bore diameter superconducting solenoid for the CMS (Compact Muon Solenoid) experiment at LHC will be the largest and the most powerful superconducting solenoid ever built. Part of the CMS design is based on that of previous large superconducting solenoids - the use of a high purity aluminium stabilized conductor, a compact impregnated winding with indirect cooling and quench back protection process. However, the dimensions and the performances of this solenoid have imposed solutions which are more than extrapolations of the previous ones : the use of a mechanically reinforced conductor and a five module winding, each module being made of four layers, internally wound.**

This design, which is now frozen, relies on numerous magnetic, mechanical and thermal calculations, on various experimental tests (characterization of structural and insulating materials, electrical joints...) and specific mock-ups. Two pre-industrialization programs, concerning the conductor and the winding process have also been carried out with industrial partners to support the foreseen solutions. Both the final design and the experimental results obtained to validate this design will be presented in this paper.

I. INTRODUCTION

The CMS detector is a compact and powerful spectrometer well matched to the physics potential of the high luminosity collider LHC. The single most important aspect of the detector design is the configuration and parameters of the magnetic field for the measurement of muon momentum. A solenoid field configuration has been chosen, with parameters following the detector requests : central field 4 T, free bore diameter 6 m, length 12.5 m.

As these characteristics are far beyond what has been achieved up to now, the CMS solenoid design cannot be a simple extrapolation of previously built large superconducting solenoids, of smaller length and lower magnetic field. The final design is consequently mainly based on upgraded solutions used for previous realizations ; these solutions must be validated by calculations, tests and pre-industrialization programs : these tasks are now completed so that the design has been frozen and the construction phase has started [1].

II. COLD MASS MAIN CHARACTERISTICS

The main geometric and magnetic parameters are recalled in Table I (dimensions are for 300 K).

TABLE I
Main CMS cold mass parameters

Magnetic length	12.500 m
Free bore diameter	6.00 m
Internal coil diameter	6.32 m
Winding thickness	262 mm
Support cylinder thickness	50 mm
Central magnetic induction	4.0 T
Maximum field on conductor	4.6 T
Total ampere-turns	42.51 MA-turn
Stored energy	2.67 GJ
Nominal current	19 500 A

The major change in the cold mass design since the TDR [2] was to come back to a modular design, whereas a monolithic design was foreseen in the TDR ; so, the coil consists now of 5 modules, with four layers of conductor each.

The main consequence of this change is the need to use an inner winding technique, because the assembly of outer wound modules seems impossible in practice. Subconsequences on the coil were the revision of the design of the external cylinder of the modules, the design of module ends, the design of the electrical junctions between layers and between modules, the use of fiber glass and vacuum impregnation rather than pre-preg for the impregnation, the assembly of the coil and its suspension system inside the vacuum tank.

The other main characteristics were not changed, but some optimizations have been done since the previous presentation of this project [3].

For the aluminium stabilized and mechanically reinforced conductor, the cable pattern was frozen to 32 strands of 1.28 mm diameter, with Cu/SC = 1.1 ; the electron beam welding (EBW) technique was retained for the welding of the reinforcement.

The conductor insulation thickness was increased from 0.25 to 0.50 mm, so as to reduce the amount of pure resin in

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local places of the impregnated coil and partly compensate conductor keystoning.

For indirect cooling in thermosiphon mode, a double circuit (one in operation and one spare) was introduced to mitigate the consequences of a possible leak developing late during the operation of the detector.

The external cylinder is used as a quench-back tube ; the normal fast discharge is done through dump resistors ; the dump voltage has been decreased from 1 kV to 0.6 kV ; however, the nominal voltage will be still kept at 1 kV and the test voltage at 3 kV for most elements, especially the conductor insulation ; this decrease of the dump voltage is without large incidence on the recovery time after a quench.

The winding of the modules will be done on the winder's site and followed by the pre-assembly of two adjacent modules on that site.

The final assembly will be done at CERN in SH5 surface hall in vertical position ; after assembly, the coil will be swivelled to horizontal position for insertion inside the vacuum tank ; then cryogenics and electrical tests will be performed.

The support of the cold mass inside the vacuum tank will be done with three sets of Ti-5Al-2.5Sn ELI (Extra Low Interstitial) titanium tie-rods.

An artist view of the cold mass is given on Fig. 1. The cold mass cross section in the inter-module area is given on Fig. 2.

III. ANALYSIS SUPPORTING THE DESIGN

Obviously the final design is based on numerous magnetic, mechanical, thermal and stability analysis calculations, most of which are presented in details in related papers presented at this conference ([5] to [10]).

A. Magnetic analysis

Using the TOSCA code [4], several 3D models were developed to get the field map and force calculations [5].

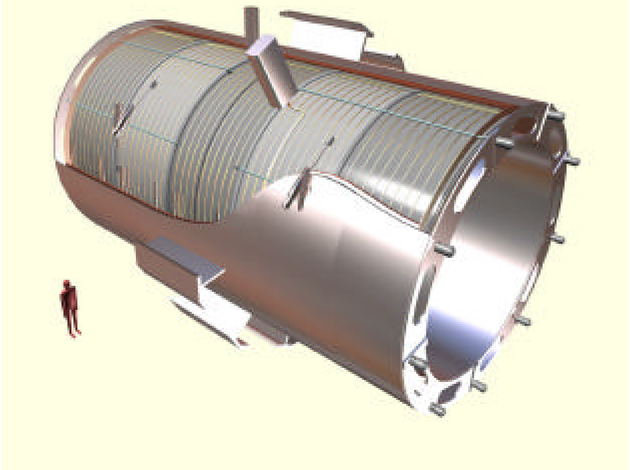

Fig.1. Three dimension view of the CMS cold mass

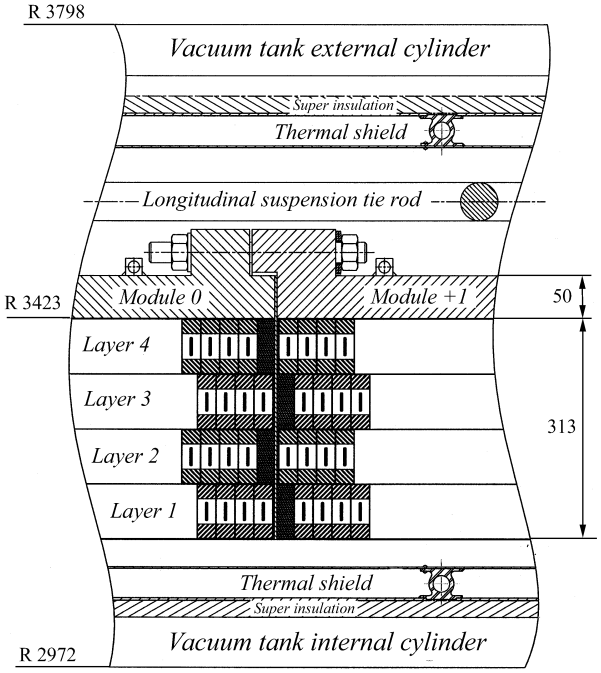

Fig.2. CMS cold mass cross section (in mm)

These calculations take into account the 5 module coil and the return iron yoke (central barrel, two end-caps and ferromagnetic parts of the hadronic forward calorimeter). They have shown that, in some regions, the field is strongly inhomogeneous. The complexity of the field behavior requires the use of the 3D field map in the detector simulations outside the coil volume as well as an accurate field reconstruction inside the free bore volume.

The forces on the coil and on the ferro-magnetic parts were calculated in order to design the mechanical structure. Typically, the total force is 860 kN (respectively 70 kN) for an axial (respectively radial) coil out-of-center of 10 mm inside the iron structure ; for a 1 mrad coil tilt, the total torque is 1000 kN m.

B. Stress analysis

The coil has been simulated with an elasto-plastic axisymmetric FE model [6]. A 3D elastic model has also been used to compute the stresses in the tie-rod shoulder region. The main results from these analyses are summarized below.

The maximum strain values (0.8 %) in the conductor pure Al are located around the Rutherford cable; these are well within the allowable limit of the plastic domain. For most of the Al cross section, this value is below 0.2 %.

The maximum Von Mises stress in the conductor reinforcement Al alloy (144 MPa) stays below the allowable value for the AA 6082 T51 retained.

The insulation stress field shown by Mohr-Coulomb plots stays within a safe envelope, considering the experimental results obtained (see § IV below) ; this stress field in the insulation is mainly due to cool down. (For insulation, the Mohr-Coulomb criterion has been adopted to take into account its elasto-brittle behaviour).

The keystoning of the conductor after winding can locally increase the volume of pure resin and so the level of stress ; an increase of the conductor insulation thickness from 0.25 to 0.50 mm was made in order to reduce this risk.

The most stressed parts in the AA5083 external cylinder are the tie-rod shoulders, where the maximum Von Mises stress is 157 MPa.

The hoop strain is limited to 0.15 % thanks to the mechanical structure, balanced between the four layers of reinforced conductor and the external cylinders.

The maximum stress in the tie rod, 308 MPa at 300 K is below the allowed value of 326 MPa.

C. *Stability and thermal analysis*

Several computations were carried out to evaluate stability disturbances of the CMS coil [7]. The Minimum Quench Energy has been estimated between 0.4 and 0.8 J, depending on the model for the current sharing effect. This value is comparable to the one for the Aleph solenoid. The minimum propagating zone is quite short, ranging between 10 and 20 cm.

Taking into account the radiation and the conduction losses, the maximum temperature gradient between the cooling tubes and the inner layer of conductor is in the range of 0.1 K for the actual cooling tube spacing (250 mm, except in the tie-rod shoulder zone, where the spacing is 350 mm) ; the maximum coil temperature stays within the allocated tolerance.

The refrigeration system dedicated to the experiment will enable the cool down from 300 K to running conditions in about 25 days. About three days will be necessary to recover the running conditions after a quench.

D. *Protection in case of quench*

In case of quench, the protection scheme is composed of an active part (an external resistor put in the electric circuit, giving a dump voltage of 600 V) and a passive one (the external cylinder of each module acts as a quench-back tube). In normal conditions, the maximum temperature in the coil after a fast discharge is around 60 K ; should a failure occur and the dump resistor not be put in circuit, this value is increased to about 125 K, which remains reasonable for a coil of this size.

IV. EXPERIMENTS SUPPORTING THE DESIGN

Large scale pre-industrialization programs for the conductor [8] and the winding as well as smaller test programs and mock-ups were undertaken to support the industrial feasibility of the realization of the coil.

A. *External cylinder*

The external cylinder of each module has several important roles, which make it an essential part of the cold mass : outer winding mandrel, mechanical reinforcement structure, indirect cooling of the coil, quench-back tube. Consequently, it must have properties (weldability, accurate machining, strength, thermal conductivity…) which are difficult to be found together.

An industrial fabrication process survey, combined with mechanical laboratory measurements at 4.2 K of actual samples have shown that Al alloy grade 5083 in the strain hardened temper H321, formed, welded, then heat treated at a temperature around 260 °C before final machining, is close to fulfilling the requirements [9].

B. *Conductor*

Numerous experimental results are reported in [8] , the most important being that long lengths of strand satisfying the specification, at the upper limit of industrial possibilities, were produced by several manufacturers (3050 A/mm^2 in the SC at 5 T and 4.2 K).

Also a 800 m long insert (cable coextruded in 4N8 Al), was successfully produced and the electron beam welding process in static conditions was understood, enabling the production of several short lengths of final conductor.

C. *Winding tests*

The aim of the pre-industrialization program for the winding was to understand the behavior of a large reinforced conductor during the different phases of the winding and to demonstrate the feasibility of at least one winding technique for such a stiff conductor. The final goal, which is now near completion, is the winding and impregnation of a model coil of the same cross section but of shorter length (0.25 m) than a CMS module, using a simplified winding machine and a dummy conductor.

During this program the bending of the conductor, its keystoning during this operation and its transfer inside the mandrel were particularly studied.

D. *Electrical junctions*

The use of a continuous 2.5 km long unit length of conductor for each coil layer was chosen to avoid internal junctions inside the winding ; all the electrical connections between layers and between modules are done on the outer part of the external cylinders i.e. in a region where the field is low and the space widely available ; accessibility is also better. A mock-up of the junctions between two modules is shown in Fig. 3.

Fig.3. Junction mock-up

Extrapolation of experimental results to the foreseen final junction length gives a resistance of a few 10^{-10} Ω per junction.

E. Conductor insulation

As previously mentioned, the decision was made to use fiber glass tape and epoxy vacuum impregnation for the insulation between turns, between layers and to ground.

Considering the high level of shear stress at insulation conductor interface (up to 28 MPa at 4.2 K), special attention was paid to the conductor surface treatment to insure a good bonding between the insulation and the conductor [10].

The use of an anodic oxidation process of the conductor surface seems to be the most interesting as shear stress values above 100 MPa at 4.2 K were measured, with low dispersion between samples ; furthermore, no ageing and no behavior difference between the two components of the conductor exposed to the process were noticed. Finally, there is no risk to produce micro-particles, as with sandblasting for example.

F. Suspension system

The suspension system of the coil inside the vacuum tank must support the 225 tonne weight of the cold mass and the magnetic forces due a coil misalignment inside the yoke, as indicated in § III.

Using external prestressing jacks, this suspension system allows also an adjustment the coil position inside the iron during the first tests of the magnet.

The support system consists of three sets of titanium alloy Ti-5Al-2.5Sn ELI rods :

- 2 x 9 longitudinal tie rods, 45 mm in diameter and 5.7 m long ;
- 2 × 2 vertical tie rods, 55 mm in diameter and 1.8 m long ;
- 2 × 4 radial tie rods, 35 mm in diameter and 1.8 m long.

A mock up of a titanium screw simulating the tie rod, pressed inside an aluminium alloy block, simulating the tie rod shoulder on the external cylinder has shown no mechanical degradation after a load of 120 tonnes was applied on the screw.

V. CONCLUSIONS

The CMS solenoid cold mass design is now frozen ; the detailed engineering phase is well advanced and the construction phase has started.

The most important points of the design have been summarized here, as well as the calculations and tests supporting this design ; more detailed technical results can be found in related papers submitted to this conference.

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