Status of the Construction of the CMS Magnet

A. Hervé, B. Blau, Ph. Brédy, D. Campi, P. Cannarsa, B. Curé, Th. Dupont, P. Fabbricatore, S. Farinon, F. Feyzi, Ph. Fazilleau, A. Gaddi, H. Gerwig, M. Greco, J. P. Grillet, V. Kaftanov, F. Kircher, V. Klyukhin, B. Levesy, R. Loveless, G. Maire, R. Musenich, Y. Pabot, A. Payn, G. Perinić, P. Petiot, F. Rondeaux, H. Rykaczewski, E. Sbrissa, S. Sequeira Tavares, S. Sgobba, R. P. Smith, L. Veillet, and G. Waurick

***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 with 6 m diameter by 12.5 m long free bore, enclosed inside a 10,000-ton return yoke. The stored magnetic energy is 2.6 GJ. The magnet is being assembled in a surface hall and will be tested at the beginning of 2005 before being transferred to an experimental hall 90 m below ground level. The design and construction of the magnet is a common project of the CMS Collaboration. The task is organized by a CERN based group with strong technical and contractual participation of CEA Saclay, ETH Zürich, Fermilab, INFN Genova, ITEP Moscow, University of Wisconsin and CERN. The return yoke, 21 m long and 14 m in diameter, is equivalent to a thickness of 1.5 m of saturated iron interleaved with four muon stations. Manufacture of the yoke and vacuum tank is completed and the first sub-detectors have been installed. The indirectly-cooled, pure-aluminum-stabilized coil is made up from five modules internally wound with four layers of a 20 kA mechanically-reinforced conductor. The manufacture of the conductor is completed and winding is in progress for a final assembly in 2004. All ancillaries are delivered or under contract. The magnet project is described, with emphasis on the present status of the fabrication.**

***Index Terms*—CMS, LHC, magnet, solenoids.**

I. INTRODUCTION

THE CMS experiment (Compact Muon Solenoid) is a general-purpose proton-proton detector designed to run at the highest luminosity at the LHC [1]. Distinctive features of the CMS detector include a high-magnetic-field solenoid (4 T) coupled with a multilayer muon system, a fully active scintillating-crystal electromagnetic calorimeter, a tile hadronic calorimeter, and a powerful inner tracking system (Fig. 1). The single most important aspect of the overall detector design is the configuration and parameters of the magnetic field for the measurement of muon momenta. The requirement for good momentum resolution, without making stringent demands on the spatial resolution of muon chambers, leads naturally to the choice of a high solenoidal magnetic field. A long superconducting solenoid (12.5 m) has been chosen with a free inner diameter of 6 m and a uniform magnetic field of 4 T. The muon spectrometer then consists of a single magnet allowing for a simpler architecture for the detector. The inner coil radius is large enough to accommodate the inner tracker and the full calorimeter. The magnetic flux is returned via a 1.5 m thick saturated iron yoke instrumented with four stations of muon chambers. The CMS experiment is built and funded by an international collaboration of High Energy Physics institutes from 36 countries,[1] and by CERN. The experiment will be installed at a depth of 90 m below ground on the Interaction Point 5 of the LHC. The CMS magnet is the backbone of the CMS experiment [2] as all sub-detectors will be supported from it. The magnet is being assembled (Figs. 2 and 3) and will be tested in a surface hall then lowered in the underground area (Figs. 8 and 9) by heavy lifting means. This decouples the work on the magnet assembly and test from the construction of the underground area. The return yoke is a 12-sided structure divided into three main components: the barrel yoke and the two endcap yokes. Its main parameters are given in Table I. The coil is an indirectly cooled, aluminum stabilized, four-layer superconducting solenoid. Its main parameters are given in Table II.

Fig. 1. A recent close-up view of the CMS experiment. The coil, situated inside the external vacuum tank, will surround the calorimeters and tracker. The return yoke, one barrel and two endcaps, comprises three layers of iron in between which will be inserted the muon detectors.

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A. Hervé, D. Campi, P. Cannarsa, B. Curé, Th. Dupont, A. Gaddi, H. Gerwig, J. P. Grillet, V. Kaftanov, V. Klyukhin, G. Maire, G. Perinić, P. Petiot, E. Sbrissa, S. Sequeira Tavares, S. Sgobba, L. Veillet, and G. Waurick are with the CERN, 1211 Geneva 23, Switzerland (e-mail: alain.herve@cern.ch).

B. Blau and H. Rykaczewski are with the Swiss Federal Institute of Technology (ETH), 8093 Zürich, Switzerland.

P. Brédy, P. Fazilleau, F. Kircher, B. Levesy, Y. Pabot, A. Payn, and F. Rondeaux are with the CEA Saclay, Dapnia, F-91191, Gif-sur-Yvette, France.

P. Fabbricatore, S. Farinon, M. Greco, and R. Musenich are with the INFN-Genova, 16146 Genova, Italy.

F. Feyzi is with the Physical Sciences Laboratory, Stoughton, WI 53589 USA.

R. Loveless is with the University of Wisconsin, Department of Physics, Madison, WI 53706 USA.

R. P. Smith is with the Fermilab, Batavia, IL 60510-0500 USA.

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[1] Armenia, Austria, Belarus, Belgium, Brazil, Bulgaria, China PR, China (Taiwan), Croatia, Cyprus, Estonia, Finland, France, Georgia, Germany, Greece, Hungary, India, Iran, Ireland, Italy, Korea, New-Zealand, Pakistan, Poland, Portugal, Russia, Serbia, Slovak Republic, Spain, Switzerland, Turkey, Ukraine, United Kingdom, United States of America, and Uzbekistan.

Fig. 2. View of the central barrel yoke ring equipped with the outer vacuum tank destined to house the superconducting coil.

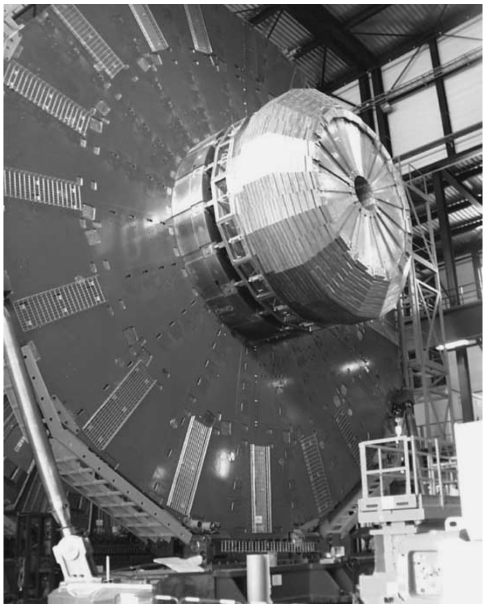

Fig. 3. View of one endcap disk (out of six), 15 m in diameter, standing on a transport cart in the surface hall. This 600-mm thick disk, weighing 700 tonnes, is supporting a 300-tonne hadronic endcap calorimeter.

TABLE I
MAIN PARAMETERS OF THE RETURN YOKE

Outer diameter on iron flats	14 m
Length of barrel	13 m
Thickness of iron layers in barrel	300, 630 & 630 mm
Mass of iron in barrel	6,000 tonnes
Thickness of iron disks in endcaps	250, 600 & 600 mm
Mass of iron in each endcap	2,000 tonnes
Total mass of iron in return yoke	10,000 tonnes

TABLE II
MAIN PARAMETERS OF THE COIL

Magnetic length	12.5 m
Free bore diameter	6 m
Radial thickness of cold mass	312 mm
Radiation thickness of cold mass	3.9 X_0
Weight of cold mass	220 tonnes
E/M ratio	11.9 kJ/kg
Central magnetic induction	4 T
Maximum induction on conductor	4.6 T
Total ampere-turns	42.5 MA.turns
Nominal current	19.5 kA
Inductance	14 H
Stored energy	2.6 GJ

For physics reasons, the radial extent of the coil had to be kept small, and thus the CMS coil is in effect a ‘thin coil’. The radiation thickness of the cold mass is 3.9 X_0 and the specific energy ratio is 11.8 kJ/kg which compare favorably with other thin coils [3].

The coil is wound using the inner winding method, and the external mandrels are used as quench-back cylinders providing intrinsic protection. The coil is indirectly cooled by saturated helium at 4.5 K circulating in the thermosiphon mode through a network of pipes welded to the external mandrels.

II. ORGANIZATION OF THE CMS MAGNET PROJECT

A. Participating Institutes

The CMS magnet project can be grouped into three main headings comprising activities and systems:

- the yoke, consisting of the barrel, the vacuum tank and the two endcaps;
- the coil, consisting of the general engineering, the superconductor, and the coil winding;
- the ancillaries, consisting of the external cryogenics, the power converter and circuit, and the control system.

This structure is reflected in the organization of the CMS magnet project. The management and general coordination is done by a CERN-based group. Work is carried out in the institutes that are members of the CMS Magnet Collaboration, and in particular:

- CERN/CMS is in charge of the barrel yoke;
- University of Wisconsin and PSL are in charge of the endcap yokes in collaboration with CERN/CMS;
- Fermilab is in charge of procuring superconducting strands and other conductor components, and also of the field mapping;
- CEA Saclay is in charge of the general engineering of the coil;
- ETH Zürich is in charge of the production of the conductor in collaboration with CERN/CMS and Fermilab;
- INFN Genova is in charge of the winding operation in collaboration with CERN/CMS;
- CERN Technical Groups are in charge of all ancillaries requiring future operation follow-up and site maintenance,

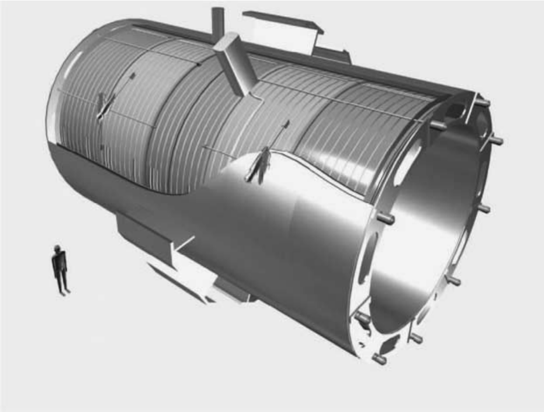

Fig. 4. Perspective view of the CMS coil inside the outer vacuum tank showing the five modules, the tie-bar suspension system, and the thermosyphon cooling circuits outside the mandrels.

such as: power converters, contactors, dump resistors, outer cryogenics, process control etc.

III. THE RETURN YOKE

The barrel yoke, designed at CERN, is split into five barrel rings, having each a mass of 1,200 tonnes, that can move in the axial direction on heavy duty air-pads to give access to the barrel muon stations.

Each endcap yoke, designed at the University of Wisconsin, is built from three independent disks (600, 600, and 250 mm thick), that can be moved on carts, supported by heavy-duty air pads, and separated to provide access to the forward muon stations and inner sub-detectors.

Construction of the yoke has been reported in [4]; it is fully assembled (Fig. 2), equipped with metallic structures to support services, and several sub-detectors are already attached to the yoke (Fig. 3).

IV. THE SUPERCONDUCTING COIL

A. Design of the Coil

The CMS coil design is based, as for a number of existing large detector superconducting solenoids, on the enthalpy stabilization concept. Important information has been gained from the previous designs, and in particular the ALEPH solenoid has been used in many ways as a reference model for the design of the CMS coil [5]. The main changes introduced for the CMS coil design are:

- a four-layer winding instead of a mono-layer one to provide the 42 M A.turns;
- a construction in five modules to allow transportation;
- a self-supporting structure based on a mechanically-reinforced conductor wound inside a thin mandrel to limit shear stresses in the insulation in spite of the large strain.

The design of the coil in five modules has been carried out at CEA Saclay, with a strong participation of INFN-Genova and ETH Zürich, and was completed at the end of 2000. An artist view of the coil is given on (Fig. 4).

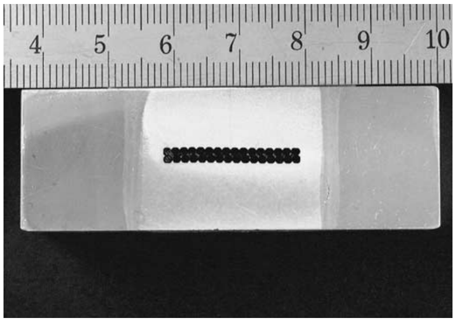

Fig. 5. Cross section of the CMS conductor. One can note the two alloy sections attached by Electron Beam welding to the pure aluminum insert comprising the 32-strand Rutherford cable.

B. The Conductor

One of the first major decisions taken at the very beginning of the project was to reinforce the pure aluminum conductor by welding, on each side of the so-called pure aluminum insert which contains the Rutherford cable, two aluminum-alloy sections to react to the magnetic force where it is created. This makes this component more complex than other aluminum-stabilized conductors previously used for thin solenoids. The cross section of the CMS conductor is shown in Fig. 5.

As the EB (Electron Beam) welding seams must be far enough from any sc. strand not to degrade it, the Rutherford cable has been limited to 32 strands, and thus the required current carrying capability of the strand has been pushed to the limit of what can be produced industrially, namely a j_c of 3140 $\mathrm{A/mm^2}$ at 5 T and 4.2 K. Monitoring of conductor quality is of major importance for such a project. In particular, an ultrasonic scanning system has been developed at EMPA (Swiss Federal Laboratories for Materials Testing and Research, Dübendorf, Switzerland) to monitor the quality of the bonding during extrusion and the quality of the welds during the EB welding operation; complete results are reported in [6]. At the end of the manufacturing process, integral samples of conductor are measured (after removing the reinforcement) in the Marisa facility at Genova [7]; in addition, extracted strands are measured at Saclay. All these measurements confirm that, in the worse conditions, the total degradation does not exceed 6% with respect to the virgin wire. A full analysis of the degradation is presented in [8]. Organization for the procurement and manufacture of the conductor have been reported in [4] and [9] respectively; detailed reports on the components can be found in [10]–[12].

Nineteen lengths (2.6 km long) have been successfully produced so far; two further lengths are needed and should be completed by October 2003.

The mechanical characteristic of the complete conductor is a fundamental parameter of the design of the coil. Numerous studies and tests have been performed to understand what will be the yield and ultimate strengths of the conductor at 4.5 K after winding and final heat treatment during the impregnation process. The results taken on the overall section of the as-produced conductor, $R_{p0.2} = 258\ \mathrm{MPa}$ and $R_m = 406\ \mathrm{MPa}$, are significantly better than the design values and they are reported in [13].

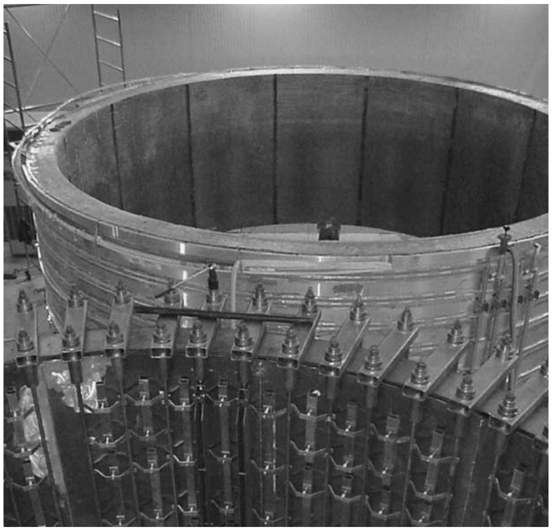

Fig. 6. First impregnated coil module in the rear, and second coil module ready to be impregnated in the front.

C. The Winding

The fact that the conductor is machined with precision at the exit of the EB welding line allows for a precise winding. After a pre-industrialization program to understand the behavior of such a stiff conductor, a final contract has been issued by INFN to Ansaldo (Genova, Italy) for the construction of the five coil modules.

One module is impregnated, a second module is ready to be impregnated (see Fig. 6) and the third module is being wound. Mechanical work is progressing on the two remaining mandrels. Detailed analysis of the module construction and winding is reported in [14].

The winding mandrels are an essential part of the cold mass as they are used also for cooling and quench-back in addition to being part of the coil mechanical structure. High-mechanical-characteristic aluminum alloys have been retained; Pechiney (France) has delivered the thick plates and Dembiermont (Haumont, France) the seamless flange rings. The mechanical performances of the mandrels have been studied and strictly followed during manufacture [15].

D. The Ancillaries

The coil will be cooled by helium circulating in the thermosiphon mode [16], [17]. The 1.5 kW external cryogenics sub-system has been designed by the LHC Cryogenic group at CERN, and procured from Air Liquide (Sassenage, France). The system is now ready to run using a dummy thermal load for commissioning the refrigerator in 2004 [18]. After connection to the coil at the end of 2004, it will be used in 2005 for the surface test of the magnet, then transferred in the underground area.

The bi-polar power converter (procured from EEI, Vicenza, Italy) will be located alongside the refrigerator cold box in the service cavern after being used for the test of the magnet. It delivers a current of 20 kA at a maximum ramping voltage of ±22 V, implying a charging time of 4 h. There are two modes for slow discharging the coil current:

- in normal operation discharge will be performed using the power converter;
- if the power converter is not available, the current can be dumped into the resistor bank set at its lowest resistance value of 2 $\mathrm{m}\Omega$.

The use of the bi-polar power converter should minimize down time of the experiment as the current will not have to be brought to zero each time the current has to be decreased. In case of emergency, a fast discharge in a 30 $\mathrm{m}\Omega$ resistor bank can be used; the time constant of the current decay is, in this case, 190 s. The discharge is activated by opening heavy duty contactors procured from Lenoir-Elec (Gorcy, France). The dump-resistor banks procured from Telema (Milan, Italy) have been positioned on the surface, 150 m from the coil, to minimize thermal disturbances in the underground experimental cavern due to the energy released during a discharge.

An important element of the electrical circuit, for the safety of the coil, is the two current leads. Those for CMS are 3 m long to cross the barrel yoke and they have been designed to stand the nominal current for 7 min to allow for a safe fast discharge. Better results have been obtained on the finished units [19].

The Magnet Control System is designed by the CERN EP Division in collaboration with Saclay. Its main feature is to distinguish with high reliability the fault situations requiring a fast discharge, from less severe fault conditions for which a slow discharge is sufficient. This is important to minimize the time lost for physics for CMS. Due to the large stored energy, more than three days will be necessary for re-cooling the coil down to 4.5 K after a fast discharge.

V. ASSEMBLY AND TEST OF THE MAGNET IN THE SURFACE HALL

It has been chosen to assemble and test the CMS magnet in a large surface hall (23.5 m high, that will be reduced later to 16 m) before lowering it into the underground experimental cavern situated at a depth of 90 m. The coil will be assembled with a vertical axis. The coil assembly will then be rotated to be cantilevered with horizontal axis, ready to be inserted inside the outer vacuum tank. This delicate operation will be performed in the surface hall using a large dedicated tool that has been manufactured by Doosan Heavy Industries (Chang-Won, Korea); the assembly procedure, has been fully tested in 2002 using the inner vacuum tank as test load. One phase can be seen in Fig. 7.

After insertion, the cold mass will be attached to the external vacuum tank by a set of titanium tie bars (in Ti 5Al 2.5Sn ELI) manufactured by Lutch (Podolsk, Russia). These tie bars will be fully tested under load at Saclay with one extremity at 4.5 K. Details of the suspension system and choice of material are reported in [20], [21].

The magnet will be fully tested at nominal field in the surface hall, using all ancillaries that will later be used in the underground area. At this occasion a precise mapping of the field will be performed inside the inner vacuum tank. Other magnetic measurements will also be made allowing normalization

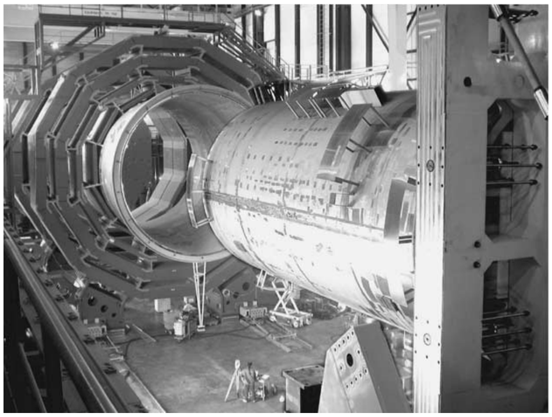

Fig. 7. Inner vacuum tank, simulating the coil cantilevered from the swiveling platform, ready to be inserted inside the outer vacuum tank.

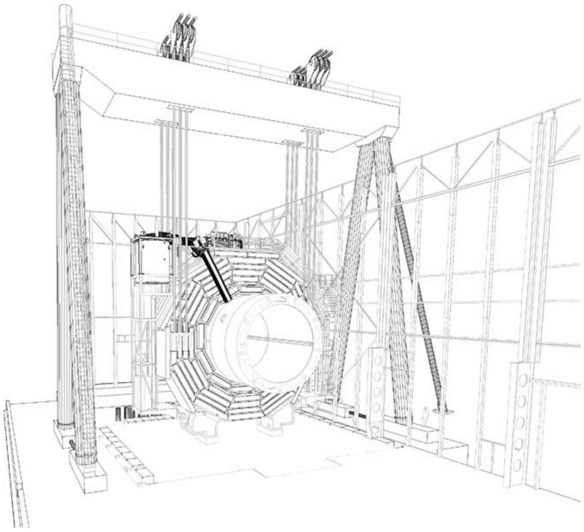

Fig. 8. The central barrel ring (with the coil inside the vacuum tank) on top of the shielding plug ready to be lifted by the gantry, to allow opening of the plug and lowering of the barrel ring through the shaft.

of the general field computation (performed using TOSCA from Vector Field) [22]. A very good field map should thus be available for particle tracking (including tracking of muons through the return yoke) at the very beginning of physics.

VI. Transferring in the Underground Area

After testing in the surface hall, the magnet will be lowered into the underground experimental cavern in 11 large pieces (5 barrel yoke rings, and 6 endcap disks) weighing from 500 to 2,000 tonnes. Thus, as shown in Fig. 8, heavy lifting means will have to be used.

The 20.4 m diameter shaft, giving access to the experimental cavern, will be separated from the surface hall by a 1,800-tonne mobile concrete plug, to be used as radiation shielding when LHC is operated. This plug, presently in construction, will also be used as temporary support structure allowing slinging of elements on top (and in the center) of the shaft (see again Figs. 8 and 9).

A market survey has been carried out to identify, world wide, competent companies ready to execute this maneuver.

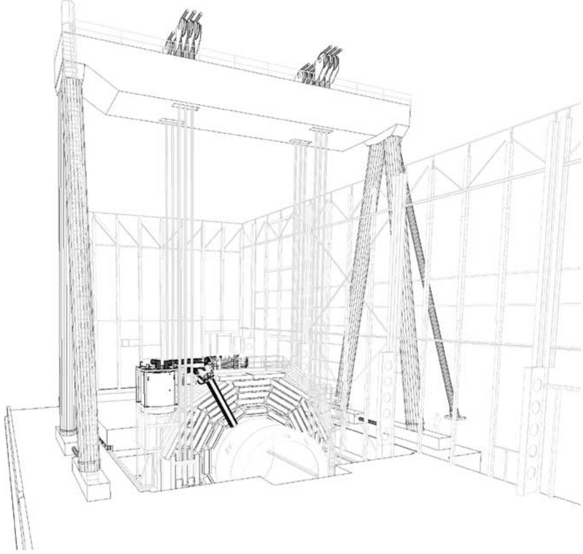

Fig. 9. After opening of the shielding plug, the central barrel ring is being lowered through the shaft by the gantry crane in the experimental area situated 90 m underground.

VII. Experimental Area

The experimental cavern has a diameter of 26.5 m and a length of 53 m. These are the minimum dimensions to allow opening of the CMS magnet for maintenance of the sub-detectors. The experimental cavern is separated from the service cavern by a 7 m thick shielding wall. In the service cavern will be situated the power converter, the contactors and the cold box. The dump resistor bank will be situated on the surface. Transfer lines and bus bars will cross the shielding wall at an angle not to degrade the shielding characteristics of the wall and thus, the service cavern will be always accessible, even when the LHC collider will run at the highest luminosity.

VIII. Cost Estimate

The total cost of the CMS magnet was estimated at the start of the project to be 122.3 MCHF (Million Swiss Francs), in 1995 prices, and today 111 MCH (i.e., 91%) have been spent or committed. The major barrel and endcap contracts have generally cost slightly below estimate; however, ancillary equipment has generally cost more. The ‘cost to complete’ of the CMS Magnet Project has been recently estimated at 15 MCHF, bringing the total cost estimate, in current prices, at 126 MCHF, i.e., an increase of 3.1%. The present breakdown is: 49 MCHF for the return yoke, 69.5 MCHF for the coil and its ancillaries, and 7.5 MCHF for the transfer and installation underground.

IX. Conclusion

The CMS magnet project is in construction, in full compatibility with the design of the sub-detectors. The underground experimental area, which is mainly constrained by the magnet requirements, is nearing completion and will be accessible in July 2004. For this reason the magnet is being assembled in the surface hall where it will be tested in 2005 before being transferred into the underground area by heavy lifting means. The surface hall has been delivered in mid 2000, allowing to start the magnet installation. The assembly of the magnetic yoke (barrel and endcaps) is finished. Eighteen 2.6 km lengths of conductor (out of twenty needed for the coil) have been produced. The first coil module has been impregnated, the second one is ready to be impregnated and the third module is being wound. After couplin a module to the next one at Ansaldo, this module will be sent to CERN, first by ship to Mâcon in France, then by road. The five coil modules will be assembled in the surface hall for the end of 2004, and the full test of the magnet will start in March 2005.

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