# The CMS Detector Magnet

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*Abstract* — **CMS (Compact Muon Solenoid) is a general-purpose detector designed to run in mid-2005 at the highest luminosity at the LHC at CERN. Its distinctive features include a 6 m free bore diameter, 12.5 m long, 4 T superconducting solenoid enclosed inside a 10,000 tonne return yoke. The magnet will be assembled and tested on the surface by the end of 2003 before being transferred by heavy lifting means to a 90 m deep underground experimental area.**

**The design and construction of the magnet is a 'common project' of the CMS Collaboration. It is organized by a CERN based group with strong technical and contractual participation by CEA Saclay, ETH Zürich, Fermilab Batavia IL, INFN Genova, ITEP Moscow, University of Wisconsin and CERN.**

**The return yoke, 21 m long and 14 m in diameter, is equivalent to 1.5 m of saturated iron interleaved with four muon stations. The yoke and the vacuum tank are being manufactured.**

**The indirectly-cooled, pure-aluminium-stabilized coil is made up from five modules internally wound with four layers of a 20 kA mechanically reinforced conductor. The contracts for the conductor and the outer cryogenics have just been awarded, and the remaining coil parts, including winding, are being tendered worldwide in industry.**

**The project is described, with emphasis on the present status.**

## I. INTRODUCTION

CMS (Compact Muon Solenoid) is a general-purpose proton-proton detector designed to run at the highest luminosity at the LHC [1]. Distinctive features of CMS 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 a good momentum resolution, without making stringent demands on the spatial resolution and the alignment of muon chambers, leads naturally to the choice of a high solenoidal magnetic field.

A long superconducting solenoid (L = 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 calorimetry.

The magnetic flux is returned via a 1.5 m thick saturated iron yoke instrumented with four stations of muon chambers, and the yoke is thick enough to allow safe identification and to enable a powerful trigger on muons.

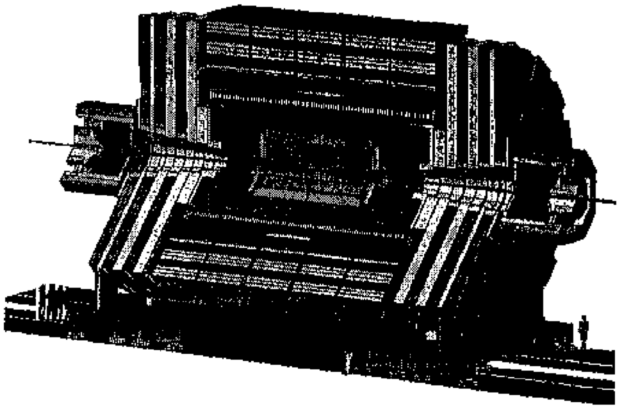

Fig. 1. Perspective view of the CMS experiment, showing the coil (outside the Hadronic Calorimeter) and surrounded by the three layers of iron (in fair color) in the barrel and in the endcaps.

The CMS experiment is built and funded by an international collaboration of High Energy Physics institutes from thirty one countries‡ and by CERN. The experiment will be installed on the interaction point I5 of LHC at a depth of 90 m below ground.

The design field of the solenoid is 4 T. The operating field requested by the CMS collaboration is between 3.5 to 4 T, 3 T being the minimum field required for doing good physics. The design has thus been carried out to maximize the chance of reaching 4 Tesla. This explains why, except for mechanical safety margins which are clearly conventional, other 'state of the art' safety margins like strain, stability, Ic margin, etc., are not necessarily met at 4 Tesla. In fact, apart for the amount of superconductor, a 3.5 T 'standard thin' solenoid would be practically identical.

The CMS magnet is first assembled and tested in a surface hall (Fig. 7) then lowered in the underground area (Fig. 9) by heavy lifting means. This allows to decouple the work on the magnet assembly and test from the construction of the underground area.

The CMS magnet consists of two main parts: the yoke and the coil, a perspective view of the open magnet can be seen in Fig. 2.

The return yoke is a 12-sided structure divided in three main components: the barrel yoke and the two endcap yokes. Its main parameters are given in Table I.

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‡ Armenia, Austria, Belarus, Belgium, Bulgaria, China, Croatia, Cyprus, Estonia, Finland, France, Georgia, Germany, Greece, Hungary, India, Italy, Korea, Pakistan, Poland, Portugal, Russia, Slovak Republic, Spain, Switzerland, Taiwan, Turkey, Ukraine, United Kingdom, United States of America and Uzbekistan.

TABLE I

Main parameters of the return yoke

| | |
|---|---|
| General outer diameter on flats | 14 m |
| Length of barrel part | 13 m |
| Thickness of iron layers in barrel | 300, 630 & 630 mm |
| Mass of iron in barrel | 6000 tonnes |
| Thickness of disks in endcap | 600, 600 & 250 mm |
| Mass of iron in each endcap | 2000 tonnes |
| Total mass of iron in return yoke | 10000 tonnes |

The coil is an indirectly cooled, aluminium stabilized, four layer superconducting solenoid. Its main parameters are given in Table II.

TABLE II

Main parameters of the coil

| | |
|---|---|
| Magnetic length | 12.5 m |
| Free bore diameter | 6 m |
| Radial thickness of cold mass | 312 mm |
| Weight of cold mass | 220 tonnes |
| Central magnetic induction | 4 T |
| Maximum induction on conductor | 4.6 T |
| Total ampere-turns | 42.5 MA-turns |
| Nominal current | 20 kA |
| Inductance | 14 H |
| Stored energy | 2.6 GJ |

Extensive 3D magnetic models have been developed to optimize the field map and obtain the magnitude of the magnetic forces both for the yoke and the coil [3]; these results have been used to dimension the coil [7].

## II. The Return Yoke

### A. The Barrel Yoke

The barrel yoke was designed at CERN. It is split into five barrel rings, having each a mass of 1200 tonnes, which can move in the axial direction to give access to the barrel muon stations. For the barrel rings, the only load is gravity, magnetic field introducing only axial forces on the rings. The central barrel ring supports the vacuum tank housing the coil. The vacuum tank, made of stainless steel plates 60 and 30 mm thick, will be welded around the coil.

A large contract has been placed by ETH Zürich for the construction of the barrel yoke and the vacuum tank with DWE (Deggendorfer Werft und Eisenbau, Deggendorf, Germany). This contract is financed by a CMS consortium (CMS 'common fund', Cyprus, Germany, Russia, USA and Switzerland).

The 450 mm thick heavy plates, necessary for the compound 630 mm thick outer layers, have been subcontracted to Izhora Zavod (St Petersburg, Russia).

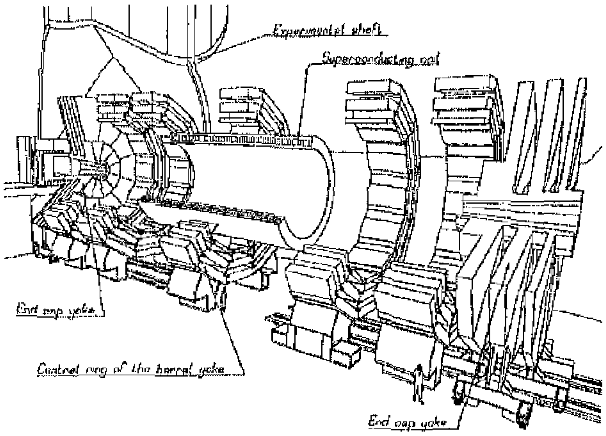

Fig. 2. Perspective view of the CMS magnet, in the opened position, without any subdetector.

The support feet for the outer barrel rings are being manufactured, as an in-kind Pakistani contribution, by SES (Islamabad, Pakistan).

A complete trial assembly is carried out at DWE, using a Ferris-wheel arrangement (see Fig. 3), and the first ring has just been assembled before shipment to CERN. Later, the final assembly of the barrel yoke will be performed at the CERN site by a consortium DWE/FCI, starting in July 2000.

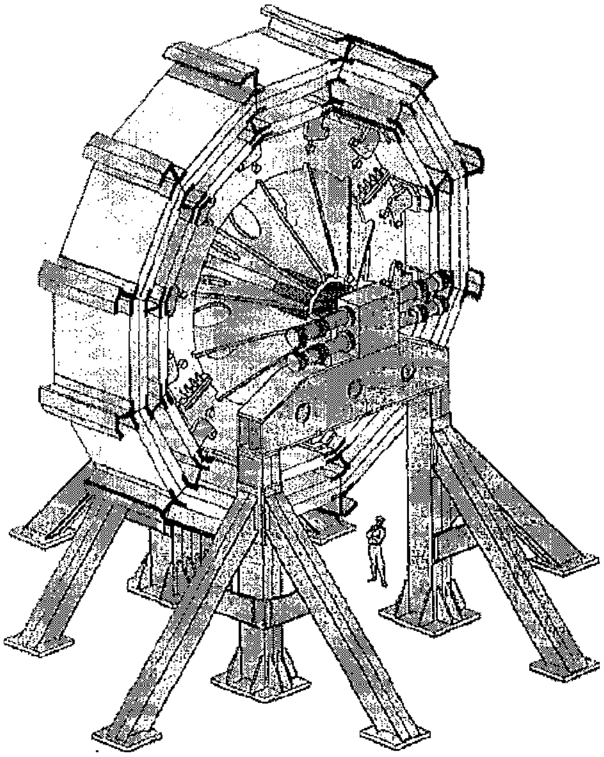

Fig. 3. Perspective view of the Ferris-wheel arrangement for the assembly of the barrel rings, shown here with two layers of absorber.

### B. The Endcap Yoke

Each endcap yoke, designed at the University of Wisconsin, is built from three independent disks which can be moved on carts (as seen on Fig. 2.), and separated to provide access to the forward muon stations and inner subdetectors. Due to the axial magnetic field the two inner disks must withstand an attraction force of about 85 MN and resist the large bending moment induced. Therefore these disks are 600 mm thick whereas the outer disk is only 250 mm thick. The disks are built from sectors connected together by large bolts (Superbolt, Carnegie, PA, USA) taking each up to 250 MN.

A contract has been signed at the end of 1998 with Kawasaki Heavy Industries (Kobe, Japan). This is a University of Wisconsin contract, with full financing from DOE.

The endcap carts are being manufactured as an in-kind Chinese contribution by HHM (Hudong Heavy Machinery, Shanghai, China).

A trial assembly of each half endcap disk will be done at Kawasaki. Later, the final assembly of the endcaps will be performed at the CERN site by FCI (Franc Comtoise Industrie, Lons le Saunier, France) starting in March 2001.

## III. 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, because it is not subject to substantial external sources of disturbances.

Important information can be 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 [4]. In particular the thermosiphon cooling mode has been retained. However, the CMS coil cannot be simply extrapolated from ALEPH; because of the very large increase in magnetic field (from 1.5 to 4 T) and the requirement of limited radial thickness, the strain at 4 T is 0.15 % [5].

The main changes introduced for the CMS coil design are:

- a four-layer winding instead of a mono-layer one to provide the needed ampere-turns,
- a construction in five modules to allow transportation,
- a self supporting winding mechanical 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 definition of the concept and the general engineering of the coil is a sub-collaboration between CEA Saclay and CERN/CMS. An agreement to this effect has been signed between CERN (acting for CMS) and CEA Saclay.

The design of the coil in 5 modules has been carried out with a strong participation of INFN-Genova and ETH Zürich. The design is now finished. An artist view of the coil is given on Fig. 4, and the detailed status of the coil design is reported in [6].

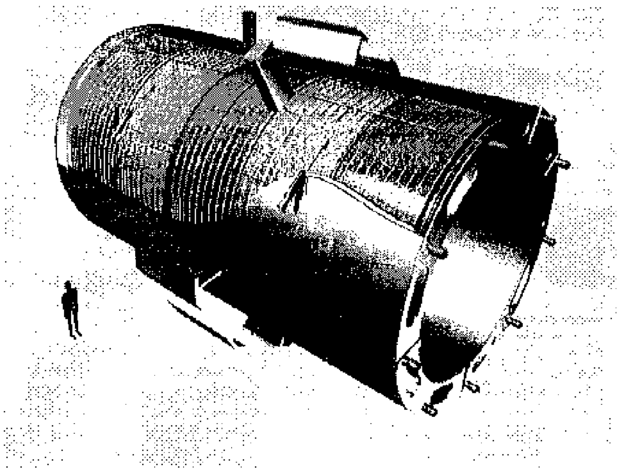

Fig. 4. Perspective view of the CMS coil inside the vacuum tank showing the five modules .

### B. The Conductor

The design of a self supporting structure obtained by mechanically reinforcing the conductor† makes this component more complex than other aluminium stabilized conductors previously used for thin solenoids. The dimensions and the component proportions are determined by the general coil design according to the mechanical strength, quench protection and stability requirements.

It has been decided to reinforce the pure aluminium conductor by welding two aluminium alloy sections. Electron Beam welding processes have been developed at ETH Zürich and CERN Main Workshop during the last years. Cross section of the CMS conductor is shown in Fig. 5, and detailed studies on the CMS conductor are reported in [8], [9] and [12].

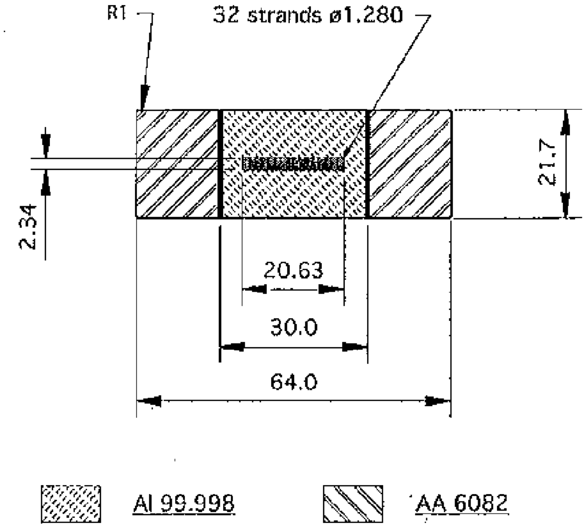

Fig. 5. Cross section of the CMS conductor. One can note the two aluminium alloy sections welded by Electron Beam welding technique to the pure aluminium stabilizer.

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† The concept of mechanically reinforcing the conductor has been originally proposed by Jean-Claude Lottin [5].

The design and procurement of the conductor is a sub-collaboration between CERN/CMS, Fermilab and ETH Zürich. An agreement has been signed to this effect with CERN acting for CMS. Several large procurements have been identified and have been organized by institutes as follows:

- Sc strands: Fermilab, contract 60 % to Outokumpu (Pori, Finland) and 40 % to IGC (Waterbury, CT, USA),
- Pure aluminium billets: Fermilab, contract to Sumitomo Chemical Company Ltd. (Tokyo, Japan),
- Aluminium alloy sections: Fermilab, is being tendered,
- Cabling as Rutherford cable: ETH Zürich, two orders to Kablewerk Brugg (Brugg, Switzerland),
- Coextrusion of pure aluminium: ETH Zürich, frame contract to ACS (Alcatel Cable Swiss, Cortaillod, Switzerland),
- Electron Beam Welding of reinforcement sections: ETH Zürich, contract to Techmeta (Metz-Tessy, France).

### *C. The Winding*

A pre-industrialization program for the winding pre-industrialization is in progress, under financial and technical control of INFN. This program was aimed 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. Studies on insulation and mandrel manufacture are reported in [11] and [13]. Fig. 6 shows a view of the tool which has been used to develop the winding concept.

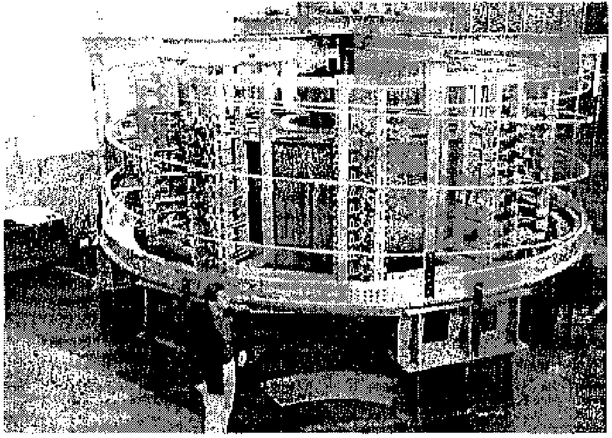

Fig. 6. View of the transferring tooling system used for the winding pre-industrialization.

The coil winding procurement is a sub-collaboration between CERN and INFN. An agreement to this effect has been signed between CERN (acting for CMS) and INFN. An international tender has been issued by INFN, and answers are currently under examination.

### *D. The Ancillaries*

The 1.5 kW external cryogenics sub-system, which is designed by the LHC Cryogenic group at CERN, comprises the compressors, the cold box, the vessels containing 200 $m^3$ of pressurized helium gas, the 6000 $\ell$ LHe container and the cryogenic lines. The cold box and LHe container will be installed near the magnet whereas the compressors and pressure vessels will be installed at the surface level. The complete system will be run temporarily on the surface for refrigerator commissioning and coil tests, as shown in Fig. 7. The contract for the outer cryogenics has been recently awarded by CERN to Air Liquide (Sassenage, France).

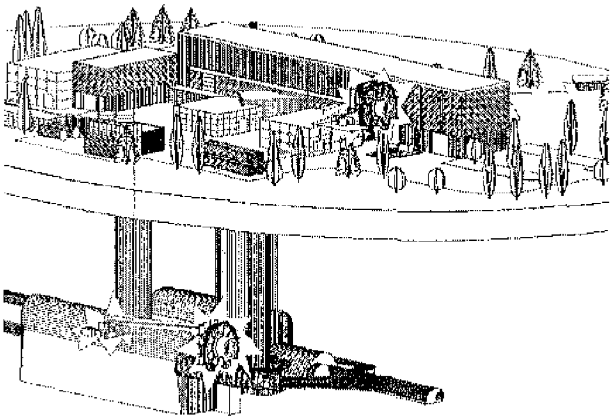

Fig. 7. Perspective view of the CMS experimental area, showing the surface position of the coil for the test of the magnet, and the final underground position around the interaction point.

The bi-polar power supply is located alongside the refrigerator cold box in the service cavern. It will deliver a current of 20 kA at a maximum ramping voltage of 22 V allowing 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 supply, or the current can be dumped into the resistor bank set at its lowest resistance value of 2 mΩ. In case of emergency, a fast discharge in a 30 mΩ resistor bank can be used; the time constant of the current decay is, in this case, 460 s.

As the temperature of the cold mass may reach 60 K after a fast discharge, then needing 3 days for re-cooling, a great effort will be made to make sure that fast discharges are only triggered by the most important alarms.

## IV. THE EXPERIMENTAL AREA

It has been chosen to assemble and test the 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 insertion of the coil inside the vacuum tank is performed in the surface hall. It requires to bring, and maintain, the 220-tonne coil horizontally in a cantilevered position. The rotation is done using the same Ferris-wheel arrangement used to assemble the barrel rings as shown in Fig. 3. Then, the central barrel ring already equipped with the outer shell of the vacuum tank will slide on heavy duty air pads over the coil which will then be suspended to the outer shell using titanium tie-bars. The same procedure will be used to slide the central-barrel-ring/coil assembly over the inner shell of the vacuum tank.

As shown in Fig. 9, heavy lifting means will have to be used as the heaviest part will weigh 2000 tonnes.

The choice of using a large surface hall rather than the underground area, allows to construct and test the magnet in parallel with the civil engineering. In fact it allows to start working on the magnet assembly already in July 2000 while LEP is still in operation. This solution also reduces to the minimum the size of the underground cavern.

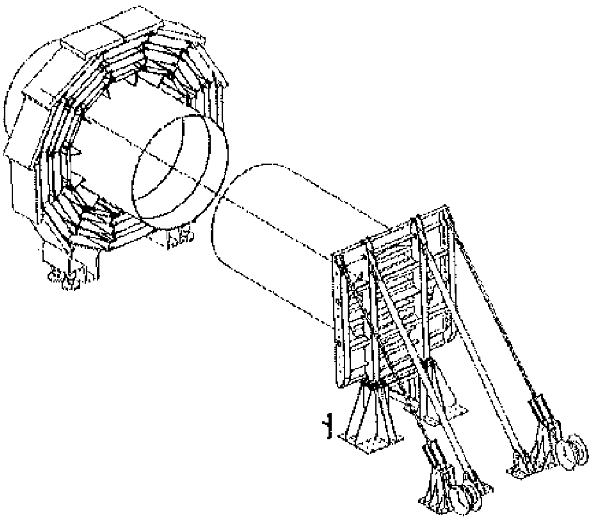

Fig. 8. Perspective view of the coil in a cantilevered position. The central barrel ring, equipped with the outer shell of the vacuum tank is ready to be slid, using heavy duty air-pads†, over the coil

The 20.4 m diameter shaft, giving access to the experimental cavern, will be separated from the surface hall by a 2000-tonne mobile radiation shielding plug which will also be used as support structure for the transfer of the magnet to the experimental cavern (see also Fig. 9).

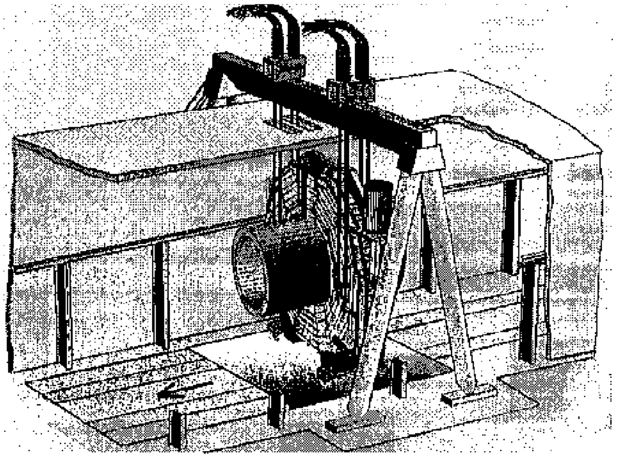

Fig. 9. Perspective view of the lifting of the central barrel ring supporting the cantilevered vacuum tank containing the coil equipped with valve box and 6000 ℓ dewar. The assembly shown here weighs 2000 tonnes. One can notice the shielding plug (in the open position, marked by the arrow) which is used to support the various pieces over the main shaft before slinging.

The experimental cavern has a diameter of 26.5 m and a length of 53 m. These are the minimum dimensions to open the CMS magnet and handle the major components.

The experimental cavern is separated from the service cavern by a 7 m-thick shielding wall.

The magnet will be lowered in 11 large pieces, (weighing from 500 to 2000 tonnes) into the underground experimental cavern. The coil will be connected to the ancillaries situated in the service cavern by bus bars and transfer lines, as seen on Fig. 10. A contract for the outer cryogenics has just been awarded by CERN to Air-Liquide (Sassenage, France).

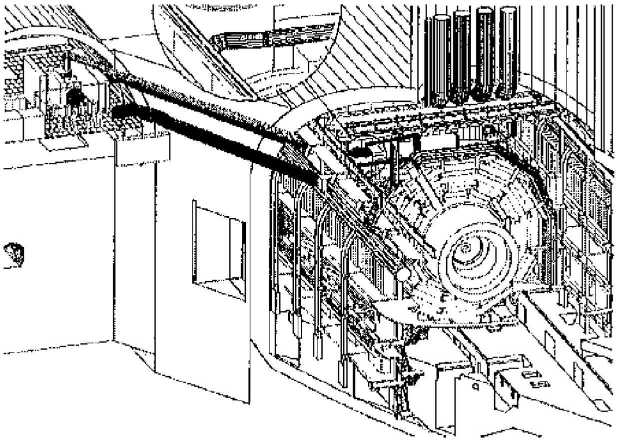

Fig. 10. Perspective view of the CMS magnet inside the experimental cavern; the bus bar and transfer line connections to the power supply and cold box in the service cavern cross the 7 m thick shielding wall.

## V. Organization of the Magnet Project

### A. *Participating Institutes*

The CMS magnet project can be grouped into three main parts 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 systems 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 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 yoke in collaboration with CERN/CMS,
- Fermilab is in charge 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 and maintenance, like:

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† 250 and 385 tonne units made by Noell (Erdmansdorf, Germany)

power supply, breakers, outer cryogenics, process control etc....

### *B. Organization of Procurements*

Major procurements are organized, when possible, following this distribution of tasks by asking participating institutes to place direct contracts in industry. In fact, procurements for the magnet project, which is a 'Common Project' of the CMS Collaboration, can be done in 3 ways :

- as in-kind contributions,
- as direct payments to contracts,
- as payment to a 'common fund'.

At present, only two in-kind contributions have been identified, but several large contracts have been placed directly by the participating institutes. The present distribution, normalized to the total cost is:

- payments in-kind: 2 %
- payments to contracts: 63 %
- payments to the 'common fund': 35 %

For large contracts, a Market-Survey is first conducted by the CERN SPL division. Contracts are awarded and funded by Institutes, or by CERN using the 'common fund', after international tendering following the local pertaining rules. Industries from countries members of CMS or/and CERN are always contacted, but very often the tendering is done world-wide.

### *C. Cost Estimate*

The total cost of the CMS magnet has been estimated, in 1995 prices, to 121.8 MCHF†. The barrel and endcap contracts have cost below estimate. Two MCHF have been attributed to the conductor manufacture for producing possible spare unit lengths; 1 MCHF have been allocated to the heavy lifting operation and 1 MCHF have been kept in reserve. Other large contracts are presently below or at the cost estimate, and today nearly 60 % is committed. The present break down is: 46 MCHF for the return yoke, 69.5 MCHF for the coil and its ancillaries and 6 MCHF for transfer and installation underground.

## VI. CONCLUSIONS

The CMS magnet project is in construction, in full coherence with the design of the sub-detectors. In particular the construction of the yoke is well advanced and the final assembly at the CERN site will start, in the surface building at Point 5 of LHC, in July 2000.

The major contracts for the manufacture of the conductor have been awarded; the offers for the winding operation are being examined and the order is expected to be awarded before the end of 1999.

The experimental area, which is mainly constrained by the magnet requirements, is in construction, and the first part of the surface hall will be delivered as foreseen, already equipped with two 80-tonne cranes, in March 2000. Assembly will start in July with the barrel yoke, followed by the endcap yoke. The assembly of the five coil modules and their insertion in the vacuum tank will follow. The magnet will be tested in the surface hall in late 2003, before being transferred in the underground area by heavy lifting means.

The schedule has been optimized, and the critical path follows clearly the procurement of the conductor and especially the winding operation.

Thus, the CMS magnet project has fully entered the construction phase; however, the schedule is tight, but the project is on schedule and on budget.

## ACKNOWLEDGEMENT

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† One Million Swiss Franc = 650,000 US $ in September 1999.