Chapter 1

Constructing a 4-Tesla large thin solenoid at the limit of what can be safely operated

A. Hervé[‡]

ETH Zürich
Institute for Particle Physics
Schafmattstrasse 20
8093 Zürich, Switzerland
alain.herve@cern.ch

The 4-Tesla, 6-m free bore CMS solenoid[§] has been successfully tested, operated and mapped at CERN during the autumn of 2006 in a surface hall and fully recommissioned in the underground experimental area in the autumn 2008. The conceptual desing started in 1990, the R&D studies in 1993 and the construction was approved in 1997. At the time the main parameters of this project were considered beyond what was thought possible as, in particular, the total stored magnetic energy reaches 2.6 GJ for a specific magnetic energy density exceeding 11 kJ/kg of cold mass. During this period, the international design and construction team[¶] had to make several important technical choices, in particular mechanical, to maximize the chances of reaching the nominal induction of 4Tesla. These design choices are explained and critically reviewed in the light of what is presently known to determine if better solutions would be possible today for constructing a new large high-field thin solenoid for a future detector magnet.

1.1. The Role of the Coil in the Experiment Lay-out

The 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

[‡]Previously at CERN, 1211 Geneva 23, Switzerland.

[§]A full bibliography for the CMS magnet in general and the coil in particular, together with the list of all collaborators, can be found at url: `http://edms.cern.ch/document/CMS-SG-MG-0002`.

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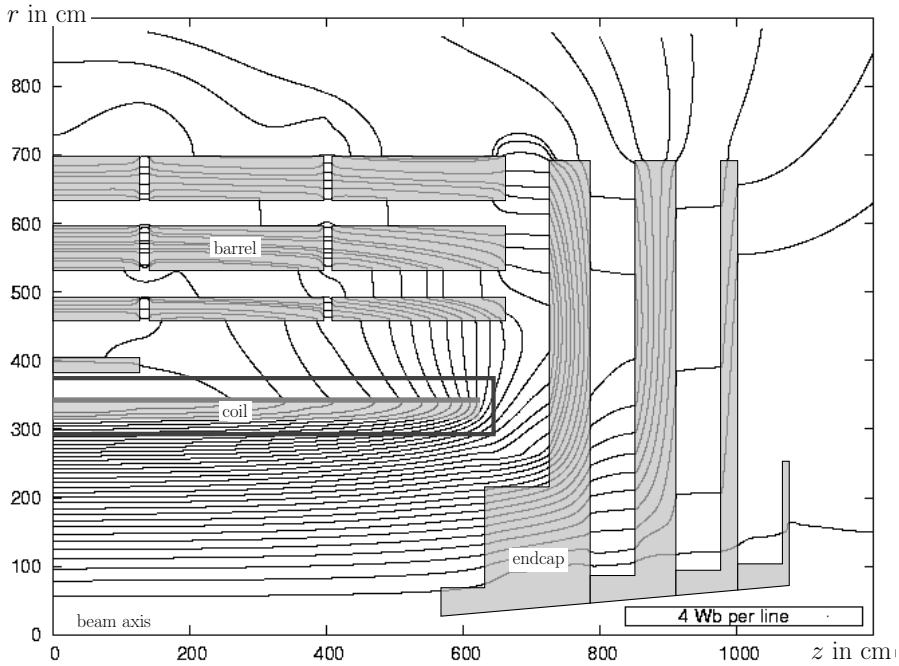

Fig. 1.1. Field lines of the CMS magnet. The coil is shown inside the cryostat, together with the iron masses of the return yoke leaving large pockets in the barrel section and large gaps in the endcap section to insert the four stations of muon stations.

with a free inner diameter of 6 m and a uniform magnetic induction of 4 T. The muon spectrometer then consists of a single magnet allowing for a simpler architecture of 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, see Fig. 1.1. The CMS magnet[1] is thus the backbone of the CMS experiment as all sub-detectors are supported from it, see Fig. 1.2. It must be noted that the thickness of the CMS yoke is minimal as a non negligible stray field is acceptable; this maybe different for future projects which plan to use a push-pull scenario accomodating for two near-by experiments.

The magnet has been assembled,[2] tested[3,4] and mapped[5] in a surface hall during the autumn 2006, and it has been lowered in the underground area by heavy lifting means, see Fig. 1.3. This bold choice has decoupled the work on the magnet assembly and test from the construction of the experimental area. The magnet has been fully re-commissioned underground during the Autumn 2008.

1.2. Coil Description

The coil is an indirectly-cooled, aluminum-stabilized, four-layer superconducting thin solenoid built in five modules. Its main parameters are given in Table1.1.

For physics reasons, the radial extent of the coil had to be kept small, and thus

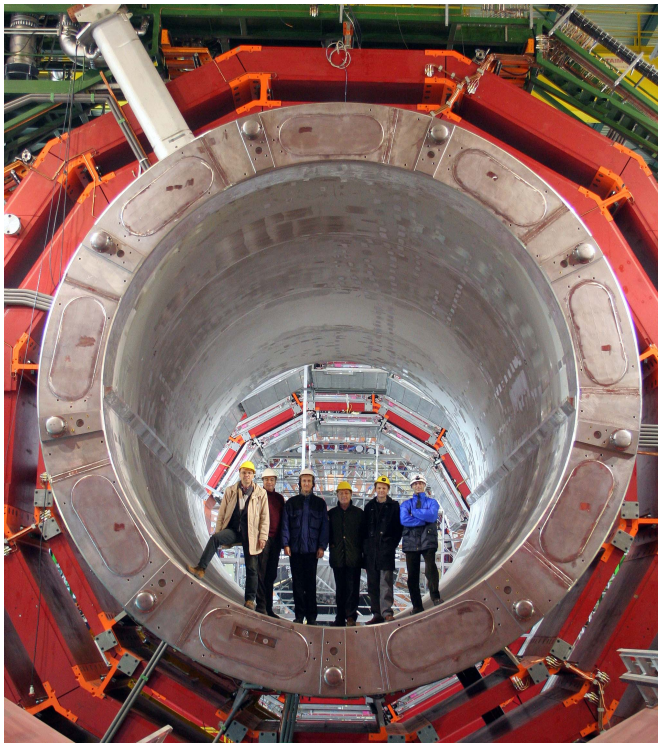

Fig. 1.2. View of the coil before the installation of any detector; one can see the pockets in the barrel return yoke to receive the muon stations, and the two side rails imbedded in the inner vacuum vessel to support the hadronic calorimeter barrel.

the CMS coil is in effect a 'thin coil'. The thickness of the coil is 3.9 X_0 (radiation length) and the specific energy ratio is 11.6 kJ/kg of cold mass. As seen in Fig. 11 of Ch. 1 this parameter compares favorably with other thin coils.

The coil has been 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.

The first large superconducting detector magnets appeared in the beginning of the 70's at CERN and DESY; the Cello and TPC magnets were the first thin solenoids ever built, culminating with the construction of the Topaz, Aleph and Delphi magnets at the end of the 80's (see[6] for a full review of the detector magnets). Thus very naturally at the inception of the CMS project, in 1990, the Aleph solenoid[7] has been taken as a demonstrator, and several of its good points were directly adopted:

(i) Use of NbTi with pure-aluminum stabilization, and aluminum-alloy construction to prevent problems with differential thermal contraction.

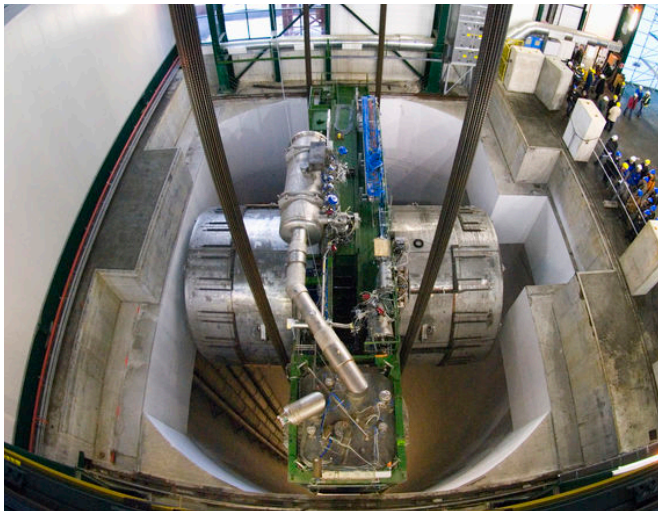

Fig. 1.3. View of the coil supported from the central section of the barrel yoke, a 2000-ton load, being lowered in the experimental area by heavy lifting means through the 15 m × 21 m shaft opening. It took 10 hours to reach destination 100 meters below.

Table 1.1. Main parameters of the CMS Coil.

Parameter	Value
Magnetic length	12.5 m
Free bore diameter	6.0 m
Central magnetic induction	4.0 T
Maximum induction on conductor	4.6 T
Nominal current	19 140 A
Average inductance	14.2 H
Stored magnetic energy	2.6 GJ
Stored energy per unit of cold mass	11.6 kJ/kg
Operating temperature	4.5 K
Temperature stability margin	1.8 K

(ii) Target 1.8 K for the stability margin.
(iii) Use an external mandrel to support an indirect cooling loop, and inner winding of the coil insulated with fiberglass and epoxy resin, potted using vacuum impregnation.
(iv) Take advantage of the external mandrel to benefit of a passive protection scheme based on the quench-back effect.
(v) Keep the mean temperature of the coil below 130 K if all the magnetic energy is taken by the enthalpy of the cold mass, in case of malfunctioning of the active elements of the protection system, and 80 K in normal cases.

1.3. Challenges of Large High-Field Epoxy Potted Superconducting Coils

1.3.1. *Quench protection method*

The protection of the coil in case of a quench is considered the most critical issue because of the large stored magnetic energy. The coil protection system is based on the so-called quench-back effect and discharging the coil on outer resistors.

The winding cylinder configuration is basically a current transformer in which the winding acts as the primary and the cylinder as the secondary. During normal coil operation or slow discharge, the induced current in the coil cylinder is negligible due to the very low rate of current variation. When a fast current decrease occurs the induced loss is sufficient to heat the mandrel and drive the coil everywhere to the normal state within few tens of seconds.

1.3.2. *Thermosiphon cooling method*

The thermosiphon cooling method[8] has been chosen because it operates continuously without the need of active pumps. In the case of a quench it spontaneously switches off, and give rise to a limited pressure rise because of the small quantity of liquid helium involved in the cooling circuit.

1.3.3. *Enthalpy stabilization*

A superconducting coil is stable if the local thermal capacity is sufficiently large to prevent excessive temperature rise. In contrast to total cryo-stability, enthalpy stabilization only allows limited thermal disturbances. This is acceptable for detector magnets as these perturbations can only be mechanical, epoxy cracking or conductor slippage.

The choice of a low current density ($\sim 30\,\%$ of today's state-of-the-art critical current density of 3000 A/mm^2 at 4.5 K under 4.6 T) results in a relatively high critical temperature of 6.3 K, giving a temperature safety margin of 1.8 K for a working temperature of 4.5 K at nominal current. Because of the presence of the low resistivity stabilizer and the heat diffusion within the winding, even short local transient temperature excursions into the resistive domain are supported.[9,10]

1.3.4. *Mechanical stresses and strains*

The Lorentz's force $\vec{f} = \vec{I} \wedge \vec{B}$ creates magnetic forces that increase quadratically with the field because B is proportional to I. As a first approximation the solenoid can be considered as a thin tube submitted to an internal pressure $B^2/(2\mu_0)$. For large coils up to 1.5 T, this was not a real concern, however, as B goes over 2.5 to 3 T, the electrical conductor alone is not sufficient to safely contain this pressure. Structural material (aluminum alloy) has to be added either as a thick mandrel or

more efficiently on the conductor itself to create a compound conductor.

In addition to the internal pressure due to the interaction of the current with the axial component of $\vec{B}$, one must not neglect the large compressive forces inside the coil due to the interaction of the current with the radial component of $\vec{B}$. This effect increases with B as the magnetic permeability of the end cap iron is decreasing rapidly with B; more flux tends to cross directly the coil without going to the end cap (see Fig. 1.1). This axial stress has to be added quadratically to the hoop stress (or alternatively the equivalent von Mises stress has to be considered) to determine the actual stress of the material and compare it to the allowable stress compatible with construction codes. In addition, everywhere inside the coil, the local strain on the stabilizer must be kept under control and, also for this, the use of a compound conductor has been considered beneficial.

1.3.5. *Glass-epoxy insulation*

The elegance and efficiency in the design and construction of this type of coils is coming from the use of glass-fiber potted with epoxy to ensure the electrical insulation from turn to turn, layer to layer and towards the mandrel. This electrical insulation is also used as 'glue' between all these elements to make the cold mass behave as a mechanically solid structural element. In addition this 'glue' is used as 'thermal conducting compound' to ensure good thermal conduction between turns and between layers towards the mandrel which is the only element cooled by circulating helium (see Fig. 1.4).

Needless to say that the good quality and stability with time of the glass-fiber-epoxy compound is fundamental to the good behavior and functioning of this type of coil, and the designer is constantly looking for solutions that decrease the shear stress on glass-fiber-epoxy boundaries. Not only any cracking of the insulation would lower the mechanical and thermal behavior of the coil but, in addition, it must be realized that the sudden cracking of a small portion of insulation when ramping the field is sufficient to generate enough heat to quench the coil. When the central field increases the general strain increases and the glass-fiber-epoxy compound is submitted to higher and higher dangerous stresses.

This is worrying as the integrity of the glass-fiber-epoxy compound is depending on its good sticking to the surfaces of the conductor and mandrel, and this sticking is depending on the good cleaning and degreasing, sand-blasting, geometrical quality of the previous layer and perfect vacuum impregnation process, all operations that are difficult to control for a large coil. The design specification of CMS mentioned that no part of the insulation should be in tension (only compression stress is allowed) and the shear stress should not exceed 30 MPa. In fact this is possible using the compound conductor and orienting the design to keep the shear stress under control everywhere, in particular near module to module interfaces.

1.4. Departing Parameters

Although the general Aleph design has been adopted, numerous improvements were needed to match the challenge of increasing the central induction to 4 T, namely:

(i) Even choosing a much higher current (20 kA), a four-layer construction in 5 modules is needed. This imposes new constraints on the quality of the winding process to keep the geometrical quality, layer after layer.
(ii) The equivalent magnetic pressure of 64 bars acting on the coil necessitates the use of high-strength aluminum alloys for structural elements.
(iii) The founding assumption of the CMS design, introduced by J.C. Lottin†,[11] was to position this high-strength aluminum alloy in direct contact with the conductor to create, in effect, a compound reinforced conductor.
(iv) The circumferential hoop-strain has to reach 0.15 % to stay within a reasonable thickness for the cold mass (310 mm) so that the radial extent of the coil system including the vacuum vessel is limited to 850 mm.
(v) In addition to the hoop-stress, a very large axial magnetic force inducing axial stresses has to be transmitted from module to module.
(vi) The stored magnetic energy being 2.6 GJ, the energy density per unit of cold mass reaches 11.6 kJ/kg, and this placed the coil away in the parameter space compared to previous superconducting solenoids (see Fig. 11 of Ch. 1), and clearly innovative solutions were needed to meet this challenging positioning.

1.5. The Compound Conductor

The classical aluminum stabilized conductor is a soft component, not able to sustain high working stresses. In the previous solenoids the magnetic stresses are low enough to be transferred to the aluminum alloy external cylinder. For CMS, this force containment method would lead to a thick external cylinder and to excessive shear stresses especially at the winding-mandrel interface. By associating directly to the conductor most of the required structural material, the winding becomes a self-supporting structure, (see Fig. 1.4).

1.6. Design Challenges at the Inception of the Project

The main design challenges have been identified, very early on, as the following:

(i) How to obtain a stabilized conductor having the necessary section to provide the 1.8 K stability margin? One must consider that the section of the stabilized superconducting element (the insert in Fig.1.5) is an order of magnitude larger than what had been produced up to 1990.
(ii) How to get a compound conductor having the necessary mechanical strength? Using a compound reinforced conductor has always been considered, by the

design team, the only way to allow controlling strains, and keep low shear stress in the insulation. The fact that there is only one element to wind (with an excellent geometry due to the final in-line milling) eases the challenges of producing a high quality multi-layer winding. Also, if well chosen, the reinforcing alloy sections even harden during the curing process; meaning that the ultimate elastic limit is obtained only after the winding process is completed.

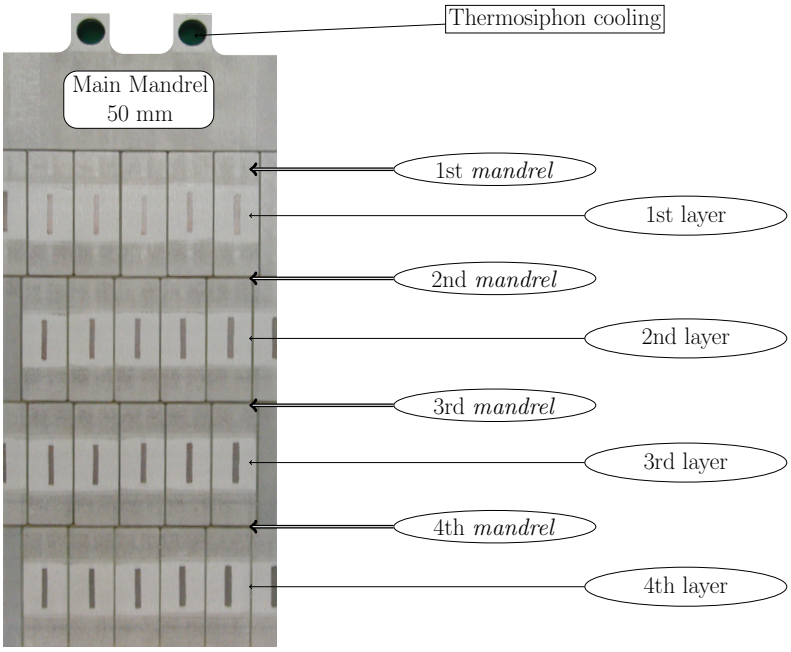

Fig. 1.4. View through a cut or the CMS coil. It must be noted how the glued combined reinforcement sections provide in effect individual *mandrels* for each layer of current carrying elements where the magnetic forces are created. The external mandrel is only 50 mm thick, and cooling is insured by conduction from the 4.5 K helium circulating in the pipes at the outside of the mandrel.

(iii) How to wind a very stiff conductor in four layers? The inertia of the compound conductor is very large compared to what had been done so far.
(iv) How to build precise mandrels? Because of the high stress, it is not possible to thermally stress-relieve the mandrels to stabilize them; nevertheless, good cylindricity is required to obtain a precise coil.
(v) How to limit shear stresses inside the coil? The use of a reinforced conductor solves this problem inside the modules; however, in the region between two modules the large compression force must be transmitted without creating undue shear stresses, particularly inside the insulation layer.
(vi) How to mount such a heavy coil (220 tons) with a horizontal axis inside the vacuum vessel?

1.7. How the Design Challenges have been Met

1.7.1. *Superconducting insert*

Building on the pioneering work done for the first thin solenoids, the superconducting element of the conductor, the insert (the inner part of Fig. 1.5), a NbTi Rutherford cable stabilized with pure aluminum in a continuous extrusion with the needed section, has been industrialized in the early 90's,[12] and the process has been subsequently used not only for CMS but also for the conductor of the Atlas toroids.

1.7.2. *Compound conductor*

Identification of the best geometry for the compound reinforced conductor occupied most of the early effort and finally, as often, the simplest geometry proved to be the best one (see Fig. 1.5).

How to attach the two reinforcement sections to the insert has been the next challenge. Ambitious solutions involving parallel co-extrusion were tried and abandoned. Continuous Electron-Beam (EB) welding[13,14] was adopted because it satisfied fully the requirements, there was expertise in the team, and a competent medium size firm interested in the manufacturing challenge, was found nearby.

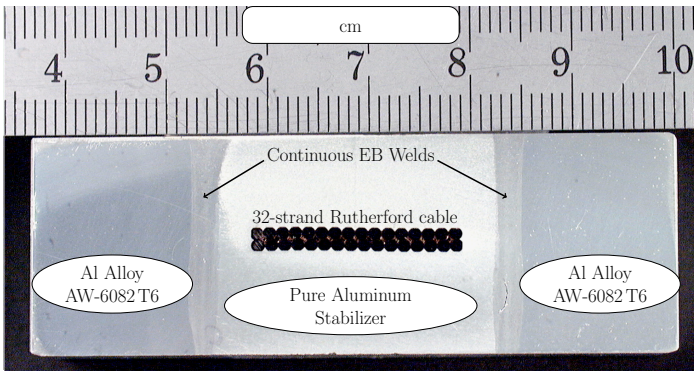

Fig. 1.5. Cross section of the CMS reinforced compound conductor. The inner part, the so-called insert, is a conventional conductor, Rutherford cable inside a pure aluminum matrix, to which is added by continuous Electron Beam process the two aluminum alloy sections.

One difficulty has been to obtain the reinforcing sections in 2.6-km lengths with good mechanical uniformity, although they were not produced by continuous extrusion.

Several high-strength aluminum alloys in various tempers have been considered for the reinforcement. The typical alloy EN AW-6082 has been selected for its high toughness, good extrudability and weldability. The underaged state (T51) allows winding to proceed with a not too stiff conductor, nevertheless resulting after the curing cycle to a T6 temper with further overall increase of the tensile yield strength,

reaching at 4.2 K a $R_{p0.2}$ of 400 MPa and a R_m of 670 MPa (see right of Fig. 1.6), largely sufficient for the application.[15,16]

1.7.3. *Selection of material for the mandrels*

To get aluminum plates with the necessary mechanical properties has been difficult. In fact, it seems impossible to build mandrels by welding plates together, having the required mechanical properties and thicker than 100 mm. This proved to be an a-posteriori justification for the use of the compound reinforced conductor. An exten-

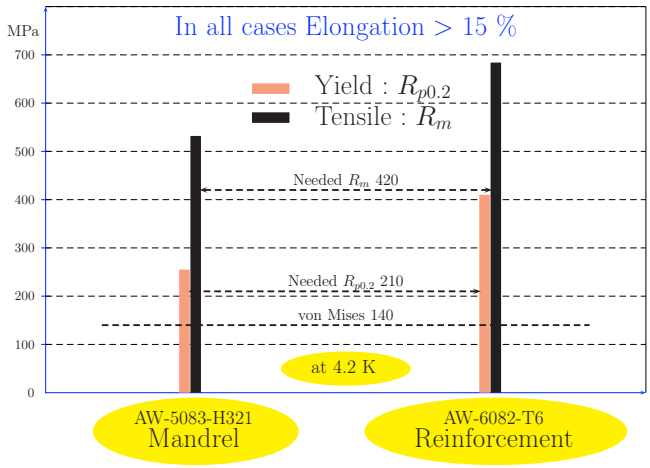

Fig. 1.6. Yield and tensile strength at 4.2 K of AW-5083-H321, used for mandrels and AW-6082-T6 used for the reinforcement of the conductor. It must be noted that the 5083 in the fully annealed O state, or in plates thicker than 100 mm, does not satisfy the requirements in weldments.

sive and comparative characterization of the low temperature properties of different aluminum alloys and their welds resulted in the selection of the general-purpose EN AW-5083-H321 as the base material for the welded fabrication of the shells. The strain-hardened and stabilized temper H321 guarantees a $R_{p0.2}$ of 254 MPa and a R_m of 510 MPa measured on plates at 4.2 K (see left of Fig. 1.6). The MIG weldability of the alloy has been proven and specified. Moreover, the $R_{p0.2}$ of the joint at 4.2 K, produced with an EN AW-5556 filler, has been measured between 210 MPa and 233 MPa, which is satisfactory for the application.[17]

Large plates 75-mm thick in EN AW-5083-H321 (to be reduced in thickness to 50 mm by machining after welding) are industrially available and certified according to ASTM B209M. Nevertheless this standard covers, for plates in H321 temper, a thickness up to only 80 mm guaranteeing a minimum Room Temperature (RT) $R_{p0.2}$ of 200 MPa. Since the strength decreases with increasing thickness, the properties associated to this temper would no longer be certified nor adequate for the flanges or the shoulders thicker than 80 mm.

As an alternative to a welded construction, the ten end-flanges are obtained from seamless rings in the same alloy.

The selection of the ring rolling technique for thick components resulted in fully satisfactory properties,[18] with improved level of homogeneity and isotropy of tensile properties compared to thick plates (minimum $R_{p0.2}$ measured at 4.2 K in the axial direction over 270 MPa), exceptional ductility in the longitudinal direction even increasing with decreasing T (from 18 % at RT to 28 % at 4.2 K).

1.7.4. *Manufacture of mandrels*

Almost all large solenoids constructed to date have used mandrels made up from bent plates in EN AW-5083-O (fully annealed). Several intermediate stress-relieving thermal heat-treatments were applied during manufacture to relax stresses and fulfill geometrical tolerances. This is not possible anymore if one wants to maintain the mechanical properties of the EN AW-5083-H321 up to the end. The firm in charge of

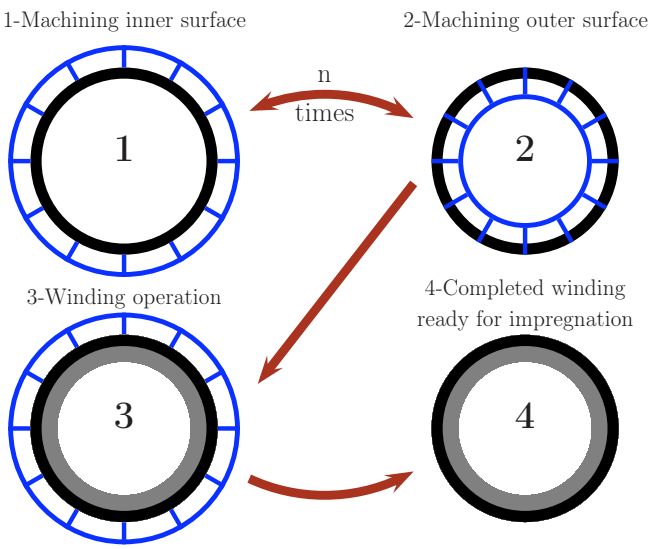

Fig. 1.7. Various phases of manufacture of mandrels and winding to obtain a cylindrical coil module without heat treating the mandrel during of after machining.

the coil winding has used a technique of construction in which referencing tooling is used, either inside or outside the mandrels, to allow machining respectively, outside or inside. Then, keeping the outer tooling, winding can proceed. Once winding is completed, its stiffness is sufficient to maintain the cylindricity of the ensemble within the 10 mm range, and the outer referencing tooling can be removed (see Fig. 1.7). A construction foreseeing seamless flanges welded to the shells helps avoiding stress relieving, compared to a fully welded construction, since the seamless rings represent also a good dimensional reference for each module.

1.7.5. *Winding a stiff conductor*

The inner winding of such a stiff conductor was a worry at first, but, in the end, after a dedicated pre-industrialization activity, it proved easy to execute using an ad-hoc winding machine.[19]

1.7.6. *Limiting the shear stress inside the coil*

Controlling the strain and keeping the shear stress low everywhere inside the cold mass has been a continuous driving goal of the design.[20]

Regions for potential high shear stress lie between modules because the full compression force must be transmitted from module to module in a very discontinuous region. To alleviate this difficulty a 220-ton coil in one unit was even considered for some time, but this design was abandoned as too ambitious. In particular, it was not possible to obtain Rutherford cables longer than 3 km without junctions.

A novel design has been suggested by Ansaldo-Superconductori. It uses a set of wedges to terminate each layer so that the end of each module is already fairly flat. The subsequent gluing, after impregnation, of 5 mm thick G11 plates and the final machining of these plates, using a vertical lathe, allowed improving the flatness thus permitting a perfect coupling from module to module.[21]

In fact, the use of a dedicated workshop to construct the mandrels nearby the winding area has proved to be a tremendous asset. Not only it saved numerous difficult transports of large pieces, but also it allowed the machining of the top flange region of each 50-ton coil module after impregnation.

1.7.7. *Coil assembly*

Coupling of the modules with their axes horizontal was abandoned because the shape of each module was difficult to control during this operation. Finally it was decided to stack the modules with their axes vertical to ensure an easy coupling between modules, thus allowing assembly of the full coil in the vertical position without any deformation (see Fig. 1.8 left). Then, taking advantage of the very large stiffness of the coil, the complete coil has been rotated by 90 degrees, cantilevered from one end (see Fig. 1.8 right), to allow insertion into the outer vacuum vessel. The same large tooling was used to insert the inner vacuum vessel inside the coil.[2]

1.7.8. *Quality control*

Having to reject any element far down in the manufacturing process has so dramatic an implication on such large projects that it must be avoided at all cost.

Structured quality control, traceability and supervision have been important and continuous actions in particular for all conductor elements, the finished conductor, the construction of the mandrels, the insulation, the winding and the impregnation.

Fig. 1.8. On the left view of the cold mass with four out of five modules stacked, and on the right a view of the cold mass with horizontal axis ready to be inserted in the cryostat.

1.7.9. *Project organization*

Constructing such a magnet is beyond the capabilities of any high-energy physics laboratory. The solution retained by CMS has been the creation of an ad-hoc Magnet Collaboration (see third footnote on page 1) allowing regrouping international laboratories, having complementary expertise in the necessary fields, and leading working groups for each main task of the project. The management structure has been adapted to reflect it, and all technical and procurement decisions have been proposed by the Project Manager and endorsed by the Magnet Technical Board (MTB) in which all participating laboratories were represented. This has allowed a very integrated project in the framework of a truly international collaboration.

1.8. Critical Review of Retained Solutions and their Relevance for Designing a new 4 or 5-T Coil

After the successful operation of the CMS coil, it is interesting to review the main technical choices made by the CMS Magnet Collaboration to maximize the chances of reaching 4 Tesla. As several similar, even larger and more ambitious, coils are being actively proposed,[27–30] it is important to examine if better solutions would be possible today for constructing a new large high-field thin solenoid for a future detector magnet, with central induction in the range of 3.5 to 5 T; indeed applying the same general design, possibly with some variations, seems possible.

1.8.1. *Critical current and stability considerations*

The electrical performances of NbTi[22] are such that there is no problem to get the needed current at 4.5 K under the maximum field that may reach 5.8 T for a 5 T coil. However, the temperature safety margin must be sufficient.

For a coil having a central field B_0 and a maximum field on conductor B_{max} for the nominal current I_0 at the operating temperature T_{op}, it is customary to consider that one continues to increase the current above I_0 (assuming also that the central field and the maximum field on conductor increase linearly with the current) until the current I reaches the critical current $I_c = kI_0$ at T_{op} and under the then maximum field on conductor kB_{max}. It is called the load line of the coil and it is usual to design the superconducting cable and chose the amount of superconducting wires so that $I_0 \sim 2/3 I_c$ (see Fig. 1.9), that is chosing $k \sim 3/2$. The nominal current I_0 is then also roughly $1/3$ of the critical current at T_{op} and under B_{max}.

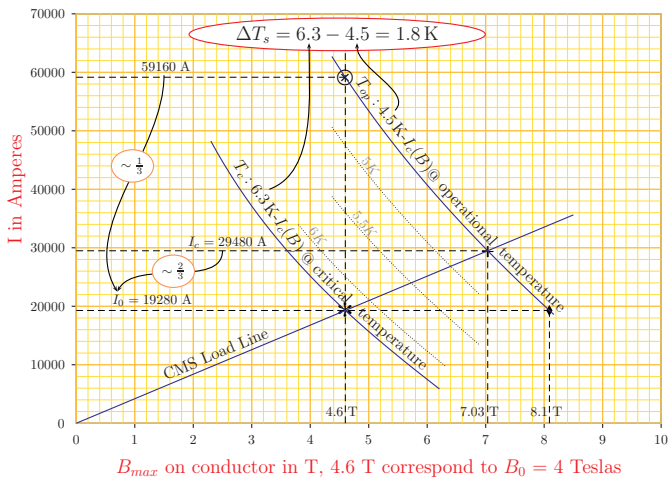

Fig. 1.9. CMS Load Line, and computation of the temperature safety margin ΔT_s.

This large safety factor on current is a simple way of specifying the temperature stability margin ΔT_s, which is not so easy to specify. The operation point of the coil is at a fixed operating temperature T_{op} and at a fixed applied maximum field on the conductor B_{max}. The perturbations are local perturbations that generate energy locally and one can easily imagine that the coil remains stable if the local temperature T_{max} does not exceed the critical temperature of the conductor carrying a current I_0 under the magnetic field B_{max}. The value $\Delta T_s = T_{max} - T_{op}$ is called the temperature safety margin. It was 2 K for Aleph at 1.5 T and it is 1.8 K for CMS at 4 T. When designing for higher central field (and higher maximum field on the conductor) one has to be prepared to reduce the temperature safety margin

and increase the amount of superconducting wires respecting the present limit of 40 strands for the cabling machine. One possibility to recover some margin is to operate the coil at 4.2 K, accepting to have the gas return circuit at a sub-atmospheric pressure.

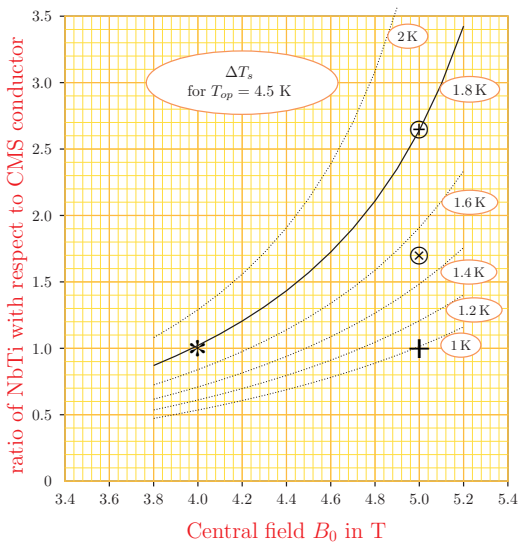

Fig. 1.10. Ratio of superconductor to be used with respect to CMS conductor to reach a given central field B_0 keeping a given temperature safety margin ΔT_s.

If one excludes accidental heating due to a bad internal joint, the remaining perturbations that may generate heat locally are basically a slippage of conductor or crack development in the fiber-glass-epoxy insulation layer, hence the importance of ensuring by design a monolithic cold mass preventing local movements, in which shear stresses are under control so that the cracking of the insulation layer is excluded. Involved studies have been carried out to identify possible local accidents, compute what energy can be released locally and the corresponding local increase of temperature.[9,10] However, this remains fairly theoretical as the possible perturbations are mainly due to manufacturing defects that are difficult to quantify for such large objects; but experience tends to show that, if we exclude coils that exhibit an important manufacturing or impregnation defect, the coil systems look more stable than expected. Clearly other defects may appear like sections of superconducting wire below specification, or bad bonding of the Rutherford cable and thus the real temperature stability margin is one of the most difficult parameter to apprehend, specify and keep under control.

One can see on Fig. 1.10 that the actual CMS Rutherford cable would still exhibit a temperature safety margin $\Delta T_s = 1$ K if used for a 5-T solenoid at 4.5 K, (+). However, to keep the same temperature safety margin of 1.8 K, at least 2.6

times the amount of superconducting wires would have to be used ($\oplus$), and at least 1.7 times the amount for $\Delta T_s = 1.5$ K, ($\otimes$).

In fact, during the testing of the CMS coil, the central field being constant at 4 T, the temperature of the coil has been allowed to drift by 0.8 K, up to 5.3 K, without inducing any quench,[4] showing that the coil has a sufficient stability margin but it does not demonstrate that this margin can be safely reduced in new projects.

The conclusion is that no clear design recommendation exists for the temperature safety margin and the present understanding between experts is that it must be as high as possible and certainly be greater than 1 K, possibly 1.5 K.

The stability with respect to suddain localized disturbances depends also of the amount, geometry and electrical resistivity of the stabilizer under field and under stress. However, for large conductors the rapid sharing of the current with the stabilizer is impaired by the time needed to diffuse the current away from the cable. In addition it is known that each stressing cycle decreases the RRR of the stabilizer[23] and, in fact, the stability margin computations for the CMS coil have been performed for a degraded pure aluminum with an apparent RRR of 400 under field. Thus the drive to procure a super-pure aluminum with a RRR of 3 000 (at zero field and no stress) seems a little vain. Thus the idea of trying to replace the pure aluminum stabilizer by an ad-hoc alloy with better mechanical properties still having a sufficient RRR.

1.8.2. *Compound reinforced conductor considerations*

To use a compound conductor for large high-field, indirectly-cooled, potted solenoids seems still a good solution. It allows incorporating in an easy way the quantity of high-strength alloy required by strain considerations.

One alternative to the compound reinforced conductor is to have a thick mandrel, but as discussed above, such a thick mandrel seems very difficult to manufacture by welding with the necessary mechanical properties, and one loses the advantage of reacting the magnetic force where it is created leading to dangerous shear stress inside the coil, in particular at the winding-mandrel critical interface region.

Another alternative to the compound conductor is to wind an aluminum alloy reinforcement section in parallel to the conductor proper. This alternative has been rejected by the design team as it would render the winding process and the module-to-module coupling much more complicated, giving a winding of inferior quality with more fragile and numerous interfaces filled with fiber-glass-epoxy or even pure resin and it is known that these are really the weak points of potted coils.

1.8.3. *Is it necessary to improve the mechanical properties of the alloys for the reinforcement and the mandrels?*

When planning to increase the field of a large thin coil, an important question arises concerning the choice of the reinforcing alloy. Do more performing grades have to be

used? In fact, the alloys used for CMS for the mandrels and the reinforcement are sufficiently performing for the next generation of coils, and thus it is not necessary to look for stronger alloys. This is coming from the fact that the stored magnetic

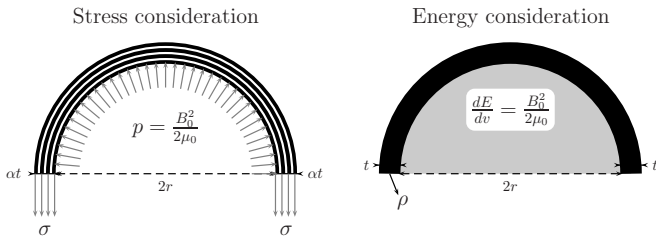

Fig. 1.11. The coil can be considered as a thin tube submitted to an internal magnetic pressure or to a mass recuperating the magnetic energy stored inside its volume.

energy per unit of volume inside the thin solenoid in J/m^3, and the equivalent pressure acting inside the thin solenoid in N/m^2 can both be expressed by the same expression: $B^2/(2\mu_0)$, in which B is the central induction in T and μ_0 is the permeability of vacuum in H/m. First, referring to the left of Fig. 1.11, we can introduce α the ratio of structural aluminum alloy inside the coil (meaning that the pure aluminium stabilizer is considered in the plastic state transmitting only pressure and taking no circumferential stress), Y its Young's modulus, σ the circumferential stress in the alloy and ϵ the corresponding elongation, we can write the force equilibrium equation for a thin tube, using also $\epsilon = \sigma/Y$:

$$2r\frac{B_0^2}{2\mu_0} = 2\alpha\sigma t = 2\alpha t Y\epsilon.$$

Secondly, referring to the right of Fig. 1.11, we can equate the magnetic energy stored per unit length of cold mass to the energy recuperated by the same unit length of cold mass (of specific mass ρ) when all the energy is dumped into it, respecting the ratio E/M:

$$\pi r^2\frac{B_0^2}{2\mu_0} = 2\pi r t\rho\frac{E}{M}.$$

Comparing the two equations, one can relate the magnetic energy per unit mass of cold mass E/M to the hoop strain ϵ of the coil:

$$\frac{E}{M} = \alpha\frac{Y}{2\rho}\epsilon. \tag{1.1}$$

Thus the hoop strain ϵ is also a measure of the stored energy per unit mass of cold mass E/M.

On one hand, it seems difficult, respecting construction codes, to exceed a hoop strain of 0.15 % as, in addition, the axial stress due to the compression force is not negligible. In the case of CMS, these combined stresses correspond to a maximum

Von Mises stress of 140 MPa, requiring alloys with $R_{p0.2} > 210$ MPa and $R_m > 420$ MPa at 4.2 K.

On the other hand, one has to be careful increasing the ratio E/M beyond 12 kJ/kg because, as the enthalpy of aluminum is negligible at $T = 4.5$ K, this ratio is representative of the mean temperature of the coil after a fast dump. In the case of CMS, as 50 % of the energy is extracted and dissipated in the dump resistors, this corresponds to a safe mean temperature of 80 K for the cold mass. It covers also the ultimate accidental case, in which the quench detection system or an active element of the dumping system is not functioning and all the energy is dissipated in the cold mass by the passive quench-back protection scheme.

Thus, one can tentatively conclude that the selected alloys EN AW-6082-T51 for the reinforcement and EN AW-5083-H321 for the mandrels are perfectly suitable for a 5-T coil designed for ultimate reliability, even in case of failure of an active element of the protection system.

1.8.4. *Improving the compound reinforced conductor by replacing the pure aluminum stabilizer*

The considerations on stability margin open the door to using a less performing stabilizer in terms of RRR in the virgin state, but more performing in terms of mechanical properties.

There is a development project[26] to manufacture 200 m of an improved CMS reinforced conductor in which the pure aluminum is replaced by the EB-weldable doped alloy Al-0.1wt%Ni developed by KEK for the Atlas thin solenoid.[24] This alloy in the cold work state reaches a yield strength $R_{p0.2}$ of 85 MPa at 4.2 K, even after a 130°-15 h curing cycle, while maintaining a RRR of 590.

This new compound conductor would be more performing mechanically as in the preceding equation 1.1 the factor α would be nearly 1. Another clear advantage would be of staying in a nearly fully elastic state, thus exhibiting constant properties with time in terms of mechanical properties and RRR.[25]

1.8.5. *Attaching the reinforcement sections to the insert*

The way the reinforcement sections are attached to the insert can certainly be reviewed. The Electron-Beam (EB) welding process may look like a deluxe one, although it has numerous advantages: the quality is superb and the process is easy to monitor and it can be stopped and re-started at any moment during the manufacturing process. In the end the EB welding proved easy to apply.

The design team considered for a while the possibility of attaching the reinforcement sections by continuous soft soldering. This looked promising but, by lack of available effort, this study was stopped as soon as the EB solution proved able to succeed. However, techniques have progressed and it is worthwhile to re-examine the situation and explore new possibilities like laser welding or friction welding.

1.9. Conclusions

At the start of the CMS coil project, in the early 1990's, several problems were identified that had no known solution, and the construction proper even started with some of these problems still in the pending state. It took years to develop and validate some of the retained solutions.

Problems connected to superconductivity were quickly solved. In fact, looking backwards, it appears that most of the difficult problems were connected to mechanics, stress and strain distribution in the cold mass and in the insulation layer, and procuring components with the necessary mechanical properties, in the required size for mandrels, or along the full conductor lengths. With the drive to increase the field, these mechanical problems are likely to become even more dominant. New processes can be developed, however, the passing of the superconductor through all the manufacturing processes imposes severe constraints to these processes not to degrade the electrical performances of the superconductor.

Knowing what is known today the CMS Magnet Collaboration, as a group, concluded that if it had to build a new large high-field thin superconducting coil, it would basically use what is now referred to as the CMS design, with the possible following improvements: replace the pure aluminum stabilizer by a doped alloy and look for an alternative to Electron Beam welding if it proved to be clearly less expensive. Otherwise the design would be maintained; the basic reason to resist changes is the fact that one cannot risk constructing a non-performing large coil by introducing more risky solutions just because they are potentially less expensive.

The CMS design, which is clearly adapted to DC fields staying within the range of NbTi with a sufficient enthalpy stability margin at 4.5 K, can thus be extrapolated up to 5 T. More demanding solenoids, designed for higher fields for example, would necessitate a different approach, like the use of cable-in-conduit technology profiting from future technical developments coming from the ITER project.

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