11. COLD MASS DESIGN CONCEPT

The cold mass is defined as the part of the CMS solenoid which operates at liquid helium temperature. It consists essentially of the superconducting winding and the quench back external cylinder to which the LHe cooling circuit is attached.

11.1 DESIGN CONSIDERATIONS

The physics requirements for the CMS magnet are a 4 T magnetic field at the centre of the detector, (see Chapt. 2). The main magnetic and geometrical design parameters of the cold mass are given respectively in Table 11.1 and 11.2.

Table 11.1

Magnetic Characteristics.

Magnetic induction at interaction point	4.0	T
Magnetomotive force	42.29	MAt
Conductor peak magnetic field	4.6	T
Winding overall current density	12.68	A/mm^2
Stored energy	2.69	GJ
Magnetic radial pressure	6.4	MPa
Axial compressive force at mid plane	148	MN
Operating current	19.5	kA
Inductance	14.15	H
Total number of turns	2168	
Turns per layer	542	
Dump resistor	0.050	W
Dump voltage	1000	V
Dump time constant	283	s

Table 11.2

Overall geometrical parameters.

Magnetic length	12.4	m
External diameter (without cooling tubes)	6.976	m
Internal diameter	6.360	m
Overall radial thickness	308	mm
Winding thickness	296	mm
Quench tube thickness	12	mm

Total mass (without supports)	220	t

In December 1994, the CMS Technical Proposal [1-1] included a complete design of the superconducting coil system. According to a general recommendation of CERN to build most of the large LHC components out of CERN site, the coil structure was designed to be compatible with road transportation; the coil was split into 4 longitudinal sections to be built in factories using the inner winding technique and then assembled in the CMS surface hall [11-1].

After detailed analysis of the challenges raised by the design presented in the TP, it was decided that, to simplify the design, a solution was to build the coil winding as a single unit provided that the winding operation could be carried out on the CERN site. In this case, the mechanical structure necessary for containing and assembling separate modules, consisting of a thick cylinder and thick flanges, could be eliminated and an external winding technique became feasible. This important evolution in the construction process interacts on the coil definition but keeps the basic concept in stabilisation, cooling mode and quench protection.

The CMS coil design is based, as for a number of existing large detector superconducting solenoids, on the enthalpy stabilisation concept. In this type of stabilisation method, only limited thermal disturbances can be tolerated in the superconducting winding, as opposed to the cryostability method. This concept has been successfully applied to detector solenoids because they are not subjected to substantial external sources of disturbance like fast varying magnetic field or particle radiation and they are operated in DC mode with low energising rate.

The basic features which have demonstrated the high quality and reliability of such magnets are the following:

- high purity aluminium stabilised conductor,
- compact impregnated winding and indirect cooling mode,
- quench back protection process.

Important information can be gained from the previous designs and construction techniques. The ALEPH solenoid, designed and built by Saclay [11-2], has been used in many ways as a reference model for the design of the CMS coil. But the CMS coil cannot be simply extrapolated from ALEPH, because of the very large increase in magnetic field from 1.5 T to 4 T and the requirement of limited radial thickness [11-6]. The main changes introduced in the coil design are:

- four layer winding instead of a mono layer one,
- self supporting winding structure based on a mechanically reinforced conductor, instead of a soft aluminium conductor,
- stronger aluminium alloy as structural material to withstand higher operating stresses due to both the higher field and the coil thickness requirement.

11.2 COLD MASS DESCRIPTION

The cold mass has an overall thickness of 308 mm. It is composed of a 296 mm thick superconducting winding and is surrounded by a 12 mm thick cylinder which acts as both cooling wall and quench back cylinder.

This cold mass is supported inside the vacuum vessel by the tie rod system described in Chapt. 18.

The winding consists of four concentric layers made from a 72 x 22.3 mm^2 compound superconducting conductor wound on its shorter edge. The conductor, described in Chapt. 12 and shown in Fig. 11.1, includes a high purity aluminium component as stabiliser and a high strength aluminium alloy component as the mechanical reinforcement, making the winding a self supporting structure.

The external cylinder provides both the cooling wall and the quench back cylinder. To improve the thermal conductivity in the longitudinal direction 1 mm thick high purity aluminium strips are laid down between the winding and the external cylinder.

The LHe cooling circuit consists of a network of pipes attached to the external side of the cylinder. Longitudinal manifolds are installed at the top and bottom of the coil and supply the semi-circular branches of the circuit. This parallel flow system works in a thermosiphon circulating mode which insures a homogeneous and stable flow distribution as demonstrated on the ALEPH solenoid [17-2], (see also Chapt. 17).

All the electrical insulation is made from glass epoxy composites. The ground insulation situated between the outermost layer and the external cylinder has a total thickness of 2 mm, that is 1 mm on each side of the aluminium strips. The inter layer and the inter turn insulation being respectively 1 mm and 0.5 mm thick.

The relatively small coil thickness results from the physics requirement for such a high compactness. It has two important consequences: first, a radial strain under field of 0.15% and secondly the stored energy density of 12.2 J/g. These basic characteristics, significantly larger than for previous detector solenoids, are fully taken into consideration in the present design.

11.3 THE CURRENT AND THE CURRENT DENSITY

These two determinant parameters are related to the coil stability and to the quench protection and they result from iterative calculations which are presented in the following chapters. However, the basic considerations are briefly resumed here to give a general understanding of the coil design.

The operating current I, and the current density J, in the pure aluminium can be related to the stored energy Es and the dump voltage U across the dump resistor by the following relation F(T), assuming an adiabatic behaviour and no normal zone propagation. This figure provides a basis for the preliminary design but it is also useful for understanding the interdependence of the parameters.

$$F(T) = \int_{To}^{Tm} \frac{Cp}{\rho} \cdot dT = \frac{J^2}{I} \cdot \frac{Es}{U}$$

T_o and T_m are respectively the initial and the hot spot temperatures, r the aluminium resistivity and Cp the conductor heat capacity per unit volume.

The stability criteria of such type of solenoid cannot provide absolute values for the parameters. It is based, in a large extent, to comparative characteristics. For the CMS coil the current density and the current sharing temperature have been determined respectively at J = 28 A/mm^2 and T_{cs} = 6.5 K, for providing the same stability conditions than the ALEPH solenoid as presented in Chapt. 15. For comparison, in the ALEPH solenoid, the current density is J = 40 A/mm^2.

For a hot spot temperature of T_m = 100 K the above relation gives a value of 20 kA for the current. In practice the coil dimensioning is based on a value of 19.5 kA. This leaves a 500 A safety margin to compensate for a possible lower filling factor.

Measurements on the ALEPH solenoid have shown that the temperature rise following a fast dump is actually much lower than the prediction given by this simplified criteria. This is mainly due to the fact that the normal zone propagation is dominated by transverse diffusion of the heat released into the external cylinder by eddy currents. Computations of the quench behaviour of the CMS coil show a similar situation and are shown in Chapt. 16. The typical calculated results are 60 K for the hot spot and 56 K for the final temperature.

The hypothetical case of the failure of the quench protection system, which is the worst case, has also been analysed. In the first period the normal zone develops without inducing significant currents in the external cylinder, but after a delay of about 80 seconds the current decay becomes fast enough to initiate the quench back effect, thus protecting the coil. The coil maximal temperature is then 146 K.

11.4 SELF SUPPORTING WINDING STRUCTURE

In the CMS coil, the aluminium alloy is not used in the shape of a thick external cylinder as was the case for the previous solenoids of this type, but is directly attached to the conductor [11-6, 11-7]. This mechanically reinforced conductor configuration has been designed essentially for mechanical reasons. However, it also provides significant advantages for stabilisation and quench protection because it increases the conductor enthalpy.

In the CMS coil, the only structural component is the conductor itself. Two requirements led to this concept:

- The first requirement is to keep a low level of shear stress between the insulating material and the aluminium alloy.
- The second requirement is related to the 0.15% hoop strain at nominal field, resulting from the radial compactness of the coil required by the CMS detector. Under this operating condition the pure aluminium component undergoes cycles in the plastic domain. It is fundamental to control the cycles of the pure aluminium by tightly fixing it to the aluminium alloy. The bonding must have a good mechanical performance and must be of a metallic nature.

11.5 NUMBER OF LAYERS

The operating current, the total number of turns and the conductor size are summarised in Table 11.3. The number of layers however is still a free parameter at this stage.

Table 11.3
Design parameters independent of the number of layers.

Operating current	19.5	kA
Total number of turns	2168	
Total length of conductor	45.400	km
Conductor cross sectional area (insulated)	1606	mm^2

The choice of the number of layers will fix the conductor aspect ratio and the unit length as shown in Table 11.4. As there is no mechanical support structure an even number of layers is necessary to compensate the conductor hoop force at the extremities of the layers. This is done by mechanically tying the conductor ends from adjacent layers and also from the first and the last layers.

From the beginning, the reference models were the existing mono layer or two layer solenoids. For the 4 Tesla CMS coil, the required number of turns cannot be contained in a two layer winding. The minimum number of layers is four and this extrapolation was found acceptable from the steady state thermal calculations, the maximum temperature difference being lower than 50 mK. However it must be kept in mind that this is only an extrapolation and that it is not easy to predict the stability behaviour when increasing the thermal barrier between the helium heat sink and the high field innermost layer. A large number of layers clearly increases this thermal barrier. Provision must also be taken for the conductor junctions inside the winding.

Table 11.4

Conductor unit length and aspect ration vs. number of layers.

Number of layers	Conductor size mm^2	Unit length km
2	144.0 x 11.2	22.3
4	72.0 x 22.3	11.3
6	48.0 x 33.4	7.6
8	36.0 x 44.6	5.7
10	29.0 x 56.0	4.6
12	24.0 x 66.8	3.8
14	20.6 x 78.4	3.2

The evolution of the winding concept into one single section and the use of an external winding method could lead to a reconsideration of the number of layers because the winding may look easier to make, bending the conductor on its smallest inertia being simpler.

It is known by experience that square shape conductors are more difficult to properly dispose in a winding, and that an aspect ratio larger than two is always preferable. Table 11.4 shows that the configurations using 6 to 10 layers use conductors of low aspect ratio cross section. A 12 layer winding uses a 24 x 66.8 mm^2 conductor of 3.8 km unit length. But it must be recalled that an increase of the number of layers brings important drawbacks, because it increases:

- the number of end junctions,
- the inter layer junction overall dimension in the axial direction,
- the number of epoxy layers and thus the thermal gradient through the winding,
- the coil geometrical defects which are cumulative with the number of layers.

This last point is one of the most important because the winding requires a high geometrical quality in order to ensure a good performance of the coil especially to prevent conductor slips or dangerous stress concentration. Winding the conductor with its smallest inertia in the axial direction greatly facilitates the stacking.

After comparing different configurations, it has been concluded that a limited number of layers and the radial orientation of the largest conductor side are favoured to build a uniform and well stacked winding, and the four layer winding has been retained.

11.6 PURE ALUMINIUM BEHAVIOUR

There are two consequences, coming from the low yield strength of the pure aluminium with respect to the coil operating point, that must be considered in more detail: first the structural function of the pure aluminium and second the evolution of its properties when accumulating cold work.

11.6.1 Structural function

The CMS coil is designed so that the aluminium does not have any mechanical structural functions because, at nominal field, the operating point will be in the plastic domain, even if improved strength aluminium is used. The pure aluminium and the aluminium alloy components have the same elongation and the respective stresses are shared according to their respective mechanical characteristics. The mechanical computations show that, at the nominal point, the aluminium is necessarily in the plastic domain. At the contrary, the aluminium alloy works far below the elastic limit with a maximum Von Mises stress of 140 MPa. The yield strength of the aluminium is improved by the cold work accumulated by the magnetic field cycles so that the pure aluminium will support a larger and larger fraction of the magnetic load. From the mechanical point of view the most stringent situation is thus the first energisation.

It is difficult to predict in which metallurgical state the pure aluminium will be in, because it will be partly affected by the assembly of the alloy over the insert and also by the curing of the epoxy resin. As a basic principle the performance of the CMS coil should not depend on the mechanical state of the pure aluminium. The reference mechanical computations have been performed using the characteristics of fully annealed aluminium. For a more realistic comparison characteristics measured on the ALEPH conductor have also been used. Before winding, the ALEPH conductor gave a yield strength of 40 MPa at 4.2 K which indicates a high level of cold work obtained by the final calibration operation through a Turk head [11-9].

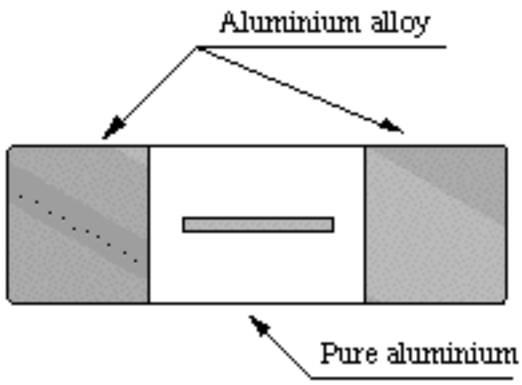

Fig. 11.1: Block conductor geometrical arrangement.

A proper geometrical arrangement for the conductor components is required to satisfy the above requirements for the pure aluminium. The best arrangement, called the box configuration, is a conductor where the alloy completely surrounds the aluminium (see also

Chapt. 12). Unfortunately it is too complex to build so a compromise has been made by using another configuration which is the block conductor [11-8]. It consists of a central aluminium insert containing the superconducting cable and two aluminium alloy sections of the same width welded on each side as shown in Fig. 11.1. The conductor is wound on its shortest side thus orienting the large side perpendicular to the magnetic field axis. This results in a winding composed of concentric cylinders in which the aluminium alloy provides the elastic mechanical structure, as can be seen on Fig. 11.2.

11.6.2 Electrical effect of the cyclic plastic strain

The electrical and thermal properties of pure aluminium change with cold work, but contrary to the mechanical effects, this evolution is a degradation. The increase of electrical resistivity is almost independent of the aluminium quality and is proportional to the total accumulated plastic strain [11-3]. In principle the resistivity and the thermal conductivity [11-4] of the aluminium can be deduced from the total amount of cold work seen by the aluminium, however, this is somewhat complicated since the degradation is partly cancelled when warming up to room temperature [11-5].

For the quench protection and stability computations the number of times the magnet is cycled is important, thus two reference values have been considered: 50 cycles for the first two years of operation and 300 cycles for the following twenty years. Table 11.5 gives the evolution of the RRR for these two values, without taking into account recovery due to the yearly warming up.

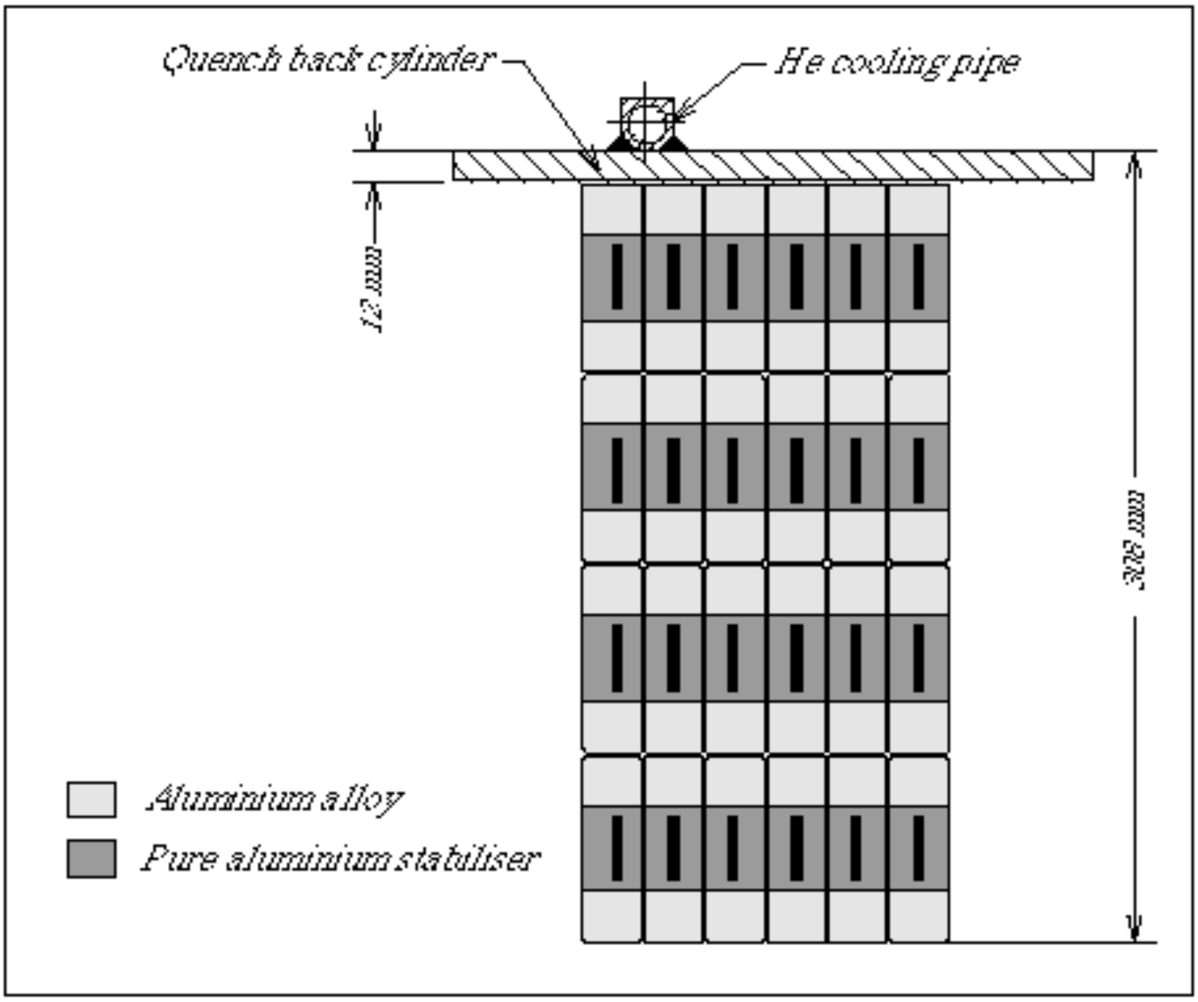

Fig. 11.2: View of the winding showing the structure in concentric cylinders.

Table 11.5

Aluminium RRR evolution.

Initial RRR	1500	1000	800
50 cycles			
Effective RRR	893	688	588
300 cycles			
Effective RRR	576	483	431

Both the stability and the quench protection analysis (see Chapt. 15 and 16) show that a RRR value of 400 is still acceptable: the long term evolution of the pure aluminium characteristics due to cyclic plastic strain will not affect the CMS coil performance.