13. INSULATION

13.1 INTRODUCTION

The technical solution proposed for the insulation of the CMS coil makes use of the semi-wet pre-preg technique. This method, employing pre-impregnated tapes was selected after exhaustive consideration of the three major processing techniques: wet winding, vacuum impregnation and pre-impregnated tape, in relation to cost, complexity, technical suitability and feasibility.

This method has already been used in the past for other similar solenoids. The coils for DELPHI and H1 for example, were manufactured using pre-impregnated tape and both coils have worked successfully for a number of years [13-1].

The CMS coil will be manufactured using a process similar to the one developed at Rutherford Appleton Laboratory for DELPHI.

13.2 TECHNICAL REQUIREMENTS

The coil is constituted of four layers of 542 turns each. This includes:

a) conductor insulation between turns, made from a semi-wet pre-preg 0.125 mm thick and wrapped around the conductor with a 50% overlap,

b) ground insulation:
   - at the inner diameter,
   - between layers,
   - between the last layer and the thermal drains,
   - between the drains and the quench-back cylinder,
   - between the quench-back cylinder and the cooling pipes to guarantee a good thermal bonding.

During the numerous stages of the coil life, the insulation will have to meet various requirements: electrical, mechanical and thermal.

<u>Electrical requirements</u>

During a fast discharge into the 0.05 W dump resistor, the maximum voltage expected across the coil is U = 1000 V, and ± 500 V with respect to ground (Chapt. 20).

The design value for the insulation has been set at 3 kV at each point, corresponding to 2U + 1000 V, that means three times the maximum voltage developed during a fast dump (Chapt. 16), as shown in Table 13.1.

Table 13.1
Maximum voltage developed inside the solenoid.

between turns	< 2 V
between layers	530 V
to ground	± 500 V
across the coil	1000 V

The turn to turn insulation will not be tested at 3 kV even if the insulation process will be qualified for this value. The layer to layer insulation however, will be fully tested at 3 kV after curing the previous layer and before winding the next one.

The breakdown voltage of the glass/epoxy system is about 50 000 V/mm, this means a minimum insulation thickness of at least 0.06 mm is needed to withstand 3 kV. The design thickness of the insulation is 0.5 mm inter turn and 1 mm inter layer, this is well above the required values.

Mechanical requirements

The reinforced conductor is designed to be self supporting and the monolithic winding coil design has been produced to minimise the level of stress in the insulating material.

As explained in Chapt. 14 a Mohr-Coulomb criterion has been adopted for the insulation. The (s_{mean}, t_{max}) distribution at 4.5 K and nominal field is shown in Fig. 14.6 and Fig. 14.7. An analysis is being carried out to assess the influence on the stress field of the winding helix and conductor corner fillet. Some experiments are underway in order to test and validate a strain based Mohr-Coulomb criterion.

Another mechanical requirement for the insulation is to ensure the mechanical continuity and allow the coil to support the gravity stress during assembly and handling, for these calculations an acceleration factor of 1.2 g has been used.

The insulation will also have to withstand the maximum pressure exerted by the tooling equipment during winding.

The mechanical calculations were made using the insulation thickness of the coil as shown in Table 13.2.

Table 13.2
Insulation Thickness.

Insulation	Thickness (mm)
inner Insulation	1
between Turns	0.5
between Layers	1
between Layer and Aluminium Strips	1
between Aluminium Strips and Quench Back	1

Thermal Requirements

The indirect cooling technique relies on thermal conduction through the coil. This means that, in addition to meeting all other mechanical and electrical requirements, the thermal conductivity of the winding must also be maximised. This requires that the bonding between the insulation and conductor and also between the layers has to be very good, therefore imposing certain requirements on the surface preparation for the conductor and on the winding process itself.

A high quality bonding between the quench-back cylinder and the cooling pipes is also needed to obtain good thermal conductivity.

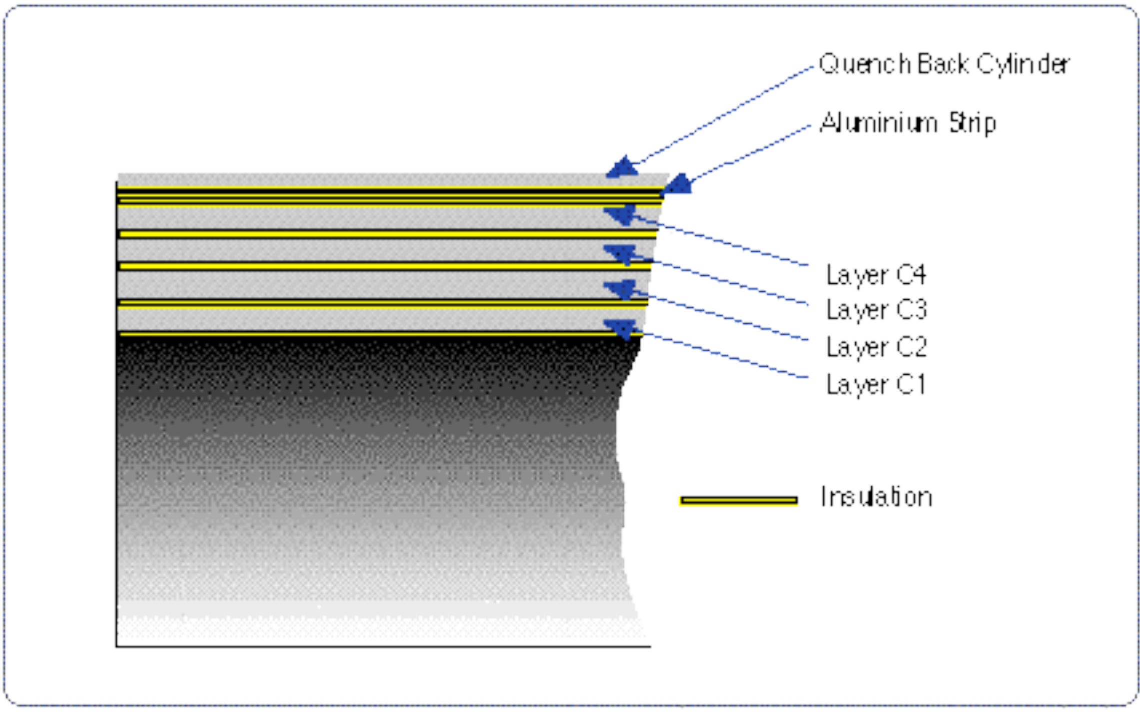

Fig. 13.1: Position of the coil insulation.

13.3 INSULATION PROCESS

The final choice for the insulating process, consists of winding the insulation with a semi-wet pre-preg technique similar to the one developed by the Rutherford Appleton Laboratory and successfully used for the DELPHI solenoid.

The winding process is carried out on a vertical mandrel using the outer winding technique as described in detail in Chapt. 19.

During winding the resin is partly released from the pre-preg due to the pressure applied. This leads to a slight decrease in the insulation thickness. During a short time creeping is expected to occur in the turns as they are wound, the insulation will then remain at the same thickness until curing. No displacement between the mandrel (or previous cured layer) and the winding will occur if both the coil and mandrel are maintained at the same temperature. For this purpose the winding mandrel has to be built in aluminium alloy to reduce differential thermal expansion.

The interlayer insulation is applied during the winding of the conductor by wrapping the insulation around the layer. A stripping cloth is then placed over it to absorb the excess resin. Some form of protection will be used to avoid exposure to humidity.

If required during the insulation process, but before the curing, it will be possible to unwind some of the turns. This requires maintaining the tensile force on the conductor and axial pressure on the winding.

Curing is carried out layer by layer and, in order to avoid any possible displacement along the mandrel or in the previous cured layers, the axial pressure provided by the winding machine will be maintained constant.

A radiant screen will be used to heat the coil. The mandrel will also be heated to avoid differential displacements between the solenoid and the mandrel, and guarantee a small temperature gradient in the coil (≤ 15°C).

To ensure the full homogeneity of the insulation, a two step polymer curing process will be established at approximately 100°C and 125°C.

After the first layer is cured the second is then wound and cured. This continues up to the fourth layer when the ground insulation is wrapped on top of it. The pure aluminium thermal drains are put into place before curing the last layer.

The quench-back cylinder, made from an extruded aluminium alloy profile, is then wound over the outer insulation and welded on line using a laser technique. Computations have shown that the temperature under the profile should remain below 100°C.

When the cold mass is completed a final curing of the full coil will be carried out to guarantee optimum polymerisation.

The insulation process requires that the wrapping of the insulation around the conductor is done during the winding of the conductor, as near as possible to the coil itself, and that the material used for the insulation has to be protected from humidity and dust throughout the whole winding process, in addition the completed turns should be protected as soon as possible.

13.4 DRAWBACKS OF ALTERNATIVE METHODS

This process has been selected after considering alternative methods for both the impregnation process and the curing process. The reasons are explained below.

13.4.1 Alternative impregnation processes

<u>Vacuum impregnation technique</u>

For a coil of this size the risks associated with vacuum impregnation have been considered too high, as any accident will mean a total rejection of the coil.

As only reliable high quality tooling is acceptable it would be both complex and expensive to use this method on a large “one off” coil.

<u>Wet winding</u>

The wet winding process presents many problems, it is unpleasant to use, has health and safety risks and is technically difficult to apply to a large coil. For these reasons this solution has been abandoned, as it was also abandoned for the DELPHI and H1 coils.

<u>B Stage pre-preg</u>

This solution was considered for a long time. Nevertheless it appears that during the curing phase axial pressure has to be maintained on the winding in order to follow the decrease of the pre-preg thickness when the resin becomes liquid. The estimated length reduction of the coil is several centimetres. The displacement of the insulated winding occurs against the full length of the previous cured layer and this could produce unacceptable voids.

13.4.2 Alternative Curing processes

Curing the whole coil in one go

This process is very challenging. It requires the use of a resin with a very long working life at room temperature, due to the duration of the complete winding process.

It also requires maintaining each completed layer under tension and axial compression while continuing to wind the other layers. It is practically impossible to prevent the first layers from moving during the winding of the last layers.

Curing in parallel with the winding

This technique requires the insulation to be heated locally, on line with the winding. A thermal gradient appears in the winding during curing and cool down to room temperature, this creates additional stresses in the insulation. Furthermore this process does not allow completed turns to be unwound if needed.

13.5 MATERIAL SELECTION

Insulating material

In order to fully quantify the process, the resin used to manufacture the wet pre-impregnated ribbon has to cope with the following requirements:

- it has to be chemically stable and in a viscous state at room temperature,
- it has to react slowly, during curing, avoiding high exothermic and fast liquid/solid transitions,
- it is required that the resin in the tape be viscous during the winding stage in order to provide good wetting, ensure that it will flow, to allow the conductor turns and layers to be compacted and have a good bonding,
- it must have a good hygroscopic behaviour because of the long duration of the winding.

Glass fibre reinforcement

The need to wrap the insulation around the conductor requires the use of a ribbon that does not risk having the fibres pulled out at the ribbon edges.

A pliable tape is required to ensure that the tape follows precisely the form of the conductor when wrapping, without leaving any unfilled gaps between the tape and the edges of the rectangular conductor.

Stripping cloth and barrier film

In order to absorb the surplus of resin released during winding, a stripping cloth is wrapped around the interlayer insulation. It has to be easily removable after the curing process, leaving a smooth surface with good bonding properties ready to start the winding of the next layer.

During the winding operation a protection system will be wrapped around the layer to layer insulation to limit its contact with air and moisture.

Bonding of the cooling pipes

The glue used to bond the cooling pipes requires a good thermal conductivity with respect to the polymer properties at low temperature.

Manufacturing method for the insulation material

The technique used to impregnate the glass fibre ribbon with resin has to fulfil the following requirements:

- it should not allow any delamination of the ribbon wedges,
- it should completely evaporate any solvents used to reduce the viscosity of the resin during the impregnation phase. Such solvents could lead to bubbles forming during the curing of the insulation,
- excess resin has to be present to ensure the tackiness of the impregnated ribbon.

Curing schedule and thermal environment

During the initial curing cycle of each layer, the resin has to be in a low viscosity state in order to complete the wetting of the conductor and eliminate any trapped bubbles that could be present after wrapping.

Up to five successive cure cycles have to be done on the resin without any consequences to the mechanical properties of the fully cured material.

The maximum temperature during the curing process should be approximately 50°C lower than the temperature at which a degradation of the polymer could start.

Storage without any degradation has to be possible for at least six months at room temperature and for two years at -18°C.

13.6 QUALIFICATION OF THE PROCESS

Starting from the results obtained at RAL for DELPHI, a series of tests has been carried out at Saclay to understand the behaviour of the resin and the preimpregnated tapes, [13-2] to [13-9].

However, to fully qualify the processes described above, it is foreseen to make a series of tests in parallel with the pre-industrialisation programs for the fabrication of the winding and the conductor manufacture.

The following paragraphs resume these activities.

Wetting

Good wetting is one of the main requirements when selecting the resin, as a reliable bond between the insulation and the conductor at cryogenic temperatures is considered to be a direct consequence of good wetting.

Viscous flow of the excess resin

As explained above, the pre-impregnated tape needs to have a excess of resin in order to flow, wet the conductor, and fill any gaps between the turns. This flow continues until the thickness of the glass fibre ribbon is reached. The ability to reach the final insulation thickness defined by the ribbon itself will have to be controlled.

Surface preparation of the conductor

The surface preparation will be qualified through bonding tests at cryogenic temperatures, similar to the wetting tests. The influence of the rugosity and the surface activity of the conductor will need to be estimated and controlled.

Local overpressure

Tests will have to be carried using the pressing system, to determine how much local over-pressure can be tolerated without damaging the fibres.

Bonding

Bonding between the insulation and the conductor has to be controlled and related to the wetting properties of the resin and the preparation of the conductor. The aim is to obtain a bond that is stronger than the resin itself, thereby designating the failure strain of the matrix material as the limiting criterion for mechanical safety at cryogenic temperatures.

Electrical tests

Electrical tests have to be undertaken to ensure that the final insulation fulfils the electrical specifications.