12. CONDUCTOR

12.1 INTRODUCTION

The design of a self supporting structure obtained by mechanically reinforcing the conductor makes this component more complex than other aluminium stabilised conductors previously used for thin solenoids. The conductor must satisfy simultaneously mechanical and industrial feasibility requirements. This fact has been identified since the beginning of the project and it has lead to developments in several parallel directions. The overall dimensions and the sub component proportions are determined by the general coil design, according to mechanical strength, quench protection and stability requirements. However, these requirements can be met by many different conductor configurations. Three of all possible configurations have been studied at length and the results of the investigations have been presented in intermediate reports, based on the information available at that time.

These studies have lead to reduce the spectrum of options and the conductor structure and possible fabrication technologies have been decided. This has resulted in the so called “block” conductor configuration which satisfies both mechanical and fabrication requirements.

12.2 THE CMS CONDUCTOR

12.2.1 Conductor overall characteristics

The CMS conductor comprises 3 components: the Rutherford type superconducting cable, the high purity aluminium stabiliser and the aluminium alloy reinforcement. The overall characteristics are given in Table 12.1.

Table 12.1

Conductor overall characteristics.

Nominal design current	20.0 kA
Rated current	19.5 kA
Critical current at 4.2 K and 5 Tesla	62.5 kA
Total length of conductor	45.4 km
Overall dimension (bare section)	72 x 22.3 mm
Component cross sectional areas	
Pure aluminium area	659 mm^2
Aluminium alloy area	892 mm^2
Superconducting cable overall area	53.6 mm^2
Cu area	24.2 mm^2
NbTi area	22.2 mm^2
Void fraction	7.2 mm^2
Total weight of components	
Pure aluminium	81 t
Aluminium alloy	109 t
Superconducting cable	16 t
Cu	9.9 t
NbTi	6.1 t
Conductor	222 t

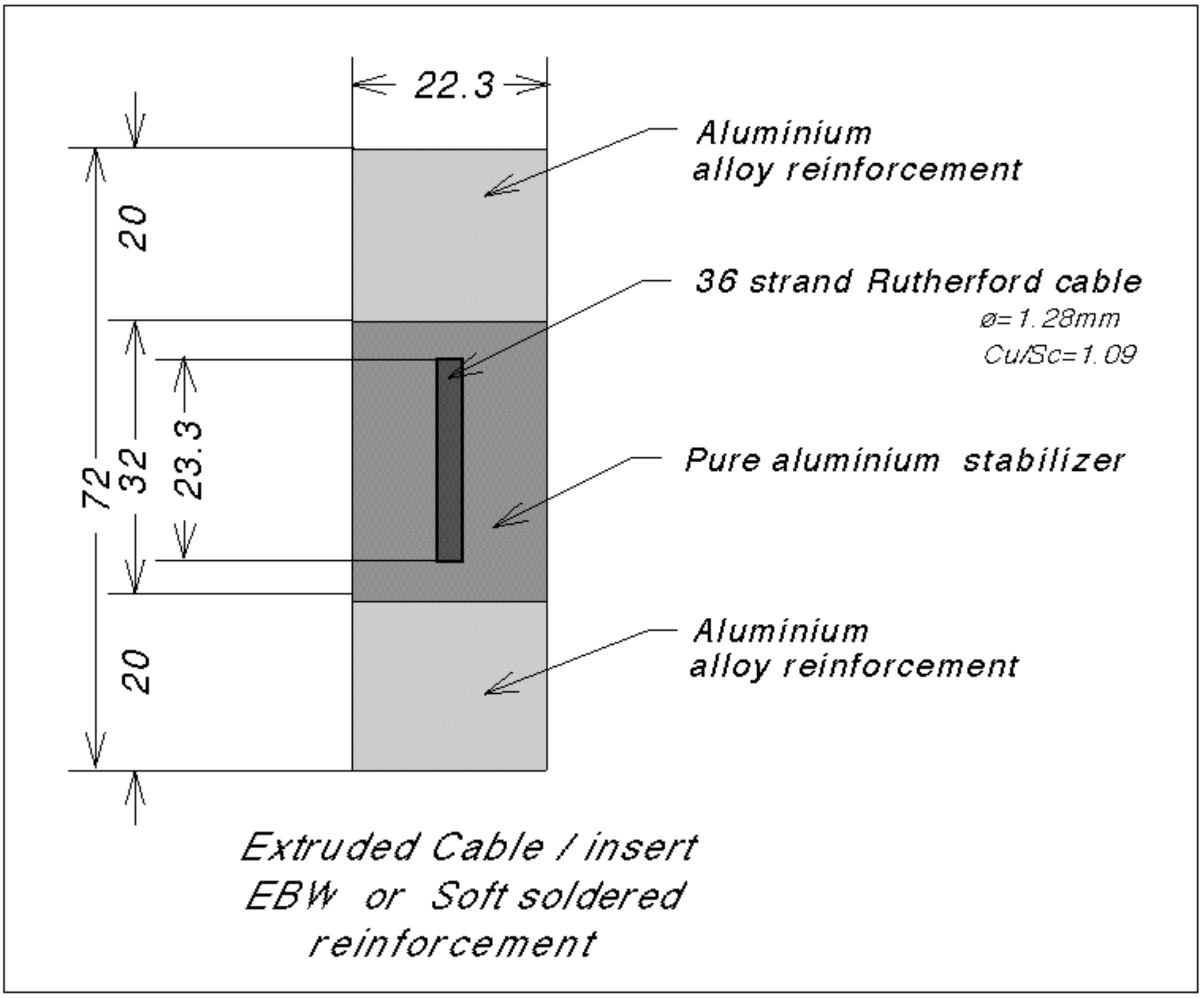

Fig. 12.1: Conductor cross section.

12.3 MECHANICAL CONSIDERATION

The thin, aluminium stabilised, solenoids developed in the past 15 years show common characteristics. As an example for all these magnets (CDF, TOPAZ, VENUS, H1, ZEUS, DELPHI, ALEPH, ...) the hoop strength is provided by an aluminium alloy cylinder, which contains the winding. Since the first development of the CMS solenoid design, it was clear that such a solution would lead to a not well balanced mechanical structure, because four layers of soft aluminium conductors should have been contained inside a thick (190 mm) aluminium alloy cylinder, in order to limit the hoop strain to 0.15% (see also Chapt. 11). This solution minimises the bonding area between conductors and reinforcement leading to some disadvantages.

- The structural part is far from the conductor, so that its heat capacity plays no role (or a minor role) in determining the stability margins.
- The total axial force (120 MN) is transferred to the reinforcement through the bonding of the outermost layer. This bonding becomes very critical for the shear strength resistance.
- The axial thermal contraction of the coil, affected by the insulating material, does not match the cylinder thermal contraction, leading to a further increase of the shear stress at the cylinder-winding bonding.

These drawbacks can be reduced by increasing the bonding area between pure-aluminium conductor and reinforcement so that a simple solution consists in distributing the reinforcement inside the winding. From a mechanical point of view, the best choice is to couple as strongly as possible the pure aluminium to the aluminium alloy, allowing a safe transfer of axial, radial and hoop magnetic force from the conductor to the mechanical structure. In this framework the heat transfer is optimised too. These preliminary considerations led to the concept of a new conductor, which provides the hoop strength (due to the inclusion of the reinforcement in the conductor structure). A solenoid can be *simply* made by winding the reinforced conductor onto a temporary mandrel and by impregnating the turns.

Three configurations, shown in Fig. 12.2, have been assessed in detail.

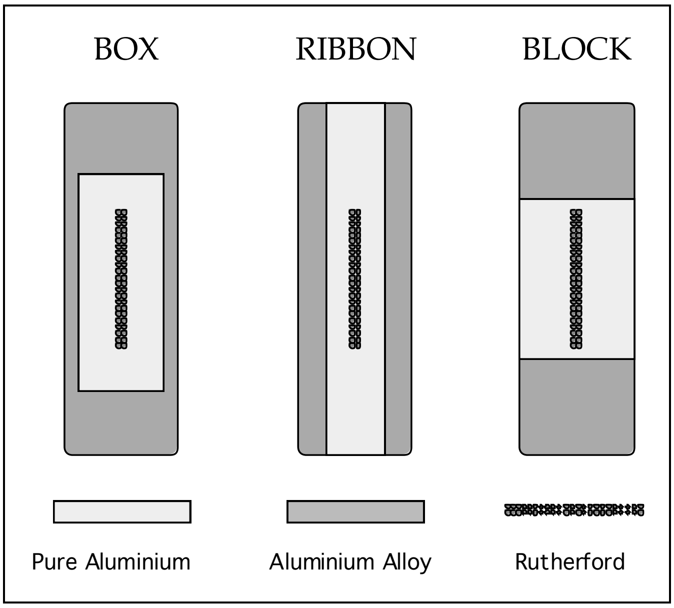

Fig. 12.2: Conductor geometrical configurations.

As it will be shown in the next chapters, these solutions are not very different as far as stability, enthalpy margin or stress distribution in the winding is concerned.

The critical issue in the choice of one or another conductor design is the working condition of the pure Al stabiliser. In fact, it is important that the structural contribution of the pure Al should be minimal. In this respect the box design seems to be the most suitable together with the block design, whereas the ribbon design seems inappropriate.

The results of the FEA carried out so far indicate that the box configuration is potentially the best one. However, in designing this kind of conductor, the manufacturing aspects should be taken into considerations. The block configuration appears as the best compromise between mechanical requirements and feasibility of long lengths.

12.4 CONDUCTOR COMPONENTS

12.4.1 SC Wire

The SC strand has been designed based on the experience acquired in the development of wires for previous Al stabilised solenoids and for the LHC superconducting dipoles. The strand layout must be optimised in order to minimise electrical properties degradation due to the conductor manufacturing process. This is very important bearing in mind that around 5 tonnes of NbTi will be needed for the whole winding.

A critical current density of 2700 A/mm^2 at B = 5 T and T = 4.22 K can be assumed as design value for the finished conductor. This value can be reached, for example, by starting from an initial critical current density of 3000 A/mm^2 and a maximum total degradation of 10% due to the manufacturing process, as recently demonstrated on a test run [12-6]. To obtain these critical current densities should be considered one of the goals of the pre-industrialisation program. The NbTi area has been sized in such a way that the current sharing temperature is equal or higher than T_{cs} = 6.5 K for the peak field value at each layer. In order to save superconducting material, NbTi content for the cable destined to each layer could be graded according to the peak field of the layer, in such a way that the current sharing temperature is the same for each layer.

The strand diameter has been chosen to be smaller then 1.3 mm in order to keep cabling degradation within few percent, as shown by the R&D activities carried out by CERN and ETH over the last four years in collaboration with industry.

The characteristics chosen are shown in Table 12.2.

Table 12.2
SC strands parameters.

Parameters for wires used in innermost layer	Value
Strand diameter	1.28 ± 0.005 mm
Cu/SC ratio	1.09
Filament diameter	< 50 µm
Ic at 5 T and 4.2 K	= 1700 A
Twist pitch	about 20 mm
RRR of copper matrix	> 100
Critical current density at 4.22 K and 5 T	2700 A/mm^2

Before closing this section it is important to stress some technological aspects.

Although NbTi wires are well known, it is necessary:
- to optimise the electrical properties at the operating peak magnetic field (4.6 T),
- to develop a suitable quality control to guarantee the electrical performances,
- to optimise the price in relation to the quantity of wires to be produced.

CMS member states companies have the know-how to produce wires of good quality. This will be ascertained through limited production runs.

12.4.2 Rutherford type cable

The superconducting strands are assembled to form a flat cable of the Rutherford type. The characteristics are shown in Table 12.3. The chosen conductor is very similar to the one developed through the CERN R&D programme (32 strand cable of 1.3 mm diameter and Cu/SC = 1.3). Unit lengths of 12 km are within industrial capabilities, as long as strand cold welds are allowed.

In this type of conductor it is recommended to use a low compacting ratio both to ensure a small critical current and to improve the bonding between the cable and the aluminium.

Table 12.3
Cable Parameters.

Number of strands	36
Cable width	23.3 mm
Cable thickness	2.34 mm
Transposition pitch	~ 200 mm
Compacting ratio	< 0.9
Cable critical current at 4.22 K , 5 T	62.5 kA

Figure 12.3 shows the I(B) diagram with the 4.5 K, 5.5 K and 6.5 K characteristics, together with the peak field load line. At constant peak field of 4.6 T the nominal current is 1/3 of the critical current.

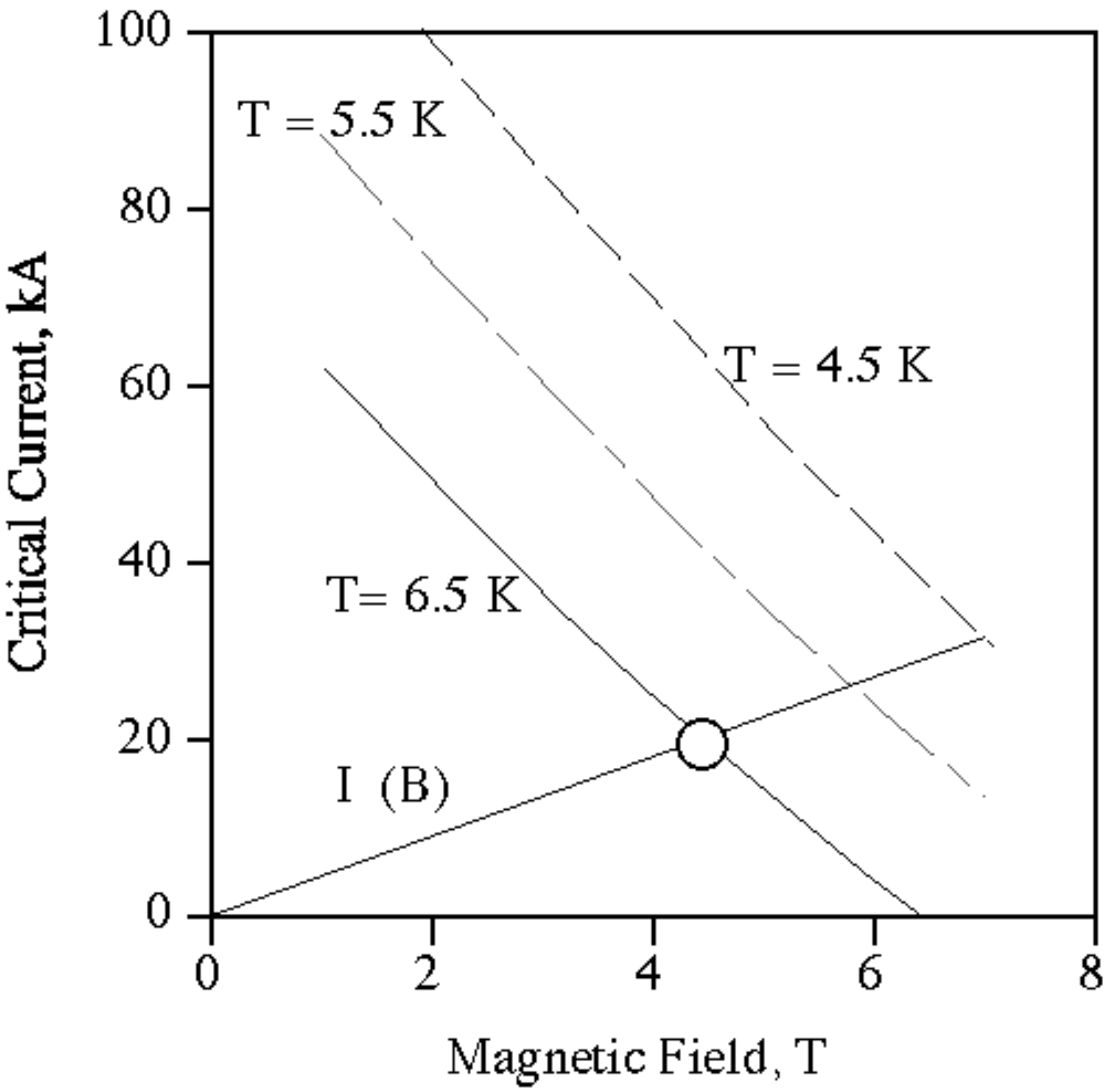

Fig. 12.3: CMS conductor current - field diagram.

12.4.3 Insert

The Rutherford is enclosed inside the aluminium stabiliser through a coextrusion process. This assembly is named *insert*. The coextrusion process requires to heat the aluminium up to 420 °C. Experiments have demonstrated that the critical current degradation can be less than 10% when the manufacturing parameters are properly adjusted. Tests are in progress to measure the performance degradation as a function of the duration of the interruption of the extrusion process.

Although the production of 12 km unit lengths of insert is in principle feasible, one must be ready to accept shorter lengths and to make a limited number of joints of good quality inside the coil. In fact, starting from a 12 km Rutherford cable, the extrusion process will be carried out until the process must be interrupted for any reason. If long enough, say more than 2 km, this length will be accepted as a production length. The lengths of insert will be joined together on the CERN site (see 12.4.5 and Chapt. 23), to provide the 12 km long insert required to wind one layer, before adding the reinforcement. Thus CMS requires long unit lengths of insert, to limit the number of joints inside a layer, however, no strict value will be imposed for the definition of a unit length, but the permissible number of joints will be limited.

If necessary, in order to improve the mechanical properties of the insert, some cold work can be obtained by bending and straightening the conductor prior machining.

Development programmes through several industrial contracts both for CMS and ATLAS conductors have demonstrated the industrial feasibility of the extrusion process on samples more than 300 m long.

12.4.4 Mechanical Reinforcement

In order to obtain the final conductor, the insert must be mechanically coupled to the aluminium alloy reinforcement. For the manufacturing of the “block” conductor two different techniques are being considered; the two reinforcement sections, which are made from a high strength aluminium alloy, are joined to the stabiliser either by soft soldering or by electron beam welding.

Different techniques, as coextrusion in one or two steps, were studied in the framework of an R&D program financed by CERN in 1993 through the LHCC Magnet Advisory Group (MAG). They were abandoned because extrusion of the aluminium alloy has to be done at a too high temperature for the superconductor.

Electron Beam Welding (EBW)

Electron beam welding is an assembly technique which allows to make high quality welds in a continuous process. It can be applied for the CMS conductor to fix a reinforcing section on each side of the extruded insert.

The electron beam makes a narrow heated region just at the metal interface and practically the temperature rise of the conductor components, the superconducting cable, as well as the aluminium materials, is limited. Measurements have shown that the temperature does not exceed 160 °C at a distance of 5 mm from the weld.

The process must be applied under vacuum in a special welding equipment which has to be continuous and fully automated. There are several industrial applications of this type in continuous operation showing that dynamic gating is an operational technique.

It must be stressed that the "block" configuration is particularly suitable for this assembly method, because the weld depth is minimised.

The use of the Electron Beam welding technique for adding the reinforcement is the retained solution as extensive laboratory tests have shown the good quality of the solution. The EB process presents some difficulties due to the short distance between the cable and the insert interface, which may lead to overheating in case of accident during the welding operation. On line protections, control and checks will have to be implemented.

Soft soldering technique

This technique, already used for conductor assembly and for conductor joints, has been considered at a time for assembling the aluminium alloy over the extruded insert.

At the present stage, developments for fixing the reinforcement by soft soldering are still in progress in parallel with the extrusion and the EB welding processes, as it presents an alternative to the base solution, should any unexpected difficulty be discovered later.

At the end of the reinforcing operation an electrolytic anodisation can be foreseen to improve the bonding and the electrical insulation performances.

12.4.5 Conductor joints

There are two types of conductor joints foreseen in the coil:

- layer to layer joints located at the end of the coil and thermally coupled to a liquid helium heat sink,
- joints inside the coil. As explained in 12.4.3, this case is mandatory for the extruded insert solution but it could also be required in any accidental case in which already manufacture lengths have to be repaired. Clearly these joints cannot be cooled locally by a liquid helium heat exchanger. The joining process must thus be fully qualified in order to produce reliable joints of high quality, especially offering an electrical resistance lower than 10^{-9}W.

The joining technique is developed in Chapt. 23.

12.5 RECENT PROGRESS IN ALUMINIUM STABILISED CONDUCTOR PRODUCTION

In addition to the production of testing lengths for the CMS project, members institutes of the CMS magnet project have been also involved recently in the industrial production of stabilised aluminium conductor for several coils destined to physics experiments.

- ATLAS race track conductor: [12.1, 12.2] based on the excellent experience gained with the development of the aluminium stabilised test conductor for the CMS detector magnet in summer 1994, CERN has put ETH Zürich in charge of manufacturing one 200m long conductor for the ATLAS race track coil. For this application, the aluminium stabilised conductor consists of a Rutherford type superconducting cable, which is surrounded by a high purity aluminium stabiliser. The Rutherford type cable itself is twisted out of 32 superconducting strands of 1.23 mm diameter and with a critical current, at 4.2 K and 5 Tesla background field, of about 1550 A each.
- Fermilab D0: [12.3] to further improve our experience, in February 1996 we finished the production of 4.5 km long aluminium stabilised superconductor for the Fermilab D0 detector magnet. Because of the small cross section of the aluminium stabiliser

we have developed a new process line by using a Conform extrusion machine.

- KEK Belle Conductor: [12.4] last year, for the manufacturing of 16 km aluminium stabilised conductor for the KEK Belle detector magnet in Japan, we have developed a conductor together with Outokumpu Oy/Superconductors. By means of already developed equipment and using the process developed for the Atlas and Fermilab D0 conductors this work could be finished in July 1996.
- The BABAR conductor: [12.5] just recently six aluminium stabilised superconductor unit lengths of about 1.8 km each have been manufactured for the BABAR detector at SLAC. This work was carried out in collaboration with INFN Genoa, Europa Metalli, Cable Cortaillod and ETH Zürich.