The CMS Conductor

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Abstract**-- The Compact Muon Solenoid (CMS) is one of the general-purpose detectors to be provided for the LHC project at CERN. The design field of the CMS superconducting magnet is 4 T, the magnetic length is 12.5 m and the free bore is 6 m.**

The magnetic field is achieved by means of a four-layer superconducting solenoid. The stored magnetic energy is 2.7 GJ at nominal current of 20 kA (at 4.5 K operating temperature). The coil is wound from a high purity aluminium-stabilized Rutherford type conductor. Unlike other existing Al-stabilized thin solenoids, the structural integrity of the CMS coil is ensured both by the Al-alloy reinforcement welded to the conductor and an external support cylinder. The flat NbTi cable is embedded in high purity aluminium by a continuous co-extrusion process. The mechanical strength of the so-called insert is substantially increased by two Al-alloy sections joined by continuous electron beam welding to the pure aluminium of the insert. During manufacturing the bond quality between the Rutherford cable and the high purity aluminium as well as the quality of the EB welding seam are continuously monitored by a novel ultrasonic phased-array system. The dimensions of the insert and of the final conductor are controlled during production by Laser micrometers.

This paper presents the main features of the CMS conductor as well as the different steps of the manufacturing process of the 45 km long conductor. First technical experience of industrial production of the complete conductor is reported.

Index Terms**-- Aluminium stabilized superconductor, CMS solenoid, co-extrusion, electron beam welding, NbTi, Rutherford cable**

I. INTRODUCTION

THE Compact Muon Solenoid, CMS, is a general-purpose particle detector designed to operate at the highest luminosity ($L>10^{34}$ $cm^{-2}s^{-1}$) at the interaction point P5 of the Large Hadron Collider, LHC, at CERN. 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, led to the choice of a strong solenoidal magnetic field. The chosen field geometry will be achieved by a single large superconducting solenoid [1], [2] with a length of 12.5 m, an inner diameter of 6.3 m and a uniform magnetic field of 4 T. The magnetic flux is returned via a 1.5 m thick saturated iron yoke. The main coil parameters are listed in Table I.

TABLE I
CMS COIL PARAMETERS

Number of layers	4	
Total number of turns	2180	
Winding self inductance	14.04	H
Operating temperature	4.5	K
Nominal current	19.5	kA
Stored energy	2.67	GJ
Total conductor length	45.1	km
Conductor weight	178	t
Cold mass weight	225	t

The coil is indirectly cooled by liquid helium flowing through pipes on the outer side of the coil utilizing the thermosiphon process.

A distinctive feature of the CMS coil design is the inclusion of the reinforcement in the conductor structure, which enables the hoop stresses to be reacted locally in the conductor without transmitting them through the whole winding pack.

II. THE CONDUCTOR

The CMS conductor is comprised of 32 copper-stabilized NbTi strands cabled into a Rutherford-type cable. The superconducting cable is embedded in a high purity aluminium (HPA) matrix whose high thermal conductivity at cryogenic temperatures ensures good stabilization. The cable and the stabilizer form together the so-called insert. Since the maximum Von Mises stress in the coil of 140 MPa exceeds by far the elastic limit of the insert, it cannot have any mechanical structural function. Thus, the insert is reinforced by two aluminium alloy sections (EN AW-6082) welded to it by continuous electron beam welding. The conductor layout is shown in Fig. 1.

The design of a self-supporting structure obtained by mechanically reinforcing the conductor makes the CMS conductor more complex than other aluminium-stabilized conductors used for thin solenoids. The conductor must satisfy simultaneously mechanical and industrial feasibility requirements. The overall dimensions and the sub component proportions are determined by the general coil design, according to mechanical strength, quench protection and

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stability requirements. However, these requirements can be met by many different conductor configurations. Several configurations have been studied [1]. Due to the constraints given by the possible fabrication technologies the optimum solution was the so-called "block" conductor configuration, shown in Fig. 1, which satisfies all mechanical and fabrication requirements.

A. *Superconducting Strands*

The superconducting strand is a multifilamentary wire made of 552 high homogeneity NbTi filaments sheathed with a Nb barrier and embedded in a high purity copper matrix. The required minimum critical current is 1925 A at 5 T and 4.2 K, corresponding to a non-Cu j_c of 3074 A mm^{-2}, which are at the upper limit of present industrial capability. The strands are heat treated at the final stage to achieve a copper RRR (residual resistivity ratio) above 100. The main parameters of the strand are summarized in Table II. The strands are produced by Outokumpu Poricopper Oy.

TABLE II
CMS STRAND CHARACTERISTICS

Superconducting material	Nb 47±1 Wt% Ti
Strand diameter	1.280±0.005 mm
(Cu+Barrier) : NbTi	1.1±0.1
Nb : (Nb+NbTi)	0.021
Filament diameter	< 40 µm
Number of filaments	≥ 552
Twist pitch	45±5 mm (Z)
Cu RRR	> 100
I_c at 5 T, 4.2 K, 10 µV/m	> 1925 A
n-value of resistive transition at 5 T	> 40
Strand unit length	2750 m

In order to identify individual strands within the 32-strand cable, distinctive patterns of filament arrangements are selected during stacking of monofilaments. Fig. 2 shows an example where three additional filaments have been added in the boundary region between filamentary zone and the pure copper core. Eight different filament patterns are used.

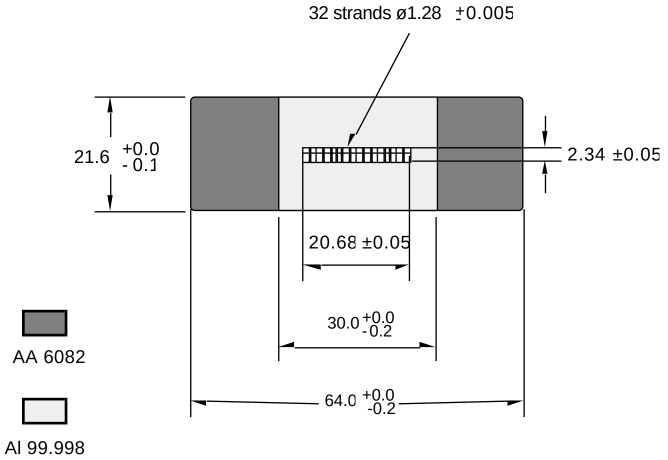

Fig. 1. Cross section of the high purity aluminium stabilized and reinforced CMS conductor.

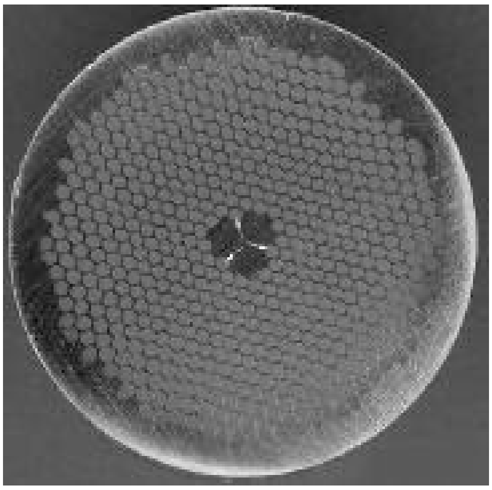

Fig. 2. Cross section of a CMS strand with 3 additional filaments (arrows) in the core region for identification purposes (strand manufacturer: OKSC)

A total of about 1760 km of superconducting strand is needed for the CMS solenoid, corresponding to about 17 t. About 60 % of the strands has been delivered to date. The I_c- and n-values of the strands from different billets are spot-checked at both ends of the wire upon delivery. The strand quality is completely satisfactory so far. All strands exceed the specification with regard to the critical current, some by as much as 9 % [3].

B. *Rutherford Type Cable*

Thirty-two superconducting strands are assembled to form a flat, Rutherford-type cable. The cable dimensions are 20.68 mm × 2.34 mm, which corresponds to a compaction ratio of about 87 %. The unit length of the cable is 2650 m. The main cable parameters are listed in Table III. Cabling one unit length requires about 12 h. To date 11 cables have been produced.

A relatively low compaction ratio has been chosen for the CMS cable in order to ensure small critical current degradation due to filament damage and to improve the bonding between the cable and the aluminium stabilizer. At both ends of each cable samples are extracted and analyzed for broken filaments. No broken filaments have been found. The degradation in I_C due to cabling is below 2 % in comparison to the same strands before cabling.

TABLE III
CMS CABLE PARAMETERS

Dimensions	20.68 mm × 2.34 mm
Number of strands	32
Cable transposition pitch	185 mm
Cable compaction ratio	87 %
Cabling direction	S

C. *Insert*

For electrical and thermal stabilization the Rutherford cable is enclosed in a rectangular high purity aluminium sheath with the dimensions 24 mm × 30 mm. This assembly is called the *insert*. The cable is embedded in the high purity aluminium by a co-extrusion process using a 3800 t aluminium press. This press, usually used for the production of aluminium sheathed power cables, allows a continuous extrusion over long lengths. The heated aluminium billets are introduced into the press from the top of the machine and the Rutherford cable enters the extrusion chamber below along a horizontal path. Before the cable enters the chamber it is mechanically cleaned and pre-heated under a non-oxidizing gaseous atmosphere. The preheating of the billets and of the cable before extrusion have been selected to achieve the minimum degradation in the current carrying capacity of the cable and to assure the best quality of bonding between the aluminium and the Rutherford cable. The co-extrusion process requires heating the aluminium up to 410 °C. The extrusion speed varies between 0.8 and 1.5 m/min. The nominal time any segment of cable is exposed to a temperature in excess of 350 °C during the extrusion process is estimated to be less than 30 s. The production of one CMS insert takes about 30 h. Eight inserts have been completed so far.

As stability and thermal calculations have shown [1], the use of high purity aluminium stabilizer with an RRR value of at least 800 (at $B = 0$ T) provides acceptable stability margin for safe operation of the magnet. Therefore, a maximum impurity of 20 ppm and a minimum RRR of 1500 at zero field has been specified for the aluminium billets. As a standard quality assurance procedure the RRR value of the aluminium is checked on samples taken from each extruded conductor on both ends. Samples of $3 \times 3 \times 40\ \mathrm{mm}^3$ are prepared by a spark machining technique. This machining technique was chosen to avoid strain-induced degradation in the samples. All samples tested so far show RRR values greater than 3000, well above the specified minimum. A plot of a typical RRR measurement vs. transverse field is shown in Fig. 3. More details about the RRR measurements are given in [4].

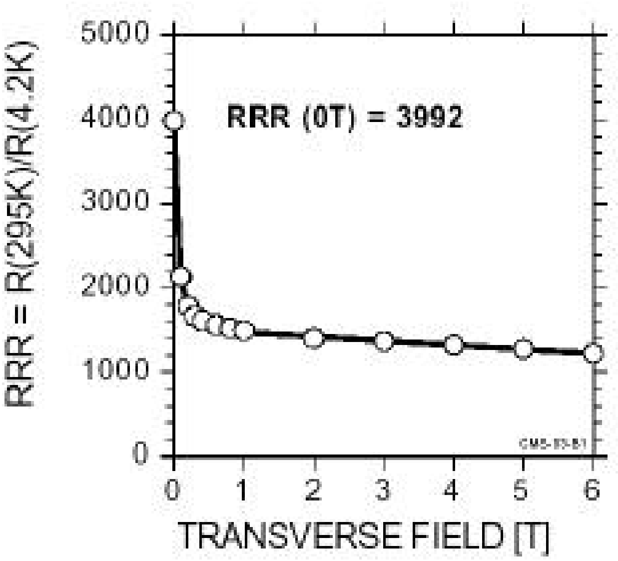

Fig. 3. Residual Resistivity Ratio RRR vs. transverse field of a high purity aluminium sample from one of the CMS inserts

For good performance of the conductor a void-free metallic bond between the high purity aluminium and the Rutherford cable must be ensured. This is essential for the thermal stability of the superconductor as well as for the current transfer to the highly conductive aluminium in case of a quench. The bond quality is continuously assessed on both broad sides of the cable over the whole width and the total length of the insert during production. This has been achieved by using a novel, special adapted ultrasonic phased-array system in conjunction with two 64-element probes (11 MHz). The probes elementary pitch is 0.65 mm and the scanning frequency is about 100 Hz. A highly sophisticated software system allows the on-line monitoring of the bond quality. Both probes and insert are immersed in water during the inspection process. Good bonding results in a small echo coming from the high purity Al / flat cable interface whereas when poor bonding is present, the echoes have a larger amplitude. The result of the scanning is a C-scan, a two-dimensional plot of the echo amplitude measured within a defined gate. Different echo amplitudes are displayed in different colors. A detailed description of the ultrasonic system used for the on-line quality assurance of the CMS conductor can be found in [5].

The knowledge of the conductor dimensions is essential for the coil winding operation. Because within a single coil module over 100 turns are placed side by side, an oversize of the conductor by only 0.2 mm causes the loss of one turn. Therefore, a profile measuring system based on laser micrometer technique has been developed. During production, two opposing laser micrometers scan the width and two others measure the thickness at different locations of the profile. Each laser micrometer measures the distance between the surface and the laser probe by a triangulation measurement. Every 15 seconds, corresponding to about every 30 cm along the insert, the laser probes are moved over the profile and the measured values are collected by a data acquisition system. From these data the thickness, width and straightness are calculated and displayed on-line on a monitor. The operator follows the production on the screen and, if necessary, can react to abnormal conditions.

D. Reinforcement

In order to withstand the large electro-mechanical forces within the coil the insert is reinforced by two aluminium alloy sections joined by continuous electron beam welding. The alloy chosen for these reinforcements is the precipitation heat-treatable alloy EN AW-6082 in an artificially underaged state. Each aluminium alloy reinforcement has a cross-section of 18 mm × 24 mm and is produced in an industrial extrusion process in unit lengths of 2600 m. The cross section is slightly oversized to get enough melted material for the electron beam welding process. Tight dimensional tolerances must be met in order to ensure the weldability, and strict control of the uniformity of the mechanical properties of the extruded sections, especially at the billet-to-billet joints, is required [6].

E. Electron Beam Welding

A dedicated production line for the continuous electron beam welding (EBW) of the insert and the two reinforcement sections has been designed, set-up and successfully commissioned. The production line has a total length of 70 m. The production speed of the line is 2 m/min resulting in a 22 h production time per conductor length. A first prototype length of 2.5 km has been successfully assembled recently, proving that the EBW assembly technique is suitable for the production of the 20 conductors.

The main advantage of the EBW process is that the energy deposition during welding is localized to a narrow melted zone at the insert/reinforcement interface. This is particularly important for avoiding severe critical current degradation of the superconducting cable located only 4.7 mm distant from the welded interface.

After unspooling, straightening and cleaning the three constituents are aligned together before they enter the vacuum chamber fitted with dynamic air locks. In the vacuum chamber two electron beam guns with a power of 20 kW each weld simultaneously the reinforcement sections to the insert. Immediately after exiting the welding chamber, the conductor is machined on all four sides and on each corner to obtain the required dimensions and surface finish. The dimensions of the finished conductor are

$$21.6\,mm^{+0}_{-0.1} \times 64.0\,mm^{+0}_{-0.2}\,.$$

A photograph of the finished CMS conductor is shown in Fig. 4. Details of the EB welding process and a description of the components of the line are published in [7].

Fig. 4. The CMS conductor after electron beam welding and machining. The conductor dimensions are 21.6 mm × 64.0 mm.

Due to the good experience of ultrasonic inspection for the co-extrusion using the phased-array technology, a second system has been set up which allows continuous monitoring of the welding seams [5]. Two 64-element probes are placed on either side of the conductor inspecting both welded zones. During production of the 2.5 km prototype length the ultrasonic control clearly indicated that the bonding between reinforcements and insert was generally of very good quality [7].

The final dimensions of the conductor are measured by means of an automatically controlled laser micrometer system and recorded by a data acquisition system.

II. CRITICAL CURRENT DEGRADATION

The current carrying capacity of the strands was carefully checked for the different production steps in order to learn the impact each step can have on the critical current performance of the conductor. Based on a 1000 m test conductor an average critical current degradation of 1 % was found due to cabling, an additional 5 % due to co-extrusion and an additional 1 % due to EBW. The total degradation of the completed conductor as compared with the virgin wires is 7 %. This is comfortably below the 9 % which was assumed when the conductor design was finalized. Furthermore, the strand design is based on a virgin strand-I_C of 1925 A, whereas the achieved strand-I_C averages 1980 A. Thus, the degradation of the completed CMS conductor as compared with nominal virgin conditions is only 5 % on average.

III. SUMMARY

To date (December 2001), about 73 % of the strands have been delivered and 70 % of the cables have been produced. 38 % of the inserts and 100 % of the reinforcements are ready for EB welding. The first prototype conductor has been successfully EB welded. It has been proven that the CMS conductor lay-out is technically feasible. Series production of all but the last step are in progress whereas for the last step, that of the EB welding, it will begin presently. The overall critical current degradation of the superconducting strands due to the various production steps is 7 %.

IV. ACKNOWLEDGMENT

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