The CMS Conductor

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***Abstract* -- The Compact Muon Solenoid (CMS) is one of the experiments, which are being designed in the framework of the Large Hadron Collider (LHC) project at CERN. The design field of the CMS magnet is 4 T, the magnetic length is 13 m and the aperture is 6 m. This high magnetic field is achieved by means of a 4 layer, 5 modules superconducting coil. The coil is wound from an Al-stabilized Rutherford type conductor. The nominal current of the magnet is 20 kA at 4.5K. In the CMS coil the structural function is ensured, unlike in other existing Al-stabilized thin solenoids, both by the Al-alloy reinforced conductor and the external former. In this paper the retained manufacturing process of the 50-km long reinforced conductor is described. In general the Rutherford type cable is surrounded by high purity aluminium in a continuous co-extrusion process to produce the insert. Thereafter the reinforcement is joined by Electron Beam Welding to the pure Al of the insert, before being machined to the final dimensions. During the manufacture the bond quality between the Rutherford cable and the high purity aluminium as well as the quality of the EB welding are continuously controlled by a novel ultrasonic phased array system. The dimensions of the insert and the final conductor are measured by Laser micrometer.**

I. Introduction

The Compact Muon Solenoid (CMS) is one of the experiments, which are being designed in the framework of the Large Hadron Collider (LHC) project at CERN. The design field of the CMS magnet is 4 T, the magnetic length is 13 m and the aperture is 6 m [1], [2].

The thin aluminium stabilised solenoids developed in the past 15 years show common characteristics. In all these magnets (CDF, TOPAZ, VENUS, H1, ZEUS, DELPHI, ALEPH etc.) 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 not lead to a well balanced mechanical structure, because four layers of soft aluminium conductors would have to be contained inside a thick aluminium alloy cylinder.

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.

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II. The Conductor

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. Several configurations have been studied. These studies have reduced 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, shown in Fig. 1, which satisfies both mechanical and fabrication requirements.

The CMS conductor comprises three components: the Rutherford type superconducting cable made of 32 superconducting strands, the high purity aluminium stabilizer and the aluminium alloy reinforcement. The overall characteristics are given in Table 1.

A. Superconducting strands

The SC strand has been designed based on the experience acquired in the development of wires for previous aluminium stabilised solenoids and for the LHC superconducting dipoles. Because of the restricted space within the aluminium stabiliser, the strand layout must be optimised in order to minimise degradation of the electrical properties due to the conductor manufacturing process. This is very important bearing in mind that around 16 tonnes of superconducting material will be needed for the whole winding.

TABLE 1
CMS CONDUCTOR MAIN CHARACTERISTICS

Nominal design current	20.0	kA
Rated current	19.5	kA
Critical current at 4.2 K and 5 Tesla	55	kA
Total length of conductor	50	km
Conductor overall dimension (bar section)	64 x 21.7	mm
Component cross section areas		
High purity aluminium area	659	mm^2
Aluminium alloy area	892	mm^2
Superconducting cable overall area	53.6	mm^2
Total weight of components		
High purity aluminium	81	t
Aluminium alloy	100	t
Superconducting cable	16	t

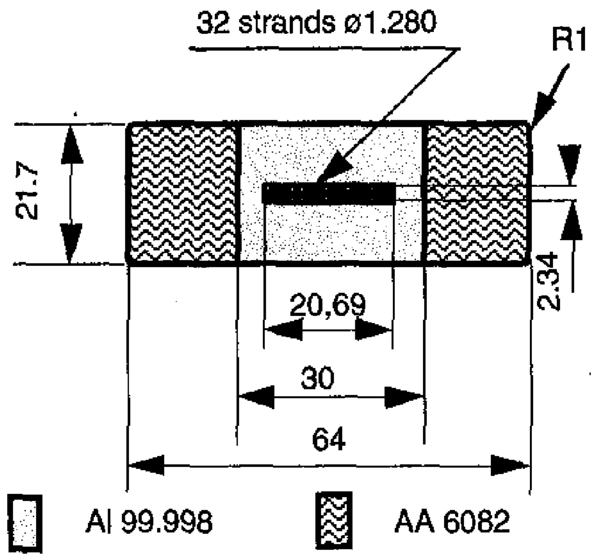

Fig. 1. Cross section of the CMS aluminium stabilised and reinforced superconducting conductor.

The superconducting strand is a multifilamentary wire made of high homogeneity NbTi alloy filaments sheathed with a Nb barrier and co-extruded in a high purity copper matrix. The required critical current density of 3140 A/mm2 at 4.2 K and 5 Tesla is at the upper limit of industrial possibilities. The finished strand is heat treated to provide a final copper residual resistivity ratio RRR > 100. RRR is defined as the ratio in electric resistivity of a material at 273 K and 4.2 K, respectively. A typical cross section of such a superconducting strand is shown in Fig. 2.

To demonstrate the feasibility of such a wire we carried out a so-called "crash program" with wire of a potential manufacturer. 36 strands were cabled to a Rutherford type cable and extruded. By cutting and machining an insert of 32 x 22 mm^2 was manufactured. By means of this insert we could prove that the process is industrially feasible and the degradation is within 10% as it is shown in Table 2.

In accordance with the above specification we asked companies to deliver wire with a critical current of 1925 A at 4.2 K and 5 Tesla. The criteria for the critical current measurement was 10 µV. Five companies delivered wires but only three companies fulfilled the above specification. In a long evaluation process finally we shared the contract for the wire between two companies.

TABLE 2
CRITICAL CURRENT DEGRADATION OF A PROTOTYPE CMS SUPERCONDUCTING STRAND

Nominal strand diameter	1.280	mm
(Cu + Nb barrier)/NbTi	1.1 ± 0.1	--
Virgin wire critical current at 4.2 K and 5 Tesla. Criteria 10 µV	1'975	A
Cabled wire critical current at 4.2 K and 5 Tesla. Criteria 10 µV	1'903	A
Extruded wire critical current at 4.2 K and 5 Tesla. Criteria 10 µV	1'820	A

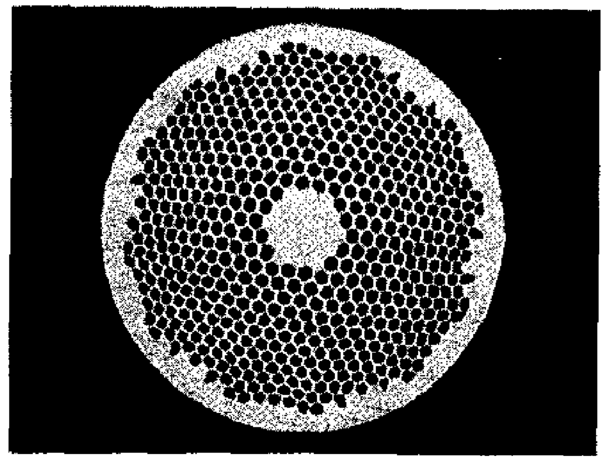

Fig. 2: Typical cross section of a superconducting strand

Strand materials, strand design, and all strand manufacturing processes and inspections, are selected by the wire manufacturers.

The unit length of the cable is 2550 m, therefore the strand will be furnished in unit lengths which are multiples of 2750 m. The total length of strand required is 1760 km (20 x 32 x 2750 m).

The characteristics and parameters of the superconducting strands are summarized in Table 3.

B. Rutherford Type Cable

The superconducting strands are assembled to form a flat cable of the Rutherford type. The cable dimensions are 2.34 x 20.7 mm^2; the compaction density is about 88%. The chosen conductor is very similar to the one we used for the "crash program"; the only difference is the number of strands. Unit lengths of 2.6 km for such a cable are within industrial capabilities.

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

TABLE 3
CMS SUPERCONDUCTING STRANDS CHARACTERISTICS

Strand Constituent	**Material**
High Homogeneity NbTi	Nb 47±1 Wt % Ti
High Purity Copper	RRR > 300
Niobium	Reactor Grade I
Strand Design Parameter	**Parameter**
Strand Diameter [mm]	1.280 ± 0.005
(Cu + barrier)/SC Ratio	1.1±0.1
Niobium Barrier	Required
Filament diameter [µm]	< 40
Number of filaments	> 500
Strand Unit Length [m]	2750 m
Strand Minimum Critical current Ic [A] (Ic Criteria: 4.2 K, 5.0 Tesla, 10 µV/m)	1925
N –value	> 40
Final Copper RRR	>100

C. High Purity Aluminium

As stability and thermal analysis calculation have shown [3], the use of high purity aluminium with an RRR value at zero field of approximately 800 is essential. Early investigations by Fickett [4] have shown that for a low resistivity of the high purity aluminium the total content of impurities is not important but the content of (Fe+Ti+Cr+V+Mn). Therefore we specified both the maximum impurity with 20 ppm as well as the minimum RRR with 1500 at zero field.

From delivered aluminium billets as well as from extruded conductor, samples of 3 x 3 x 40 mm were prepared by spark machining technique. This technique of machining was chosen to avoid strain-induced degradation in the samples. A chart of RRR measurement vs. transverse field is shown in Fig.4. More details about RRR measurements are given in [5].

D. Co-extrusion Process

Because of the low Cu/SC ratio the conductor has to be electrically stabilised by addition of high purity aluminium sheath. For this sheathing of the Rutherford type cable with high purity aluminium, a continuous 3800 ton aluminium press was used at Alcatel Cable Suisse (ACS) S.A. Cortaillod. This press is usually used for the production of aluminium sheathed power cable and allows a continuous extrusion over long length of time. The aluminium ingots are introduced into the press from the top of the machine and the Rutherford cable is horizontally inserted along a straight line. While advancing, the cable is mechanically cleaned and pre-heated under a neutral gaseous atmosphere. The preheating of the ingots and of the cable before extrusion have been selected to have the minimum degradation on the current capacity and assuring the best quality of bonding between the aluminium and the Rutherford cable. The co-extrusion process requires heating the aluminium up to 420 °C.

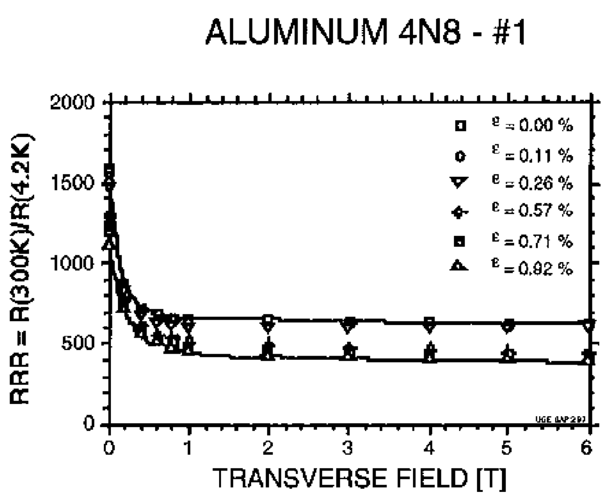

Fig. 4: Magneto-resistivity of high purity aluminium in transverse field between 0 and 6 Tesla.

E. Aluminium Alloy Reinforcement

In order to withstand electro-mechanical forces within the coil the above described extruded insert is reinforced by electron beam welding in a continuous process on both side with an high strength aluminium alloy. The alloy chosen for these reinforcements is the precipitation heat-treatable alloy AA 6082 in an artificially aged state. The aluminium alloy is delivered in unit lengths of 2'600 m wound onto wooden spools. The cross section is slightly oversized to get enough melted material for the EB welding process. About the characterization of this alloy more information is given in [6].

F. Electron Beam Welding

In order to obtain the final conductor, the insert must be mechanically coupled to the aluminium alloy reinforcement. Different techniques, as co-extrusion in one or two steps, were studied in the framework of an R&D program They were abandoned because extrusion of the aluminium alloy has to be done at a temperature of about 500 °C, which is excessive for the superconductor integrity.

As described elsewhere [7] electron beam welding (EBW) tests at CERN have initially been performed on the "ribbon" conductor configuration, and subsequently on the "block" conductor configuration, shown in Fig. 1. Aluminium alloy candidates for the reinforcement material require having good mechanical properties at cryogenic temperatures and good weldability to pure aluminium: 6082 T6 and 2219 T87 were retained for the tests. The issues of cost, availability and corrosion resistance of 2219 will also require careful consideration in making the final selection. Alloys 5083 and 7020 were rejected on the grounds of their insufficient low temperature strength and toughness, respectively.

EBW is an assembly technique, which allows making high quality welds in a continuous process. It can be applied to the CMS conductor to fix a reinforcing section on each side of the extruded insert. The energy transfer during EBW is localised to a narrow melted region at the stabiliser-reinforcement interface. The absence of a heat affected zone is an indication that the general temperature rise of the superconducting cable and the aluminium materials is limited.

The process must be applied under vacuum in 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. Two Electron Beam generator systems will provide the heat source required for heating up the surface to be welded, and a dedicated tooling will be installed to pressurise the heated zone in order to form the welded joint. As shown in schematic drawing (Fig. 5), guiding rollers assure the precise handling of the material through the entire welding system.

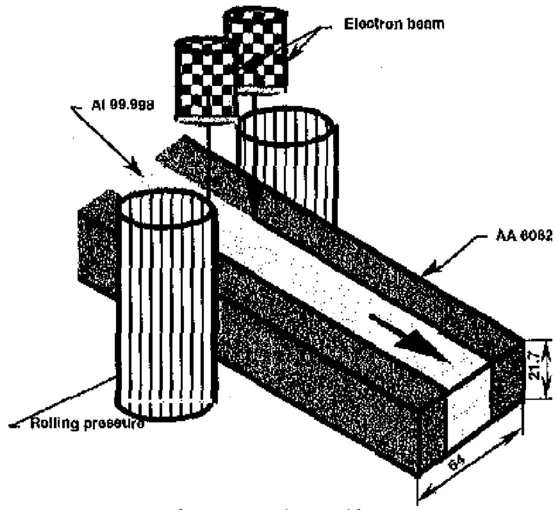

Fig. 4: Schematic view of the EB welding machine

III. ON-LINE QUALITY ASSURANCE

Apart from numerous short sample tests and standard continuous control methods we have developed two systems for the on-line quality assurance. The one is a multi-probe ultrasonic system for the bond measurement during extrusion and for the weld quality control during EB welding, the other one is dimension measurement equipment.

A. Continuous bond quality control

For satisfactory operation of the conductor good bonding between the different constituents must be guaranteed. The main reasons are cooling efficiency of the superconductor, current transfer to the high-purity aluminium in case of an emergency shutdown and mechanical stability. Modern ultrasonics is a well-known non-destructive technique to detect regions of disbonding. For short samples conventional mechanical C-scanning is appropriate [8]. For CMS- and ATLAS conductors, however, a new concept was necessary. Subsequently, we have developed an inspection system based on phased-array technology. Two ultrasonic probes, each having 64 independent elements, allow a continuous bond quality control of the whole width on both sides of the conductor. The inspection is done in-line during production (1.5-5 m/min). In Fig. 6 phased-array C-scans of two 12 m long conductors are depicted. The images show the echo amplitude due to the interface high-purity aluminium / superconductor. The upper sample reveals good bonding, whereas the lower sample has disbonded areas (dark regions). Up to now about 15 km of CMS and ATLAS conductors have been successfully inspected with the phased-array system. The same technique will be applied for the control of the electron-beam welding of the reinforcement of the CMS conductor.

B. Conductor Dimensions Measurement

The knowledge of the conductor dimensions is essential for the coil winding operation. Because within a single 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 we developed a profile measuring system based

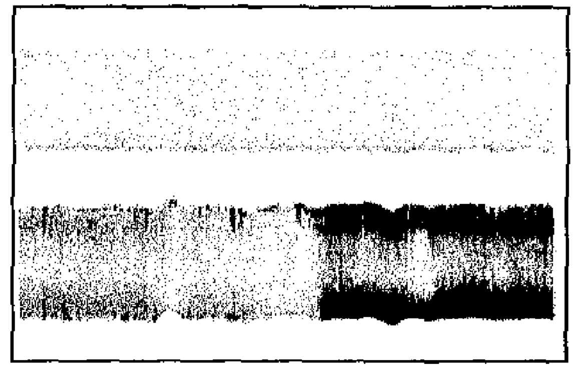

Fig. 6: Phased-array C-scans of two 12 m long conductors. The upper sample reveals good bonding between the high-purity Al and the flat-band cable, whereas the lower sample has disbondings along the edges (dark regions).

on laser micrometer technique. Always two laser micrometers are placed on either side of the profile, which measure the distance between surface and the laser probe by the triangulation measurement. Every 15 seconds the measured values are collected by a data acquisition system. A computer connected to the system calculates the thickness and the width of the conductor. The operator follows the production on the screen and if necessary, he can react. After the production is finished a protocol of the measured data will be printed out.

IV. SUMMARY

The design field of the CMS magnet is 4 T. This high magnetic field is achieved by means of a 4 layer, 5 modules super-conducting coil. The coil is wound from an Al-stabilized Rutherford type conductor. For the cable 32 sophisticated superconducting strands are used. The insert is manufactured by a co-extrusion process in a continuous aluminium press. To improve the mechanical stability of the conductor, on either side of the insert two profiles of AA 6082 are attached by electron beam welding. For the quality control novel systems were developed.

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