Electrical characterization of S/C conductor for the CMS solenoid

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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. It will produce a magnetic field of 4 T in a bore 6 m in diameter and 12.5 m long. The coil is wound from 20 high purity aluminium-stabilized NbTi conductors with a total length of 45 km. The main peculiarity of the CMS magnet among other existing thin detector solenoids is its sandwich-type aluminium-stabilized superconductor. This special feature was chosen in order to have a mechanically self-supporting winding structure.**

We measured the critical current of all the 21 finished conductors in fields up to 6 T using the Ma.Ri.S.A. test facility at INFN-Genova. We compare these results with the critical current of single strands measured by CEA-Saclay, extracted from the conductor after the co-extrusion.

A comparison among the measurements provides information about the possible critical current degradation and assures an accurate quality control of the conductor production.

We also qualified the method used for making the joints between the layers within a single module and between the five modules and the bus bars. Measurements on both round and straight TIG-welded samples were carried out, in Genova and at CEA-Saclay, respectively.

Index Terms— **Critical Current, Al Stabilized Conductors, Detector Magnets, LHC project.**

I. Introduction

THE CMS (Compact Muon Solenoid) experiment is a general purpose proton-proton detector designed to run at the highest luminosity at LHC. 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. As reported in detail elsewhere [1], the main peculiarity of the CMS magnet among other detector solenoids is its sandwich-type aluminum stabilized conductor. The coil is made of five modules (named CB±2,CB±1,CB0 from the outer to the inner one), four layers each. Twenty-one conductors, each having a length of 2250 m, were used. This special feature was chosen for having a self-supporting winding structure. The CMS conductor consists of 32 NbTi/Cu strands wound into a Rutherford-type cable (Fig. 1). The cable is embedded in a high purity aluminum matrix for electrical and thermal stabilization. The so-called insert is reinforced by two aluminum-alloy sections through an electron-beam procedure (EB-welding).

This paper discusses the statistics of critical current measurements made on the finished twenty-one conductors during the whole production. These results are compared with the critical current of single strands extracted from the conductor after the co-extrusion and measured by CEA-Saclay.

The survey on the critical currents of the finished conductors is of fundamental importance since it yields the current capability of the conductor under the most similar conditions to the operations in the magnet [2]. The goal to be achieved is a magnetic field as high as 4 T in the center of the magnet. The critical current must be greater than 56000 A at 4.2 K at 5T in order to meet the technical specifications.

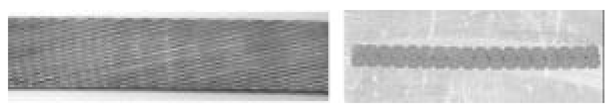

Fig. 1. Rutherford cable and insert of the CMS conductor.

This implies a field distribution in the four layers of the five modules, as shown in Fig. 2 and Table I [3].

It is worthy to note that in the fourth layer of the most outer modules CB±2 the magnetic field is higher than in the third layer of the more inner modules CB±1. This means that the choice of the conductors is a delicate operation to be carried out in order to prevent undesired quenches. Collecting the statistics of the critical current for each conductor can really help.

Another fundamental characterization of the CMS conductors is to study their properties when a joint is welded. Indeed, being the conductors wound into five distinctive modules, twenty-one external joints are to be made for the magnet.

TABLE I
FIELD ON EVERY CONDUCTOR LAYER

Layer/Module	B (T) CB±2	B (T) CB±1	B (T) CB0
1	4.2	4.3	4.4
2	3.4	3.2	3.3
3	3.2	2.2	2.3
4	2.9	1.2	1.2

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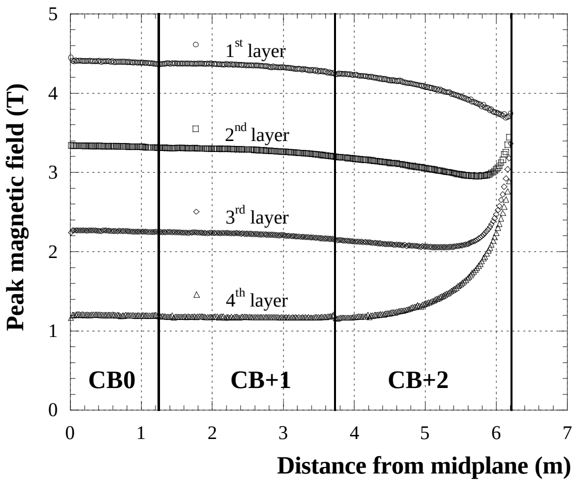

Fig. 2. Peak magnetic field distribution in the four layers of 3 modules composing the CMS magnet (CB-1 and CB-2 are equal for symmetry)

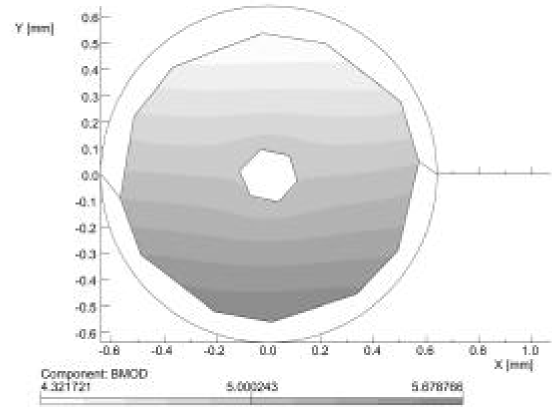

Fig. 3. Self-field distribution when a current of 1860 A is flowing in a single strand.

These external joints are exposed to a 1 T field at maximum. The magnet is operated at a nominal current of 20 kA at liquid helium temperature, so the electrical resistance should be kept low (<10^{-9}) in order not to alter the enthalpy margin and endanger the magnet stability. This current value is about one third of the specification value (56 kA) that is the lower limit for the critical current of each conductor. Furthermore, the joining techniques must not degrade the superconducting properties of the Rutherford cable.

Measurements on both round and straight welded samples were carried out, in Genova and at CEA-Saclay, respectively, for qualifying the fabrication method.

II. Samples and Field Distributions

The critical current properties were traced all through the conductor fabrication, after the cabling, the co-extrusion and the EB-welding process. Using a distinctive cable pattern, the same strands were extracted after the different production steps and their critical current measured by CEA-Saclay. The strands are arranged in hairpin geometry.

We measured the critical current of the finished conductors using the Ma.Ri.S.A. facility in the INFN Lab of Genova [4,5]. The cables under measurement were arranged in a loop with the wide face normal to the magnetic field. Table II shows the main geometrical characteristics of the strands and of the cable.

We used the voltage criterion 0.1 μV/cm for the critical current measurements. This choice allows defining the critical current without ambiguity, while the definition of the critical field is not unique. Indeed, the current flowing through the wire generates a self-field, which, depending on the sample geometry, is not constant across the wire cross section. If the sample is of the hairpin type or any kind of straight geometry, the self-field is the typical one of a long wire carrying a current, i.e. it is zero along the centerline and increases linearly with radius. The vectorial sum of self-field and applied field results in a peak field at one point placed on the conductor edge. As an example, we show the field distribution in a strand when a current of 1860 A is flowing (Fig. 3). When performing critical current measurements on multi-strand cables, the determination of the critical field becomes even more difficult and delicate, first because the field distribution is more complex and then because the self-field strength may be as high as the applied field. Fig. 4 shows the magnetic field distribution for the Rutherford cable when in each strand a current of 1860 A flows and an external field of 3.18 T is applied.

The question that arises is how to compare the critical current measurements of the single strands and of the finished conductors. We extensively studied this problem [6]. According to us, the best way to do this comparison is to apply to the finished conductor an external field so that the strands in the cable at higher field experience a mean field equal to that of the single-strand distribution. We made in Ma.Ri.S.A. some measurements on co-extruded samples to compare our results with the critical current values of single strands. The critical current values are comparable within the error value of 2%. Under these conditions we can appropriately compare

TABLE II
FEATURES OF SINGLE STRANDS AND RUTHERFORD CABLE

Property	Single strand	32-Strand Cable
Diameter/ Dimensions (mm)	1.28	20.63 × 2.24
Cu/Sc ratio	1.1/1	1.1/1
Number of NbTi filaments	500 to 700	32 × (filaments in one strand)
Twist pitch (mm)	45	180-190
Sample holder	Straight /hairpin	Circular
Ic measurement	Direct	Transformer

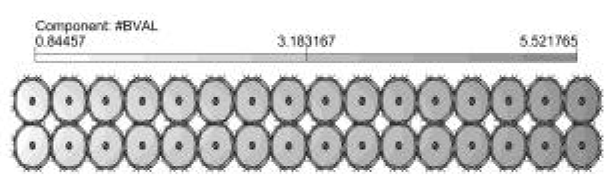

Fig. 4. Magnetic field distribution in the Rutherford cable, when an external field of 3.18 T is applied.

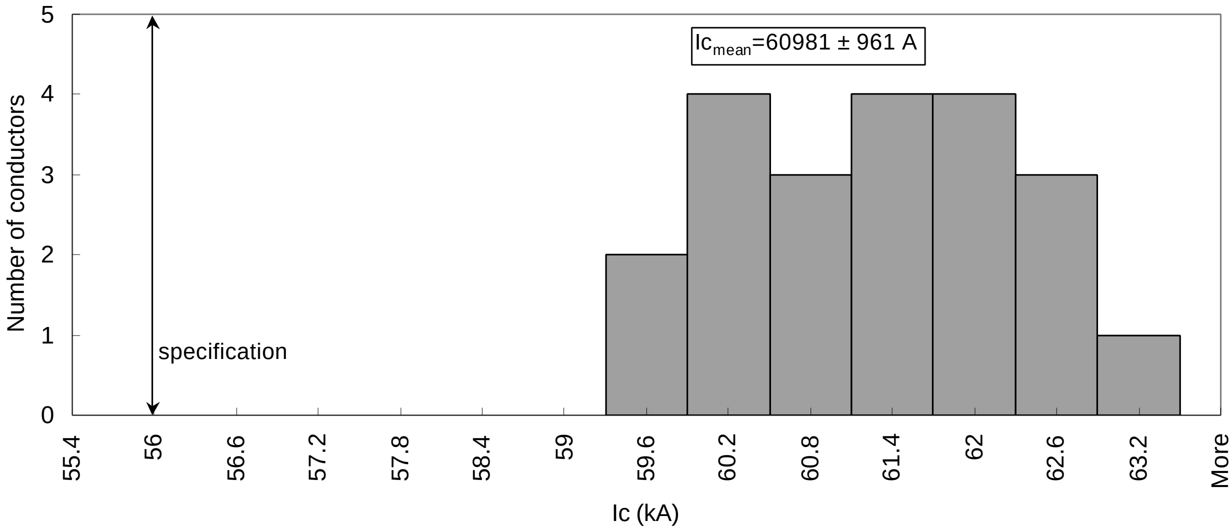

Fig. 5. Distribution of the measured critical currents referring to the specification value. The mean critical current is 60981 A.

INFN and CEA-Saclay results.

III. Conductor Statistics

In Table III we report the critical current statistics of the samples extracted from the head and the tail of the conductors. Twenty conductors were used for winding the CMS magnet, while the first one (ebw01-cms02) was used for the prototype production.

We show the critical current of the strands as declared by the producer firm, Outokumpu, the critical current of the strands extracted after the co-extrusion process and after the final EB-welding. The specification value is 56 kA at 4.2 K and 5 T (that is 1750 A per strand). In the last column of the Table, the total degradation is shown with respect to the critical current value of the virgin strands.

TABLE III
CRITICAL CURRENT FOR ALL THE CONDUCTORS OF THE CMS MAGNET

	Ic (A) Virgin strands	Ic (A) Co-extruded strands	Ic (A) Conductor ring /32	Total degradation
ebw01-cms02	1991	1936±23	1856	-6.8%
ebw02-cms01	1921	1892±17	1856	-3.3%
ebw03-cms03	1991	1886±14	1875	-5.8%
ebw04-cms04	2008	1887±21	1897	-5.5%
ebw05-cms05	2002	-	1894	-5.0%
ebw06-cms08	2058	1960±30	1938	-6.0%
ebw07-cms06	1994	1937±30	1881	-5.7%
ebw08-cms07	2035	1936±71	1963	-3.6%
ebw09-cms09	2040	1943±15	1894	-7.0%
ebw10-cms10	2030	2003±21	1875	-7.4%
ebw11-cms12	2048	1947±1	1933	-5.7%
ebw12-cms13	2040	1974±27	1938	-5.0%
ebw13-cms14	2057	1941±55	1945	-5.4%
ebw14-cms15	2028	1980±14	1926	-5.0%
ebw15-cms16	2023	1921±15	1907	-5.8%
ebw16-cms17	2008	1942±22	1917	-4.6%
ebw17-cms19	2003	1961±19	1920	-4.2%
ebw18-cms20	2000	1936±12	1924	-3.9%
ebw19-cms18	2013	1972±17	1904	-5.5%
ebw20-cms21	2015	1969±18	1909	-5.3%
ebw21-cms22	2017	1989±24	1951	-3.3%

All the measurements are carried out at 5 T and 4.2 K. The error on the Ma.Ri.S.A. measurements is ±2%, while the error on CEA measurements is evaluated as the standard deviation.

Fig. 5 shows the histogram with the distribution of the critical currents referring to the specification value. The mean critical current is 60981 A. All the samples have a critical current at least 6% higher than the specification value. The best conductor can carry a current 11.4% greater than 56 kA.

The total degradation in the worst case is equal to 7.4%, while in the best case is 3.3%.

IV. Joint Resistance Tests

In order to achieve joint electrical resistances lower than 10^{-9} Ω, Tungsten Inert Gas (TIG) welding are performed. Finite element modeling showed that the electrical resistance due to the pure aluminum stabilizer is less than 10% of the total resistance, hence non full penetrating processes such as TIG are enough [7]. The retained joint configuration is the "praying hands" configuration (Fig. 6), which gives the possibility to have long conductor lengths on the external cylinder of the CMS magnet (Fig. 7).

In the final configuration, Ansaldo Superconduttori welds the

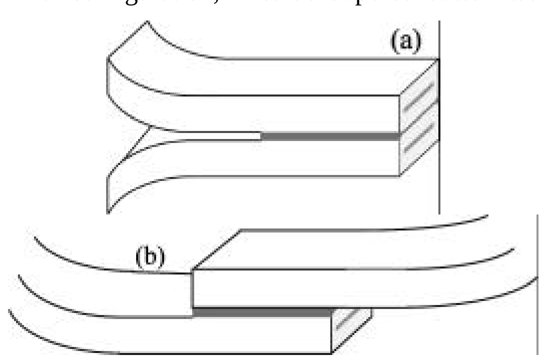

Fig. 6. "Praying hands" (a), "shaking hands" (b) configuration for the joints

joints according to the following procedure. A chamfer 4.5 mm deep, at an angle of 45° is machined. Only one pass is performed with a fore heating of 120 °C and a maximum temperature of 320 °C during welding. In order not to overcome this temperature, the welding is spottily performed.

We have measured round samples in Ma.Ri.S.A. facility using the "shaking hands" configuration (Fig. 8). With an external applied field of 1 T, we measured a joint resistance cm of 4.9 10^{-9} Ω on a length of 28 cm. This means that we need a joint length of at least 140 cm to be under the requested specification.

We also measured the critical current degradation. With an applied field of 2.58 T, that is a total field of 4.66 T, we measured a degradation of 12% (from 66 kA to 58 kA). The measurement at an external field of 1 T, that is in the working operation conditions, the sample showed a critical current of 87 kA, safe enough for preventing quenches.

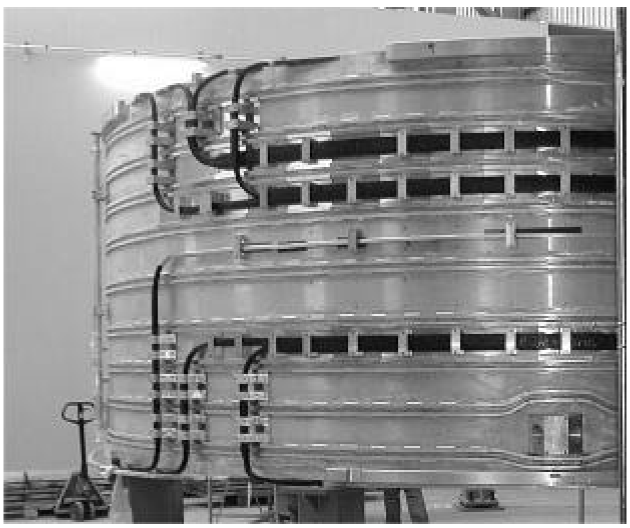

Fig. 7. Electrical joints in the "praying hands" configuration on the CB-1 module of the CMS cylinder..

In the test-facility at CEA straight samples in the "praying hands" configuration were measured. They are cooled down inside a dedicate cryostat, connected to a bipolar 10 kA power supply, allowing to ramp the current up and down. The resistance value is obtained by measuring the voltage drop: typical measurements are in the range 1-10 μV with an error of 10%. With an applied external field of 1 T on a length of 99.3 cm, the joint resistance has a mean value of 7.8 10^{-10} Ω. This means that a length of about 77 cm is needed to match the requested value.

According to these measurements, the CMS Magnet Technical Board has decided a conservative length of two meters for the CMS joints and qualified the used procedure.

Fig. 8. A TIG-joint round sample in the "shaking hands" configuration for measurements in Ma.Ri.S.A.

V. Conclusion

We have electrically characterized the S/C conductor for the CMS solenoid at CERN.

All the conductors used for winding the magnet have a critical current at least 6% higher than the specification value. The total degradation from the virgin strand to the finished conductor is in the worst case 7.4%.

We also qualified the method used for making the electrical joints between layers in a single module and between modules and bus-bars. Both round and straight samples were measured. According to these measurements, it has been decided a conservative length of two meters corresponding to a resistance of 3.8 10^{-10} Ω with an external field of 1 T.

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