Superconducting Strand Properties at Each Production Stage of the CMS Solenoid Conductor Manufacturing

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Abstract—The Compact Muon Solenoid (CMS) detector is one of the general-purpose particle detectors presently being built for the LHC project at CERN. The superconducting CMS solenoid 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 aluminum-stabilized NbTi conductors with a total length of 45 km. The main part of the structural integrity of the CMS coil is ensured by aluminum-alloy reinforcement welded to the high purity aluminum stabilizer of the conductor. The Rutherford type superconducting cable within the stabilizer consists of 32 copper-stabilized multifilamentary NbTi strands each with Nb barrier. The strands are optimized with respect to a high critical current density ($> 3000 \text{ A/mm}^2$ at 5 T, 4.2 K).

Approximately 1950 km of superconducting strand has been produced from 148 extrusion billets and cabled in unit lengths of 2.65 km. All strands within a cable can unambiguously be identified by distinctive patterns of the NbTi filaments. The statistics of I_c measurements, n -value, copper RRR and $(\text{Cu} + \text{Nb})/\text{NbTi}$ ratio are presented. Since the strands are subjected to potentially dangerous high temperatures and mechanical strain during the different conductor production steps it was important to trace the critical current properties of the strand as it progressed through the conductor fabrication process. The paper presents results of I_c measurements, which were performed on all individual strands extracted from conductor samples taken at each step of the manufacturing process. The comparison among the measurements assured accurate quality control during the whole process of conductor production. In addition, I_c measurements in fields up to 6 T on the complete CMS conductors using the MaRiSA test facility are reported.

Index Terms—Aluminum stabilized super-conductors, CMS solenoid, NbTi, strand properties.

I. INTRODUCTION

THE CMS experiment (Compact Muon Solenoid) is a general-purpose proton-proton detector designed to run at the highest luminosity at the LHC. Distinctive features of the CMS detector include a high magnetic field solenoid coupled with a multilayer muon system, a fully active scintillating crystal electromagnetic calorimeter, a tile hadronic calorimeter, and a pow-

Fig. 1. The distinct feature of the CMS conductor is its sandwich-like structure. The high purity aluminum stabilized NbTi conductor is mechanically reinforced by two high yield strength AA sections.

erful inner tracking system. The design field of the superconducting CMS solenoid is 4 T, the magnetic length is 12.5 m and the free diameter of the bore is 6 m [1].

As reported previously in detail, e.g., in [2], the main peculiarity of the CMS magnet among other existing thin detector solenoids is its sandwich-type aluminum-stabilized superconductor. This special feature was chosen in order to have a mechanically self-supporting winding structure. The coil is made of 20 conductors each having a length of 2550 m. The CMS conductor consists of 32 NbTi/Cu strands wound into a Rutherford type cable. The cable is embedded in a high purity aluminum sheath for electrical and thermal stabilization by using a special adopted co-extrusion technology [2]. This rectangular assembly is called the *insert*. Since the yield strength of high purity aluminum is not sufficient to counteract the electromagnetic forces of the coil, the conductor is reinforced by two aluminum alloy (EN AW-6082) sections as shown in Fig. 1. The yield strength of this material at 4.2 K is $R_{p0.2} = 428 \text{ MPa}$ (in final T6 temper) [3]. The aluminum alloy sections are joined by continuous electron beam welding to the insert, using a specially designed production line [4].

Nineteen lengths of CMS conductor have been successfully finished to date. Completion of conductor production is expected for November 2003. The production time of the conductor was about three years starting with the cabling of the first Rutherford cable and ending with the welding of the last unit length.

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TABLE I
CMS STRAND CHARACTERISTICS

Parameter	Quantity
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

About 1950 km of superconducting strands were used to produce the required number of conductors. This paper discusses the statistics of various strand parameters, which were monitored over the whole production. Since the strands are subjected to potentially dangerous high temperatures and mechanical strain during the different conductor production steps it was important to trace the critical current properties of the strand as it progressed through the conductor fabrication process. The comparison among the measurements assured accurate quality control during the whole process of conductor production.

II. THE SUPERCONDUCTING STRAND

The superconducting strand is a multifilamentary wire with a diameter of 1.28 mm composed 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 critical current density of 3074 A/mm² in the superconductor, which is 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 required parameters of the strand are summarized in Table I. All 708 contractual unit lengths, i.e., 1947 km (corresponding to 18 650 kg), were produced by Outokumpu Poricopper Oy and delivered on 158 spools. The material was sufficient to produce 22 cables. The strand produced from one billet had a length of typically 14 000 m.

Intensive quality control was performed on the CMS strands during manufacturing, including continuous eddy current checks and diameter measurements after final drawing. On test samples taken from both ends of each finished strand the critical current, the n-value, the (Cu + barrier)/NbTi ratio and the copper RRR were measured. In contrast to a former publication [5] the statistics of various strand parameters presented here comprise the measured data of all 158 delivered spools required for the CMS solenoid.

A. Critical Current

I_c was measured at 4, 5, 6, and 7 T at 4.2 K using a 10 µV/m criterion. In Fig. 2 the I_c values at 5 T of all delivered lengths are presented. All samples exceeded the specification. The average

Fig. 2. Critical currents at 5 T and 4.2 K of strand samples from all delivered lengths.

Fig. 3. Statistics on the n-values (at 5 T) of all CMS strand samples.

critical current is 2029 ± 32 A corresponding to a critical current density of 3240 ± 51 A/mm².

B. n-Value

The n-value which characterizes the transition from the superconducting to the resistive state was derived from I_c measurements at 5 T. It was calculated by using the equation

$$n = \left(\log \left(\frac{I_{c,100 \mu V/m}}{I_{c,10 \mu V/m}} \right) \right)^{-1}$$

The higher the n-value, the sharper the transition and the better the wire quality. The minimum required value for the CMS strand was 40.

The statistics of all measured samples is shown in Fig. 3. The average value of all 294 strand samples was found to be 44.6 ± 2.6 . None of the samples had a value below 40.

C. The (Cu + barrier)/NbTi Ratio

The parameter which describes the ratio between the amount of normal conducting to superconducting material is the (Cu + barrier)/NbTi ratio. We regard the pure Niobium barrier material here also as nonsuperconductive material since Niobium becomes normal conducting at the magnetic field levels this

Fig. 4. Statistics on the $(\text{Cu} + \text{barrier})/\text{NbTi}$ ratio of all CMS strand samples.

Fig. 5. Statistics on the strand copper RRR of all CMS strand samples.

conductor will be applied to. This ratio is experimentally determined on short samples by etching away the copper matrix and weighing the remaining NbTi filaments. The statistics for all 294 strand samples is shown in Fig. 4. On average a ratio of 1.06 ± 0.02 was found. All strands meet the specification, which is 1.1 ± 0.1 .

D. Strand Copper RRR

The residual resistivity ratio RRR of the copper matrix of the strands is required to exceed 100, both for electrical and thermal stability of the strand and for sufficient ductility, which is important for the cable manufacturing process. A final annealing heat treatment is performed on the strands during production leading to a good level of uniformity among the different strands as can be seen in Fig. 5, which shows the statistics of all 294 samples. The mean value of the copper RRR was found to be 156 ± 11 .

III. COMPARISON OF STRAND I_c PROPERTIES DURING DIFFERENT STEPS OF CONDUCTOR FABRICATION

Due to the special design of the CMS conductor the superconducting strands are subjected to potentially dangerous high temperatures during extrusion and electron beam welding as well as to large mechanical strain during cabling. In order to assure good quality control it is therefore necessary to monitor the current carrying capabilities during different production

Fig. 6. Enlarged photograph of a CMS cable section displaying three strands with different configuration of filaments in the core region for identification purpose (indicated by arrows).

Fig. 7. Statistics on the I_c degradation on extracted strands from the CMS conductor due to the cabling (gray) and the extrusion (black) process.

after cabling and extrusion and typically three strands were extracted from each sample to determine the critical current. The key point is that always the same strands were extracted from the different samples of one conductor in order to have a direct comparison of the I_c properties of each single strand. To trace individual strands within the 32-strand Rutherford cable, eight distinctive patterns of filament arrangements were selected during stacking of monofilaments. Each cable is made with an individually defined cabling pattern. The cabling pattern is recognizable with the help of a microscopic analysis of the sample cross section. With this information it is possible to extract always the same specific strands from all samples of one conductor production. Fig. 6 shows a microscopic photograph of a section of the Rutherford cable where three strands with distinct filament pattern in the boundary region between filamentary zone and the pure copper core are visible.

A rather low compaction ratio (87%) has been chosen for the CMS cable in order to ensure small critical current degradation due to strain and filament damage. In Fig. 7 the I_c degradation due to cabling (gray columns) is presented for three strands of each of the twenty conductors to be used in the CMS magnet. All I_c measurements were performed at CEA Saclay. The degradation, which was found, varies between 0 and 5.0%, the average being 1.0%. The same plot also displays the additional degradation due to the extrusion process. Since the strands were subjected to extrusion temperatures as high as 400°C for several seconds some degradation was expected. On 59 strands coming

Fig. 8. Statistics on the critical current of 16 finished CMS conductors.

from all twenty conductors degradation due to extrusion between 0.2 and 6.7% was found with an average of 3.1%. Based on these data a mean total degradation of $4.1 \pm 1.8\%$ can be evaluated. The average I_c value (at 5 T, 4.2 K) of the 60 virgin strands considered here is 2029 A, i.e., 5% above the specified value of 1925 A. The average I_c value which was found on the extracted strands from the extruded conductor is 1947 A, i.e., even after cabling and extrusion the average strand critical current is still 1% above the specified virgin value.

IV. I_c MEASUREMENTS ON THE COMPLETE CMS CONDUCTOR

The last step in the production of the CMS conductor is the electron beam welding of the two reinforcement bars to the insert. The main advantage of the electron beam welding process is that the energy deposition during welding is localized to a narrow melted zone. This is particularly important for avoiding severe critical current degradation of the superconducting cable located only 4.7 mm distant from the welded interface. For final quality control the critical current of the complete CMS conductor is measured by using the MaRiSA test facility at INFN-Genova [6]. These measurements are the supreme tests because they yield the current carrying capabilities of the conductor under most similar conditions to the operation in the magnet.

Fig. 8 shows the statistics on the critical current at 5 T and 4.2 K of the 16 CMS conductors measured to date. The mean critical current is 61.0 ± 1.0 kA. The accuracy of the MaRiSA facility is about $\pm 2\%$. These results show that all values are at least 6% above the specified value of 56 kA for the finished conductor. For comparison, the nominal current of the CMS coil at 4.2 K is 19.5 kA creating a field of 4.6 T at maximum on the conductor.

In order to evaluate the additional degradation due to electron beam welding we divide the measured conductor current by 32 to get the average strand I_c . This can be compared with the mean value of the measured strand I_c 's extracted from samples of the corresponding insert. Fig. 9 shows the additional degradation derived by this method for all sixteen conductors measured to date. Due to the fact that both the strand I_c values of the insert values have 2% uncertainty the error bars are rather large in some cases.

Fig. 9. Additional degradation of critical current of the CMS conductor due to electron beam welding.

It can be seen from the plot that the additional degradation due to electron beam welding is very small, if there is any. Purely arithmetically, we find an additional mean degradation of 1.7%. In the worst case it is 6.4%.

V. CONCLUSIONS

The production of the CMS conductor will be finished in November 2003. Because of the unconventional design of the CMS conductor it was of great importance to trace carefully the critical current properties of the superconducting strands as they progressed through the conductor fabrication process. A careful set-up of the various steps of the fabrication process assured that the total I_c degradation does not exceed 9% with respect to the critical current of the virgin strands. In detail we observed degradation of 5.0% at maximum due to cabling, of 6.7% in worst case due to extrusion and of 6.4% at maximum due to electron beam welding. The actually measured average critical current of the virgin strand is 2029 A at 5 T and 4.2 K instead of 1925 A, which was specified, i.e., 5% above the specification. Due to the rather challenging conductor fabrication process a total degradation of 9% with respect to the design value of the strand I_c was allowed, i.e., a conductor critical current of $91\% \cdot 32 \cdot 1925 \text{ A} = 56 \text{ kA}$ was specified. The actually measured critical current we found was 59.4 kA or higher, thus at least 6% above specification.

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