The Superconducting Strand for the CMS Solenoid Conductor

B. Curé, B. Blau, D. Campi, L. F. Goodrich, I. L. Horvath, F. Kircher, R. Liikamaa, J. Seppälä, R. P. Smith, J. Teuho, and L. Vieillard

***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. Approximately 2000 km of superconducting strand is under procurement for the conductor of the CMS superconducting solenoid. Each strand length is required to be an integral multiple of 2.75 km. The strand is composed of copper-stabilized multifilamentary Nb–Ti with Nb barrier. Individual strands are identified by distinctive patterns of Nb–Ti filaments selected during stacking of the monofilaments. The statistics of piece length, measurements of Ic, n-value, copper RRR, (Cu+Nb)/Nb–Ti ratio, as well as the results of independent cross checks of these quantities, are presented. A study was performed on the CMS strands to investigate the critical current degradation due to various heat treatments. The degradation versus annealing temperature and duration are reported.**

I. Introduction

The LARGE Hadron Collider (LHC) is the next important project of CERN, the European Laboratory for Particle Physics. The Compact Muon Solenoid (CMS) detector for LHC is based on a solenoidal superconducting magnet. The design central field of the CMS magnet is 4 T, with a magnetic length of 12.5 m and a free bore of 6 m [1].

The technology of high purity aluminum stabilized superconductors is applied to the design and manufacture of this magnet. The dimensions and the proportions of the conductor sub-components were determined taking into account the requested electrical characteristics of the coil, the thermal properties of the coil, the quench protection and stability, and the mechanical strength [2]. The conductor consists of a Rutherford type cable embedded in a high purity aluminum matrix using an extrusion process, joined by a dedicated continuous electron beam welding process to two aluminum alloy profiles acting as mechanical reinforcements [3], [4].

Manuscript received September 24, 2001.

B. Curé and D. Campi are with CERN, the European Organization for Nuclear Research, 1211 Geneva 23, Switzerland (e-mail: benoit.cure@cern.ch).

B. Blau and I. L. Horvath are with the Swiss Federal Institute of Technology (ETH), 8093 Zürich, Switzerland.

F. Kircher and L. Vieillard are with CEA Saclay, Dapnia/STCM, 91191, Gif-sur-Yvette, France.

R. P. Smith is with the FNAL, Fermi National Accelerator Laboratory, Batavia, IL 60510-0500 USA.

L. F. Goodrich is with the National Institute of Standards and Technology, Boulder, CO 80305 USA.

R. Liikamaa, J. Seppälä, and J. Teuho are with Outokumpu Poricopper Oy, 28101 Pori, Finland.

Publisher Item Identifier S 1051-8223(02)03891-5.

TABLE I
CMS Superconducting Strand Specification

Strand Constituents	**Material**
High homogeneity Nb-Ti	Nb 47±1 Wt % Ti
High Purity Copper	RRR > 300
Niobium Barrier	Reactor Grade I
Strand Design Parameters	**Parameters**
Strand Diameter	1.280 ± 0.005 mm
(Cu+Barrier)/Nb-Ti ratio	1.1 ± 0.1
Filament diameter (mm)	< 40
Number of Filaments	≥ 552
Strand Unit length (m)	2750
Twist Pitch	45 ± 5 mm Z (RHS screw)
Strand Minimum Critical Current Ic (A) (Criteria : 5 T, 4.2 K, 10 μV/m)	1925
n-value 5T	>40
Final copper RRR	>100

In particular the superconducting strand layout was optimized both to allow the manufacture of a 32 strand cable with dimensions permitting it to fit in the available space inside the pure aluminum, and to minimize the degradation of the electrical properties of the strands during the conductor manufacturing process.

II. The Superconducting Strand Design

The design of the superconducting strands is based on the experience derived from the previous aluminum stabilized solenoids and from the LHC superconducting dipoles. The superconducting strand is composed of high homogeneity Nb–Ti alloy filaments sheathed with a Nb barrier, and co-extruded in a high purity copper matrix.

The characteristics and parameters of the superconducting strands are summarized in Table I. The requested minimum critical current is 1925 A at 5 T and 4.2 K, with a strand diameter of 1.28 mm and a (Cu + barrier)/Nb–Ti ratio of 1.1 ± 0.1, parameters which place the design at the upper limit of industrial possibilities. The minimum acceptable critical current density is 2994 A/mm^2 at the maximum allowed Nb–Ti content. The strand is heat treated at the final production stage to have a final copper Residual Resistivity Ratio (RRR, here defined as the ratio of the electrical resistivity at 273 K and 4.2 K) above 100.

In order to identify the 32 strands inside a cable, distinctive patterns of Nb–Ti filaments are selected during stacking of monofilaments. The CMS strands are identified by adding one, two or three Nb–Ti filaments at defined positions in the central copper core of each filament.

Two strand cross sections with different central patterns are shown in Fig. 1. For the CMS cables a total of 8 different patterns was requested and successfully achieved.

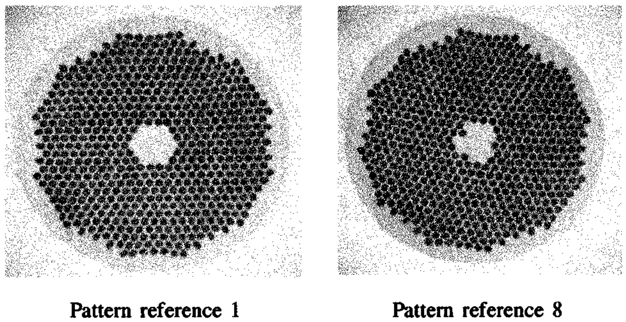

Fig. 1. Cross section of two different strands showing two Nb–Ti filament patterns for strand identification.

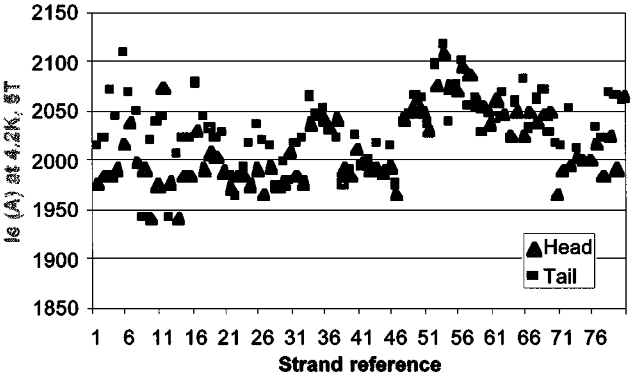

Fig. 2. Strand critical currents, data from Outokumpu.

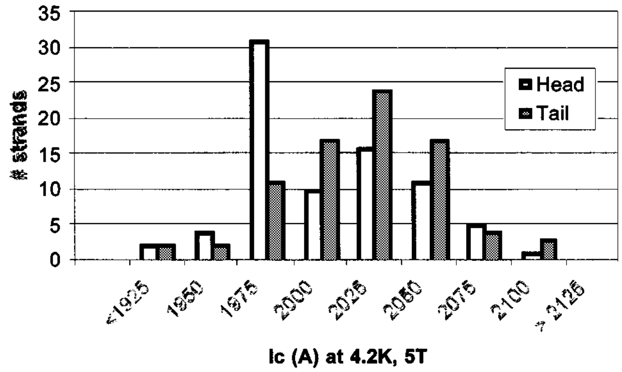

Fig. 3. Critical currents at both strand ends, data from Outokumpu.

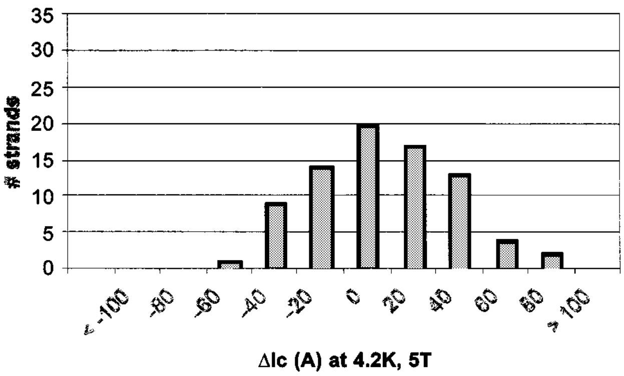

Fig. 4. Ic difference: Ic (Tail)–Ic (Head), data from Outokumpu.

III. The Superconducting Strand Characteristics

Intensive quality control is performed on the CMS superconducting strands during manufacturing (continuous eddy current check, Cu/non-Cu, and diameter measurements during final drawing) and on test samples taken from finished strands. In particular, key parameters like the critical current and n-value, the (Cu+Nb)/Nb–Ti ratio, and the copper RRR are measured for each strand at the beginning and end of each length.

A. Strand Unit Lengths

A total of about 2000 km of superconducting strand is needed for the CMS conductor, corresponding to about 18 tons. To achieve the requested magnetic field, a total of 2180 turns is needed in the CMS coil, for an operating current of 19 500 A [2]. Because the conductor is wound in 4 layers and the coil is made from 5 modules, a total of 20 conductor lengths, each 2.5 km, long is needed. This requires the strand unit length to be an integral multiple of 2.75 km, taking into account the cabling operation and the tuning and sampling lengths on the conductor manufacturing line. About 80% of the strands delivered have a length slightly exceeding five times the minimum value of 2.75 km, and another 10% are delivered in lengths slightly greater than 4 times this value.

B. Strand Critical Currents, Critical Current Densities and N-Values

The critical current Ic is measured at 4, 5, 6 and 7 T at 4.2 K, and 10 μV/m. A temperature correction is applied to express the critical current value at 4.2 K precisely. In Fig. 2 the critical current values measured on samples of 80 delivered lengths are presented. The samples are taken at both extremities, distinguished as "head" and "tail." The critical current Ic is 2015 $\pm$ 96 A at the heads and 2033 $\pm$ 90 A at the tails. As shown in Fig. 3, a peak in the Ic distribution is observed at the heads in the range 1975 A to 2000 A, while it is in the range 2025 A to 2050 A at the tails.

Very good homogeneity is observed in the critical current comparing measurements at head and tail for each strand. This difference between head and tail favors the tail over the head by somewhat less than 20 A, as seen in Fig. 4. The mean difference between head and tail is 1%, and the absolute value of this difference is lower than 2% for 75% of the strands. The maximum difference observed on any strand between head and tail is 4.6%.

From the measured critical current Ic and (Cu+Nb)/Nb–Ti ratio (see Section III-C), the critical current density Jc is calculated and shown in Fig. 5 for the 80 delivered strands. The mean value is 3258 $\pm$ 111 A/mm^2 at head and 3263 $\pm$ 159 A/mm^2 at tail.

The critical current n-value characterizes the transition from superconducting state to resistive state. It is calculated from Ic measurements at 5 T at both head and tail samples for each delivered length. The higher the n-value, the sharper the transition and the better the wire quality. For CMS strands, the n-value was specified to be higher than 40, at 10 μV/m. It was calculated using the formula

$$n = 1/\log[Ic(100\ \mu\mathrm{V/m})/Ic(10\ \mu\mathrm{V/m})]. \quad (1)$$

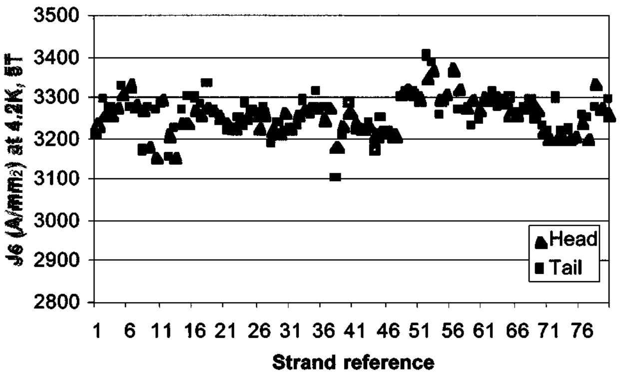

Fig. 5. Strand critical current densities, data from Outokumpu.

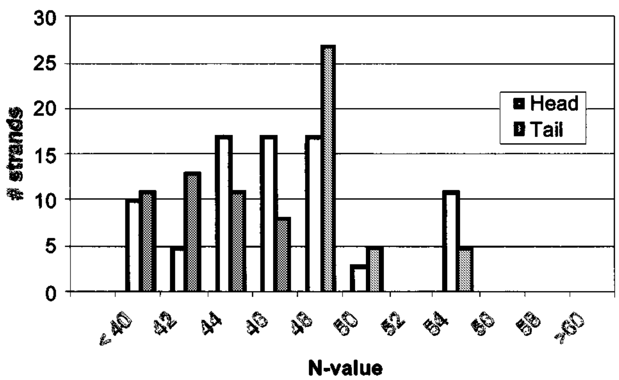

Fig. 6. n-value at both strand ends, data from Outokumpu.

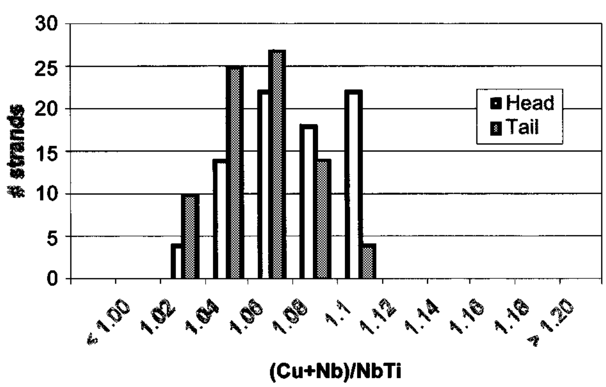

Fig. 7. (Cu+Nb)/Nb–Ti ratio at both strand ends, data from Outokumpu.

The specification is fully met and the n-value at head and tail are similar, with a mean value of about 46.5 $\pm$ 6.5, as shown in Fig. 6.

C. Strand (Cu+Nb)/Nb–Ti Ratio

This parameter gives the proportion of superconducting material in the strand. It is calculated from measurements on short samples at the head and tail of the delivered lengths, by etching the copper and weighing the samples.

Results in Fig. 7 indicate the ratio is higher at the heads than at the tails. The mean value is 1.08 $\pm$ 0.06 at the heads and 1.06 $\pm$ 0.04 at the tails. This can be related to the Ic measurements, as illustrated by the correlation shown in Fig. 8: the strands with higher Ic have a greater fraction of Nb–Ti.

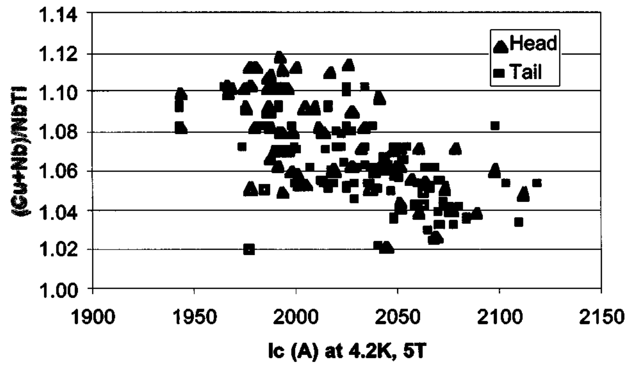

Fig. 8. (Cu+Nb)/Nb–Ti ratio versus critical current, data from Outokumpu.

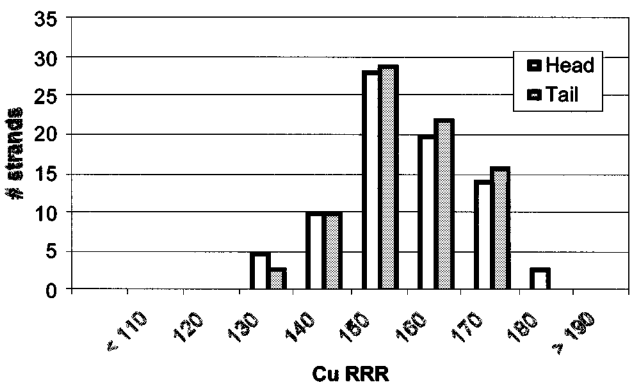

Fig. 9. Cu RRR at both strand ends, data from Outokumpu.

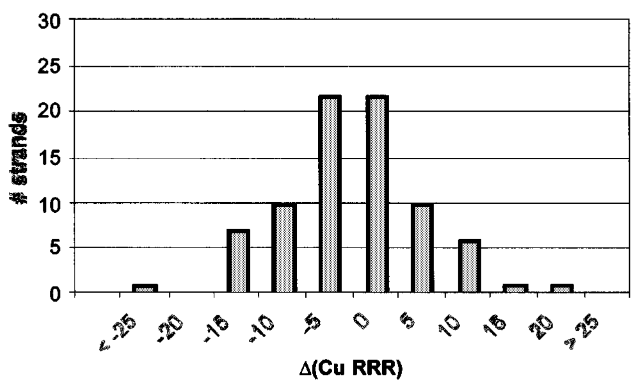

Fig. 10. Cu RRR difference: Tail–Head, data from Outokumpu.

D. Strand Copper RRR

The strand copper is required to have an RRR above 100, both for stability of the superconducting strand and to have enough ductility for cabling. A final annealing heat treatment is performed on the strands and leads to a good level of uniformity (see Figs. 9 and 10 giving the RRR measured from samples at the head and tail of each strand and the difference of this parameter). Furthermore, the values are well above the specification. The mean RRR value is 159 $\pm$ 25.

IV. Independent Cross Checks

Cross checks were performed at CEA-Saclay (France) and NIST-Boulder (US). Critical currents, (Cu+Nb)/Nb–Ti and Cu RRR were measured on the samples (see Fig. 11 to Fig. 13) to

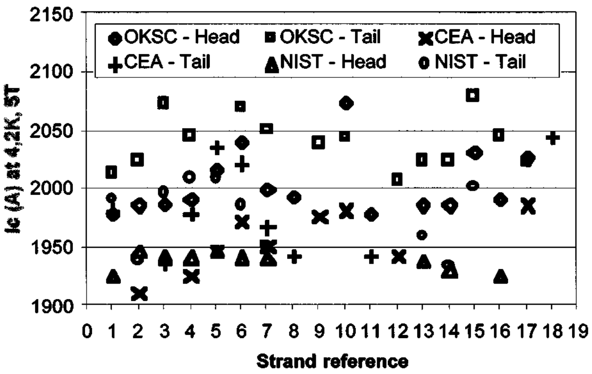

Fig. 11. Strand critical currents cross checks.

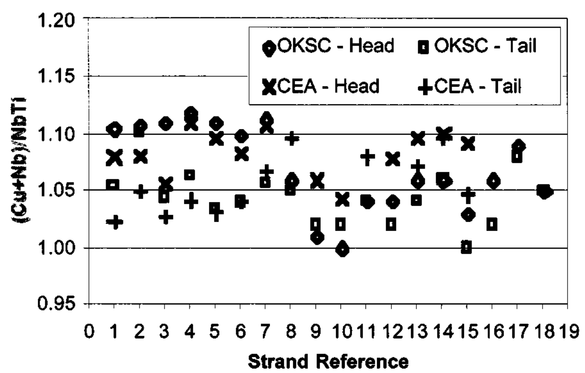

Fig. 12. (Cu+Nb)/Nb–Ti cross checks.

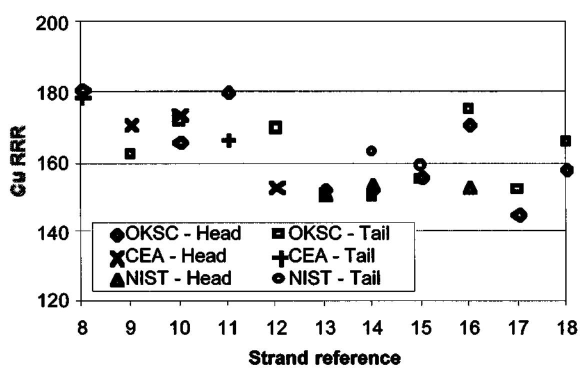

Fig. 13. Cu RRR cross checks.

cross check results from Outokumpu (OKSC). Ic values from CEA are typically 4% lower than OKSC, but with measurements still above specification. The measurement accuracy is approximately 2%. NIST results show an Ic 3.3% lower than OKSC, also above specified values. The (Cu+Nb)/Nb–Ti ratio measured at CEA is about 1% lower than values from Outokumpu, and lower values of this ratio correspond to higher Ic. The Cu RRR results from CEA and NIST are within 2% agreement with results from OKSC. The n-values were measured in both laboratories and found to be above specifications, and in agreement with OKSC. These tests confirm the excellent performance of the strands and the accuracy of the cross check measurements.

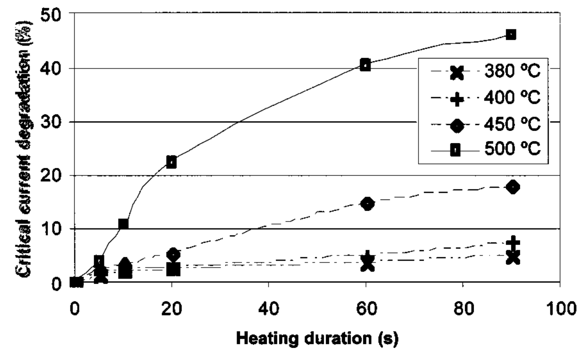

Fig. 14. Ic degradation at 5 T versus heating duration at various temperature.

V. Effect of Heat Treatment on Critical Current

Strand samples were heat treated at several temperatures for defined durations. Results of critical current measurements are reported in Fig. 14. The initial critical current of the strand used in these tests is 1962 A at 5 T, 4.2 K. This study is performed to check the degradation of the wire in case of exposure to high temperature, for instance, during a stop of the co-extrusion press. During the co-extrusion the pure aluminum is heated to 420 °C [3], and the superconductor cable is exposed to slightly lower temperature for a duration typically of the order of 10 s, which leads to about 3% degradation according to Fig. 14. A stop for one minute at 420 °C would result in 9% degradation of the Ic at 5 T.

VI. Conclusion

The quality control tests performed by the manufacturer and the cross check test campaign confirm the excellent properties and performance of the CMS strands manufactured at Outokumpu. The strands fully meet the specifications.

Acknowledgment

The authors would like to thank the CMS collaboration, the laboratory teams involved in these measurements, and Outokumpu Poricopper Oy for providing all the data for quality control and for the effort of manufacturing wires according to CMS specification requirements.

In this document, certain commercial materials are identified to adequately specify the experimental study. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials identified are necessarily the best available for the purpose.

References

[1] A. Hervé, "Status of the CMS magnet," *IEEE Trans. Appl. Supercond.*, submitted for publication.
[2] F. Kircher *et al.*, "Final design of the CMS solenoid cold mass," *IEEE Trans. Appl. Supercond.*, vol. 10, no. 1, pp. 407–410, Mar. 2000.
[3] B. Blau *et al.*, "The CMS conductor," *IEEE Trans. Appl. Supercond.*, submitted for publication.
[4] R. Folch *et al.*, "Continuous EB welding of the reinforcement of the CMS conductor," *IEEE Trans. Appl. Supercond.*, submitted for publication.