Italian Development of a Superconducting Cable for the Main Dipoles of the Large Hadron Collider

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Abstract

In the frame of a collaboration between CERN and INFN *(Istituto Nazionale di Fisica Nucleare)* for R & D on Superconductivity, INFN has financed a program aimed to produce 2.7 km of cable with J_c=1190 A/mm² @ 8 tesla - 4.2 K, and 4.7 km of cable with J_c=2270 A/mm² @ 6 tesla - 4.2 K. The cables will be used for winding the inner and the outer layers of two full size superconducting dipole prototypes. In this paper we present the status of the work and discuss the influence of the main parameters affecting the critical current, like NbTi filament diameter and the the Nb barrier thickness and the cabling process (degradation).

1 INTRODUCTION

INFN has launched a program to deliver to CERN, at the beginning of 1993, two full size LHC twin dipoles [1]. In order to produce the superconducting cable for those dipoles, in 1989 a program started in conjunction with LMI, the Italian manufacturer of superconducting cable, and under CERN technical supervision. At that time the Italian industry had no specific experience with NbTi fine filaments requiring protection barrier.

The conductor quality was checked by means of dimensional measurements, mechanical stability of the cable—which is very important in the winding process—and critical currents of strands both in virgin strands and extracted from cable.

In Table 1 the specifications of the two conductors are listed and the minimum acceptable current is given.

Table 1: main characteristics of the superconducting cable

	inner layer	*outer layer*
strand diameter (mm)	1.29 ± .01	.84 ± .01
Filament diameter (μm)	≤ 10	≤ 10
α (Cu : non Cu)	≥ 1.6	≥ 1.8
Copper RRR	≥ 60	≥ 60
cable thin edge (mm)	2.02 ± .02	1.30 ± .02
cable thick edge (mm)	2.48 ± .02	1.63 ± .02
cable width (mm)	16.85 ± .015	16.85 ± .025
cable edge radius (mm)	≥ 0.3	≥ .03
No. of superc. strands	26	40
minimum I_c at 1.8 K (A)	13,000 @ 11 T	15,500 @ 9 T
minimum I_c at 4.2 K (A)	13,000 @ 8 T	15,500 @ 6 T
J_c non copper (A/mm²)	990 @ 11 T	1960 @ 9 T
unit length (m)	300	525

2 CONDUCTOR FABRICATION

2.1 Wire

For the first layout of both conductors, the filament diameter was chosen equal to 6 μm. A double extrusion was necessary in order to accommodate the required filament number in the wire, approximately 18,000 and 7,000 respectively for the inner and outer layer.

With so fine filaments, the interfaces between NbTi and Cu play a predominant role. Optimisation of the current density at 8 tesla calls for longer thermal treatments and higher temperature than the usual ones. Diffusion processes and formation of intermetallic compounds take place during heat treatment at the Cu-sc. interfaces leading to a sausaging of the filaments.

To avoid brittle intermetallic compounds Nb barrier clad NbTi-46.5wt.%- ingots (provided by TWCA - USA) were used. Based on the information available in 1989 the Nb barrier was selected equal to 2% (in cross section) of the NbTi core. Such a barrier was found inadequate to protect filaments with diameter less than 7 μm, a result reported also in [2]. In Fig. 1 the measured non copper J_c vs. filament diameter is shown. Following these results we decided to have a new billet design aiming to a filament diameter of 7.8 μm.

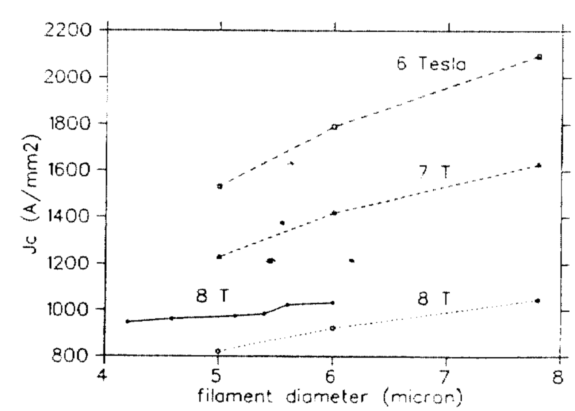

Figure 1: Critical current density versus filament diameter.

In order to maximize the total drawing strain we tried to insert some cold strain into the extrusion. An attempt to perform an hydrostatic extrusion at 150 °C was not satisfactory. We found that, in the final stage of the drawing, longitudinal cracks develop along the conductor probably due to insufficient bonding between the components.

Since raising the extrusion temperature did not solve out definitively the problem (in some billet the longitudinal cracks developed again during drawing) and in order to start from bigger billets to have larger effective strain in the wire, we decided to use the hydraulic extrusion for this R&D phase.

Different heat treatments were tried and a four stage heat treatment schedule was selected. Samples with such a treatment showed a current density in excess of 1050 A/mm^2 at 8 T 4.2 K. We found very difficult to get the proper copper section, having generally 10% more copper than the nominal value for both type of cable.

For the first piece length of the inner cable the extra copper was machined away mechanically between different drawing steps, thus reaching an $\alpha = 1.62$. The current is better but the current density is slightly deteriorated.

The filaments quality looks good, with little sausaging along the filament, and uniform pattern of the composite cross section, see Fig. 2. This is confirmed also by good n-values of the transition curves, 20÷25 at 8 T and $\simeq$ 30 at 6 T.The filament spacing is 1 μm.

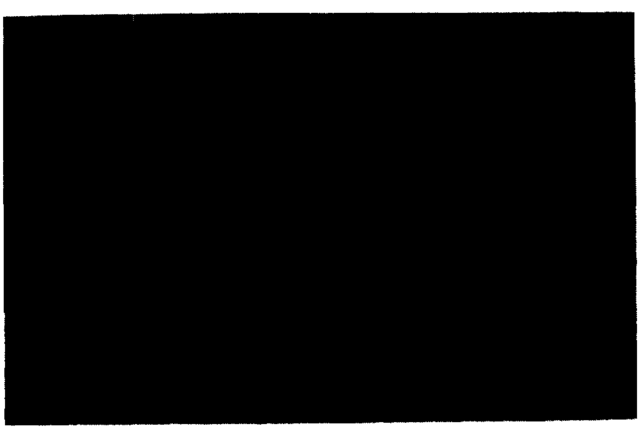

Figure 2: SEM micrograph showing a transverse cross section of the composite for the outer cable.

2.2 Cable

Cabling 40 strands (for the outer cable) without no type of soldering is a difficult task. The cable must withstand handling during the insulation and severe bending during the coil winding. After the cabling of the dummy (copper) cables, an extensive campaign of cabling tests was carried out by using 0.84 mm wires left from the HERA production and cabled in a 40 strands conductor as in the outer cable, to understand the influence of the many parameters on the current degradation. In Fig. 3 the histogram collecting the experimental results on 30 strands measured both in virgin state and after cabling is shown. The current degradation is less than 3%, and this value was confirmed in the production for LHC, for both cables.

RRR measured both on wire and cable was found 60 for the inner cable and 70 for the outer one.

The dimensions of both cables are inside the specified tolerances and the mechanical stability is good.

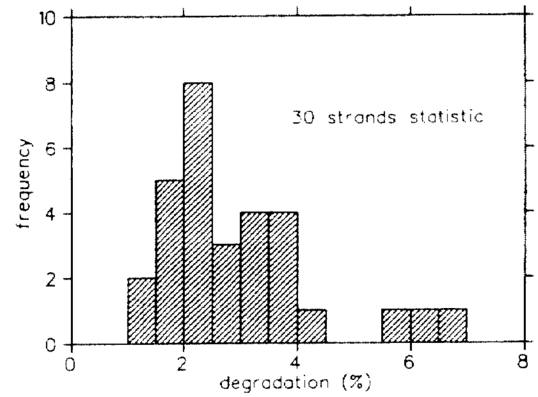

Figure 3: Degradation of the critical current of 0.84 mm strands before and after cabling—30 strands measured at 6 tesla.

3 CRITICAL CURRENT

3.1 Technique

The transport critical current was measured mainly in liquid helium at atmospheric pressure between 5 and 9 tesla. Few strands were measured at reduced temperature around 2.2 K by means of a λ-plate in a subcooled helium bath. The measurements were performed on helix samples, with the external field perpendicular to the conductors and normalized to 4.22 K. I_c data on strands are not self-field corrected. As a rule the selected I_c criterion was $10^{-14}\,\Omega$m.

The measurements on wire were carried out mainly in the LMI lab and in the LASA lab, the main difference being the bobbin diameter the sample is wound onto—70 mm and 42 respectively— and the fact that in the LMI lab the wire is soft soldered onto a stainless steel strip fixed to a G10 cylinder while in LASA lab the wire is simply wound in a grooved G10 cylinder, sometimes with the help of grease to cope with the movements induced by the high Lorentz forces for the bigger strands. The measurements carried out in the two systems agree within 1%, which is their accuracy. The α was determined by weight.

3.2 Results

In Fig. 4 the critical current of the strands of inner cable #1 is reported, both in virgin and extracted state. The mean value of I_c degradation is 3%.

For this cable α is around 1.62 but for the other 3 piece lengths of inner cable so far produced α is more than 1.8. In Fig. 5 the non copper current density of strands of the cable #4 measured at different temperature is plotted vs. the applied field.

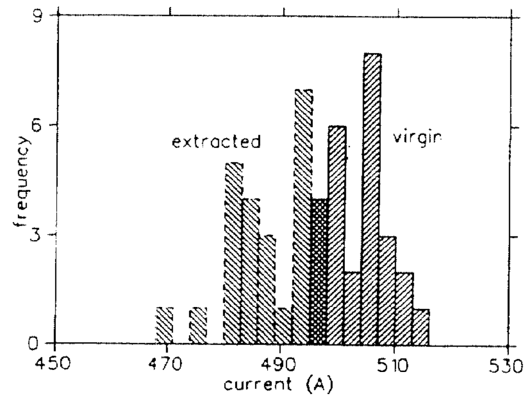

Figure 4: Histogram of the critical current of individual strands from from inner cable #1 at 8 T. Average values are 503 A for the virgin and 487.6 for the extracted strands.

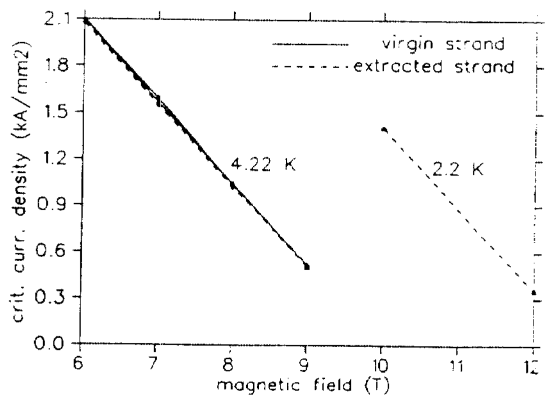

Figure 5: Critical current density vs. field measured at 4.2 K and 2.2 K of strands of inner cable #4

The strands for the outer cable have a critical current well above the minimum required. For the first length the I_c at 6 T is 408 A over the first 12 strands extracted from cable.

Again the copper content is too high, $\alpha = 1.95$. The non copper current density vs. field of typical strands measured at 4.2 and 2.2 K is plotted in Fig. 6.

3.3 *Preliminary Measurements on Cables*

One short sample of the inner cable #1 and one of the outer cable #0 have been measured at BNL [3]. The data are self-field corrected and normalized at 4.22 K.

When the field is perpendicular to the broad face and with peak field at the thin edge, i.e. the worst condition, $I_c = 16{,}061$ A at 6 tesla for the outer cable and $I_c = 17{,}300$ A at 7.32 tesla for the inner one. Assuming the decrease of I_c between 7 and 8 Tesla is the same as in the strands (about 250 A/T $\times$ 26) we can estimate I_c-thin edge- at 8 T to be about 12,900.

The I_c values when the peak field is at the thick edge

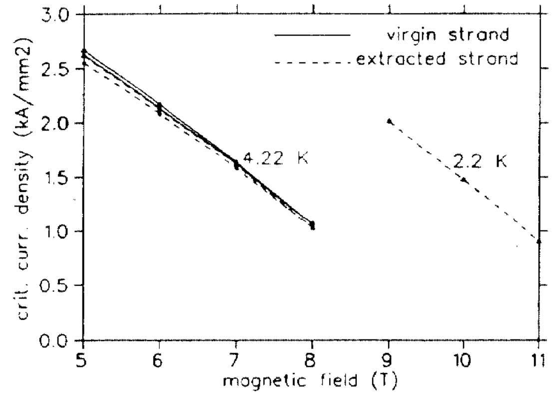

Figure 6: Critical current density vs. field measured at 4.2 K and 2.2 K for strands of outer cable #0

is higher. The mean values of I_c at thin and thick edge are 16,225 A at 6 T for the outer cable and 13,500 A at 8 T (extrapolated) for the outer cable. These values can be compared with the I_c calculated from strands measurements when self field is taken into account. They are 17,100 A at 6 T for the outer cable and 14,100 A at 8 T for the inner cable, with a degradation from strands to cable of 5.3% and 4.4%, respectively.

4 CONCLUSIONS

Cable for LHC dipoles is under production at LMI, Italy. Current density more than 1000 A/mm^2 for the inner cable and 2100 A/mm^2 for the outer one has been reached at 4.2 K and 8 and 6 tesla, respectively. Further R&D is on course especially on the best Nb barrier thickness in order to reach the final goal of 1190 A/mm^2 at 8 tesla with 5 μm of filament diameter.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

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[3] Courtesy of Dr. M. Garber of Brookhaven National Laboratory - Magnet Division, Upton,N.Y., USA.