Critical Current Density in Superconducting $\mathrm{Nb-Ti}$ Strands in the 100 mT to 11 T Applied Field Range

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***Abstract*—The knowledge of the critical current density in a wide temperature and applied magnetic field range is a crucial issue for the design of a superconducting magnet, especially for determining both current and temperature margins. The critical current density of LHC-type $\mathrm{Nb-Ti}$ strands of 0.82 and 0.48 mm diameter was measured by means of critical current and magnetization measurements at both 4.2 K and 1.9 K and for a broad magnetic field range (up to 11 T). For the magnetic field range common to both measurement methods, critical current density values as extracted from transport current and from magnetization data are compared and found fairly consistent. Our experimental data are compared to other sets from literature and to scaling laws as well.**

***Index Terms*—Critical current density, magnetization, superconducting wires, titanium alloys.**

I. Introduction

THE KNOWLEDGE of the critical current density (J_c) in a broad temperature and magnetic field range is a very important issue for designing a superconducting (SC) magnet. Indeed this allows for determining maximal magnetic field achievable and margins for both magnet operating current and temperature. For several years, the $\mathrm{Nb-Ti}$ multifilamentary strands composing the Rutherford cables of the LHC SC magnets [1] are produced in the industry. As part of their qualification, the critical current and the magnetization loop of these strands are systematically measured at CERN [2]. In this work, the J_c, as extracted from direct transport current measurements and as derived from magnetization hysteresis measurements, are presented for two LHC-type $\mathrm{Nb-Ti}$ strands, respectively 0.82 and 0.48 mm in diameter and for a wide applied magnetic field range (from 100 mT and up to 11 T) at both 4.2 K and 1.9 K. In the case of 0.48 mm wire, there is a magnetic field range common to both measurement methods. The J_c values as extracted from transport current and magnetization data are then compared and found to fairly agree. The experimental data are also compared to other measurements from literature and to Bottura's scaling law [3].

II. Experimental Evaluation of J_c Data

The measurements used for determining J_c values from either transport current or magnetization methods were performed at CERN strand test facilities. The setups and procedures for measuring critical currents and magnetization hysteresis curves were already described in detail in, respectively, [4]–[6]. One should mention that contrary to magnetization measurements, where the applied magnetic field is perpendicular to the measured sample, the critical current sample is at an angle of 84° relatively to field axis [4]. This reduces the external field component perpendicular to the sample by ~0.5%. However, the impact on J_c value is not substantial (up to 0.9%) and this effect was thus not accounted for in the present work.

For extracting the J_c values from transport measurements, the critical current, I_c, is measured at given conditions of temperature and applied field according to the $10^{-14}\ \Omega.\mathrm{m}$ total section resistivity criterion. The J_c within the $\mathrm{Nb-Ti}$ filaments is then obviously given by

$$J_c = 4(1+\alpha)\frac{I_c}{\pi d_s^2} \tag{1}$$

where α is the copper-to-superconductor volume ratio as measured by chemical etching and d_s is the strand diameter.

For deriving the J_c data from magnetization measurements, the curve of the magnetization per unit volume of strand is measured under a transverse applied magnetic field by cycling the field, ramping it up from 1 mT to 1.5 T and back down to 1 mT. In such a way, a hysteresis curve is obtained and the curve magnetization width, $\mu_0\Delta m$, can be estimated as a function of the applied field. Neglecting the coupling effects due to filament proximity and assuming that the $\mathrm{Nb-Ti}$ filaments are perfectly round, the hysteresis width and the J_c can be related on the basis of the Critical State Model [7]. The J_c value can then be provided by the following expression:

$$J_c = \frac{3\pi}{4\mu_0}(1+\alpha)\frac{\mu_0\Delta m}{d_f} \tag{2}$$

where $\mu_0\Delta m$ is the magnetization width expressed in T and d_f is the filament diameter as estimated from strand design.

The overall precision of J_c values as derived from critical current and magnetization measurements [Expressions (1) and (2)] is better than 1%.

III. Results for LHC Outer Layer Cable Strands

The $\mathrm{Nb-Ti}$ SC strands composing the main dipole outer layer and quadrupole cables of LHC are 0.825 mm in diameter and they have a copper-to-superconductor volume ratio of 1.95 and $\sim 6\ \mu\mathrm{m}$ diameter filaments. These strands are manufactured by five firms. In Table I, the J_c values, as averaged over the strands fabricated during the last three years, are summarized for each firm for 4.2 K and 6 T applied field and for 1.9 K and 9 T. These values represent the average of J_c data for several hundreds of strand samples measured at CERN critical current

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TABLE I
AVERAGE CRITICAL CURRENT DENSITIES FOR OUTER CABLE STRAND

Company	J_c(4.2 K, 6 T) [A/mm^2]	J_c(1.9 K, 9 T) [A/mm^2]
A	2278	2275
B	2344	2279
C	2338	2376
D	2333	2361
E	2328	2330

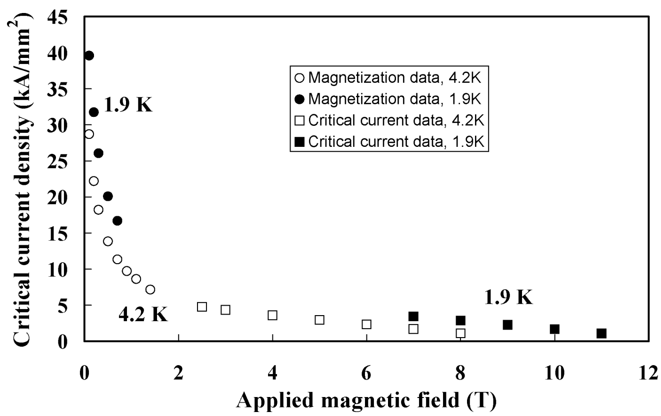

Fig. 1. Critical current density as a function of the applied magnetic field (no self field) for the CERN reference wire as derived from magnetization (round symbols) and transport current (square symbols) measurements for both 4.2 K (hollow symbols) and 1.9 K (full symbols).

facilities. As shown by Table I, the J_c values averaged for the various suppliers are consistent within 4% for both 6 T and 9 T. It is interesting to note that, even if considering other LHC-type strands (0.48, 0.74 and 1.06 mm in diameter), their J_c data agree with those listed in Table I within 10%. This is despite the different optimization heat treatments undergone by the various strand types.

A LHC outer cable strand is routinely measured as a reference wire in both CERN critical current and magnetization stations. In Fig. 1, the critical current densities as estimated for the reference strand according to critical current (square symbols) and magnetization (round symbols) are presented for both 4.2 K (hollow symbols) and 1.9 K (full symbols), as a function of the applied magnetic field, i.e. without taking into account any self-field effect. In Fig. 2, the J_c of the reference wire, at 4.2 K and as normalized to its value at 5 T, is presented as a function of the applied magnetic field (full line) and is compared to Spencer *et al.*'s data [8] and to Somerkoski *et al.*'s data [9]. As clearly shown by Fig. 2, there is a very fair agreement between LHC data and those from literature.

As shown by Fig. 1, there is no overlap between magnetic field ranges of both I_c and magnetization measurements. This is due to the DC power supply limitation to 1000 A for the I_c setup and to the magnet limitation up to ~1.5 T for the magnetization station. In order to allow for a comparison between J_c values as derived from both methods, transport current and

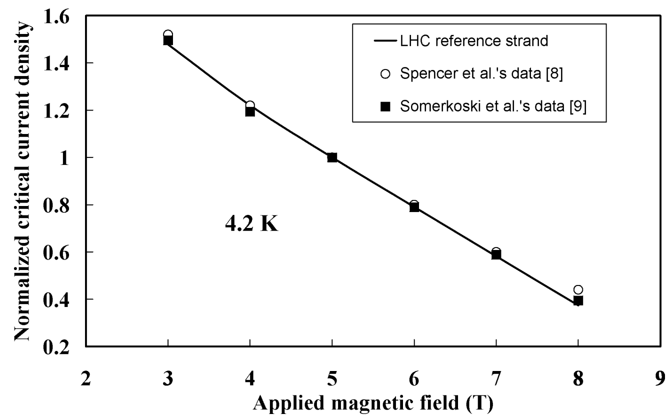

Fig. 2. Critical current density normalized to 5 T value for 4.2 K and for the LHC reference strand as measured at CERN (full line) and compared to data of Spencer (hollow symbols) and Somerkoski (full symbols).

magnetization measurements were performed on a thinner wire (0.48 mm diameter) for which such a comparison is possible.

IV. RESULTS FOR LHC INSERTION QUADRUPOLE STRAND

A. Characteristics of the Measured Strand

The strands measured to compare J_c values as derived from critical current and magnetization methods are the wires used to fabricate the Rutherford cables of one of the LHC insertion quadrupole magnets. The data were collected on two different strands of the same mentioned type. Since J_c results for both wires agree within 2%, the results of a single strand, for which the data are the most complete, are presented here.

This strand is 0.479 mm in diameter. It has a copper-to-superconductor volume ratio of 1.678 and a twist pitch of ~15 mm. It contains ~ 6 μm diameter filaments.

B. Self Field Calculations

For comparing J_c values extracted from both measurement methods, the total magnetic field, i.e. the sum of applied external field and self field, should be determined for transport-derived J_c data. A precise evaluation of the self-field contribution is not an easy task.

In this work, the SC strand is assumed to be a straight wire with straight filaments, thus neglecting both spiral wire shape (due to its winding on the sample holder) and filament twist. Considering the wire as straight infinite is a sound approximation since calculations showed that the helical effect on the self field is of the order of 5% in the case of a LHC outer strand, for the sample holder geometry used at CERN [10]. For the wire considered in this section, the effect should be even less significant due to a smaller strand diameter (0.48 mm versus 0.82 mm). The filament twist effect can be neglected since the twist pitch (~15 mm) is much larger than the external radius of the strand composite zone (~0.2 mm).

In SC strands of this type, the filamentary composite Cu/Nb − Ti region is embedded between a copper core and an external copper ring. For the sake of simplicity, the composite region is considered as a homogeneous SC medium with a superconductor filling ratio (typically ~0.7). The filamentary zone is roughly a ring with inner and outer radii, r_1 and r_2 (respectively ~0.1 mm and ~0.2 mm). At a given r between r_1 and r_2, the self field value is then given by

$$B_{sf}(r) = \frac{\mu_0 I(r)}{2\pi r} \tag{3}$$

where $I(r)$ is the current enclosed up to r. In order to determine $I(r)$, the current density within the composite area should be known. However, this density obviously depends on the total magnetic field which we just want to calculate.

For low applied magnetic field (up to 1 T), the field dependence of J_c can be extracted from magnetization versus field profiles. Magnetization profiles from either BNL measurements [11] or from CERN measurements were considered and the self-field values, as calculated according to the method just described below, agree within 3%. The radial self-field dependence can be numerically calculated in the following way. The filamentary area is divided into numerous and thin concentric layers. For the most outer layer, the self-field value is given by (3) with $r = r_2$ and $I(r) = I_c$. The local J_c value is then calculated for this layer with the total magnetic field (i.e. the sum of applied field and $B_{sf}(r_2)$). The current enclosed in the layer is subsequently calculated. This current is subtracted from the total critical current and the same procedure is iteratively applied to the second outer layer and to the other ones down to r_1. At the end, the J_c profile is normalized to ensure that the sum of all layer currents equals the total critical current. In such a way, the self field radial dependence is calculated and is averaged between r_1 and r_2 to provide the self-field contribution. This average contribution is added to the applied field to obtain the total magnetic field of the transport-derived J_c values.

For external fields higher than 1 T, there are no complete magnetization data available for J_c versus field profile. Thus the layer method, just described, can not be implemented. For calculating self-field radial dependence, the J_c versus field dependence is neglected and it is then assumed that the current is equally distributed within the filamentary region. This hypothesis is obviously correct at high fields for which the self-field contribution is low as compared to applied field and for which the field sensitivity of J_c becomes lower. In such a case, the current distribution in the composite area is mainly governed by applied field and then it is expected to be roughly uniform. However, the validity of this approximation is questionable for intermediate fields (i.e. between 1 and 3 T). In order to verify its consistency, the self-field values for 1 T external field and both 4.2 and 1.9 K as calculated on the basis of uniform current distribution were compared to values evaluated according to layer method. Both values appeared to agree within 3% (4.2 K) and 7% (1.9 K), thus strengthening the reliability of the approximation. Therefore, assuming a uniform current density, the self-field is given, at radius r within the composite zone, by the following expression:

$$B_{sf}(r) = \frac{\mu_0 I_c}{2\pi\left(r_2^2 - r_1^2\right)}\left(r - \frac{r_1^2}{r}\right). \tag{4}$$

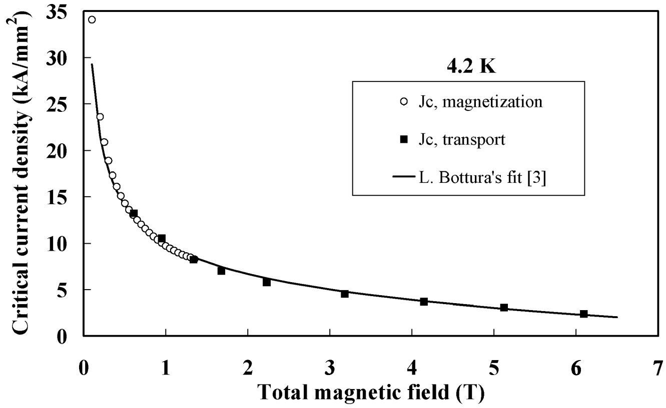

Fig. 3. The critical current density versus total magnetic field (including both applied and self field contributions) for the LHC insertion quadrupole strand, at 4.2 K. The hollow round symbols represent magnetization-derived values whereas full square symbols are critical current measurements. Bottura's fit [3] is presented (full line) for comparison.

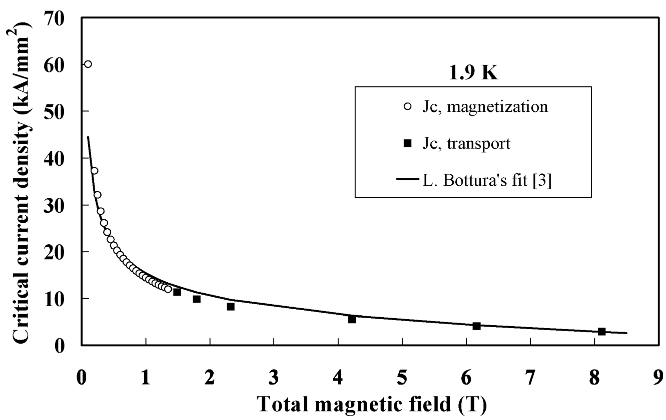

Fig. 4. Same as Fig. 3, for 1.9 K.

Averaging (4) between r_1 and r_2, the self-field contribution considered for applied field larger than 1 T is

$$B_{sf}^{av.} = \frac{\mu_0 I_c}{\pi\left(r_2^2 - r_1^2\right)^2}\left(\frac{r_2^3}{3} - r_1^2 r_2 + \frac{2r_1^3}{3}\right). \tag{5}$$

C. J_c Data

For the measured insertion quadrupole (IQ) strand, the J_c results as derived from magnetization curves (hollow round symbols) and from critical current measurements (full square symbols) are presented as a function of total magnetic field, respectively for 4.2 K and 1.9 K, in Figs. 3 and 4. As shown by Fig. 3, magnetization and transport values are fairly consistent for 4.2 K, within less than 5%. For 1.9 K (Fig. 4), there is a small magnetic field gap between both measurements and a direct comparison is thus not possible. However, the magnetization result as extrapolated to 1.49 T agrees with the corresponding transport-derived J_c value within 3%.

For comparison, the fit of Bottura [3] is presented together with the measured J_c data in Figs. 3, 4. The parameters used for this fit are those given by this author in his article, in the case of a R&D LHC-type outer strand. At 4.2 K, the fit is fairly consistent with our data, the maximal deviation being 16% (at 0.1 T field). For magnetic fields larger than 0.2 T, this deviation does not even exceed 7%. At 1.9 K, the agreement between the experimental data and the fit is not as good with a maximal deviation of 35% (at 0.1 T also). This deviation is up to 15% for fields higher than 0.2 T. The measured J_c data were fitted with the double bending fit function recently developed by Schwerg and Vollinger [12]. The agreement between data and fit values is within 2%.

When comparing between the J_c values reported for the outer reference strand (Section III) and the IQ strand, it is observed that magnetization-derived values for the latter strand are higher by 3 to 6% for 4.2 K and magnetic fields down to 0.2 T. However, this deviation grows up to 19% for 0.1 T. At 1.9 K, this phenomenon is even more substantial since IQ strand value is higher by ∼6% for fields higher than 0.3 T, the deviation growing up to 10% at 0.3 T, 17% at 0.2 T and even 52% at 0.1 T. The J_c value of the IQ strand as estimated from magnetization curves thus appears to be overestimated at very low field when compared to the outer strand. This is also consistent with the discrepancy mentioned above between insertion strand experimental values and Bottura's fit which is also based on LHC outer strand data. This disagreement can be explained by the filament coupling by means of persistent currents through the copper matrix [13]. This effect, known as the proximity effect, is supposed to be quite negligible in the case of LHC outer strands for which the filament spacing is typically 1 μm [13]. For IQ strands, this spacing is 0.6–0.7 μm and an anomalous magnetization effect is expected at low fields. This is probably why the magnetization appears to be overestimated at 0.1 T and 4.2 K. At 1.9 K, due to higher critical current density, the coupling effect is more significant as underlined by the results up to 0.2–0.3 T.

V. Conclusion

In this work, the critical current density as derived from both magnetization and critical current measurements was presented in a broad magnetic field range and at both 4.2 K and 1.9 K, for two different LHC-type strands (∼0.82 mm and ∼0.48 mm in diameter). The results of both strands are compatible within a few percent, except at very low field (up to ∼0.2 T) for which filament proximity effect induces an overestimation of the magnetization-derived data by a few tens of percent for 0.48 mm wire. The presented results are thus thought to be representative of "state of the art" Nb − Ti superconducting strands, for fields larger than 0.2 T. Critical current densities as evaluated from both measurement methods were found to fairly agree thanks to a self-consistent self-field evaluation. Further investigations of the proximity effect on LHC strands should be performed in near future.

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