Self-Field Effects on Critical Current Measurements of Large Multi-Strand Conductors

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***Abstract*—We have studied the methods for comparing the values of the critical current measured on superconducting strands with the ones obtained on a complex Rutherford cable made of the same strands. This problem is related to the definition of critical magnetic field for strands and cables carrying a given current, which generates a not negligible and inhomogeneous self-field. The method is based on the evaluation of the electrical field along the conductors carrying currents around the critical value. The developed criteria are adopted for comparing the critical currents measured on short samples of strands and Rutherford cables made of 32 strands embedded in pure aluminium matrix.**

***Index Terms*—Critical current, Superconducting Filaments and Wires, Superconducting Accelerator Magnets.**

I. Introduction

FROM an operative point of view, the critical current of a superconducting wire is defined as the current flowing through the wire causing a given voltage drop along the sample in presence of an external magnetic field applied normally to the current direction. For NbTi conductors some criteria for the electrical field are used (0.1 to 1 μV/cm) or elsewhere a resistive criterion is involved (10^{-15} to 10^{-14} Ωm) [1]. These criteria are based on the physical consideration that the current is critical when the dominant dissipative regime is the thermally activated flux creep.

In this regime the electrical field is a power function of the current ($E \propto I^n$) according to a power index *n*, related to the pinning energy and to the quality of superconductor. Any criterion allows defining the critical current without ambiguity. On the contrary, the definition of the critical field is not unique. 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 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 centreline 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. Different geometries of the sample under measurement lead to different field distributions. 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 [2], [3].

Our aim was to develop a simple and reliable method for assigning a critical field to a measured critical current of any wire or cable. The consistency of the method was verified comparing the critical currents of the strands and the cables, made from the same strands, involved in the winding of a large superconducting coil for high energy physics applications: i.e. the solenoid for the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC), in construction at CERN [4].

II. Samples and Field Distributions

We will compare the critical currents measured on strands arranged in hairpin geometry with the ones of Rutherford cables made of 32 strands. The cables under measurement are arranged in a loop with the wide face normal to the magnetic field. Table I shows the main geometrical characteristics of

TABLE I
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

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strands and the cable. In this section we review in detail the field distribution for both cases.

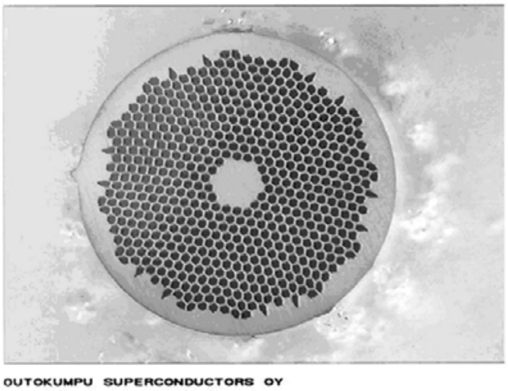

Fig. 1. Cross-section of a NbTi strand made by Outokumpu for CMS conductor.

A. Strand

The strand under consideration is shown in Fig.1. When a current is flowing through the sample, a self-field is generated. The calculation of the self-field can be easily done, considering the axial-symmetric geometry and supposing a homogeneous current density in the large shell containing the filaments. A more detailed computation can account for the geometry of the filamentary region, delimited internally by a hexagon and externally by a dodecagon; a numerical code can help in this case (OPERA®, Vector Fields Ltd).

We start from the experimental fact that the measured critical current (at the electrical field of 0.1 μV/cm) is at least 1860 A, when a magnetic field of 5 T is applied normally to the wire at 4.2 K. Fig. 2 shows the self-field, Fig. 3 shows the field plus the self-field distributions calculated in this special case.

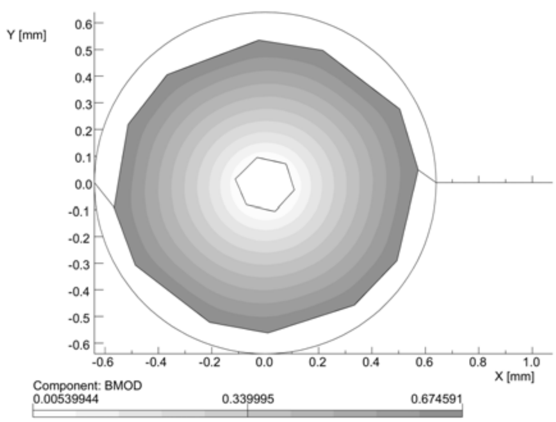

Fig. 2. Self-field distribution when a current of 1860 A is flowing in a single strand.

We can now make some considerations:

- The field at the conductor ranges from a minimum of B_{min}= 4.32 T to a maximum of B_{max}= 5.68 T. The question is: which particular field value in this range shall be considered as the critical one?

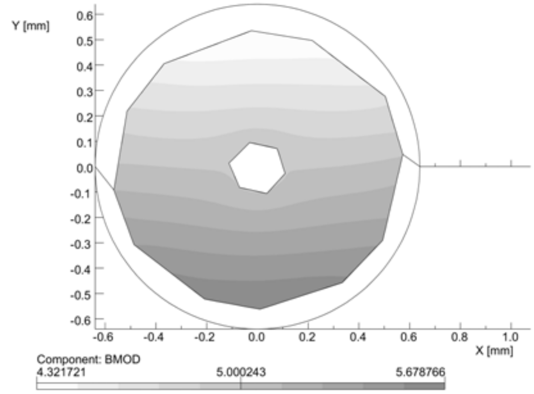

Fig. 3. Field plus self-field distribution when an external field of 5 T is applied normally to the wire.

- According to the peak field criterion, the critical field would be 5.68 T. Nevertheless only very limited fractions of the conductor cross- section is exposed to this field
- What the people usually consider the critical field is the applied one (5 T). Nevertheless we have a large fraction of filaments exposed to a field much higher. Considering the power law for the *E(J)* curve, the contribution to the voltage drop of these filaments is much higher than the one of the filament at lower field.

Indeed, the most objective statement that we can make is the following: when the sample is exposed to a field ranging in continuous way from B_{min}=4.32 T to B_{max}=5.68 T (or to an applied field of strength within the range 5 T ± 0.68 T), the critical current is 1860 A. The problem is how to use this statement for understanding its connection with the critical current of the multi-strand cable or with the critical current of the magnet wound with that cable?

B. Rutherford Cable

As shown in Table I, the cable is obtained by the composition of 32 strands. In order to measure its critical current, a transformer method is used, so to be able to feed currents as high as 60 kA. In particular the direct transformer method is involved [5], [6]. The sample is bent on its larger inertia and arranged to form a loop of inner radius 178.25 mm. The two ends of the loop are overlapped and electrically jointed. For completeness of information we must say that the measurement is not done directly on the Rutherford cable, but rather on a subsequent step of the CMS conductor construction. After cabling, the Rutherford is co-extruded in a pure aluminium matrix to form the stabilised insert (Fig. 4 shows the cable and the insert).

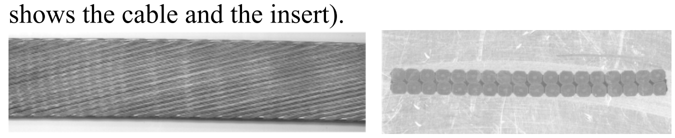

Fig. 4. Rutherford cable and insert of the CMS conductor.

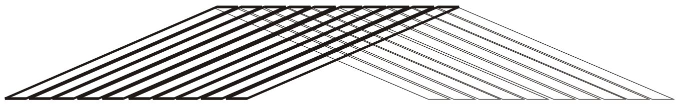

Fig. 5. Sketch of the cross-section of the Rutherford cable, placed in the x-y plane. Moving along the cable a strand in the position i moves to position i+1 after a displacement Δz=Lp/N, where Lp is the twist pitch.

The I_c measurement is carried out on the insert, taking advantage from the aluminium stabilization. Nevertheless these experimental details have no effects on our discussion about field distribution, but the small currents flowing through pure aluminium in proximity of the superconducting to normal transition.

Let us consider the cable under measurement. In view of a comparison with the field distribution of a single strand, we can model any generic cable composed by N strands in a discrete way. Fig. 5 shows the cross section of the cable (placed in the *x-y* plane). Moving along the cable (*z* direction), a strand in the position i moves to the position i+1 after a displacement $\Delta z=L_p/N$, where L_p is the twist pitch (the strand in position N moves to position 1). When moving along the strand we have to consider the geometrical slope of the strands, which are oriented along a direction *t* not coincident with *z*. If Δy_0 is the dimension of the cable wide face and $\beta=\arccos(2\Delta y_0/L_p)$ the segment along the strand, we have $\Delta t=\Delta z/\cos(\beta)$ corresponding to a displacement Δz. The external magnetic field B_{ext} is applied along *x*. When a current *I* is flowing along *t* direction, the field decreases at one edge (position 1 and N), while increases at the opposite one (positions N/2 and N/2+1). At any position, the field distribution at the strand is as complex as the distribution in a single strand.

Moving to our example of the CMS cable, we can carry out a simple field computation in two different situations:

1. We apply a homogeneous external field of 3.17 T and consider a current of 59520 A (32 times 1860 A of the single strand) flowing in the cable. Fig. 6 shows the field at the cable. For any strand (or alternatively for any position i) we can define the field as a central value B_{imean} with an oscillation of maximum amplitude ΔB_i. As an example (Fig. 7) for strands at locations i=16 – 17 we obtain B_{imean}= 5 T and ΔB_i=0.52 T. The peak field is 5.55 T. This field distribution is not exactly the one obtained for the single strand, for which ΔB_i=0.68 T.

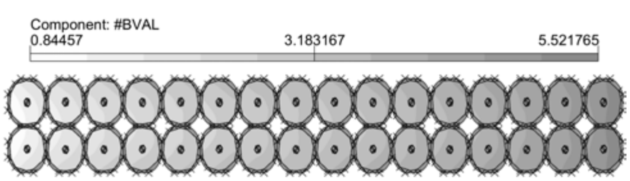

Fig. 6. Magnetic field distribution in the Rutherford cable, when an external field of 3.17 T is applied.

2. Alternatively we can apply that external field giving a peak field of 5.68 T at position i=16 – 17. This result is obtained by applying B_{ext}=3.33 T (Fig. 8). In this case the mean field value at position 16-17 is higher (B_{imean} =5.16 T).

Before deciding between these two cases, which better simulates the field distribution experienced by a single strand, we have to demonstrate that the strands in position N/2 and N/2+1 (16-17 in our working case) really determine the measured *V-I* characteristics.

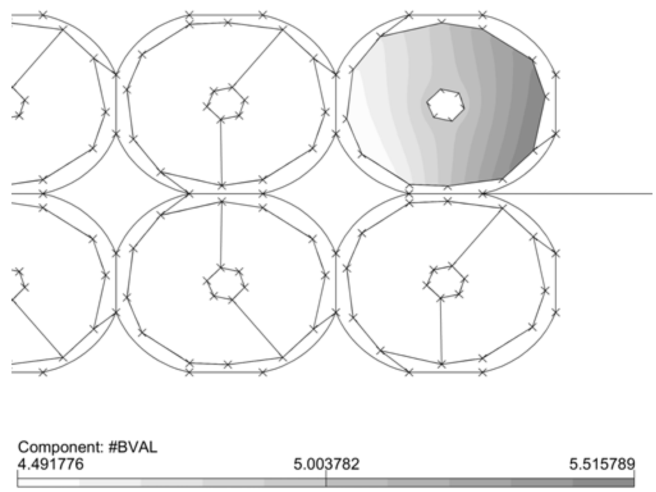

Fig. 7. Peak field at locations i=16-17 when B=3.17 T is applied to the Rutherford cable: the mean field of 5 T is the same as in the single strand.

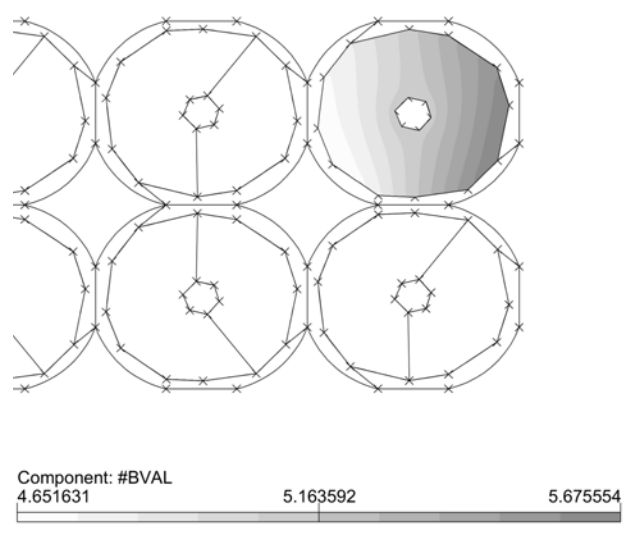

Fig. 8. An external field of 3.33 T must be applied to the Rutherford cable to obtain the same peak field of the single strand.

III. Voltage Drop Along the Cable

In this paragraph we will compute the voltage drop along any strand of the cable during the transition from superconducting to normal state, to show that nearly all the contribution comes from the very small portion placed at the higher field, i.e. when any strand is in positions N/2 and

N/2+1. We have supposed that any strand carries the same current along its whole length (i.e. at any position).

Due to the symmetry of the problem we will limit our attention to strands in positions 1 to N/2. Let us suppose that we can define the critical current of the strand $I_c=I_c(B)$, which is an ideal definition and it has nothing to do with the measured critical current of the strand (we have seen that the field is not homogeneous). Due to the field variation, the critical current along the strand ranges from a maximum (in positions 1, where the field is lower) to a minimum (in positions N/2, where the field is higher). In order to proceed in our analysis, we need to involve for any position a single value of the magnetic field: we will use the central local value $B_{i\ mean}$. The critical current can be written as $I_{ci} = I_c(B_{i\ mean})=I_{c0}(1-\alpha B_{i\ mean})$ at position i.

The voltage drop along any strand carrying a current I can be calculated as:

$$\Delta V(t) = E_c \Delta t \left(\frac{I}{I_c(B_{i\ mean})} \right)^n = E_c \Delta t \left(\frac{I}{I_{c0}(1-\alpha B_{i\ mean})} \right)^n$$

where E_c is the criterion for the critical field. For our case, considering that at B=5 T, I_c=1860 A, and α=0.1 [7], we have I_{c0}= 3720 A. Furthermore setting n=40 (typical for those wires), we are able to evaluate $\Delta V/E_c\ \Delta t$ as function of the position i when a current of 1860 A is flowing through any strand. From Fig. 9 we can observe that the most relevant contribution comes from position 16 (that one at higher field), which gives 98% of the total voltage drop.

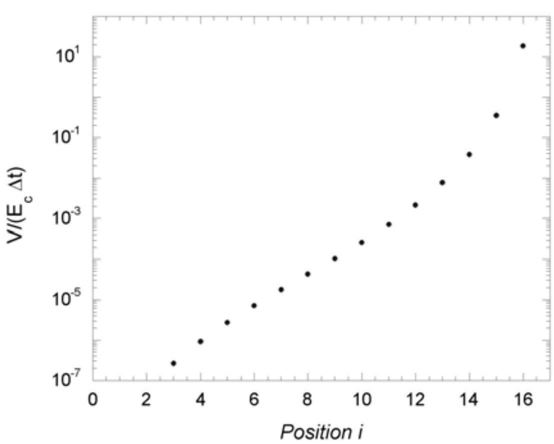

Fig. 9. Evaluation of the voltage drop along the Rutherford cable as a function of the single strand position. The most relevant contribution comes from position 16.

IV. Comparison between Single Strand and Strand Placed in the Cable

After determining that the voltage drop is localized at position 16 only, we can compare the field distribution in the three cases: 1) Single strand carrying a critical current I_{cs} at 5 T field (peak field 5.68 T); 2) Strand in the cable at position 16 carrying, as well as all other 32 strands, I_{cs} with a central field of 5 T (peak field 5.52 T); 3) Strand in the cable at position 16 carrying, as well as all 32 strands, I_{cs} with a central field of 5.16 T (peak field 5.68 T).

TABLE II
Comparison between Critical Currents

	Single strand I_{cs} (A)	Rutherford cable I_c (B_{imean}=5 T)	Rutherford cable Ic (B_{imean}=5 .16 T)
a	1895	1881	1824
b	1918	1880	1823
c	1853	1810	1756
d	1838	1861	1802

The experimental data are taken from the experiments carried out on the CMS conductor. In Table II the measured critical currents of single strands extracted from different CMS inserts (CEA, Saclay) are compared to the values measured using Ma.Ri.S.A. facilities [8].

From the analysis of the experimental data, the critical current of single strands compare better with that of the Rutherford cable when the mean value of the field experienced by the Rutherford strands at higher field (i.e. in positions 16-17) is 5 T. We can then assume as a rule of thumb that the best way to compare the critical current measurements of single strands and Rutherford cables corresponds to apply 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.

V. Conclusion

We have developed a simple and reliable method for assigning a critical field to a measured critical current of any wire or cable. We have verified that the best way to compare the critical current measurements of single strands and Rutherford cables corresponds to apply 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. The consistency of the method was verified comparing the critical currents of the strands and the cables used for the winding of CMS solenoid at CERN.

References

[1] A. F. Clark and J.W. Ekin, "Defining critical current," *IEEE Trans. Magn.* , vol. 13, pp. 38-40, 1977.

[2] M. Garber, A. K. Ghosh and W.B. Sampson, "The effect of self field on the critical current determination of multifilamentary superconductors," *IEEE Trans. Magn.*, vol. 25, pp.1940-1944, 1989.

[3] P. Fabbricatore, R. Musenich, R. Parodi, S. Pepe and R. Vaccarone, "Self field effect in the critical current measurement of superconducting cables and wires ," *Cryogenics,* vol. 29, pp. 920-925, 1989.

[4] A. Herve et al., "Status of the CMS magnet (MT17)," *IEEE Trans. Appl. Super.* , vol. 12, pp. 385-390, Mar 2002.

[5] P. Fabbricatore and R Musenich, "Critical current measurements of superconducting cables by the transformer method," in *Handbook of Applied Superconductivity,* B. Seebers, Ed., IoP Publishing,1998, pp.325-343.

[6] P. Fabbricatore, R. Musenich and R. Parodi, "Inductive method for critical current measurement of superconducting cables for high-energy physics applications," *Nucl. Instr. Meth.* A, vol. 302, pp. 27-35, Apr 1991.

[7] M. Lubell , "Empirical scale formulas for critical current and critical field for commercial NbTi", *IEEE Trans. Magn.*, vol. 25, pp.1940-1944, 1983.

[8] M. Greco, P. Fabbricatore and R. Musenich, "Critical current measurements on the CMS stabilized conductor", *IEEE Trans. Appl. Super.* , vol. 12, pp. 381-384, Mar 2002.