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Investigation of Power Dissipation Mechanisms in Coated Conductors at High Current Densities Based on Ultra-Fast Pulsed Current Measurements

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***Abstract* — In this contribution, we report and discuss the physical meaning of pulse current measurements carried out on coated conductors (CCs) consisting of a superconducting YBCO film deposited on a Hastelloy substrate and coated with a thin metallic layer. The high current (up to 1000A) and short duration pulses (from 10 μs to 1 ms) have allowed us to determine the current-voltage characteristics of two different samples in a situation near that of zero injected energy, and therefore remove the bias resulting from the temperature rise during the measurement. The characteristics obtained show a flux creep region and two linear regimes. The first linear regime is the flux flow regime. In this regime, we show that the vortex velocity is a constant that depends on the metal film resistivity. The second linear regime is ohmic and his origin is less clear. We propose models describing both linear regimes, that are in agreement with the measurements. Finally, we discuss the consequences of these results for the applications of the coated conductors in devices for power systems, especially fault current limiters and power transmission cables.**

***Index Terms* — Fault current limiters, Flux flow, High-temperature superconductors, Resistivity measurement, Superconducting tapes, Yttrium compounds.**

I. INTRODUCTION

YBCO-based coated conductors (CCs) consist of a high temperature superconducting film of the $YBa_2Cu_3O_{7-\delta}$ family deposited on a metallic substrate (here Hastelloy) covered with one or several buffer layers. The superconducting film is covered with a metallic layer and the whole system may be or not encapsulated. Coated conductors are considered as a promising component for power devices such as transformers, motors/generators, power transmission cables and especially superconducting fault current limiters (SFCLs). A major challenge for their use in power applications is the generation of hot spots that occur if the transport current becomes larger than the critical current at some locations in the superconducting film. The resulting heating effects and thermal instabilities can damage the conductor or even destroy it. This is the reason why the CCs includes a metallic layer that is supposed to divert an important part of the excess current from the YBCO film and contribute to prevent a thermal runaway. However, little is known about the phenomena occurring in CCs subjected to overcritical currents. To clarify these aspects, very fast Pulsed Current Measurements (PCM) have been carried out on two types of CC samples. In previous work reported in literature, large pulses durations, in the range of milliseconds to tens of millisecond, have allowed the investigation of the thermal effects of the overcritical currents (see for examples [1][2][3]), but not that of the intrinsic physical processes occurring in the superconducting films and in the metallic layers. Shorter pulses durations are required for this purpose [4][5][6].

In this contribution, we present and discuss PCMs on coated conductors carried out with a custom built pulse current source. By extrapolating properly the measured voltages, these conditions have allowed us to estimate the voltage corresponding to the current injected in the samples discarding thermal effects [6]. We have studied the behaviour of two CCs from the same manufacturer, but protected with different metallic layers.

In section II of this contribution, we describe the experimental set-up and the investigated samples. Section III is devoted to the presentation of the results and to the description of the processes occurring in the flux flow regime. In section IV, we discuss some aspects of these processes, as well as their consequences for the applications.

II. EXPERIMENTAL DETAILS

A. *Characteristics of the samples*

The samples characterized in this experiment were commercial CCs provided by SuperPower [7]. Two different samples were considered, namely:

1) S1: SCS4050 (2 μm of Ag + 40 μm of Cu stabilizer)
2) S2: SF4050 (2 μm of Ag only)

In both cases, the distance between the voltage taps was

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$L = 4.2$ cm, the width of the samples was $w = 4$ mm, and the thickness of the YBCO layer was $d_s = 1$ µm. The latter was deposited on a stack of insulating buffer layers covering a 50 µm thick *Hastelloy* substrate. There was also a 2 µm layer of silver coating on top of each YBCO layer (for the purpose of thermal stabilization). For S1, there was one additional 20 µm copper layer (copper clad) on each side of the tape deposited with the purpose of providing a good thermal stabilization and shunt path to transport current. Therefore, the total thickness of metallic stabilizer was 42 µm for S1 and 2µm for S2. The shunt resistance of sample S1 (R_{S1}=1.35mΩ) is ten times smaller than that of sample S2 (R_{S2}=13.6mΩ). Since the resistivity of silver is very near that of copper, this suggests that only the metallic layer in contact with the superconductor played a significant role for carrying current in our experiments and we'll take d_m=22 µm for sample S1 and d_m=2 µm for sample S2.

B. *Experimental I-V curves at high current densities*

Both samples have a critical current density (I_{cr}) in the range of 90 to 100 A (manufacturer specification that is based on the classical 1 µV/cm criterion). Since we are interested in the over-critical current conditions, we used a pulsed current measurement technique (PCM) in order to obtain the I-V data for currents up to 8-10I_{cr} without overheating or destroying the sample. A custom-built system, devised at École Polytechnique de Montréal (Canada), was used for this purpose. The system could generate square current pulses up to 1000 A, with a rise time as short as 3-10 µs. Experimental details and the procedure used to extract the electric field at zero temperature rise from the measurements can be found in [6].

III. RESULTS

A. *Measured data*

The current-voltage characteristics obtained from the measurements above show three regimes above the critical current, (see Figs 1): a low voltage non linear regime followed by two first linear regimes (regime L1 and L2). The reason why the voltages measured above 500 A on S1 are not on the same line as the preceding one is probably due to an experimental error.

The non linear regime corresponds to the well known flux creep regime. In this article, we focus on the two linear regimes L1 and L2. The slopes of the I-V characteristics in regimes L1 and L2 are different from one another. In addition, the current I_{cff} extrapolated to V=0 is different from zero in regime L1 while it is $I \approx 0$ in regime L2. This is the reason why we identify regime L1 as a flux flow regime, while regime L2 is an ohmic regime. We now discuss the properties of these regimes.

B. *The flux flow regime (regime L1)*

In this regime, the measured voltage takes the form:

$$V = R_m \left(I - I_{cff} \right) , \qquad (1)$$

TABLE I EXTRAPOLATED CURRENT TO ZERO VOLTAGE IN THE FLUX FLOW REGIME (REGIME L1), I_{CFF}, GLOBAL RESISTANCE OF THE METALLIC LAYERS OF THE CCS AT THE MEASUREMENT TEMPERATURE (77 K), R_S, AND DYNAMIC RESISTANCES MEASURED IN REGIMES L1 AND L2, R_M AND R'_M ,RESPECTIVELY.

	I_{cff} (A)	R_s (Ω)	R_m (Ω)	R'_m (Ω)
S1	109	0.00135	0.00244	0.00117
S2	120	0.0136	0.025	0.0116

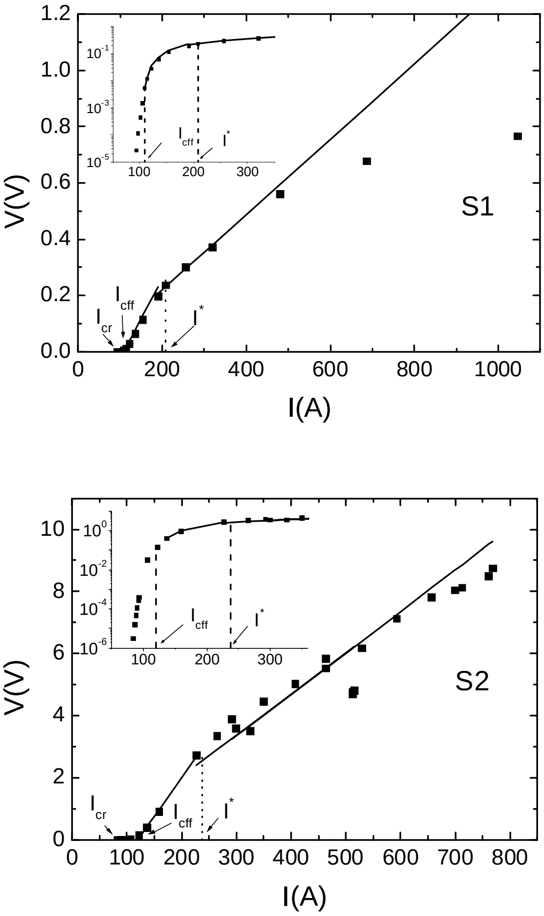

Fig. 1 Experimental current-voltage characteristics of samples S1 and S2 at 77K (symbols) and voltages calculated in the flux flow and ohmic regimes (full lines); I_{cr} is the sample critical current, I_{cff} is the current extrapolated to zero voltage of the flux flow characteristic, and I^* is the current at the transition between the two linear regimes. The insets show the same characteristics in the vicinity of the critical current on a semi-log scale

where R_m is the dynamic resistance (i.e. local slope) of the coated conductors. Since the superconductors are in a resistive state, we could suppose that the equivalent electrical circuit in this regime is the shunt resistance, R_s, in parallel with that of the YBCO film. However, the R_s and R_m values reported in Table I show that this cannot be the case since, since for both samples, $R_m > R_s$. Colauto *et al.* [8], have shown that there is an interaction between the vortices moving in a superconductor and a neighbouring metallic layer. From these observations, we assume that the vortices flowing in the superconductors are the source of an inductive voltage in the shunts, V'=MV with 0<M<1. The equivalent electrical circuit is shown in Fig. 2. The current I_2 flowing in the shunt and the corresponding voltage V respectively take the form

$$I_2 = \frac{V(1-M)}{R_S} \text{ and } V = \frac{R_S}{1-M}(I - I_1) \tag{2}$$

where I_1 is the current flowing in the superconducting film. Comparing (1) to (2) yields

$$R_m = \frac{R_s}{1-M} , \tag{3}$$

and $I_1 = I_{cff}$. As a first consequence, the current flowing in the superconductor in the flux flow regime is constant and equal to I_{cff}, while that in the shunt is $I-I_{cff}$. We also stress out that R_m does not depend on the flux flow resistance of the YBCO film, but only on the resistance of the metallic layer(s) and on the coupling factor, whose value is $M \approx 0.45$ for both samples. The I_{cff} values yield to the conclusion that, in the flux flow regime, most of the current flows in the superconductor. We now establish expressions for the vortex velocity and the flux flow resistance.

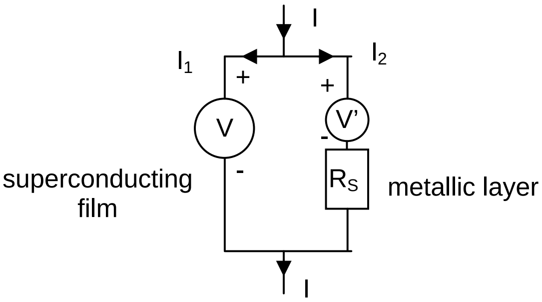

Fig.2 Electrical circuit equivalent to the system consisting of the superconducting and the metallic layer(s) in the flux flow regime.

1) *Vortex velocity*

The equation of motion for the vortices is

$$J_1\phi_0 = \eta v_L d_s . \tag{4}$$

In (4), η is the Bardeen-Stephen viscous drag coefficient. The surface current density in the superconductor, J_1, and as a result, the vortex velocity, v_L, are constant. The power dissipated in the superconductor therefore takes the form

$$P_1 = VI_{cff} = \eta v_L{}^2 n d_s wL , \tag{5}$$

where *n* is the surface density of the moving vortices. In [9] it was established that, as a general rule, the vortex density in a film carrying current can be written as

$$n' = \frac{\mu_0 I}{2d_s\phi_0} , \tag{6}$$

where ϕ_o is the flux quantum. In our case, we must take into account that the current flowing in the shunt of thickness d_m results in a magnetic field that contributes to the vortex density and that, for $I_1 < I_{cff}$, no vortex is in the flow regime. This results in

$$n = \frac{\mu_0}{2(d_s + d_m)\phi_0}(I - I_{cff}) . \tag{7}$$

We point out that, according to (7), the density of the moving vortices is proportional to the mean density in the whole CC of the current in excess of I_{cff}. The Bardeen-Stephen drag coefficient takes the form: $\eta = B_{c2}\phi_0/\rho_n$. In this expression, B_{c2} is the YBCO upper critical field and ρ_n the resistivity of the superconductor in the normal state. For coated conductors, it is reasonable to assume that the backflow currents generated by the motion of the vortices mostly flow in the parts of the shunt adjacent to the vortex cores with resistivity $\rho_m = R_S w d_m/L << \rho_n$. Based on this assumption, the resulting vortex velocity is

$$v_L = \frac{\rho_m}{w}\sqrt{\frac{2I_{cff}}{\mu_0(1-M)B_{c2}}\left(\frac{1}{d_s}+\frac{1}{d_m}\right)} . \tag{8}$$

We can estimate the upper critical field with the expression $B_{c2} = \varphi_0 / 2\pi\xi^2$, taking for the coherence length the Ginzburg-Landau expression $\xi = \xi_0 (1-T/T_c)^{-1/2}$. The vortex velocities calculated for samples S1 and S2 are reported in Table II, taking ξ_0=1.3 nm. The difference in the vortex velocities is rather small. The difference in the dissipated powers must be at first ascribed to the low vortex density in S1 as compared to that in S2.

TABLE II CALCULATED VORTEX VELOCITY V_L, MEASURED AND CALCULATED DYNAMIC RESISTANCE, R_M, FOR SAMPLES S1 AND S2 IN THE FLUX FLOW REGIME (L1). P* IS THE POWER DISSIPATED FOR $I=I^*$.

	v_L (m/s)	R_m (Ω) calculated	R_m (Ω) measured	P* (W)
S1	2.26	0.00284	0.00244	48
S2	2.84	0.025	0.025	687

2) *Dynamic resistance in the flux flow regime*

The voltage resulting from the vortex motion is inductive and can be written as

$$V = Lnv_L\phi_0 . \tag{9}$$

From (1), (8) and (9), we have

$$R_m = \frac{\mu_0 L v_L}{2(d_s + d_m)} . \tag{10}$$

The dynamic resistances calculated with (10) are reported in Table II, and they are close to the measured values. The corresponding voltages are reported in Fig.1.

C. The ohmic regime

In this regime, we would expect that the parallel resistance model will apply. However, the calculation of the resistance of the superconducting films gives very different values in the case of S1 and S2, while the normal state resistance is an intrinsic property that should not depend on the shunt resistance. This suggests that the ohmic regime is in fact a vortex regime, not the normal state of the superconductor. Further work is needed in order to understand the nature of this regime.

IV. DISCUSSION

In this section, we sum up the conclusions yielded by this work on the role of the metallic layers in the CCs and we discuss the implications for some applications.

A. The role of the metallic layers regarding power dissipation in the flux flow and ohmic regimes

The results reported in section III show that the role of the metallic layer(s) is not just that of a shunt or of a heat sink. In the flux flow regime, only the current in excess of I_{cff} flows in the metallic layer(s) and the low resistivity of metals causes the vortex velocity to drop to a low value, reducing strongly the power dissipation with respect to what would be observed in pure YBCO films at similar current level.

The other important effect limiting the power dissipation in the flux flow regime is the reduction of the mean excess current density in the coated conductors as the thickness of the metallic layer increases and, as a result, the reduction of the density of the moving vortices in the YBCO films. These effects result in that the CCs dynamic resistance depends only on the electromagnetic coupling factor M and on the metallic layer(s) resistance. The coupling factor takes the same value in S1 and S2, which suggests that it depends neither on the material used for the metallic layer nor on its thickness (at least for high conductivity metals and if the thickness is larger than 2 μm).

The ohmic regime is not the normal state but probably a vortex regime.

B. Applications to fault current limiters and superconducting cables

The resistivity of an ideal SFCL should increase strongly above a given threshold current, while dissipating as little power as possible if it is subject to over-voltages due, for example, to short circuits occurring in the power system. This means that the currents in SFCLs are voltage driven. Then, from (3), the current flowing in a SFCL and the dissipated power must be written, respectively, as

$$I = V\frac{(1-M)}{R_s} + I_{cff} \ , \qquad (11)$$

and

$$P = \frac{V^2(1-M)}{R_s} + VI_{cff} \ . \qquad (12)$$

The minimization of these quantities requires large R_s and M values. The resistance R_s depends on the metal resistivity and on the thickness of the metallic layer, while the factors that determine the value of M are not clear yet.

Over-critical currents in cables occur at the locations where, for some reason, the YBCO film critical current becomes lower than the nominal value. Over-critical situations in cables are current driven, and the dissipated power can be written as

$$\mathrm{P} = \frac{\mathrm{R_s}}{1-\mathrm{M}}\mathrm{I}(\mathrm{I}-\mathrm{I_{cff}}) \ . \qquad (13)$$

The conditions required for minimizing P are that R_s and M are as small as possible. As a consequence, coated conductors with a structure similar to S2 are well suited for making SFCLs while those similar to S1 are better for power transportation. The performances of both SFCLs and cables could probably be enhanced if we could find a mean for controlling the value of the electromagnetic coupling factor M between the superconducting and the metallic films.

V. CONCLUSION

In this paper, we have reported and discussed pulsed current measurements carried out on coated conductors. The pulsed current technique used here consisted in the application of square current pulses, thus basically “short DC pulses”. In the flux flow regime, our results support the idea that the superconducting and the metallic layers are electromagnetically coupled (DC coupling due to vortex motion, since the current is perfectly constant at the end of the pulse). We have highlighted the facts that the current flowing in the superconductor is a constant, and that the vortex velocity depends on the metallic layer(s) resistivity in this regime, while the dissipated power is strongly dependent on the thickness of the metallic layers. However, the exact description of the electro-magnetic interaction between the metallic and superconducting layers is yet to be investigated.

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REFERENCES

[1] T. Aytug, M. Paranthaman, J. R. Thompson, A. Goyal, N. Rutter, H. Y. Zhai, A. A. Gapud, A. O. Ijaduola and D. K. Christen Appl. Phys. Lett. 83, 3963 (2003)

[2] Y. Iwasa, J. Jankowski, S. Hahn, H. Lee, J. Bascuñán, J. Reeves, A. Knoll, Y.-Y. Xie, and V. Selvamanickam, IEEE Trans. Appl.Supercond.15, 1683 (2003)

[3] E.Martınez, L. A. Angurel, J. Pelegrın1, Y. Y. Xie and V. Selvamanickam, Supercond. Sci. Technol. 23, 025011 (2010)

[4] M. Therasse, M. Decroux , L. Antognazza , M. Abplanalp and Ø. Fischer, Physica C 468, 2191 (2008)

[5] F.Sirois, J.Coulombe and A.Bernier, IEEE Trans. Appl. Supercond. 19, 3585 (2009)

[6] F.Sirois, J.Coulombe, F. Roy and B. Dutoit, Supercond. Sci. Technol. 23, 034018 (2010)

[7] SuperPower Inc., available on-line at http://www.superpower-inc.com/

[8] F. Colauto, E. Choi, J. Y. Lee, S. I. Lee, E. J. Patiño, M. G. Blamire, T. H. Johansen and W. A. Ortiz, Appl. Phys. Lett. 96, 092512 (2010)

[9] P. Bernstein and J. F. Hamet, J. Appl. Phys.95, 2569 (2004)