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Flux pinning distribution and E-J characteristics of 2G YBCO Tapes

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Abstract.
E-J characteristics of SuperPower YBCO 2G tapes have been measured in the temperature range 15K-80K. It was found that the E-J characteristics deviate significantly from the standard power-law behaviour with apparent power exponent decreasing continuously at high voltage with increasing current. The deviation of E-J characteristic from the standard power-law was found to be consistent with a Weibull distribution of critical current. The identical scaling of E-J characteristics above 40K suggests a common critical current distribution. At lower temperature the critical current distribution becomes narrower to give higher apparent power exponent at lower temperature. With the critical current distribution model it is shown that the dissipation can be correlated directly to the flux flow resistance of Bardeen. The distribution of the critical current can be associated with a distribution of pinning potential of collective pinning and the headline pinning range is obtained as function of temperature.

1. Introduction

The development of 2G YBCO tapes has led to the availability of practical conductors suitable both for medium/high-field applications at liquid helium temperature and at intermediate temperature range. E-J characteristics of these tapes at such conditions are essential for magnet design, however they are not yet available in the literature due to the difficulties of transient measurement without liquid cooling. A systematic study of E-J characteristics over a wide range of temperatures (80K-40K) has been carried out and presented in previous work [1]. Experimental measurements conducted on YBCO tapes evidenced a deviation of transition characteristics from power-law behavior; this deviation has been interpreted in the frame of a collective pinning model. Although the collective pinning model is believed to describe the depinning mechanism of 2G tapes, the parameters introduced do not permit simple comparisons between conductor performances. In this work measurements have been extended to lower temperatures (80K-15K) by using a semi-transient protocol. A simpler statistic model based on a spatial distribution of critical current is used to describe the non-linear behavior observed.

2. Methods

2.1. Sample holder and semi-transient protocol used for measurements

The sample used in this work was standard 4mm wide Cu stabilised YBCO conductor produced by SuperPower Inc. Measurements at variable temperatures were carried out using a cryostat refrigerator cooled by a Sumitomo cryo-cooler, as described in [2]. Measurements were made on a 1 mm bridged structure, obtained by transversely milling the conductor from either side, as described in [1]; the milling does not cause degradation. A pair of hybrid HTS leads were used to inject current up to 600A to reduce the heat load to the system. The E-J measurements were conducted over more than four decades of voltages by a combination of DC current measurements at low voltages (0.1-10 μV) and of transient current measurements at higher voltages, recorded at 10kHz.

2.2. E-J characteristics of flux flow due to a Weibull distribution of flux pinning

It has been reported previously [1] that the E-J characteristic of standard YBCO tape at 77K deviates from the simple power-law, as shown in fig.(1) where the underlying superconductor E-J (●) is also presented with the current sharing by the stabilizing copper removed. The solid line shows that the deviation from power-law (dashed line) can be accounted from a distributed depinning model [3] where the depinned flux lines/bundles contribute to local dissipation in the fully flux flow regime by

$$E_e(J_C, J) = \rho_{FF} \cdot (J - J_C)\,, \qquad J > J_C \tag{1}$$

where ρ_{FF} is the flux flow resistivity and J_C is the spatially distributed critical current. Flux flow resistivity ρ_{FF} dependence on temperature has been calculated according to Bardeen's relation $\rho_{FF} = \rho_n(T) \cdot (B_{sf}(T) + B_{ext})/B_{C2}(T)$ which has been proved to hold for YBCO epitaxial films in the range of temperature 85K-76.5K. B_{ext} is the external field applied whilst B_{sf} is the self field contribution, which has been calculated as a function of the tape geometry according to [6]. The calculation of the flux flow resistivity allows to establish the dissipation level (based on empirical data) giving strong support to the model. The depinning probability of flux bundles has been found to be well described by a Weibull distribution [7], given by

$$P(J_C) = \begin{cases} \frac{m}{J_0} \cdot \left(\frac{J_C - J_{Cmin}}{J_0}\right)^{m-1} \cdot \exp\left[-\left(\frac{J_C - J_{Cmin}}{J_0}\right)^{m}\right] & J_C > J_{Cmin} \\ 0 & J_C < J_{Cmin} \end{cases} \tag{2}$$

where J_{Cmin} is the minimum value of the distribution,J_0 is a scaling parameter which is roughly equal to the width of the distribution and m is the exponential parameter which determines the shape of the distribution. The macroscopic E-J characteristic can be obtained by summing the contribution to dissipation of different domains

$$E(J) = \int_{J_{Cmin}}^{J} P\left(J_C\right) \cdot E_e(J, J_C) \cdot dJ_C = E_C \cdot \left(\frac{J - J_{Cmin}}{J_{C0} - J_{Cmin}}\right)^{m+1} \tag{3}$$

This E-J leads to a local power-law index $n_J = d(lnE)/d(lnJ) = (m+1)/(1-(J_{Cmin}/J))$ which reduces with increasing current and approaches $n = (m+1)$ when $J \to \infty$. The equivalent power law exponent for the commonly used critical current $J_{C0} = J_{Cmin} + [(J_0^m \cdot (m+1) \cdot E_C)/\rho_{FF}]^{\frac{1}{m+1}}$ at $E_C = 1\mu V/cm$ is correlated to the Weibull exponent m and the critical current threshold J_{Cmin} i.e. $n_{J_{C0}} = (m+1)/(1-(J_{Cmin}/J_{C0}))$. Note that J_{C0} with a smaller $n_{J_{C0}}$ is increased by a wider distribution of a lager J_0 (blue line in fig.(1)).

3. Results and discussion

3.1. E-J characteristics of 2G YBCO predicted by depinning model

The E-J characteristics predicted by depinning model are shown and compared with the respective experimental data in fig.(1). The interpolating curve has been obtained by varying the exponent m until a good fitting was observed and by calculating J_{Cmin} as a function of m

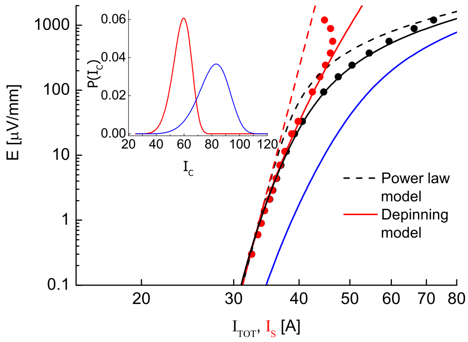

Figure 1. E-J characteristic of bridged 1mm 2G YBCO with (●) and without (●) current sharing contribution compared with power-law (dashed lines)and distributed depinning model (solid lines).

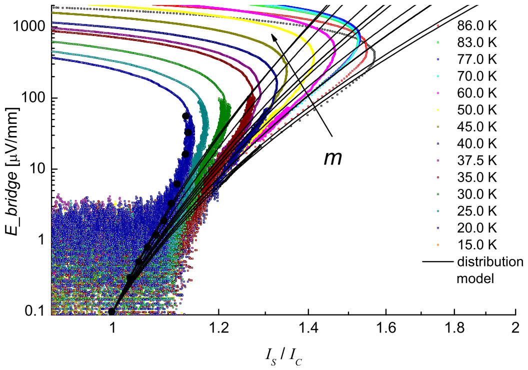

Figure 2. E-J characteristics measured on 1 mm YBCO tape in a range of temperature (86K-15K). Distributed depinning model predictions once current sharing distribution has been removed (black solid lines)

for each attempt according to eq.(3). The fitting parameters obtained are demonstrated to be independent of the engineering current criteria chosen, returning the same parameter m and J_{Cmin}.

Deviation from power-law behaviour has been observed across the temperature range 15K-86K. The equivalent n-number $n_{J_{C0}}$ has been found to remain constant at a value of 30 in the temperature range 40K-86K, and to slowly increase up to 40 at 15K, as observable in fig.(2). The resistance temperature dependence has been taken into account according to [8]. The data set of E-J characteristics can be satisfactory predicted with the depinning model law as shown in fig.(2), although curves at very low temperature are strongly affected by heating at low dissipation levels ($\sim 10\mu V/mm$) making data fitting difficult. The parameter m has been found to have a dependence on temperature qualitatively similar to the n-number as shown in the inset of fig.(3). The respective set of distribution curves, normalised with the pinning range I_0, shows a narrower bell as the lower temperature is approached, as shown in fig(3).

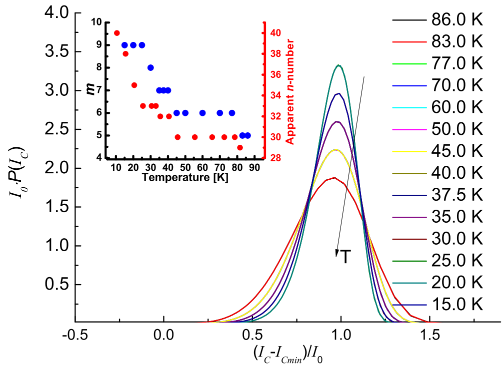

Figure 3. Current distribution of 2G tape in a range of temperature (86K-15K). Inset- Dependence of equivalent n-number $n_{J_{C0}}$ and exponent m on temperature.

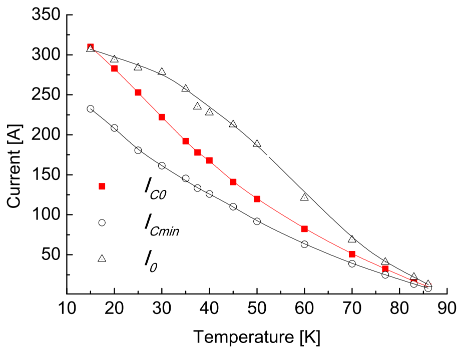

Figure 4. Weibull distribution parameters I_{cmin} and I_0 and critical current determined with the electric field criteria I_{C0} dependence on temperature.

3.2. Characteristics of Weibull distribution parameters

The dependence of the Weibull distribution parameters I_{Cmin} and I_0 on temperature is highlighted in fig.(4) and compared with the critical current I_{C0}.

The pinning threshold I_{Cmin} shows a similar temperature dependence of critical current I_{C0} with an accelerated increase at lower temperatures, which signifies the extended influence of the thermal activated flux flow [9]. In contrast, the pinning range I_0 shows a moderating increase with reducing temperature. Such a behaviour is similar to the depinning current and suggests that the pinning range is related to the underlying pinning strength of the material.

In order to demonstrate the effect that these parameters have on the E-J characteristic, a transition characteristic with same current threshold I_{Cmin} and same Weibull exponent m of the curve which fits the data, but with a greater pinning range I_0, has been included in fig.(1) (solid blue line). In the inset of the figure, the critical current distributions associated with the data fitted to the experimental results and with the data obtained using a greater pinning range, are compared. The bell of the distribution associated with the greater pinning range is broader than the one corresponding to the real data, and corresponds to a conductor with stronger pinning centres, which is thus more stable.

A good quality superconductor is conventionally considered to have a larger n-number, however this comparison shows that this criteria is artificial because the more stable conductor presents an E-J characteristic with a higher I_{C0} and in turn smaller $n_{I_{C0}}$, as expressed in eq.(3). Surprisingly, the distributions curves observed in the data set presented in fig.(3) are narrower at low temperatures. This phenomenon is attributed to a strong dependence of I_{Cmin} on temperature, when compared to I_0. Furthermore, an increment in temperature has a faster effect on I_{Cmin} rather then on I_0, as shown in fig.(4), which shows that I_0 tends to saturate at low temperatures. The latter observation indicates the presence of strong pinning centres that are not particularly affected by temperatures, whilst weak pinning centres quickly appears and contribute in dissipation as the temperature is increased.

4. Conclusion

Transport measurements at different temperatures on 2G YBCO conductor revealed an underlining E-J characteristic described by inhomogeneous distribution of critical current. The model does not furnish macroscopic information about the depinning mechanism, which is still believed to be described by collective pinning of small flux bundles, but it is of practical utility since it introduces parameters that can be related to tape performance such as J_{Cmin} and J_0 and permits comparisons between conductors with different critical current densities. Future studies will relate the model presented in this work to the collective pinning model.

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