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E-J Characteristic of 2G YBCO Coated Conductor Tapes at Different Temperatures

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Abstract

The E-J characteristics of High temperature superconducting (HTS) composite are not only fundamental to the understanding of flux dynamics and flux pinning but also the quench behaviour of HTS at an extended temperature range. The present work present the E-J characteristics of state-of-the-art 2G YBCO Tapes of SuperPower^{TM} measured at different temperatures between 40K and 80K. The results revealed a appreciable deviation from the power-law E-J characteristics, an established framework for 1G 2223 conductors. In contrast, the equivalent power exponent *n* was found to decrease with increasing current, resulting in a reduced rate for the non-linear increase of voltage at higher current. The softening of E-J characteristic remain unchanged as the temperature is lowered. Furthermore the power exponent *n* at the critical current appears to be constant increasing at lower temperatures. Analysis presented in the work shows that the collective pinning of vortex glass gives a satisfactory quantitative description of the E-J characteristics of 2G YBCO tapes. A constant collective pinning potential $U/k_BT \sim 15$ and vortex glass exponent $\mu \sim 2$ were found for temperatures between 45 K and 80 K.

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1. Introduction

The voltage-current (E-J) relation is a crucial characteristic of superconducting materials, relevant to the fundamental understanding of flux pinning, the optimization of material performances and several

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aspects of magnet applications including the quench dynamics/protection and the persistent mode stability. The progress in the performance and commercial availability of second generation (2G) YBCO tapes has resulted in a marked increase in the research activities on their applications to a wide range of magnet components and power devices. Unlike 1G counterpart, 2G conductors bring an enhanced flux pinning in medium to high magnetic fields at intermediate temperatures between 4.2 K and 77 K. Most new applications are designed for cryogen-free operation at 20-50 K depending on the magnetic field required. A systematic study of the E-J characteristics of 2G conductors is necessary.

The E-J characteristics of YBCO materials have been the subject of intense research focus 15-20 years ago when the understanding of flux dynamics at higher temperatures and very short coherence length was developed. A collective pinning mechanism in a vortex glass was shown to be predominant in YBCO materials. However, most published E-J data were at high temperatures where the melting of the vortex glass was the main focus and measurements could be made reliably on high quality single crystals and films at relative small current. The availability of stabilized 2G tapes presents an opportunity for extending the YBCO E-J data to a wider temperature range.

This work was carried out in the practical and fundamental context outlined above.

2. Methods

2.1. Samples and Measurements

The samples used in this work were standard 4mm wide Cu stabilized YBCO 2G conductor produced by SuperPower Inc. Measurements at 77 K were carried out with samples immersed in a liquid nitrogen pool. In order to extend the current range in the obtained E-J characteristics, it was necessary to use two large current contacts (each 35 mm long) separated by a short length (1.2 mm) in between for voltage measurement. After measurements at 77 K the samples were further prepared for measurements at lower temperatures with cooling by a cryo-cooler. Firstly the narrow gap between the current contacts was filled up with epoxy to support the free-standing tape in between. Subsequently a narrow bridge of 1 mm wide was constructed by milling away transversely 1.5 mm of the conductor from either side of the filled gap. The milled sides of the narrow bridge were sealed with epoxy to protect the HTS thin film in the conductor. The milling was confirmed to cause no degradation to the tape as a quarter of the overall critical current at 77 K was always retained. The narrow bridge was necessary for extending the measurements to lower temperatures and minimizes the heat generation in the current contacts. The short distance between the current contacts was also important for reducing the temperature gradient along the narrow bridge in a cryogen-free cooling arrangement. The lowest temperature and the maximum current

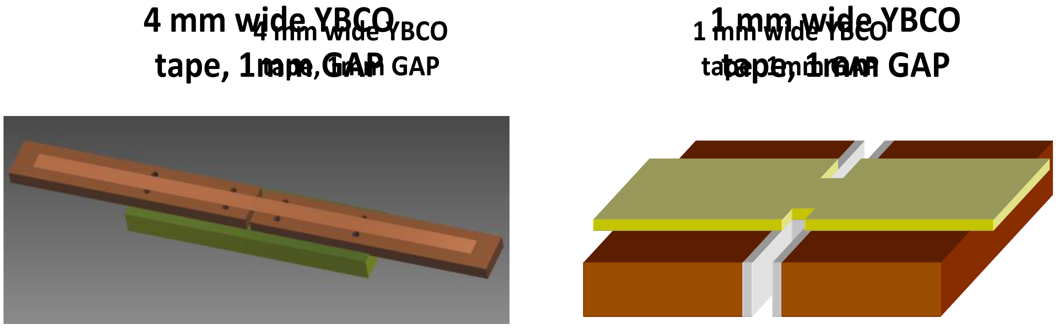

Fig. 1. Schematic view of 4mm YBCO tape soldered on bridged sample support and 1 mm narrow bridge sample;

obtained were not only limited by the capacity of the current leads but also by the management of the heat dissipation within the current contacts and the sample bridge. The latter was further reduced by attaching a supplementary copper shim with GE-varnish over the bridge via a thin insulating layer of paper.

The cryostat for measurements at variable temperatures using a cryo-cooler was described in [1] and [2]. A pair of hybrid HTS leads with a capacity of 300 A were used to reduce the heat load to system. The E-J measurements was conducted over more than four decades of voltages by a combination of DC currents at low voltages (0.1-10 μV) and a series of square current pulses of (1-10 s) at higher voltages. The voltages were recorded at 10 kHz during the pulsed current measurements.

The sample was protected from burn-out by a quench protection system which cut off the current source when the voltage exceeded 10 mV.

2.2. E-J characteristic and current sharing

For the most commonly used power-law E-J characteristics, we have $E(I) = E_0(I/I_C)^n$ where the critical current I_C typically defined at $E_0 = 1$ μV/cm is a function of temperature, and so is the power exponent n. The inverse function in this case is simply $I_S(E) = I_C(E/E_0)^{1/n}$.

Collective pinning is the accepted flux pinning mechanism of vortex glass in single crystals and high quality thin films of YBCO. The associated E-J characteristics is expresses as

$$E = E_0 \exp((1-(I_C/I)^{\mu})U/(k_B T)) \qquad (1)$$

where U is the pinning potential/energy and the critical current I_C is defined is also defined at E_0. The power exponent μ is the glass exponent. The corresponding inverse function is

$$I_S = I_C\,(1-\ln(E/E_0)k_B T/U)^{-1/\mu} \qquad (2)$$

For E-J representation over several voltage decades, ln$E$-ln$I$ plot is usually used, as shown in Fig. 1. The slope of the E-J in log-log scale is $d(\ln E)/d(\ln I) = (I_C/I)^{\mu}\,\mu U/k_B T$, which reduces with increasing current and a larger curvature is found at a higher glass exponent μ. The equivalent power-law exponent at $I = I_C$ is related to the pinning potential and glass exponnet, i.e., $n_{Ic} = \mu U/k_B T$. It is also noted that the power-law of constant exponent n is a limit case of (2) at $\mu = 0$ and $U \rightarrow \infty$ with $n = \mu U/k_B T$ = finite. The power-law E-J is represented by a straight line in ln$E$-ln$I$ plot with a constant slope n as shown in Fig. 1.

Current sharing between the superconductor and the stabilization copper occurs gradually as the current is increased beyond the critical current I_C. The voltage-current relation as measured is embedded with the current sharing contribution by the normal sheath. The underline E-J characteristics of the superconductor can be extracted with

$$I = I_S(E) + E/R(T) \qquad (3)$$

where $I_S(E)$ the current carried by the superconductor at a given electric field and is the inverse function of the E-J characteristics expressed as $E(I)$ for current instead of current density; $R(T)$, the resistance of the sheath in per unit length of the conductor, is typically temperature dependent given by the underline resistivity $\rho(T)$ of the normal conductor: $R(T) = \rho(T)/A$ for a sheath conductor cross-section A. As the E-J characteristics are typically non-linear functions, closed form solutions for (3) do not readily exist.

As the result of current sharing, the intrinsic E-J characteristics are superimposed with the contribution for the normal resistive sheath, addition a further curvature in the ln$E$-ln$I$ plot at high voltage and current. To extract the underline E-J characteristics, an accurate knowledge of the sheath resistance $R(T)$ is required. For the 2G conductors in this study, the conductor resistivity measured in [2] below T_C and used in the current share analysis in the following. With the standard 4 mm tape, R(77 K) and R(45 K) are respectively 12.6 μΩ/mm and 3.13 μΩ/mm.

3. Result and discussion

3.1. E-J characteristics of 2G YBCO do not follow power-law

As an example, the E-J characteristic of the standard 4 mm 2G YBCO tape at 77 K is shown as log$E$-log$I$ in the inset of Fig. 3 (○, I_C = 103 A). Also shown in the inset is the corresponding E-J characteristic (▽) when the 2G sample was subsequently prepared with a narrow bridge of 1 mm x 1mm. The data confirms that the critical current was proportionally reduced to 24.5 A while retaining a similar slope in log$E$-log$I$.

For the analysis on current sharing and underline E-J in the superconductor, the Fig. 1 shows the data presented against the reduced current I/I_C. The coincidence between the standard 4 mm tape (●) and 1 mm bridge (○) gives further assurance that latter was not degraded by milling and hence representative of the original 4 mm sample. The black solid line represents a power-law E-J of n_{Ic} = 35 at I_C while current sharing with a sheath resistance of 12.6 μΩ/mm for the 4 mm tape. For the 1mm bridge, the line applies equally assuming the same power-law E-J with reduced I_C = 24.5 and a proportionally higher sheath resistance of 26 μΩ/mm. The experimental data showed a slower rate for voltage increase at high current in a noticeable deviation from power-law. A lower E-J voltage is considered significant as it could not be the result of heating, which is a common challenge for transport measurements. Furthermore such a deviation from the simple power-law E-J cannot be accounted for by increasing current sharing by a reduced sheath resistance, which would result in increasing the curvature initially but undershooting the experimental data as the current is further increased.

The departure from power-law E-J in the 2G YBCO tape is contrasted by 1G 2223 conductors, whose E-J characteristics can be satisfactorily described by a constant power exponent n. An example is shown in Fig. 3 (● red solid line) for an AMSC Ag sheathed 2223 tape with I_C = 150 A.

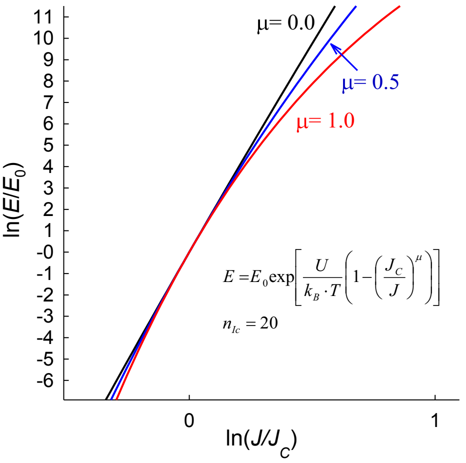

Fig. 2 Collective pining model with glass exponent μ=0.0, μ=0.5, μ=1.0.

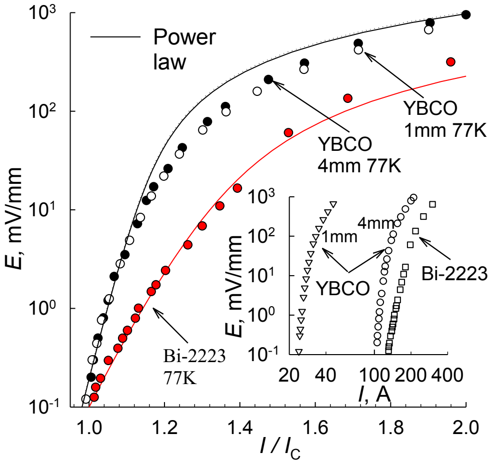

Fig.3 E -J characteristics of standard 4 mm 2G YBCO tape, bridged 1 mm 2G YBCO tape and 1G 2223 tape, with relative power law fitting (solid lines).

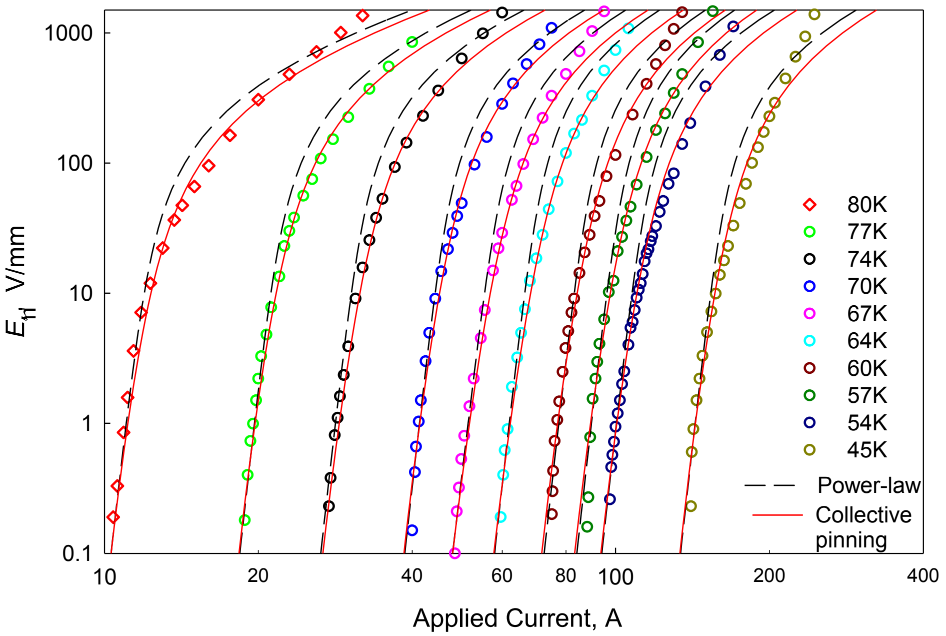

Fig. 4. E-J characteristics measured on 1 mm bridged 2G YBCO tape in a range of temperatures (80 K-45 K). Current sharing analysis is also shown for E-J characteristics with a simple power-law (black dash lines) and collective pinning (red solid lines)

Measurements at different temperatures also confirmed that power-law E-J characteristics also failed at other temperatures. Ten sets of data are shown in Fig. 4 for the measured E-J results at temperatures form 45 K to 80 K. Note that the data covers consistently four decodes of electrical field. The dashed lines, corresponding to a power-law fit using the *n* value at I_C, consistently failed to match to the data for all the temperatures.

3.2. E-J characteristics of 2G YBCO imply collective pinning in vortex glass

As discussed above, the E-J characteristic of collective pinning of vortex glass of a non-zero glass exponent μ has an inherent reduced slope in log$E$-log$I$ at higher current. The red solid lines in Fig. 4 correspond to the outcome of applying the collective pinning model to the respective experimental data at different temperatures, in conjunction with current sharing by the normal sheath with a temperature dependent $R(T)$ from [2]. It is perhaps not a total surprise that the pinning model originally proposed for YBCO single crystal films was found in better agreement with experimental observations on 2G YBCO tapes, where the superconducting component is in the form of bi-axially textured films. In order to highlight the consistent deviation from the power-law across the temperature range, a scaled plot of $E/I_CR(T)$−I/I_C is shown for the whole data set in Fig. 5(a). All the data should approach unity at high current when current is mostly carried by the sheath. While it is rather unexpected that data for different temperatures collapsed together, their difference from the power-law (black dashed lines) is shown evidently.

The solid lines are scaled from the same lines shown in Fig. 4 and correspond to the collective pinning in a vortex glass and current sharing with $R(T)$. The fitting has two free parameters: the pinning potential U/k_BT and glass exponent μ. The coincidence of all the scaled data in Fig. 5(a) implies that both parameters are almost independent of temperatures. It also follows unexpectedly that a *constant* equivalent power exponent n_{Ic} ~ 35 at corresponding $I_C(T)$ at different temperatures. The pinning potential relative to thermal excitation U/k_BT is almost a constant of 15 at different temperatures only showing a noticeable reduction at 80 K. The glass exponent μ fluctuates slightly around 2.2, a value considerably larger than μ=0.4 found in YBCO epitaxial films [3], but consistent with collective movements of vortex bundles under a driving current leads to μ=19/8 for small flux bundles ($r < \lambda_{ab}$) rather than medium ($r<\gamma\lambda_{ab}$ μ=14/8) or large ($r > \gamma\lambda_{ab}$, μ=9/8) bundles. The results presented here are from self-field only scenario, where the flux density is rather low. Preliminary measurement showed that μ was significantly lower at 1.7 in an applied field of 0.3T at 77 K. Fig. 5(b) also shows the critical current linearly increasing with

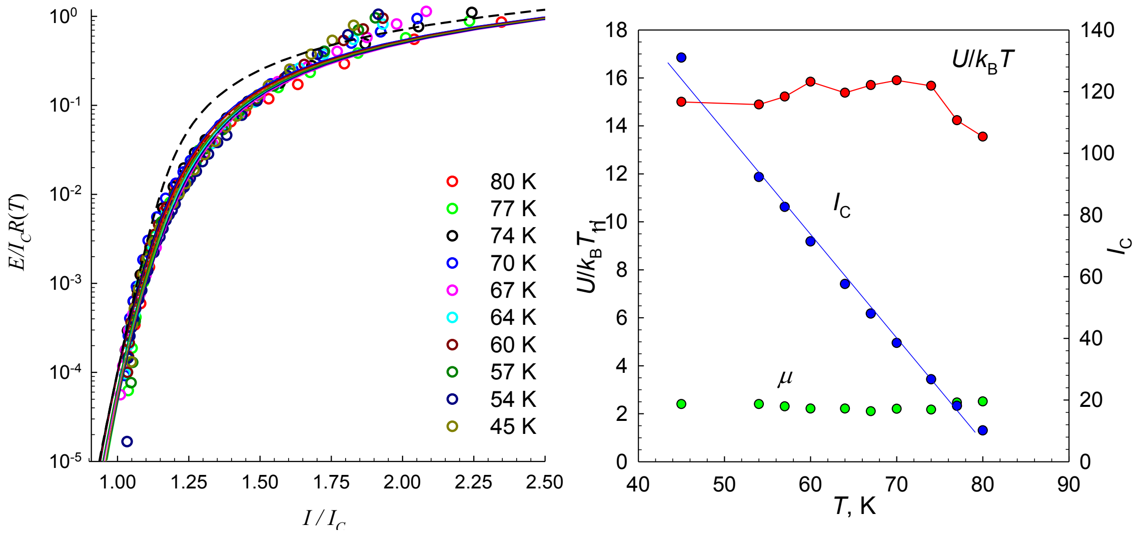

Fig. 5. (a) Scaled E-J characteristics at different temperatures are shown and compared with power-law (black dashed line) and collective pinning (solid lines); (b) The collective pinning potential U/k_BT and vortex glass exponent μ are almost constant for different temperatures, the I_C of the 1mm bridge increases linearly with temperature.

4. Conclusion

Transport measurements at different temperatures on 2G YBCO conductor revealed an underline E-J characteristics described by collective pinning of small flux bundles in a vortex glass. The pinning potential and glass exponent were found to be largely constant in the temperature range of 45 K to 80 K, implying unexpectedly that the equivalent power-law exponent remain constant instead of increasing with reducing temperatures. Further studies at lower temperatures and in applied fields shall be carried out.

References

[1] E. A. Young, C. Friend, Y. Yang, “Quenche characteristics of a stabilizer-free 2G HTS conductor”, *IEEE Trans on App. Supercon.*,2009;**19**,3, :2500-2503

[2] E. A. Young, I. Falorio, Y. Yang, “Quench characteristics of a Cu-Stabilized 2G HTS Conductor”, *IEEE Trans on App. Supercon.*,2011;**21**,.3:3062-3065

[3] R. H. Koch, V. Foglietti, W. I. Gallagher, G.Koren, A. Gupta, and M. P. A. Fisher, “*Experimental Evidence for Vortex-Glass Superconductivity in Y-B-Cu-O*”, Physical Rewiew Letters,1989; **63**,14:1511-1514

[4] D.R. Nelson, V.M. Vinokur, Boson Localization and correlated pinning of superconducting arrays. *Phys Rev B* 1993;**48** :13060-97