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Time dependent electric field and E-I curves in Bi-2223 tapes carrying DC currents and exposed to perpendicular AC magnetic fields

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Abstract. A study of the time-dependent electric field, E(t), and E-I curves of BSCCO/Ag tapes at 77 K is presented. Measurements were performed on tapes carrying DC transport current and exposed to external AC (0–500 G, 4–400 Hz) magnetic fields perpendicular to the broad side of the tape. E-I curves measured at frequencies exceeding 50 Hz and at amplitudes of the AC field below 400 G are well described by power law in the range between 0.1 and 10 μV/cm of the electric field. The results within this domain of parameters are discussed, assuming a narrowing down of the DC current path under the application of a perpendicular AC field. Nearly linear dependency of electric field on transport current was observed at the frequency-amplitude domain below 10 Hz and above 500 G. Using magneto-optical techniques we are able to determine that in this domain the AC magnetic field fully penetrates the tape. Behaviour of E-I curves under these conditions can be elucidated using the "dynamic resistance" model in conjunction with the assumption that the magnetic field fully penetrates the superconductor.

1. Introduction

The influence of external alternating magnetic fields on the transport properties of HTS wires and tapes is a crucial aspect in coil design intended for power applications. A study of this problem also contributes to a better understanding of the transport properties of HTS. In previous works we have studied V-I curves of Bi-2223 tapes carrying transport current and subjected to AC magnetic field applied parallel or perpendicular to the broad side of the tape [1, 2]. We have found that the E-I curves are well described by power law at frequencies above 40 Hz.

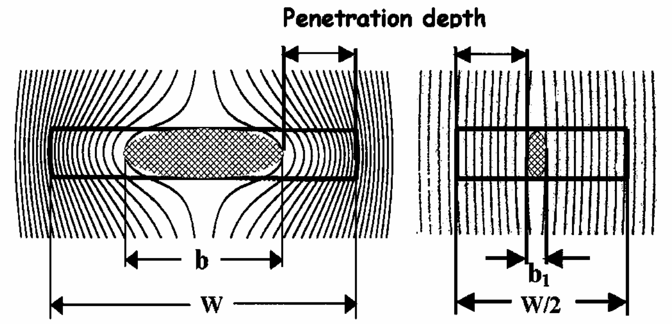

Figure 1. Illustration of magnetic flux lines inside tape. AC magnetic field is applied perpendicular to broad side of the tape. w is the width of the tape and b is a width of the central field-free zone. Difference in b/w ratio between samples of different widths is roughly illustrated.

Application of AC field resulted in a linear decrease of the critical current. We interpreted the results by assuming that DC transport current is confined to the central region of the tape, a region free of AC field (Figure 1). The contraction of this region with increasing AC field was confirmed by magneto-optical techniques [2]. The described conduct has no adequate theoretical description, although several works acknowledge its existence [3, 4].

In this paper we present measurements of the time-dependent voltage signal, E(t), conducted on high current density Bi-2223 tape subjected to AC magnetic field applied perpendicular to the broad side of the tape. Relevant V-I curves are presented as well. Additionally, penetration of the AC field into the tape was measured and analyzed by magneto-optical means.

2. Experimental

Measurement setup was similar to the one used in our previous works. For a detailed description of the experimental setup see references [2, 5]. Single tapes and bifilar configuration samples were measured at 77 K. It is worth pointing out that when comparing results for bifilar and single tape, one has to consider the frequency dependent effect of screening AC fields by the adjacent tape in a bifilar configuration. The time dependent voltage signal was measured using a differential preamplifier. Zero-current signal was subtracted from the measured signal. In order to verify the method's credibility, E-I curves obtained by integration of the time-dependent voltage signal were compared with those measured with a DVM under the same conditions and were found to be identical. Measured samples were taken from industrial lots of AMSC reinforced tape and high current density tape [6]. Magneto-optical setup and measurements performed for this work will be discussed elsewhere.

3. Results and discussion

3.1. I-E curves measurements

A typical set of E-I curves measured at frequencies of 4.65 - 103 Hz is shown in figure 2. Curves measured at fields less than 400 G and frequencies above 50 Hz are well described by the power law, $E = E_O\left(I/I_C\right)^n$, and can be associated with electric field driven flux creep.

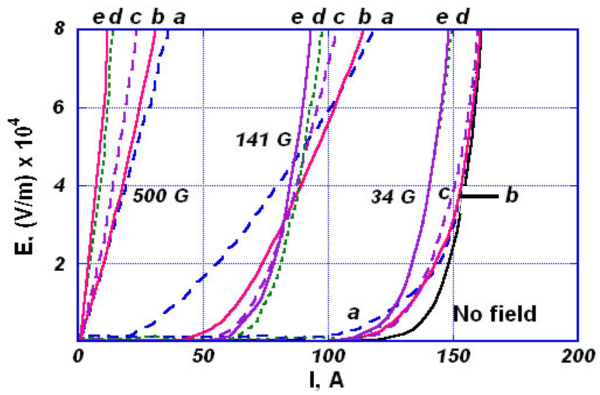

Figure 2. The typical set of E - I curves measured at frequencies: 4,65 Hz (a), 11 Hz (b), 22 Hz (c), 73 Hz (d), 103 Hz (e)

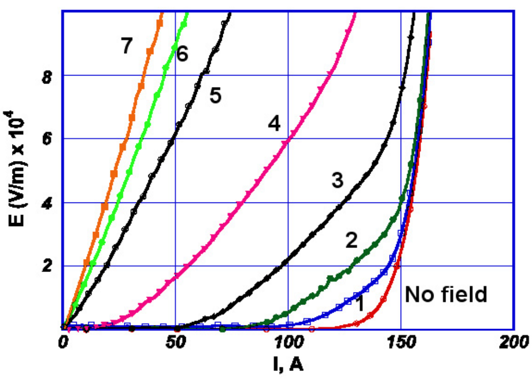

Figure 3. E - I curves measured at frequency 4.6 Hz. Amplitudes: *23 G (1),46 G (2), 80 G (3), 141 G (4), 295 G(5), 438 G (6), 500 G (7)*

At AC fields with amplitudes exceeding 400 G, the electric field appeared immediately after introducing a transport current and grew almost linearly with current. This piece of evidence can be explained as a consequence of the AC field fully penetrating the tape, encouraging the depinning of the vortices. Similar behaviour was observed at low frequencies, yet the situation is not quite the same. In fact, E-I curves measured at a frequency of 4.65 Hz have also shown a nearly linear dependency on current at all amplitudes (figure 3), but for a different reason. Full penetration at low frequencies is reached differently than that at higher frequencies. In the former, there exists a threshold current at which electric field appears. This field depends on the magnetic field amplitude. Magneto-optical measurements (see below 3.2) show that at these low frequencies full penetration of the AC field into the tape indeed occurs, and a penetration into a separate filament can be observed simultaneously. As shown in [2, figure 4] at a frequency of 55 Hz the tape behaves as a continuous superconductor. The E-I curves presented in figure 3 are very similar to curves measured with magnetic field parallel to the broad side of the tape [2], where full penetration takes place at high frequencies due to the relatively small size of tape which lies in the direction perpendicular to applied magnetic field.

3.2. Magneto-optical study of the penetration of AC field into the tape

We have demonstrated that AC field at a frequency of 55 Hz penetrates the multifilamentary tape as it would a continuous superconductor. Proportionality of penetration depth to the AC field amplitude supports the ‘geometric model’ with the addition of AC field. (Figure 1).

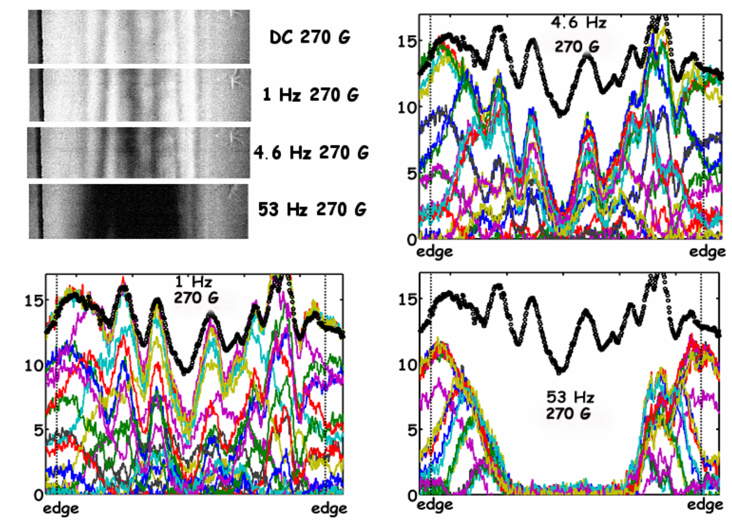

Figure 4. Magneto-optical images of the multifilament Bi-2223 tape in DC and AC magnetic fields (a). b, c, d – induction profiles of the magnetic field measured with field frequencies of 1 Hz (b), 4.6 Hz (c) and 53 Hz (d). The black line at the top of all figures is the induction profile acquired with DC field given for comparison.

In this study we have also examined the penetration of AC field with frequencies of 1 Hz to 103 Hz at constant amplitude of 270 G into the multifilamentary tape and compared the results with the penetration nature of DC field of the same flux density. Magneto-optical images, acquired with a DC field and an AC field, are shown in figure 4a. At low frequencies (1 Hz, 4.6 Hz) we observed penetration of the field into separate filaments, over all width of the tape, similarly to that occurring at a DC field. At higher frequencies the field does not penetrate the wide, innermost, element of the tape and, we suppose, it has no influence on the transport current in this region (field profile is shown in figure 4d). The results show that low frequency AC field changes the state of the tape and can strongly affect its transport properties. Induction profiles, measured under AC field, are steeper than those measured under DC field; this observation suggests that current density in the AC field penetration area can be higher than the current density of the screening currents after full relaxation.

3.3. Time dependent electric field

It is likely, that electric field induced by AC magnetic field is modulated in time with a frequency comparable with that of the magnetic field. Such modulation has been predicted [5]. In figure 4 we present the modulation of the electric field and show it is dependent on the transport current at a fixed frequency and amplitude of the magnetic field. The signal frequency is twice the frequency of the magnetic field.

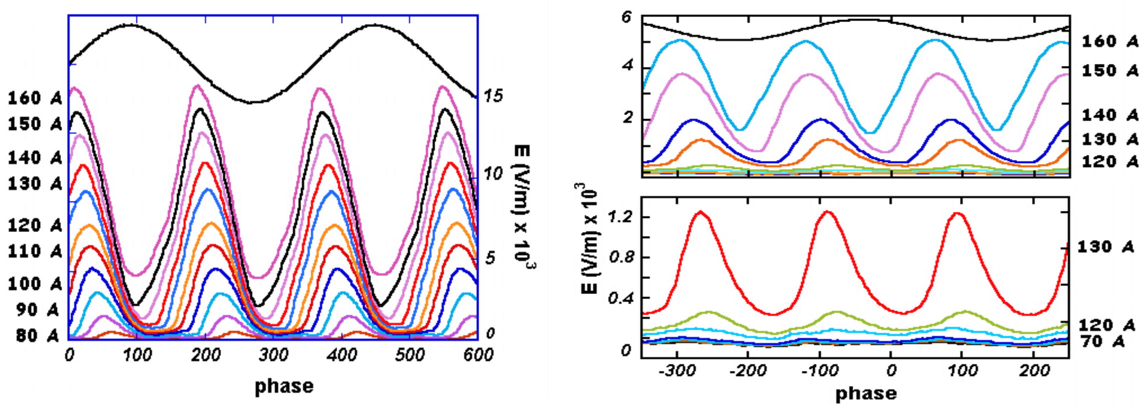

Figure 5. Time dependent electric field of the Bi-2223 tape exposed to AC field at a frequency of 73 Hz and amplitudes of 141 G (a) and 34 G (b). Dependencies on the transport current are shown.

It is clear from figure 5 that the peaks grow linearly with increasing transport current. Similar growth is observed with increasing AC field. Also, with an increase of the transport current, position of the peaks moves towards the zero value of the external field. At the time of writing this paper, not enough data has been gathered for discussing the phase difference between electric and magnetic fields. We encourage the development of a detailed model that takes into account both relaxation processes in the tape and its anisotropic characteristics.

Summary

E-I curves are well described by power law only when penetration of the AC magnetic field into the tape is partial. In the present work time dependent electric fields were measured. At low enough frequencies (below 10 Hz) full penetration of AC magnetic field into the tape enables the use of the dynamic resistance model for data analysis. Furthermore, full penetration was observed at higher frequencies and at greater amplitudes of magnetic field. Analysis of these results can shed some light on the mechanism of the vortex shaking. Magneto-optical analysis shows that the relaxation time of screening currents in Bi-2223 tapes at 77 K is comparable with the period of the AC magnetic field at the studied frequencies and must be considered in E-I curves investigation. The results imply that flux creep processes as well as geometry considerations play a key role in shaping E-I curves of Bi-2223 tapes exposed to AC fields.

Acknowledgment

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References

[1] Shaked N, Friedman A, Sinvani M, Kopansky F, Wolfus Y and Yeshurun Y 2004 *Physica C* 2004 **401** 201-205
[2] Friedman A, Wolfus Y, Kopansky F, Kalisky B, Roitberg V, Soshnikov I and Yeshurun Y 2005 *IEEE Transactions on Applied Superconductivity* **15** 2891-2894
[3] Mikitik G P and Brandt E H 2001 *Phys. Rev.* **B 64** 092502
[4] Brandt E H and Mikitik G P 2002 *Phys. Rev. Lett.* **89** 027002
[5] Shaked N, Friedman A, Sinvani M, Al-Omari I A, Wolfus Y, Shaulov A and Yeshurun Y 2001 *Physica C* **354** 237-241
[6] www.amsuper.com