# I-V Curves of BSCCO Tape Carrying DC Current Exposed to Perpendicular and Parallel AC Fields

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***Abstract*—A study of the DC I-V curves of BSCCO tapes exposed to AC perpendicular and parallel magnetic fields is presented. AC magnetic fields with amplitudes up to 700 G and frequencies from 1 to 430 Hz have been applied perpendicular and parallel to tapes carrying DC currents at $\mathbf{T = 77\ K}$. Both field orientations result in a significant DC electric field increase, in comparison to applying DC magnetic fields of the same intensity. However, the observed I-V curves behavior is different for the perpendicular and parallel cases. In the perpendicular case, we distinguish between two frequency regimes: for frequencies above 40 Hz, the observed I-V curves obey the empirical power law dependence with current density, $\mathbf{J_C}$, and power index, n, that strongly depend on the field amplitude. For frequencies below 20 Hz, the observed I-V curves deviate from power law description. In the parallel field case, the I-V curve can be regarded as a superposition of an additional DC voltage over the no field I-V curve. This additional voltage increases with increasing current, peaks near the critical current and decreases thereafter. The results are discussed assuming a narrowing down of the DC current path under the application of a perpendicular AC field. Shaking of the pinned vortices under the application of a parallel AC field is assumed for explaining the results in this case.**

***Index Terms*—AC field, Bi-2223 tape, critical current, I-V curve.**

## I. Introduction

The use of Bi-2223 tapes in power devices requires detailed characterization of its behavior in magnetic fields and an understanding of the underlying physics responsible for the appearance of electric fields in the tapes. In particular, the influence of alternating magnetic fields on the transport properties is of great importance. When used for power applications, HTS tapes and coils are always subjected to some level of alternating magnetic fields that might cause substantial energy losses. In previous works [1], [2] we have studied a SMES demonstration model and found that the charging and discharging processes of the coil proceed by current steps that produce alternating magnetic self-fields. It was shown that a small AC field on the coil causes additional voltage [2] therefore decreasing its critical current. The electric field in superconductor carrying transport current subjected to AC magnetic field was observed in Nb-alloys [3] and analyzed by Ogasawara [4], [5]. The phenomenon was regarded as a "dynamic resistance" which is amplitude and frequency dependent. As shown in monograph [6],

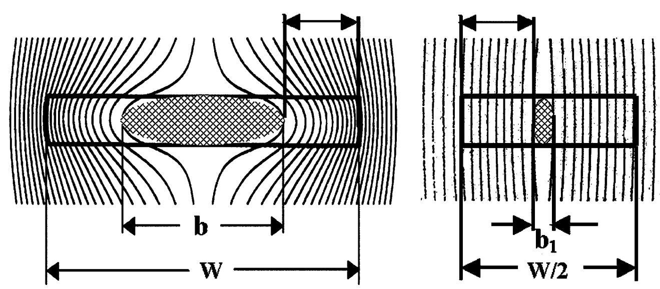


Fig. 1. Magnetic flux lines inside the tape for AC field magnetic field perpendicular to broad side of the tape. w is the width of the tape and b is a width of the central zone free of AC field.

the dynamic resistance is typically present in cases of full penetration of the AC field into the superconductor. In these cases, electric field appears for any finite transport current value. The case of partial AC field penetration was regarded in [7] where resistance-free current was assumed to flow in the central zone of a round cross-section superconducting wire. The dimensions of the wire are of crucial importance for the size of the current carrying zone in a given AC field value.

Dynamic resistance behavior was also studied in Bi-2223 tapes in [8]–[11] by the investigation of AC losses under various conditions. In [12] the problem was studied for YBCO tape. At the same time, many works (for example [13]–[15]) have studied the decay of the magnetic moment (i.e. decay of the screening currents) in magnetization measurements.

In a previous work we analyzed the I-V curves of Bi-2223 tapes exposed to AC magnetic fields, perpendicular to the broad side of the tape, with amplitudes up to 20 mT and frequencies in the 50–430 Hz range [16]. We have found that the I-V curves are well described by power law. The application of the AC field resulted in a linear decrease of the critical current independent of the frequency of the magnetic field. We interpreted the results by assuming a confinement of the DC transport current in the central region of the tape, a region free of AC field (Fig. 1).

Low DC current density is assumed to flow in the region penetrated by the AC field because flux flow regime is realized in this zone [6]. The transport current then flows in the central, AC field-free zone. The expression for the current can be written [16] as:

$$I_c = t\left[J_c^{fc}(B) * b + J^{ff}(B) * (w - b)\right], \qquad (1)$$

where $t$ is the tape's thickness, $w$ is its width, $b$ is the width of the central, AC field-free region, and $J_c^{fc}(B)$ and $J^{ff}(B)$ are the field dependent current densities in the flux creep and flux

Manuscript received October 5, 2004. This work was supported in part by the Israeli Ministry of Infrastructure.

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Digital Object Identifier 10.1109/TASC.2005.848256

flow regimes respectively. Because both regions are 'parallel connected', $J^{ff}(B)$ is determined by the voltage developed in the central region.

In this work we present I-V curves of Bi-2223 tape exposed to AC magnetic field perpendicular or parallel to the broad side of the tape (always perpendicular to the transport current). The amplitude range was extended to 700 G and the frequency range to 0.1–430 Hz. Magneto-optical (MO) measurements were used to observe the AC field penetration into the tape. The results confirm the model discussed above for the case of perpendicular AC fields, yet show that an additional refinement of this model is necessary. In parallel AC fields, power law cannot describe the observed I-V curves. Rather, the measured voltage behaves as a superposition of an additional voltage signal on the I-V curve obtained without field. This additional voltage is evident already for small DC currents, peaks close to the zero-field critical current and decreases thereafter. Shaking of the pinned vortices under the application of a parallel AC field is assumed for explaining the results in this case.

## II. Experimental

We present voltage measurements of nontwisted Bi-2223 multifilamentary tapes manufactured by AMSC. The tapes carried DC transport current being subjected to alternating sinusoidal magnetic field perpendicular to the current flow direction. The measurement setup is similar to the one used in [17]. Both single tape and bifilar configuration samples were measured. Bifilar configuration has the advantage of minimizing self-fields effects. Also, because the current leads to/from the bifilar sample are close together, it is relatively easy to prevent AC induced currents in the DC transport current circuit. For frequencies above 10 Hz, voltage measurements have been performed using 8.5 digits, 1271 Datron DVM in its DC voltage mode. For frequencies below 10 Hz, voltage values have been obtained by integrating the time dependent voltage signal measured by Tektronix-420A digital scope with differential preamplifier ADA400A. The zero-current signal was always subtracted from the measured signal. Both methods give identical I-V curves at the same conditions.

## III. Results and Discussion

Fig. 2 exhibits a series of I-V curves of a single tape sample in AC magnetic fields, perpendicular to the plane of the tape, with amplitudes up to 700 G at 105 Hz frequency. I-V curves obtained for AC field amplitudes up to 350 G can be fitted to power law with a critical current, $I_C$, and a power index, n, that decrease with the increase of the AC field amplitude $B_0$ (Fig. 3). For amplitudes above about 500 G, the I-V curves become almost linear and the voltage is evident for any finite current. These results are in agreement with the above-described model (Fig. 1). In the zone penetrated by the AC field, flux lines are depinned [7], [16] and flux flow resistance appears. As a result, transport currents are confined to the central, AC field free region, where the resistance is governed by flux creep. In high enough amplitudes, the AC field fully penetrates the tape and finite voltage values are obtained for all transport current values.

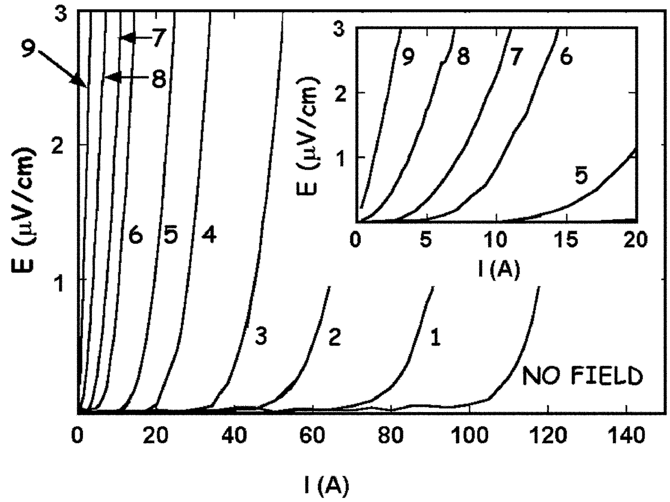


Fig. 2. E-I curves of bifilar Bi-2223 tape in perpendicular AC field. Field values: 1—70 G, 2—140 G, 3—220 G, 4—280 G, 5—350 G, 6—420 G, 7—490 G, 8—560 G, 9—630 G, 10—700 G.

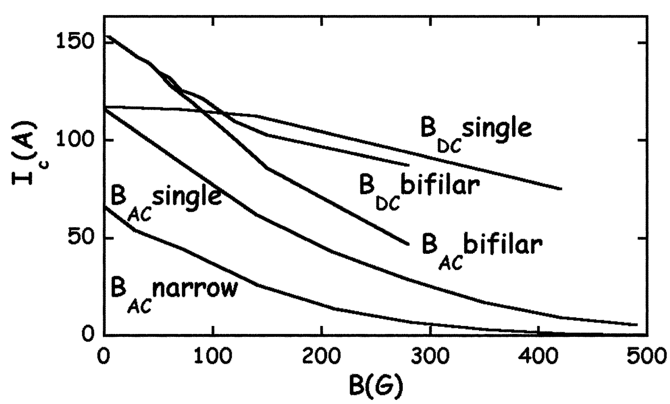


Fig. 3. $I_C(B)$ dependence bifilar sample, single tape and narrow tape along with the DC $I_C(B)$ dependence.

To further check our interpretation, we've performed MO measurements to map the AC field distribution in the tape. Measurements were performed at $T = 70$ K for better contrast images. The sample carried no DC transport current because our setup does not support this feature for high currents. Fig. 4 displays the field profile across the sample for a perpendicular AC field at 55 Hz frequency and various amplitudes up to 600 G. Many momentary field profiles taken at different times are plotted together to form the field envelope displayed in Fig. 4. The results clearly show that AC field amplitude of 180 G (upper frame) leaves a relatively large AC field-free region in the sample. This region shrinks with the increase of the amplitude to 360 G (mid frame), until at 630 G the sample is fully penetrated by the AC field (lower frame). Although we cannot deduce directly from the results obtained at 70 K and no DC current to the results obtained at 77 K with DC current, the MO data support the scenario of current confinement in the AC field-free region.

Another supporting evidence is obtained by measuring a half-width tape. The tape was cut along its length and measured under the same conditions as the full width tape. As expected, $I_C$ of the half-width tape decreases with amplitude faster then in

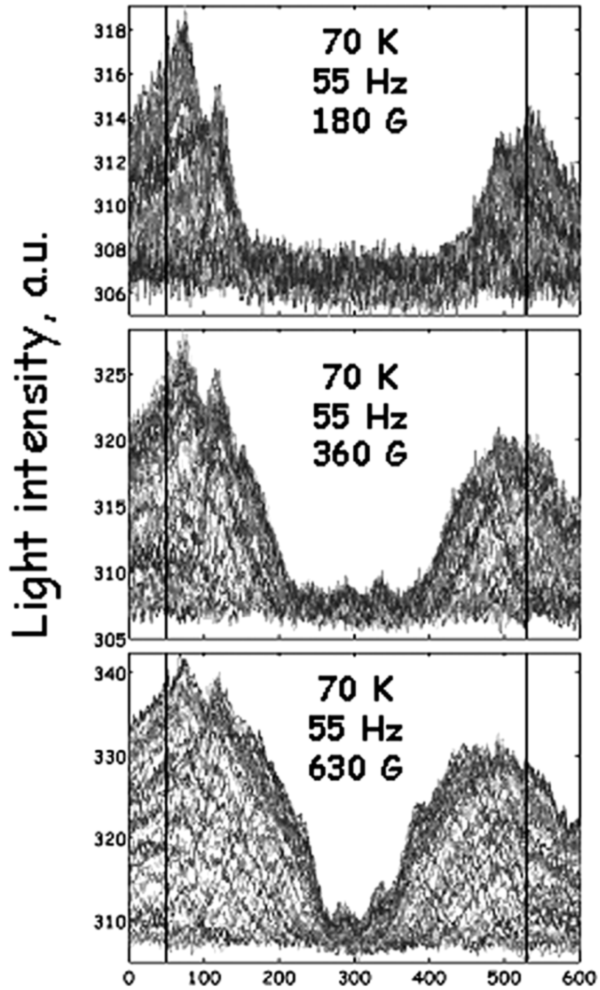


Fig. 4. MO field profiles for perpendicular AC field at $\mathrm{T} = 70$ K.

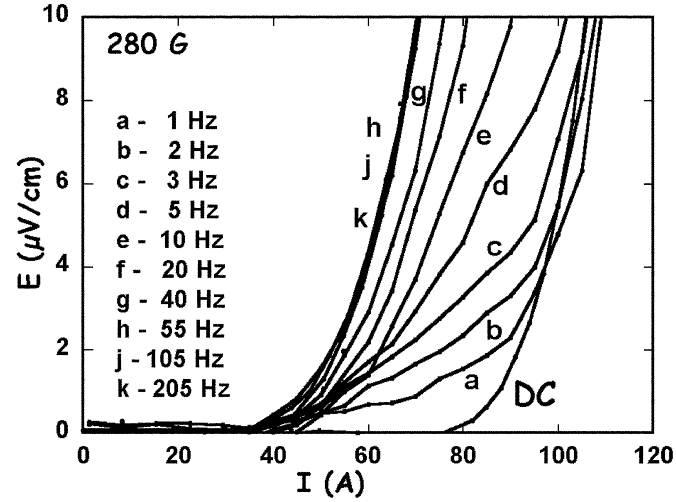


Fig. 5. E-I curves of the bifilar Bi-2223 tape in perpendicular AC field with amplitudes 280 G and in DC field of 280 G.

the full width tape. The amplitude dependent $I_C$ for single and bifilar configurations and for the half-width "narrow" sample, is shown in Fig. 3 along with the dependence of $I_C$ on the DC field. In the linear portion of the $I_C(B)$ curve, the "narrow" tape curve roughly scales with the full-width tape curve by a factor of 2.

Also evident in Fig. 3 is that at low magnetic fields the $I_C(B)$ curves measured for bifilar samples coincide for DC and AC applied fields. This is valid up to fields of about 70 G at which the curves split and the DC $I_C(B)$ curve shows a weaker field dependence than the AC curve. The convergence of the DC and AC curves implies that $I_C$ is frequency independent. For example, at amplitude of AC field of 30 G for frequencies from 2 to 430 Hz I-V curves are described by power law with almost identical $I_C = 144.6 \pm 1$ A and $n = 16 \pm 1$. The results cannot be interpreted in the framework of "dynamic resistance" models where a linear frequency dependence of the measured voltage is expected [4].

Fig. 5 shows I-V curves measured in field amplitude of 280 G for various frequencies in the range of 1 to 430 Hz along with the DC I-V curve. These results extend the frequency range of our previously reported measurements [16] showing frequency independent I-V curves in low fields. In contrast to the low-field frequency independent I-V curves, the results obtained for fields above 70 G show clear frequency dependence that increases with increasing amplitudes. The measured voltage exhibits a strong dynamic behavior even in frequencies as low as 1 Hz. With increasing frequency, the frequency dependence weakens until above 55 Hz the measured I-V curves are practically frequency independent. Again, this behavior contradicts the behavior expected in the "dynamic resistance" regime where a linear voltage dependence on frequency is predicted. The measured I-V curves can be fitted to power law dependence for frequencies above 20 Hz. For lower frequencies the curves deviate from power law implying that the field dynamics involve other mechanisms beside flux creep or "dynamic resistance". Better understanding of the underlying mechanisms requires further investigations.

I-V curves of a single tape subjected to parallel AC fields are displayed in Fig. 6. The curves obtained for a parallel field qualitatively differ from the curves obtained for a perpendicular field. The existence of electric field in the tape is evident for almost every finite current value (Fig. 6(a)). I-V curves are very "shallow" in comparison with the perpendicular field curves and the sharp knee, typical of power law dependence, is absent. In fact, the measured voltage for the parallel field case may be regarded as a superposition of an added voltage signal over the zero field I-V curve. The inset to Fig. 6(a) shows the superimposed voltage obtained by subtracting the zero-field I-V curve from the measured voltage signal. This additional contribution to the electrical field exhibits monotonic amplitude (Inset to Fig. 6(a)) and frequency (Fig. 6(b)) dependence and nonmonotonic current density dependence, peaking near the zero-field $I_C$.

The high aspect ratio of the flat shaped tape results with a full penetration of the AC parallel field already at very low amplitudes. The AC field inside the tape interacts with the transport current vortices. Several models were proposed to explain the influence of parallel AC field on the decay of the screening currents in HTS sample [13]–[15], [18]. Different "shaking" mechanisms have been proposed resulting in depinning of the vortices by the parallel AC field. In principle these mechanisms can be applied also to the sample carrying a transport current however

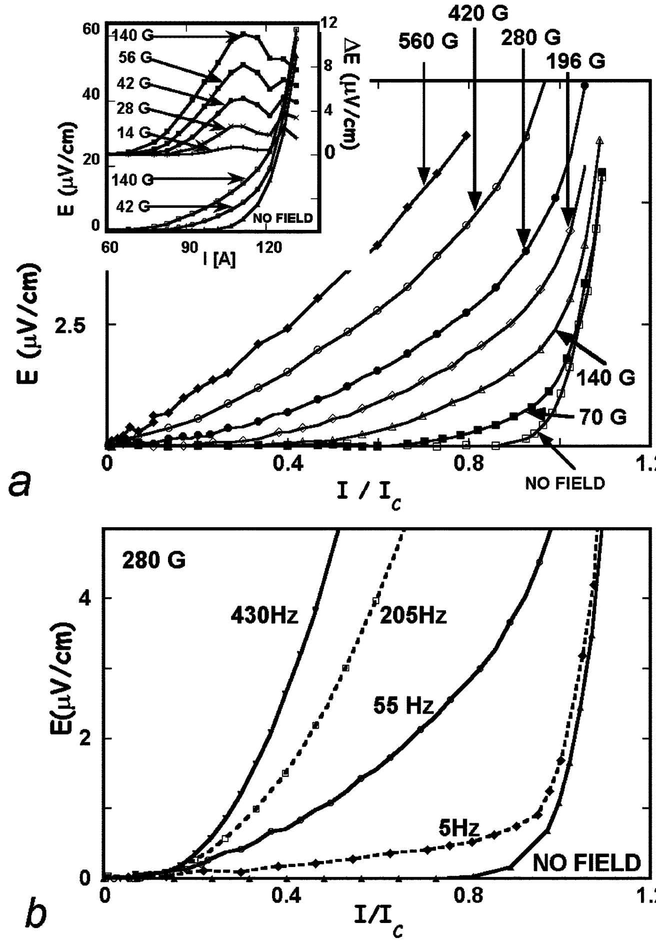


Fig. 6. E-I curves of Bi-2223 tape subjected to parallel AC fields, (a) at fixed amplitude of 280 G and various frequencies, (b) with different amplitudes at fixed frequency 205 Hz (a).

more detailed investigation is required to explain the details of the additional voltage behavior observed in tapes carrying transport currents subjected to parallel AC fields.

## IV. Summary

We've measured the DC electric field in Bi-2223 tapes carrying transport currents subjected to AC magnetic field perpendicular to the current direction. Qualitatively different I-V curves were obtained for AC fields perpendicular and parallel to the broad side of the tape. The results for the perpendicular field orientation suggest a decrease of the effective cross section for the current flow with the increase of the AC field at frequencies above 40 Hz. However, further understanding is required to explain the results obtained for frequencies below 20 Hz and/or for low field amplitudes where a strong deviation from power law dependence is observed. For AC fields parallel to the broad side of the tape, the observed I-V curves do not obey power-law dependence. The parallel AC field results in an additional voltage that strongly depends on frequency. This additional voltage is evident for low current values, increases with the current and peaks approaching the zero-field critical current. Preliminary interpretation suggests that the parallel AC field shakes the vortices out of their pinning sites and cause a 'flux-flow like' behavior in currents well below the critical current. More experimental results are necessary to adopt this model for tapes carrying transport currents subjected to parallel AC fields.

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