Electric Field in Bi-2223 Tape Carrying DC Current and Exposed to AC Parallel Magnetic Field

S. Asulay, A. Friedman, Y. Wolfus, F. Kopansky, and Y. Yeshurun

Abstract—**A study of the degradation of the critical current of Bi-2223 tapes under AC magnetic fields is of great importance for HTS power applications. In particular, in a common AC coil design, the field component parallel to plane of the tape is much stronger than the perpendicular component. In this work we present the results of electric field measurements of Bi-2223 tape exposed to AC magnetic field parallel to the broad side of the tape with various frequencies and amplitudes. The observed E-I curves can be described as an additional voltage to the E-I curve superimposed on the zero-field curve. This additional voltage increases with amplitude and frequency of the AC magnetic field and grows almost linearly with DC current, peaks close to the zero-field critical current and decreases thereafter. We analyzed the correlation of the electric field with indicated parameters on the base of the theoretical predictions of H. Brandt and G Mikitik and found a striking agreement of the calculated and observed values. Measurements of the time dependent electric field exhibit double-frequency features and strong dependence of the electric field on the amplitude and frequency of the AC magnetic field.**

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

I. Introduction

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. There are two main types of the Bi-2223 coils in use in power devices: AC coils carrying AC transport current and subjected to AC magnetic field (as in transformer or resistive Fault Current Limiter—FCL) and DC coils carrying DC transport current with a small AC component causing AC self-field (e.g. Superconducting Magnetic Energy Storage device—SMES) or subjected to external AC magnetic field (as in 'saturated core' FCL). Thus application of HTS tapes 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.

Several works, performed on BSCCO and YBCO samples, show that the application of an AC field parallel to the a-b plane suppresses the magnetic moment measured along the c axis [1]–[5]. This phenomenon was regarded as shaking of Abrikosov vortices causing their depinning and attenuation of the screening currents flowing in a-b plane. The mechanism of the observed phenomena was analyzed by experimentalists [1]–[5] and also in several theoretical works [6]–[8]. There are the essential problems in comparison of results of magnetization measurements with a theory: measurements of the magnetic moment give information on the state with zero and not defined current density distribution. In most cases on suppose that current density has only one value: critical current density corresponding to zero electric field. We consider that transport measurements give more information because we can study a wide range of current densities and electric fields.

When studying a behavior of the HTS tapes carrying a transport current and subjected to AC magnetic field we have to consider electric field in the tape caused by vortices motion accelerated by AC field application. The additional voltage was observed in Bi-2223 coil carrying DC transport current with small oscillating component [9] that was explained as effect of the AC magnetic field. E-I curves of the Bi-2223 tapes were measured in AC magnetic field directed parallel and perpendicular to the broad side of the tape [10]–[14] and the striking difference in two cases was observed [14]. It is worthy to mention that E-I curves in [12], measured on pancake coil in axial external AC field, i.e. when AC field is parallel, are similar to observed in [14] at the same configuration. The mechanism of accelerating the vortices motion by AC field in the current carrying tape has to be similar to observed in magnetization measurements. In this paper we analyze electric field in the case of parallel AC field, i.e. the geometry similar to used in mentioned magnetization studies. In this work we analyze the electric field in Bi-2223 tape carrying DC current depending on the amplitude and frequency of AC magnetic field directed parallel to the broad side of the tape and compare the results with theoretical model [6]–[8]. In addition we studied firstly the time dependent electric fields that enable the more detailed analysis of the electric field peculiarities.

II. Experimental

The tapes carried DC transport current subjected to alternating sinusoidal magnetic field parallel to the broad side of the tape. The measurement setup immersed in liquid nitrogen is similar to the one used in our previous works [15]. Special precautions were taken to prevent AC induced currents in the DC transport current circuit. Voltage taps were placed in a way that allows minimizing the signal induced in measurement loop. The SC tape and the voltage wires were fixed between two parallel surfaces; the voltage taps being of the same thickness as the SC tape and lying exactly in its plane. E-I curves voltage measurements have been performed using 8.5 digits, 1271 Datron DVM. The time dependent voltage signal was measured by Tektronix-420A digital scope with differential preamplifier ADA400A. The zero-current signal was always subtracted from

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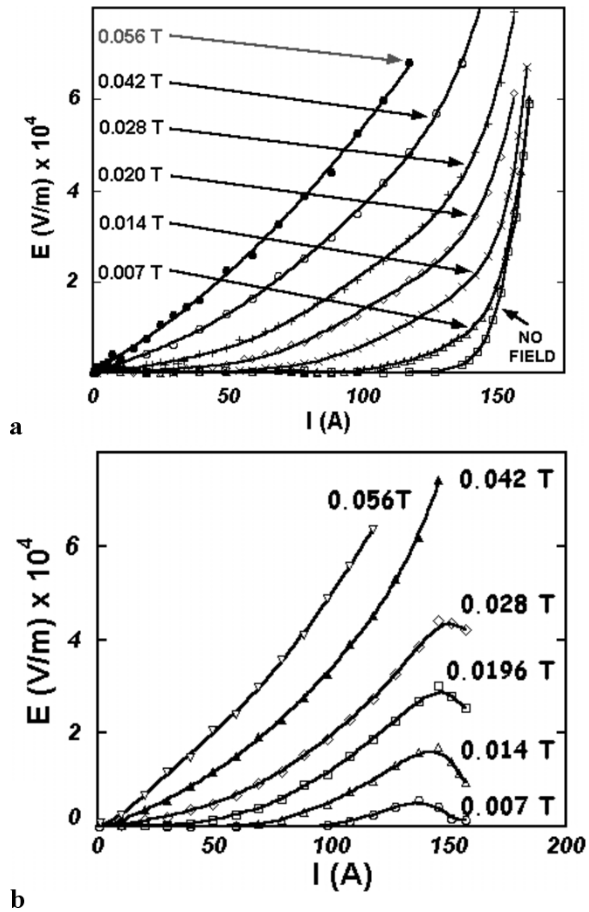

Fig. 1. (a) E-I curves of BSCCO tapes exposed to AC magnetic field at various amplitudes and frequency 105 Hz, (b) "additional electric field" curves, obtained by subtracting the "no field" curve from the other curves in Fig. (1a).

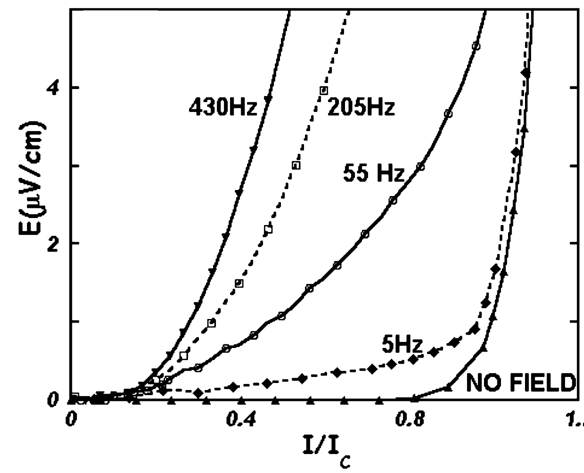

Fig. 2. E-I curves of BSCCO tapes exposed to AC magnetic field with various frequencies at the amplitude 0.028 T.

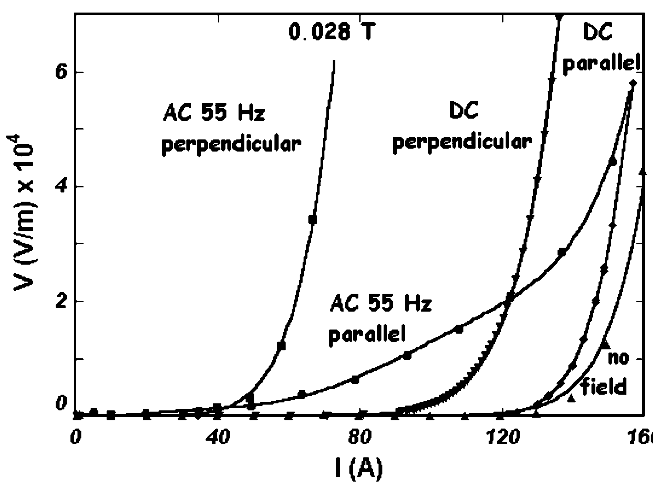

Fig. 3. E-I curves measured with AC magnetic field with amplitude 0.028 T directed parallel and perpendicular to the broad side of the Bi-2223 tape.

the measured signal. Integration of time-dependent signal enabled to build E-I curves that were identical to E-I curves measured with DVM at the same conditions. It proves fidelity of the method. The sample studied was taken of industrial lot of AMSC reinforced tape [16].

III. Results and Discussion

A. Measurements of the Current Dependent Electric Field (E-I Curves), at Various Amplitudes and Frequencies of AC Magnetic Field

E-I curves measured at various amplitudes and constant frequency of 105 Hz are shown in Fig. 1. The electric field appears at some amplitude dependent threshold current and increases almost linearly with increasing current approaching to the no field curve at high currents. This feature is more pronounced if one examines the graph of the difference between the curves obtained with the AC field on and the no field curve (Fig. 1(b)). This difference achieves a maximum at the vicinity of the self-field critical current and decreases thereafter. The threshold current strongly decreases with AC field amplitude. Fig. 2 exhibits E-I curves obtained at amplitude of 0.028 T and various frequencies. Clearly, for a given current, E increases sharply with increasing frequency.

E-I curves of tapes exposed to parallel and perpendicular AC magnetic field of the same frequency and amplitude are compared in Fig. 3. While the general power law of the DC field is preserved in the perpendicular field case, this power law dependence is lost for the parallel field case.

When the AC field fully penetrates the tape, one may try to use the results of the theoretical analysis [6]–[8] for interpreting the results. Ref. [6]–[8] give the below formula defining the relation between E, I, frequency, f, and amplitude, h of the AC magnetic for a tape of thickness d:

$$E = 2\mu_0 f d \left(\frac{I}{I_C}\right)[h - h_P(I)], \qquad (1)$$

where I_C is the critical current and $h_P(I)$ is the threshold field. We have measured several sets of E-I curves similar to those shown in Fig. 1 at frequencies 50–400 Hz. When we plot the

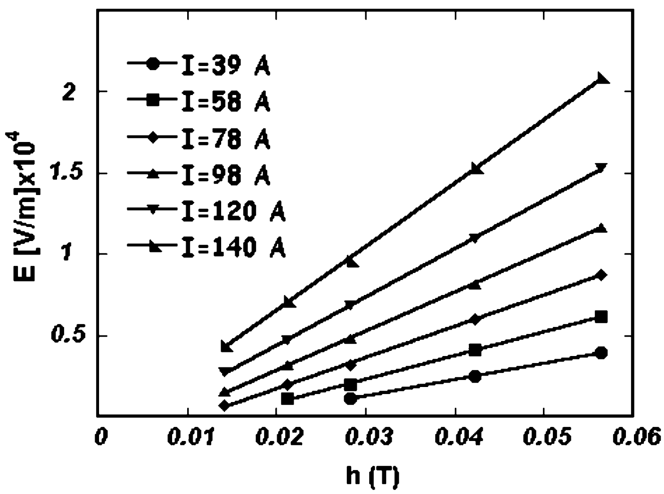

Fig. 4. Dependence of the electric field E on the AC magnetic field amplitude, h, for different transport currents at fixed frequency of 105 Hz.

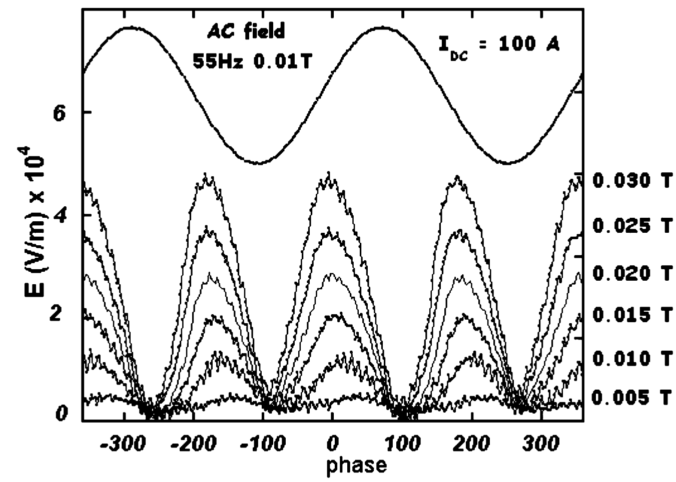

Fig. 6. Time-dependent voltage signal (reduced to electric field) recorded at various magnetic field amplitudes. $\mathrm{I} = 100\ \mathrm{A}, \mathrm{f} = 55\ \mathrm{Hz}$.

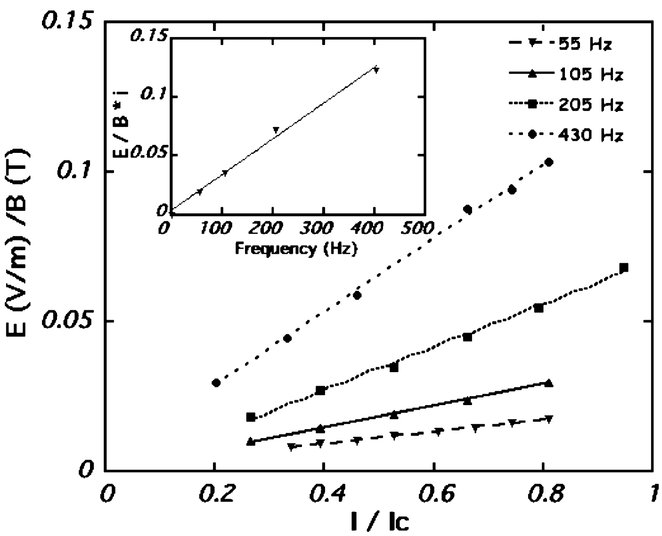

Fig. 5. Dependences of slope of the plots E vs. h on reduced transport current. The graph in the insert presents the dependence of the slope of the lines in Fig. 5 on frequency.

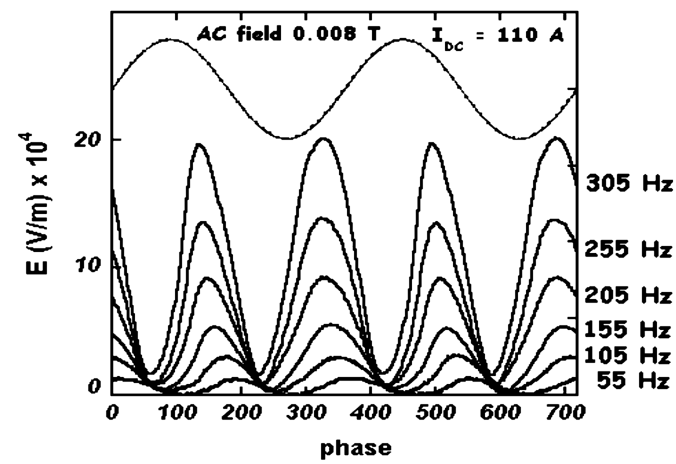

Fig. 7. Time depended voltage signal (reduced to electric field) at various frequencies of the magnetic field at transport current of 110 A at fixed amplitudes of 0.008 T.

electric field E vs. the AC magnetic field amplitude, h, for different currents at fixed frequency we obtain linear dependences (Fig. 4). In the measured frequency range, the slope of these plots linearly depends on current (Fig. 5), demonstrating a qualitative agreement between the experimental data and (1). As we could expect from (1), the slope also exhibits linear frequency dependence (insert to Fig. 5). According to (1), this slope has to be equal to $2d = 0.0004\ \mathrm{m}$. In our experiment (Fig. 4, 5), we obtained the value of $2d = 0.0003\ \mathrm{m}$, in good agreement with (1). It is instructive to mention that expression (1) has been obtained in [8] for describing a model of 'walking' vortices and in [9] for describing a model of continuous transfer of the vortices ("dynamic resistance"). Our results cannot distinguish between the two models.

B. Time Dependent Electric Field

It is likely that the contribution to the electric field, induced by AC magnetic field, is modulated in time with a frequency related to the magnetic field frequency. In [9] such modulation is predicted.

In Fig. 6 we present the modulation of the electric field at various amplitudes of the magnetic field with fixed frequency and transport current. The signal has almost sinusoidal form with the frequency doubled relative to the magnetic field frequency. The low level of the signal is constant while the peak grows linearly with increasing amplitudes. The peak position appears to slowly shift with h, however always in the vicinity of the external field node. More results are required to characterize the phase dependence on the amplitude.

Fig. 7 displays the modulated signals at various frequencies for fixed amplitude and transport current. In this plot we see that both the base level of the signal and peak increase with increasing frequency. A more pronounced change of the base level is observed when comparing electric field values obtained at different transport currents (not shown here). The amplitude dependence of the modulated signal qualitatively agrees with the prediction of [9], although the calculated form is much more asymmetric. A detailed model has to take into account both relaxation processes in the tape and the anisotropy of its properties.

IV. Summary

The electric field arising in Bi-2223 tapes exposed to an AC magnetic field parallel to the broad side of the tape was measured at various amplitudes and frequencies. Analysis of the results shows a good agreement with theoretical models developed for the case of the full penetration of the AC magnetic field into the tape. Time dependent electric field waveforms, induced by the AC magnetic field, were been measured. These waveforms feature doubled frequency as compared with the external magnetic field waveform. Further investigations are required to shed a new light on the mechanism of the vortex shaking.

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