Energy Loss and Regimes of Flux Dynamics in BSCCO Tapes Above the Engineering Critical Current

G. Lukovsky, A. Friedman, Y. Wolfus, L. Burlachkov, and Y. Yeshurun

***Abstract*—Time dependent measurements of the electric field in BSCCO tapes carrying DC current and exposed to AC magnetic fields reveal new and rich details about the electric field behavior. In particular, E(t) curves obtained for currents above the engineering critical current exhibit "double peak" feature for each half-cycle of the external magnetic field. For currents lower than I_c, E(t) exhibits a usual sine ("single peak") with amplitude and frequency dependent phase shift relative to the external field. Similar behavior is obtained for currents above I_c for low frequencies and/or high amplitudes of the magnetic field. However, with the decrease of amplitude and/or increase of frequency, a "second peak" emerges and gradually becomes dominant. This "second peak" is in phase with the external magnetic field. We interpret the results by assuming a crossover between two regimes of flux dynamics affecting the mechanism for energy loss generation in the tape. In the "quasi-DC", low frequency—high-field regime, flux lines enter the tape from one side, cross it entirely and leave from the other side, causing a dissipation, which is in phase with the external field. In the high frequency—low-field regime, flux lines enter and leave the tape from the same side and some annihilation of vortex and anti-vortex occurs at the central region of the tape. In this regime the dissipation and its phase are frequency and amplitude dependent.**

***Index Terms*—Electric field measurement, high-temperature superconductors, superconducting wires.**

I. Introduction

When used for power applications, High-Temperature Superconductors (HTS) tapes and coils are almost always subjected to some level of alternating magnetic fields that might cause substantial energy losses. There are two main situations in which HTS tapes and coils are used in power devices: conductors/coils carrying AC transport current and subjected to AC magnetic field as in transformers or in resistive Fault Current Limiters (FCL), and coils carrying DC transport current. In the last case the DC coil can have a small AC component causing AC self-field as in Superconducting Magnetic Energy Storage (SMES) device or the DC coil can be subjected to external AC magnetic field as in the "saturated core" FCL.

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Therefore, the application of HTS tapes in power devices requires detailed characterization of its behavior in AC 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 crystals, 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 de-pinning and attenuation of the screening currents flowing in a-b plane. The mechanism of the observed phenomena has been analyzed in experimental [1]–[5] and theoretical works [6]–[8]. When studying the behavior of HTS tapes carrying transport currents and subjected to AC magnetic fields, one has to consider the electric field in the tape caused by vortices motion accelerated by AC field application. An additive DC voltage has been observed in Bi-2223 coils carrying DC transport current exposed to small oscillating magnetic fields [9] that was explained in the framework of flux creep models. E-I curves of Bi-2223 tapes were measured in AC magnetic field parallel and perpendicular to the broad side of the tape [10]–[14] and a striking difference between the two cases has been observed [14].

In this work we study the electric field behavior in Bi-2223 tapes carrying DC current and exposed to AC magnetic fields, and analyze its dependence on amplitude and frequency of the AC magnetic field. We've used time dependent measurements of the electric field for monitoring the momentary behavior of E and revealed new features in the E(t) curves. In particular, a cross over between single and double peaks in E(t) curves was found suggesting a cross over between two regimes of flux dynamics.

II. Experimental

The measurement set is similar to the one used in previous works [15], [17]. Single tapes of Bi-2223 manufactured by American Superconductor Corp. (AMSC) were measured at 77 K. The tapes carried DC transport current and were subjected to AC magnetic field perpendicular to the wide side of the tape. The positions of the voltage taps and the twisted wires used for the measurements were carefully adjusted to minimize induced signal in the measurement circuit. The time dependent voltage signal was measured by Tektronix-420 A digital oscilloscope with differential preamplifier ADA400 A. The E-I curves measurements have been performed using 8.5 digits, 1271 Datron DVM.

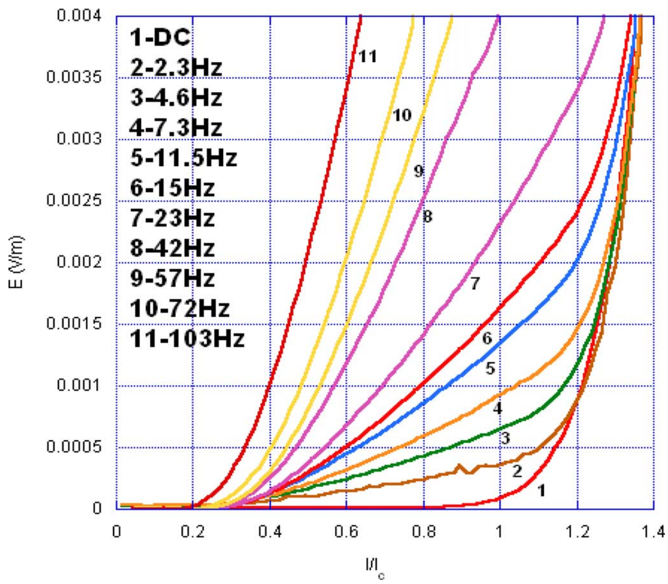

Fig. 1. Set of E-I curves of Bi-2223 tape measured in 220 G rms perpendicular magnetic field at frequencies 2.3–103 Hz.

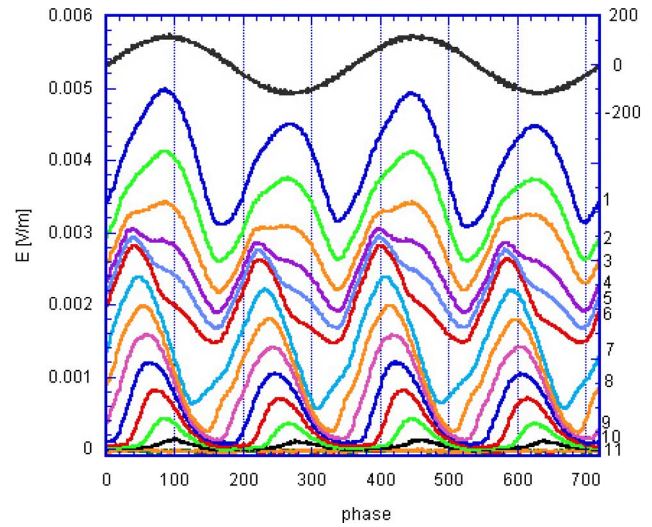

Fig. 2. E(t) graphs of Bi-2223 tape exposed to AC magnetic field at 23 Hz, 80 G rms. E(t) curves are shown for DC currents of: 170 A(1), 168 A(2), 166 A(3), 164 A(4), 162 A(5), 160 A(6), 150 A(7), 140 A(8),130 A(9), 120 A(10), and 100 A(11).

III. Measurements Results

A. E-I Curves at Different Magnetic Field Frequencies

Fig. 1 presents a series of E-I curves of Bi-2223 tape in perpendicular AC magnetic field of 220 G rms at frequencies 2.3–103 Hz. The first line is obtained for DC magnetic field of 220 G and it is well described by the power law, $E = E_0(I/I_c)^n$

With the presence of AC magnetic fields, E-I curves deviate from the power law dependence. Generally speaking, the measured curve can be divided into two deferent regions: in low currents the curves are close to linear, and at high currents the curves converge into the DC curve, and therefore it can be described again by the power law. These two parts of E-I curve appear only at low frequencies (2.3–23) Hz. At higher frequencies the graphs cannot be describes by neither power law nor linear fit and the curves no longer converge to the DC curve (within the measured range of DC currents that is limited by overheating of the tape). For all used frequencies, the measured DC voltage increases with increasing frequency, however in the low frequency range at high currents the E-I curves converge into the DC curve and difference becomes negligible.

B. E(t) Measurements

Measurements of the time dependent electrical field $E(t)$ provide greater details on the field dependent electrical field as they describe the momentary value of E. Such measurements reveal new information and could provide better insight to understanding flux dynamics in HTS tapes. Fig. 2 presents a set of E(t) curves recorded for AC transverse magnetic field with 80 G rms amplitude and frequency of 23 Hz. Different curves are obtained for different DC currents. The signal has double the frequency of the AC magnetic field. The doubled frequency behavior is naturally explained by unidirectional Lorenz force and constant direction of the moving vortices relating to magnetic field created by transport DC current.

For low transport currents (below I_c), the momentary electrical field increases with increasing DC current and the peak of the signal is out of phase in comparison with the external magnetic field. At currents of about 160 A, a "shoulder" appears every half cycle and grows with rising transport current. This "shoulder" evolves into a second peak and becomes dominant at higher currents. This "second peak" is in phase with the external magnetic field. Similar results are obtained for other values of amplitudes and frequencies of the external magnetic field. The current, at which the "shoulder" appears, depends on the amplitude and frequency. An example for this dependence is shown in Fig. 3. In this figure an external field of 400 G rms, 23 Hz is applied and the "shoulder" is shifted to lower currents and first appears in currents of about 120 A. Detailed results for the amplitude and frequency dependence of the two regions in E(t) will be described elsewhere.

IV. Discussion

The results presented here show two regions in the E(t) behavior: a region of low DC currents and high frequencies, where the electric field modulation is out of phase with the magnetic field and the phase shift depends on the magnetic field and the DC current, and a "quasi-DC" region observed at low frequencies and high currents, where the electric field modulates in phase with the magnetic field. We could explain the two regions of E-I graphs and two peaks at E(t) graphs by vortex contribution to energy dissipation in the wire (i.e., to appearance of voltage) if either this vortex crosses the entire wire throughout, entering at one side and leaving at another one, or if it annihilates within the wire with antivortex (vortex of different polarity). Thus we have two different mechanisms for voltage appearance, and two competing peaks on E(t) plot within one half-period of the external magnetic field.

The in-phase peak is an adiabatic one. This means that in the regime where this peak dominates the characteristic time scale of magnetic flux relaxation in the wire (or, in other words, the time that is required for a vortex to cross the entire wire) is much

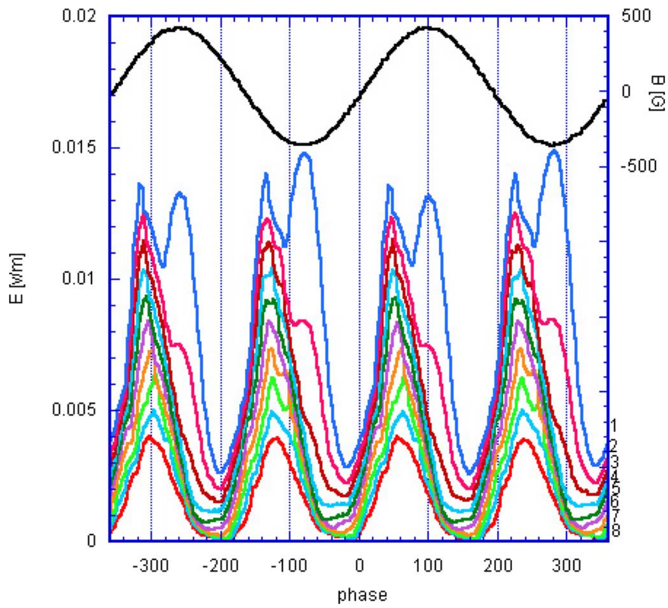

Fig. 3. E(t) graphs of Bi-2223 tape exposed to AC magnetic field at 23 Hz, 400 G rms. E(t) curves are shown for DC currents of 140 A(1), 130 A(2), 120 A(3), 110 A(4), 100 A(5), 90 A(6), 80 A(7), 70 A(8).

less than the period of the external field. In the in-phase regime the external field can be considered as quasi-stationary, and most vortices cross throughout the entire wire. As a result, maximal dissipation (voltage) corresponds to maximal magnetic field and is proportional to the amplitude of the magnetic field and to the transport current. It is clear that in-phase peak should dominate at higher fields and transport currents and at low frequencies of the external magnetic field.

Contrary to the in-phase peak, the out-of-phase one dominates in the situation where the characteristic time scales for flux relaxation are of order and greater than the period of the external field. In this case vortices do not have enough time to cross the sample within one semi-period of the external field. This is the regime of weak fields and currents and high frequencies. In this regime, vortices and antivortices enter the wire from different sides during two semi-periods of the external field, move towards each other, driven by the transport current, and annihilate.

Another mechanism that might be responsible for the appearance of the out-of phase peak might be the surface barrier (of Bean–Livingston [18] or other type) that the vortices have to surmount when entering and exiting the sample. However, the fact that higher frequencies favor domination of the out-of-phase peak, rule out this mechanism. It is clear that the higher is frequency the higher are surface currents. The latter diminish the surface barriers that should in turn suppress the out-of-phase mechanism at higher frequencies, whereas the experimental data show just the opposite picture.

V. Summary

Measurements of the time dependent electric field, E(t) in HTS tapes carrying DC current and exposed to AC magnetic fields reveal "double peak" behavior suggestive of two regimes of vortex dynamics. Possible explanation of the results could suggest that in the "quasi-DC", low frequency—high-current regime, flux lines enter the tape from one side, cross it entirely and leave from the other side, causing dissipation, which is in phase with the external field. In the high frequency—low-current regime, flux lines enter and leave the tape from the same side and some annihilation of vortex and anti-vortex occurs at the central region of the tape. In this regime the dissipation and its phase are frequency and amplitude dependent.

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