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Informal Report

Ac LOSSES IN CONDUCTORS BASED ON HIGH T_c SUPERCONDUCTORS

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Prepared for:
Tokyo Electric Power Company for Japanese Fiscal Year 1999

Materials and Chemical Sciences Division
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BROOKHAVEN
NATIONAL LABORATORY

ac LOSSES IN CONDUCTORS BASED ON HIGH T_C SUPERCONDUCTORS

A Report to Tokyo Electric Power Company for Japanese Fiscal Year 1999

March 17, 2000

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Executive Summary

In electrical power devices, ac losses from a superconductor is a primary factor which determines their usefulness as commercial power equipment. For this reason, extensive studies have been carried out on the losses of $Bi_2Sr_2Ca_2Cu_3O_{10}$/Ag, [Bi(2223)/Ag], tapes. These studies were mostly limited to a single isolated tape. However, a conductor in a power device is surrounded by other conductors and the precise magnetic field distribution around it is very different from that for a single conductor carrying currents or in ac fields. Since the precise field distribution in and around a superconductor is critical in determining the losses, it is very important to measure and to understand the losses in Bi(2223)/Ag tapes which are surrounded by other tapes as in a power device. Taking this fact into consideration, recently we have studied ac losses in stacks of Bi(2223)/Ag tapes in parallel and perpendicular applied fields and shown that we can calculate the losses in these cases utilizing the critical state model if a number of appropriate factors about properties of the tape are taken into a consideration. However, in a power device such as a transformer, magnetic fields near the ends of a solenoid vary from parallel to perpendicular with the tape face. Thus, it is important to learn the behavior of the losses in the stacks of Bi(2223)/Ag tapes with respect to the variations in the angle between the applied field direction and the tape face. In order to accomplish this, we measured the angular dependence of the losses in the stacks which were made from two different Bi(2223)/Ag tapes. Here we report this result and discuss under what conditions we can calculate the losses with a reasonable accuracy.

The angular dependence of the losses in ac applied fields were measured using a series of stacked Bi(22230/Ag tapes having the angles with the direction of applied fields of 0, 7.5, 15, 30, 45, 60, and 90 degrees. The measured values of the losses were compared with the calculated values. The calculations were performed using the measured losses for the 0 and 90 degrees orientations and assuming the losses can be separated for the currents circulating in the plane of and across the tapes. It was shown that at very high fields, i.e., well above the full penetration fields, this assumption was justified by the observed good agreement between the measured and the calculated losses for both tapes. However, at the low fields, significant deviations between the calculated

and the measured were seen for both of the tapes. One possible contributing factor to this discrepancy is the non-ideal shape of the tape cross sections. This can causes the field distribution near the edges of the slabs to deviate from that for an assumed uniform infinite slab. This makes the actual fields at the edge regions to be greater than the applied fields. Thus, the losses will be higher than those calculated. Although not having a full understanding of the losses at low fields is of concern, it will not be of a great importance in the designs of power devices in practice. This is due to the fact that the values of the losses at low fields are orders of magnitudes lower than those at high fields and thus the primary concern for the power device development is the reduction of the losses at high fields.

I. INTRODUCTION

In recent years, significant improvements in critical currents in $Bi_2Sr_2Ca_2Cu_3O_{10}$/Ag, [Bi(2223)/Ag], composite tapes have been made to the extent that technological utilization of these superconducting tapes for large devices in electrical power applications are seriously being considered.[1] Also, along with such technological developments and testing of substantially sized model devices, a large number of studies on ac losses in the tapes have been reported.[1,2]. These studies have shown that there is a sufficient understanding of the losses due to ac transport currents in a single isolated tape. In particular, the relationship, derived by Norris [3] for the losses in terms of critical currents, appears to describe the experimental results quite well in most cases. Surprisingly, this is the case in spite of the act that the derivation is for an isotropic superconductor, while the superconducting properties of Bi(2223)/Ag tapes are highly anisotropic along the perpendicular and parallel directions with respect to the tape face since the crystallites in these tapes are highly aligned. Also, a good understanding of the nature of the losses in a single tape is being developed for simultaneous applications of ac transport currents and ac external magnetic fields. Using a new calorimetric technique for the loss measurements[4], an expression for the losses was found describing the losses as a function of currents at a given ac field, or of magnetic fields at a specific ac current.[5] This technique also allows the measurement of the losses in the condition at which applied currents and magnetic fields are not in phase.[4,5] Finite-element numerical calculations are also applied to this problem by approximating the resistive transition of a superconductor by a power law, $\rho(J) \sim J^n$, where n is a number.[6] The calculations for a single tape in magnetic fields and/or under transport currents are generally in agreement with the experimental results. The losses in ac magnetic fields was also measured for a Bi(2223)/Ag tape when the directions of the fields were varied with respect to the face of the tape.[7,8] However, most of these studies to date were performed on a single isolated tape rather than on a tape surrounded by other tapes as they are found in electrical power devices except for the losses which were measured and calculated for long thin transformer windings.[9] Furthermore, because the tapes have highly anisotropic superconducting properties, the losses of a tape in a device are expected to be significantly different from those of a single isolated tape since the magnetic field distributions are significantly different around the tapes among the other tapes from those for an isolated single tape. Thus, studies of the losses of the tapes in this more complex environment are needed to advance the understanding of the nature of the losses, and thus the capability to predict the losses in the devices.

Magnetic measurements of the losses can be made for a tape in a magnetic environment which is similar to those in a device, e.g., a transformer. However, we have found significant discrepancies between the magnetically measured losses for these tapes and those which were calculated by using Bean's critical-state model.[10] For example, a factor of two or greater discrepancy was often seen between the values of critical currents which were determined by the self-field dc-transport currents and were deduced from the application of the Bean model to the hysteresis losses of the tapes in parallel fields.[11,12] One of the main factors which contributes to these discrepancies is the fact that the transport critical current of a tape is not measured in the identical magnetic field profiles as it is in magnetic ac loss measurements. This is important since the critical currents of these tapes are highly sensitive to the direction of magnetic fields relative to the tape face. Thus, unless we develop a detailed understanding of the nature of the losses in these highly anisotropic superconductors, we will not be able to estimate the losses in power devices.

Earlier we reported that one of the important fact about calculating the losses based on the critical state model is to properly measured critical currents of a tape for the electro-magnetic environment in which the tape is placed in for ac loss measurements.[13] In other words, as also described below, the commonly used self field critical currents $I_c^S(0)$ are not appropriate values of I_c for applied magnetic fields in neither parallel nor perpendicular directions. Thus, it is important to measure or estimate I_c of a tape under the exactly same magnetic field distribution for the loss measurements, and then use these values to calculate the losses. For the analysis of the losses from stacks of Bi2223/Ag tapes in perpendicular applied magnetic fields.[13,14], it was necessary to take in account the following additional considerations into the calculations of the losses: 1) in determining the current densities, the cross-sectional areas of the entire tapes be used,[15] 2) the field-dependent critical currents such as the Kim model be incorporated, and 3) the frequency dependence of the losses at high fields be minimized.

Then, as shown earlier, the calculated losses for high fields, i.e., H > the full penetration field, were in a reasonably good agreement with the measured. However, at low fields, there still exist significant discrepancies between the calculated and the measured losses. This is possibly due to the fact that the stack of the Bi2223/Ag at low fields cannot be assumed as homogeneous superconducting slabs because of the geometry of the filaments at the edges or the nature of the electro-magnetic coupling among the filaments are different at low fields.

The above studies provide a reasonable understanding of the losses in the perpendicular as well as parallel fields. However, we still require the knowledge of the angular dependence of the losses in order to estimate the losses from a solenoid. This is due to the fact that the direction of magnetic field continuously varies near the ends of a solenoid and the losses due to the perpendicular field components dominate the losses in these tapes. Thus, we will report here the results of the **angular dependence of the losses** by measuring the losses from a series of stacked tapes with the tape face having varying angles with applied ac magnetic fields. Here, we will not be calculating the losses from the known angular dependence of $I_c(H)$. Instead, we take into account of the fact, as shown earlier[13,14], that we can calculate the losses where ac applied fields are directed toward parallel and perpendicular to the tape face and we measure the variations of the losses with angles. Then, we compare the results with the calculated variations in the losses with the angles assuming that we can separated the losses into two components, those due to the circulating currents in and across the plane of the tapes.

In the following, we initially summarize, for completeness, the hysteresis model for the losses and the factors have to be incorporated to calculate the losses with the reasonable accuracy as well as the method of the loss measurement which was employed here. Then, we will discuss the measurements of the angular dependence of the losses and the results. Then these will be compared with the calculated losses which is based on the above mentioned assumption.

II. Hysteresis-Loss Models and Critical Currents for the Calculations

In order to facilitate the discussion of the observed losses with the hysteresis models for the losses in a superconductor, a brief summary of the models is given below.

We consider the losses based on the Bean critical-state model, and on a modification to this model by including Kim's magnetic field dependence of critical currents [16] for the perpendicular field case.

A. Bean Model

As is well known, the hysteresis loss from an infinite slab of a superconductor is given by the Bean critical-state model as:[10]

$$P = (2/3)\mu_0(H^3/H^*), \qquad H < H^* \tag{1}$$

$$= 2\mu_0 HH^*(1-2H^*/3H), \qquad H > H^* \tag{2}$$

where P is in J/m^3-cycle, and H and H^* are the amplitude of ac applied magnetic field and the full penetration field in A/m, respectively. μ_0 is the magnetic permeability of free space. The Bean full penetration field is given by $H^* = WJ_c$ where W is one half width of the tape perpendicular to the direction of the applied fields, and J_c is the critical current density of a superconductor. However, for a stack of tapes, it is more convenient to rewrite it as:

$$H^* = I_c/4D \tag{3}$$

where 2D is the thickness of the tape including Ag. As it will be pointed out below, it is very important to realize that an appropriate thickness of the cross section (in Eq. 3) for the stack in perpendicular fields is 2D rather than that of the core region, 2d.[15] (Note that H* for the parallel field case is simply dJ_c, i.e. the pertinent thickness is the core region only. Also, see Fig. 1 for the identification of the various dimensions of a tape and a stack of the tapes and w = W when θ is 90°). We will use I_c rather than J_c in these expressions since I_c is the directly measured value. Since in the Bean model, $I_c(H)$ is constant, we define I_c as the value at zero applied field.

The induced currents only circulate in the surface region of a superconductor at low fields. Consequently it is instructive to consider the measured losses in terms of the unit surface area parallel to the applied fields P_s (J/m^2/cycle). In this case, Eq. 1 becomes:

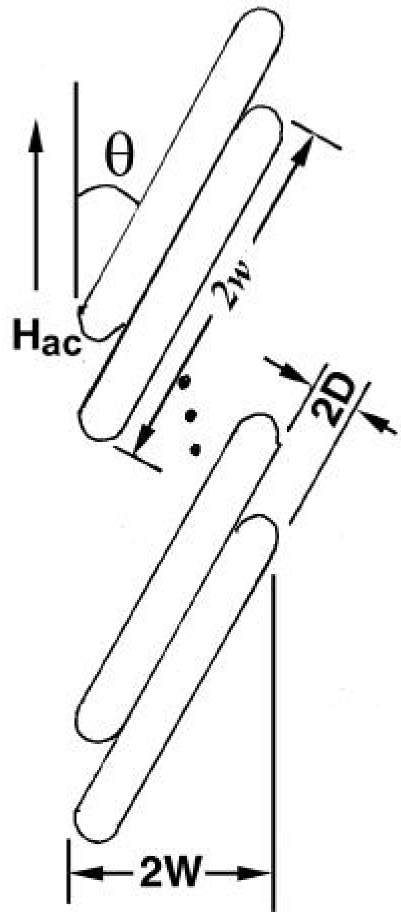

Fig. 1. A schematic cross section of a tape stack for the measurements of the losses as a function of the angle between the tape face and the direction of applied ac fields.

$$P_s = (2/3)\mu_0(H^3/H^*)Wl/(2W + l), \qquad H < H^* \qquad (4)$$

where l is the length of a stack of the tapes.

B. Angular Dependence

In the case of the angular dependent losses, we will assume that we can separate the losses due to the induced currents circulating in the plane of and across the tape due to the field components perpendicular and parallel to the tape, respectively, as also assumed earlier [7,8]. Then, we can express the angular dependence of the losses in terms of the losses at high fields, (H >> H*) in the parallel and the perpendicular orientation case as follows:

$$P(\theta) = (H\cos\theta)P(//) + (H\sin\theta)P(\perp) \qquad (5)$$

where P(//) and P(⊥) are the losses for the parallel and perpendicular applied field, respectively, given by Eq. 2.

At low fields (H << H*), we assume again that the losses can be separated for the currents circulating in two mutually perpendicular planes and a similar relationship as Eq. 5 can be used, i.e.,

$$P_s(\theta) = (H\cos\theta)P_s(//) + (H\sin\theta)P_s(\perp) \qquad (6)$$

where $P_s(//)$ and $P_s(\perp)$ are the surface losses due to the parallel and the perpendicular components of applied fields.

Earlier, we have already shown that both P(//) and P(⊥) can be calculated reasonably well by the above critical state model. Thus, here we will only use Eqs. 5 and 6 to compare the measured angular dependent losses using the measured losses for the perpendicular and the parallel cases, i.e., P(//) and P(⊥), and $P_s(//)$ and $P_s(\perp)$, respecitively. The validity of the assumption in the separation of the losses to each field component will be tested by the experiment below.

C. Critical Currents $I_c(0)$

In the above discussion we used $I_c(0)$ without specifying how this is to be determined, but as will be discussed below, it is very important to use appropriately measured $I_c(0)$, i.e., not simply the self-field values $I_c^S(0)$, for calculations of the hysteresis losses in the magnetic loss measurements. In determining the losses in a single tape under transport currents, this is not a problem since the induced magnetic field distributions around a tape are the same for the measurements of dc self-field critical currents and of ac losses by transport currents. However, in the cases of the magnetic loss measurements in parallel or perpendicular field, the currents, which are induced by applied ac fields, are due to purely parallel or perpendicular fields, respectively, while the self-field induced by transport currents consists of both components. This difference is very important since Bi2223/Ag has highly anisotropic magnetic properties in the directions along the normal and the parallel to the surface. Thus, one expects that the critical currents $I_c(0)$ for the *truly* parallel and perpendicular fields are significantly different from each other and from those by the self-field measurements. In fact, it was shown that dc critical currents $I_c^S(0)$ by self-fields could be significantly increased by simply placing a couple of non-current-carrying tapes over and under the tape for which I_c was measured.[17] This is caused by the lessening of the perpendicular component of the self-field. This indicates the importance of the precise field distribution about the tape in determining $I_c(0)$. More recently, careful measurements of the self-field critical currents, where the perpendicular components of the fields were minimized by appropriately adjusting currents in the top and the bottom tapes, showed that the self field $I_c(0)$ in this case could be as large as 1.5 times the value which was measured as a single tape.[18] Thus, one can approximate the value of $I_c(0)$ for the parallel field case by such a measurement to be used for estimating the ac losses in parallel fields. If these values of $I_c(0)$ are used, the better agreements were found between the measured $I_c(0)$ by transport currents and the deduced $I_c(0)$ by the ac loss measurements in parallel applied fields.[13,14]

Unfortunately, it is not clear how one can devise a measurement scheme for the critical current $I_c^{\perp}(0)$ where the induced field by a transport current is made purely perpendicular to the tape face. Thus, below we approximate the values of $I_c^{\perp}(0)$ for perpendicular fields by the extrapolated values of I_c at H = 0 form the fitted $I_c(H)$ in perpendicular dc fields using Eq. 7 below. As shown below, it turned out that the Kim's $I_c(H)$ [16] model generally fitted most of the $I_c(H)$ data quite well for the field region, ,

$0.003 < H < 0.15$ T. (See below.) Although we are not sure that this extrapolated $I_c(0)$ is a true $I_c^{\perp}(0)$ for perpendicular fields, we believe that this value is closer to $I_c^{\perp}(0)$ than the self-field $I_c^{S}(0)$. Thus, we will use this value of $I_c(0)$ for the calculation of ac losses in the stacks of Bi2223/Ag tapes.

D. Kim's $I_c(H)$

Since the critical currents I_c of these tapes depends strongly on perpendicular applied fields, it is expected that the values of ac losses in this geometry will be influenced by the I_c variation with the field. In order to study this possibility, we consider Kim's expression [16] for the field dependence of $I_c(H)$ for calculating the losses in perpendicular fields.

$$I_c(H) = I_c(0)\, H_o/(H + H_o), \quad (7)$$

There are other expressions which could describe $I_c(H)$ better, but it is easier to see the physical significance of the fitting parameter H_o and its influence on the losses in this model. H_o is the characteristic field at which the value of $I_c(H)$ becomes one half of its value at $H = 0$, i.e. $I_c(0)$. Since no simple analytical expression for the hysteresis losses can be obtained using this expression for I_c, we will first discuss the condition under which the use of Kim's relationship becomes important for calculating the losses in these tapes. Then, we will compare the numerically calculated losses and the measured losses at the end of this article.

The full penetration fields H^* and H_K^* for the Bean and the Kim models, respectively, can be related by an expression through the above characteristic field H_o:[18]

$$H_K^* = H_o\,[(2H^*/H_o + 1)^{1/2} - 1]. \quad (8)$$

From this relationship, one notes that H_K^* is reduced to H^* if this ratio $2H^*/H_o$ is small as in the case of parallel fields. Thus, H_K^* would not be sufficiently different from H^* unless H^*/H_0 is at least a few tenth or greater. When this ratio is large, the full penetration field becomes $\sqrt{2}$ times the logarithmic average of H^* and H_o. It turns out that the values of H^*/H_o range from 0.5 to 0.7 in the Bi2223/Ag tapes and thus it is important to take the field-dependent I_c into account in calculating the losses. Also, since a simple analytical expression for the losses cannot be obtained, it is instructive to calculate the values of the penetration fields using Eq. 8 to compare with the experimental results before calculating the losses by a numerical method.

III. Experimental Procedure

A. Specimens

In this study, two multifilamentary Bi(2223)/Ag tapes were used. Their self-field critical currents $I_c^S(0)$ were ~36 and 60 A at liquid N_2 temperature for the Tape A and B, respectively. Here the I_c criterion was the standard 0.1 mV/m. The over all cross sectional dimensions are given in Table I. For the measurements of the angular dependence of the ac losses in applied fields, each tape was cut to 25-mm-long pieces. Then, these segments of the tapes were stacked in Teflon forms and glued with an instant epoxy to form a slab. The forms were made such that the tapes lay with angles, 7.5, 15, 30, 45, 60, and 75 degrees with the surface of the so-formed slab and the directions of applied fields. A schematic cross section of a stack of the tapes as shown in Fig. 1. In order to ensure that the tapes in the stacks have the intended angles after they were glued, the widths of the stacks were measured. When the measured widths are significantly different from the expected from the intended angles, one end of each of these stacks was mechanically polished and the angles of the tapes with an edge of the stack were measured from photo-micrographs. (Two examples of the cross sections of the stacks are also shown in Fig. 2 from Tape A.) The intended angles and the calculated angles from the measured widths are tabulated in Table I. For calculations of the losses, the measured widths in Table I were used. The intended and the measured angles for each of the stacks

Table I. The angles of the Bi(2223)/Ag tapes in and the widths of the stacks

	Specimen A		**Specimen B**	
Θ_I (degrees)	width (meas.) (mm)	Θ_M (degrees)	width (meas.) (mm)	Θ_M (degrees)
0	0.213	0	0.178	0
7.5	0.485	7.9	0.414	8.6
15	0.91	15.1	0.85	17.9
30	1.65	27.8	1.91	43
45	2.55	45	2.34	57.6
60	3.07	60	2.49	64
90	3.54	90	2.77	90

Θ_I is the intended angle while Θ_M is the measured angles.

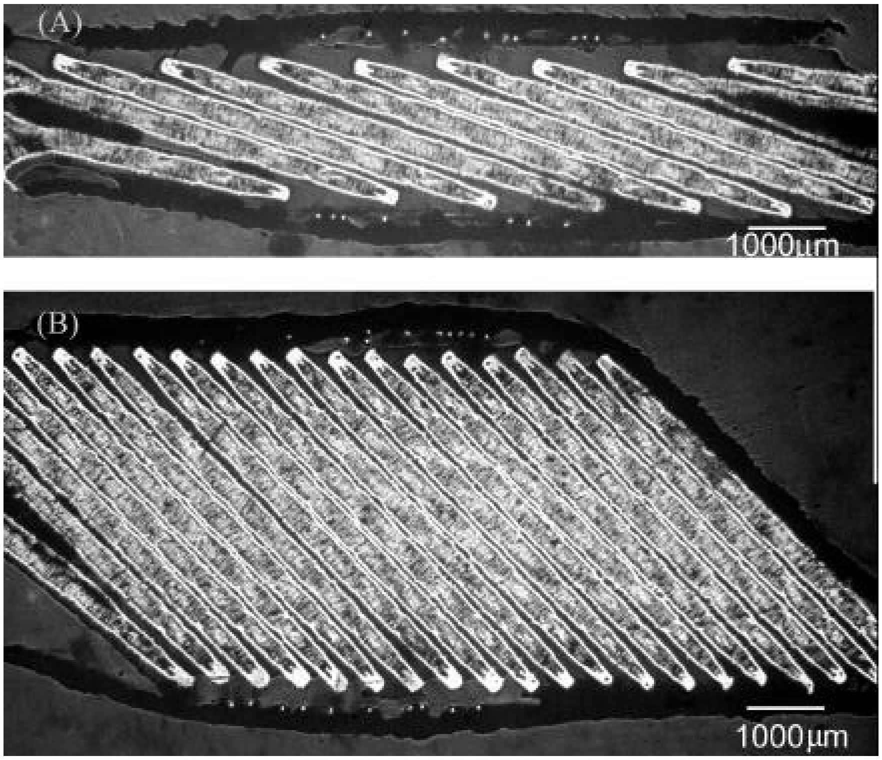

Fig. 2. Photomicrographs showing the cross sections of two stacks from Tape A. (a) 15° and (b) 45°.

are also listed in Table I. As shown in the table significant deviations from the indented angles were observed in some cases, particularly for Tape B stacks. We believe that this is due to the small tape dimensions for Tape B which made it difficult to place them at the precise angular positions in the fabrication of the stacks. As in the previous measurements, two single segments and a vertical stack of 25 pieces of the 25 mm long tapes were used, respectively, for the parallel and perpendicular field measurements.

B. Magnetic ac loss measurements

The measurement technique for the losses used for the present experiment is a magnetically induced current method, which we have previously used for Nb_3Sn, bulk $YBa_2Cu_3O_7$, and Bi(2223)/Ag tapes in parallel fields. It utilizes a pick-up coil (loss-coil) which is wound directly on the specimen. This assemblage is placed inside a solenoid which is wound with a Cu wire and is powered by a variable–frequency power supply. The ac magnetic field is measured by another pick-up coil (field-coil) located above the specimen. The wave forms from both pick-up coils are collected by a digital storage oscilloscope (Nicolet 2090-III) after the voltages are amplified by a pair of preamplifiers (SRI Sr-560). These are then transferred to a desk-top computer, where the power loss *per unit length* (W/m) of a superconductor along the field direction is calculated by the relationship:

$$P = \frac{1}{N\tau}\int_{o}^{\tau} H(t)e_f(t)dt \qquad (9)$$

Here, N is the number of turns of the loss-coil and τ is the period of the applied ac field. The loss voltage $e_f(t)$ and the ac magnetic field H(t) are measured by the corresponding pick-up coils. Note that the voltage $e_m(t)$ from the field coil is integrated to give H(t) before performing the calculation of the loss in Eq. 9. In order to cancel a large inductive voltage from the loss coil, a portion of the signal from the field-coil is used to buck most of it out. It should be noted that this method of measuring the losses is only applicable for a long uniform specimen where an infinite slab or rod can be assumed. This is due to the fact that the loss coil is generally short along the length of the specimen and the loss voltage along the length has to be uniform.

A very convenient feature of this particular approach for ac loss measurements is the fact that details of the induced loss voltage wave forms are easily observed as well as the hysteresis curves in the B-H plane. For example, the waveforms of the loss voltages can be compared with the theoretically expected forms form the Bean critical-state model. Or if there is a possible phaseshift due to eddy currents in the exterior Ag matrix of a composite tape, this can also be easily noted.[11] In addition, another advantage of this technique is that it does not require a calibration using a standard material for which the loss is well known. However, the disadvantage is that specimens, other than long rods or slabs, can not be measured in this set up.

The sensitivity of the measurements depends on a number of factors. The obvious ones are, for example, the number of turns of the loss coil, the quality of the preamplifiers, and the ubiquitous ground loops. What is not so obvious is the back-ground loss which is proportional to the square of the amplitude of the field and the frequency. Thus, it appears that it originates from the eddy currents which are generated in the Cu wire in the ac magnet, and it limits the sensitivity of the measurements at high fields. With the particular magnet used, (~ 300 turns of #17 Cu wire and ~ 30 and 120 mm in diameter and in length, respectively, immersed in liquid N_2), the magnitude of this background loss can be reduced to < 15 W/m^3 (= 900 J/m^3-cycle) at 10^4 A/m rms (= 1.4 x 10^4 A/m) and 60 Hz with an empty loss coil which is similar to those for the measurements of the losses. (Here the loss was calculated assuming an empty slab of the same size as a specimen.) This value can be compared with the calculated eddy- current loss of an annealed Ag tape (0.27 mm thick and the measured resistivity of 3.1 x 10^{-9} Ω–m at 77 K) which was 44 W/m^3 (= 2460 J/m^3-cycle) in the same parallel magnetic field. Thus, with care the background loss can be reduced sufficiently to measure the loss in thin Ag tapes. However, the background loss can be significantly higher (~ 5x) in many occasions due to other uncontrollable noises. Fortunately, the losses in Bi(2223)/Ag tapes, particularly in those with perpendicular applied fields, are mostly at least two orders of magnitude greater than that of the background loss, and it does not interfere with the measurements.

There are two important concerns about the measurements of the losses of the stacks of the tapes by this method in perpendicular magnetic fields. 1) Under what conditions can a stack be treated as an infinite slab? 2) Are the penetration of the fields different for the cut ends and the long edge of a tape ? The latter is a particular concern since the entire specimen is placed within the loss-coil. Earlier we have shown that a stack of 25 tapes or greater can be treated as an infinite slab as longs as the loss coil is wound right at the central region of the stack. Thus, we assume here that we can treat our stacks as infinite slabs as long as the width of a stack is less than ~ ½ of its height and they all satisfy this criterion. In regard to the second concern, we have also shown that the penetration of the currents are uniform around the stacks including the edges since the superconducting filaments in a tape are electro-magnetically coupled at power frequencies and a tape behaves as if it is a single core composite rather than a multifilamentary tape.[11,12]

Another concern with this arrangement of the tapes is whether the internal field distribution in the stack would be close to that which is expected for a homogeneous superconductor. This question is raised because the superconducting cores in a stack are separated by the outer Ag sheath. Fortunately, this was answered by Matawari [15] in his theoretical calculations of the field profiles in a stack of thin superconducting platelets in applied perpendicular fields. As shown in Fig. 3 of Ref. 15, the field profiles in the stack are essentially those of the Bean critical state model except for the small regions at the very edge and the center of the stack if the ratio of the distance between the platelets in a stack D and the half width of the platelets w is less than ~ 0.2. The ratios for the present tapes are 0.12, and 0.09, for the Tape A and B, respectively. Thus, again, it is assured that these stacks of tapes can be treated as an infinite slab for the analysis of the losses in perpendicular fields as well as the perpendicular field component of the field when the field and the tape face makes an angle. Furthermore, it is also shown that the full penetration field for the stack is wJ_c as in the Bean model, but this J_c is the averaged value over the entire cross section of the tape[15] as pointed out in the discussion related to Eq. 3. In another words, a stack behaves as if it is a homogeneous superconducting slab having J_c which is averaged over the entire stack including Ag.

As mentioned above, the losses in a stacked tape in perpendicular fields become frequency dependent for H above its full-penetration field. The exact source of the extra loss is not yet understood, and the details of the phenomenon will be given elsewhere. These extra losses only set in beyond the penetration field H_K^*, and the additional losses per cycle are linear with frequency for a given field amplitude. Thus, even though the losses were measured at 60 Hz as well as 15 Hz, we use only the losses measured at 15 Hz for the present discussion of the angular dependence of the losses.

IV. Results and Discussion

In Fig. 3 and 4, the variations of the losses (W/m^3) as a function of applied fields at 15 Hz are shown for the stacks with different angles of the tapes with respect to the applied field directions for Tape A and B, respectively. For clarity, only the losses for the selected angles are shown in these figures. In both cases, the losses from the parallel and the perpendicular orientations cross over as the fields are increased. This comes about due to the relative thickness of the stacks and the losses which changes according to Eqs. 1 and 2. The losses/volume is lower from a wide stack at low fields because the

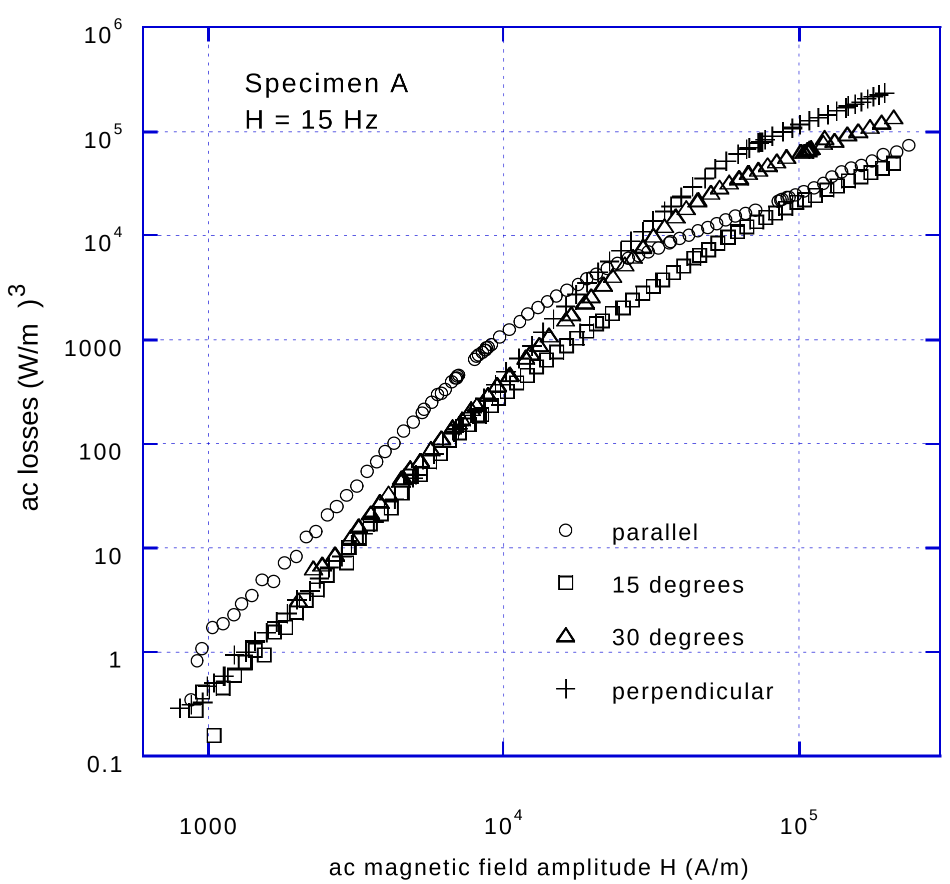

Fig. 3. The losses vs. applied ac field amplitudes for the angles, 0, 15, 30, and 90 degrees for Tape A.

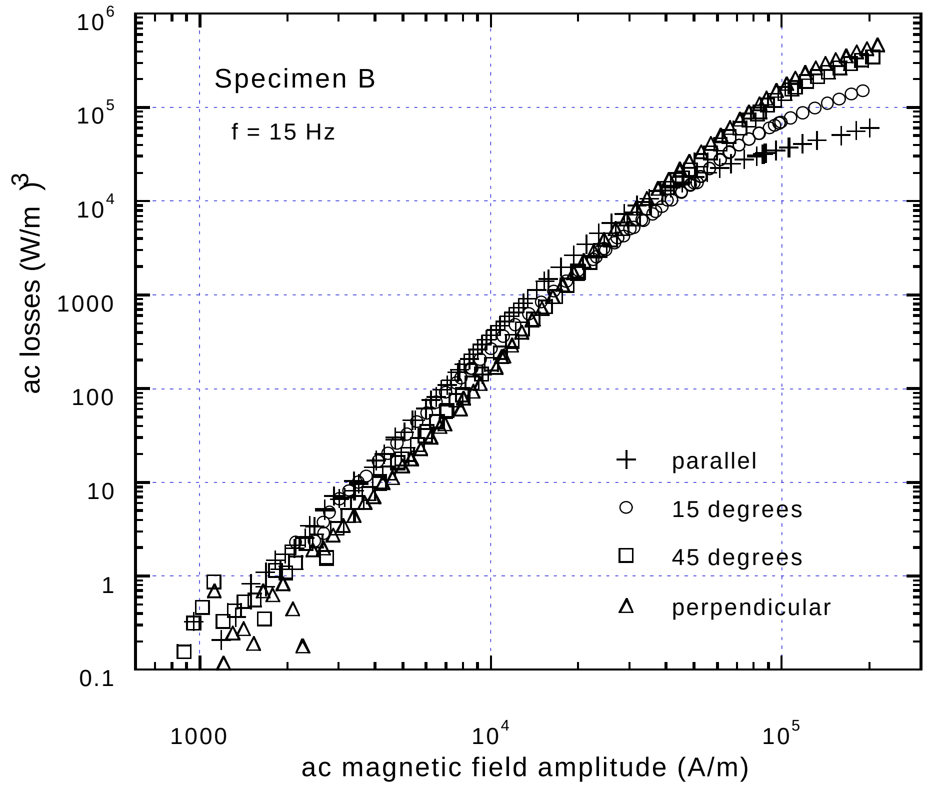

Fig.4. The losses vs. applied ac field amplitudes for the angles, 0, 15, 45, and 90 degrees for Tape B.

faction of the stack penetrated by the fields is small for a wide stack than those for the thin stack as in Eq. 1. However, at high fields, the losses are higher for a large width stack than that for a thin stack according to Eq. 2.

In order to examine that the applicability of the assumption that the losses can be separated to those due to the mutually perpendicular induced currents, we plot the angular dependence of the losses at the fields, 8000 and 10^4 A/m for Tape A and B, respectively, and 2 x 10^5 A/m for both tapes. These values of the fields are well below and above the respective full penetration fields. These are shown in Figs 5 and 6, and 7 and 8, for Tape A and B, respectively. Also, shown in these figures are the calculated angular

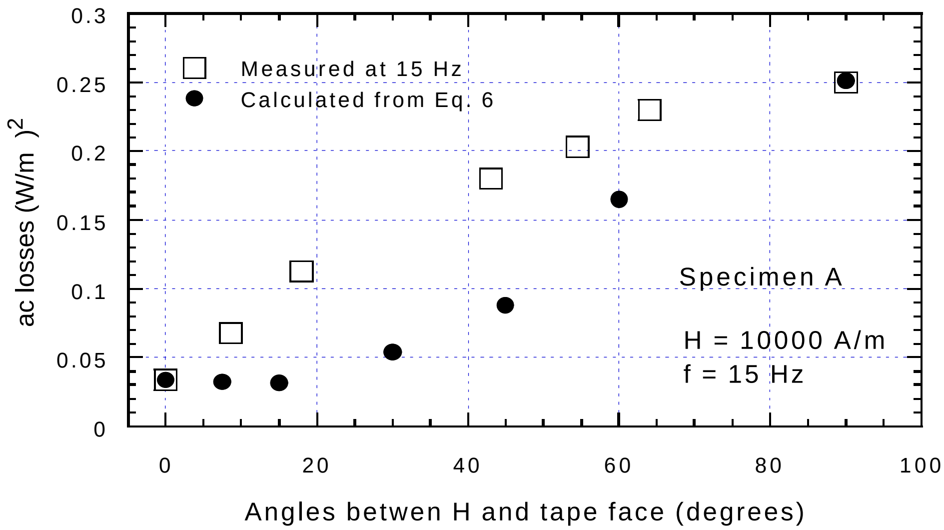

Fig. 5. The losses as a function of the angle between the tape face and the direction of applied fields for Tape A at H = 8000 A/m.

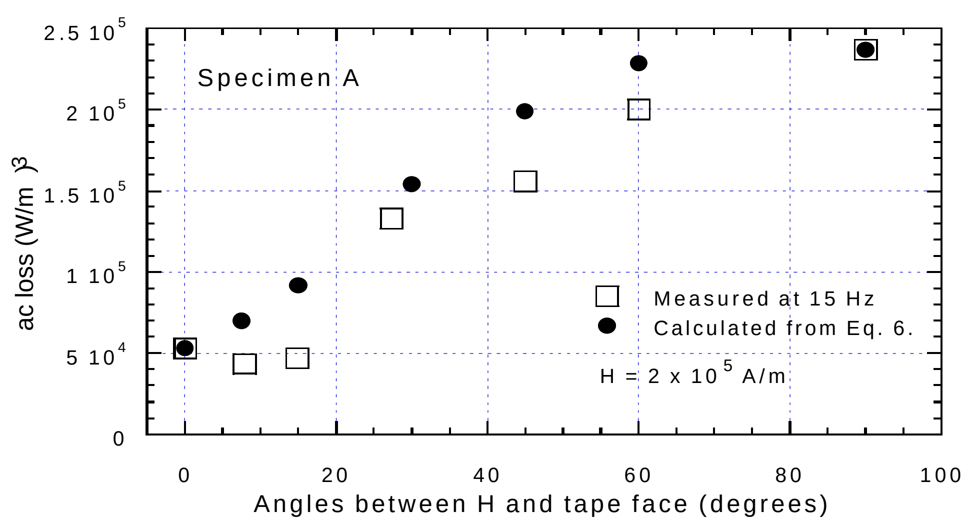

Fig. 6. The losses as a function of the angle between the tape face and the direction of applied fields for Tape A at $H = 2 \times 10^5$ A/m.

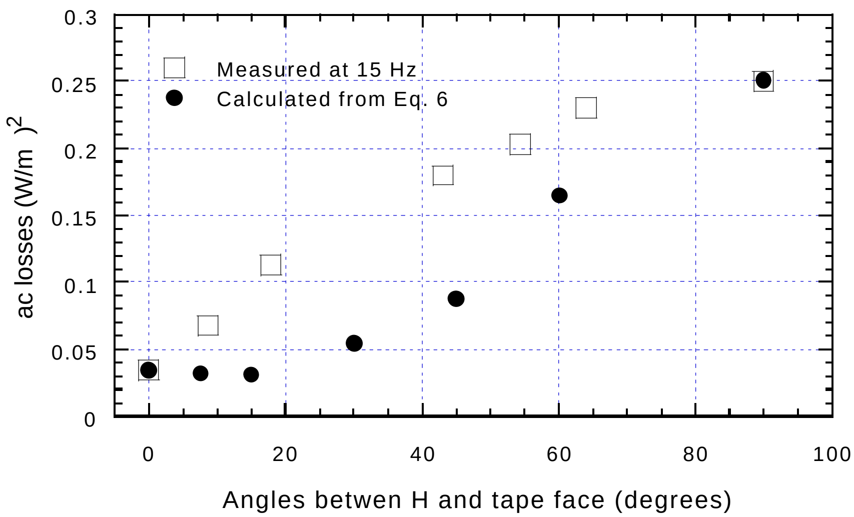

Fig. 7. The losses as a function of the angle between the tape face and the direction of applied fields for Tape B at $H = 10^4$ A/m.

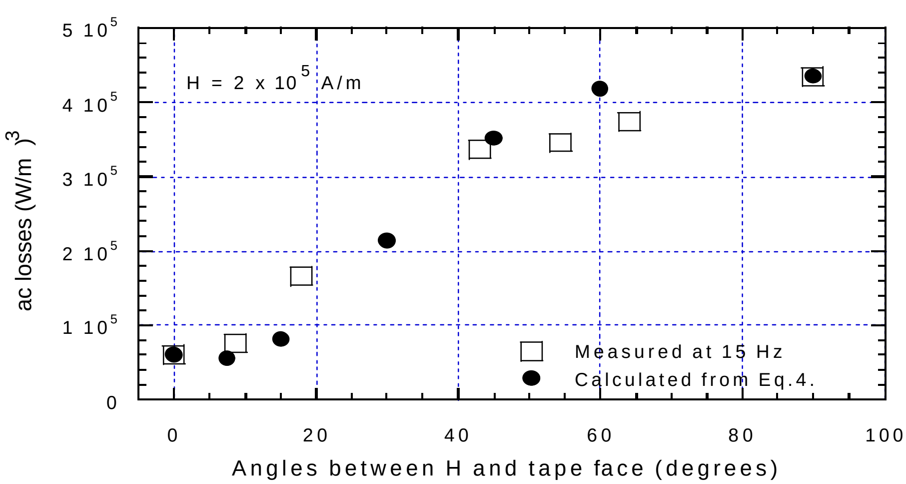

Fig.. 8. The losses as a function of the angle between the tape face and the direction of applied fields for Tape B at $H = 2 \times 10^5$ A/m.

dependence of the losses using Eq. 5 and 6 and the measured values of the losses for the parallel and the perpendicular orientations.

From Fig. 6 and 8, one concludes that the separation of the losses in two field orientations, or the use of Eq. 5 is reasonably justified since the agreement between the measured and the calculated losses with Eq. 5 are very good for Tape B and reasonable for Tape A. However, it is not the case for the low field losses. For both tapes, the calculated values using Eq. 6 significantly underestimate the losses at the middle angle ranges in comparison with the measured values as shown in Fig. 5 and 7. Perhaps, this is due to the fact that the tape cross sections are not true rectangles, i.e., the edges of the tapes are significantly narrower than the middle of the tapes as clearly observed in Fig. 2. This causes larger gaps between the tapes in a stack at the edge regions than at the center of the stack at low fields. This may cause the field penetration to be very different from that in a uniform slab. In another words, the fields near the edges in these stacks are higher than those for a uniform slab due to the demagnetizing effect. Such field distortion can lead to high losses than those values expected for a uniform field penetration at low fields, but such distortion is expected to be negligible at high fields. Thus, we expect that the agreements between the measured and the calculated are significantly better at high fields as shown in Fig. 6 and 8.

V. Summary

The angular dependence of the losses in ac applied fields were measured using a series of stacked Bi(22230/Ag tapes having the angles with the direction of applied fields of 0, 7.5, 15, 30, 45, 60, and 90 degrees. The measured values were compared with the calculated values assuming that the losses can be separated for the currents circulating in the plane of and across the tapes. It was shown that at very high fields, i.e., well above the full penetration fields, this assumption was justified by the observed good agreement between the measured and the calculated losses for two different tapes. However, at the low fields, significant deviations between the calculated and the measured were seen for both of the tapes. We attribute this discrepancy, in part, to the non-ideal shape of the tape cross sections which cause the specimens to deviate from an assumed uniform infinite slab. This makes the actual fields at the edge regions to be greater than the applied fields. Thus, the losses will be higher than those calculated by using Eq. 6 and the values of the losses for the parallel and the perpendicular field orientations. In practice, one is more concerned with the losses at high fields where the losses are the highest. Thus, this finding that the angular dependence of the high fields losses can be estimated with a reasonable accuracy from the losses in parallel and perpendicular orientations is important in designs of devices where the direction of the fields varies with the tape face.

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