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Thickness dependence of ac losses in circular disks of $YBa_2Cu_3O_7$ films in perpendicular magnetic fields

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The ac losses in three disk-shaped $YBa_2Cu_3O_7$ (YBCO) films, which were deposited on $SrTiO_3$ by the pulsed-laser-deposition technique and had thicknesses, d, of 0.2, 1.0, and 3.0 μm, were measured in perpendicular applied ac magnetic fields to ~0.14 T at 10 Hz in liquid nitrogen. The losses at low fields were found to be a strong function of the film thickness. The measured losses were compared with the theoretically calculated losses. The ac losses calculated using a field-independent critical-current density, the Bean model [J. R. Clem and A. Sanchez, Phys. Rev. B **50**, 9355 (1994)], agreed very well with the 0.2-μm-thick film, while the calculated losses agreed well with the measured ones when a field-dependent critical-current density, the Kim model [D. V. Shantsev, Y. M. Galperin, and T. H. Johansen, Phys. Rev. B **61**, 9699 (2000)], was used for the films of thickness 1.0 and 3.0 μm. However, a surprising discrepancy was found in the values of B_c and B_0 for thinner YBCO films depending on whether they were determined by ac or dc measurements. B_c is defined as $B_c = \mu_0 J_c(0)d/2$, B_0 is the characteristic field in the Kim-model critical-current density $J_{cK}(B_a) = J_c(0)/(1 + B_a/B_0)$, and $J_c(0)$ is the critical-current density at applied magnetic field $B_a = 0$. © *2004 American Institute of Physics.* [DOI: 10.1063/1.1630695]

I. INTRODUCTION

With the continued impressive development[1,2] of so-called "coated conductors" using a high-critical-temperature superconductor, $YBa_2Cu_3O_7$ (YBCO), a number of applications such as power transmission cables, transformers, motors, and generators are being planned using these conductors. In these devices, ac losses in the superconductors will play a very important role in determining their efficiencies and thus their technological viability. Furthermore, the perpendicular component of the ac magnetic fields in these devices dominates the losses in most cases, since these YBCO conductors are made in the form of thin tapes with large aspect ratios.[1,2] Thus, it is important to understand the behavior of YBCO films in perpendicular ac magnetic fields. Previously, we reported measurements of ac losses in 1 μm thin-film YBCO circular disks in perpendicular ac applied magnetic fields. We found that the losses agreed very well with the theoretically calculated losses using the Kim critical-current model, as long as the field penetration around the circumference was uniform on the scale of a few tenths of a mm.[3,4] The calculated losses based on the Bean critical-current model[5] were also shown to agree well with the measured ones at low fields. Since both of these theories predict a strong dependence of the losses on the thickness of the films at low fields, and the critical-current densities J_c of YBCO films are known to decrease significantly as the thickness increases from ~0.2 to a few μm,[6,7] it is of interest to investigate the thickness dependence of the losses. Here we report on measurements of the losses in YBCO films in perpendicular ac fields as a function of film thickness from 0.2 to 3.0 μm, and on analysis of the losses using the above theories.

II. EXPERIMENTAL PROCEDURE

All of the films, 0.2, 1.0, and 3.0 μm thick, were prepared on $10\times 10\ mm^2$ $SrTiO_3$ substrates by a pulsed-laser-deposition (PLD) technique under similar conditions as described elsewhere.[8] For the measurements of the losses, the films were patterned into circular disks of diameter of ~5.3 mm using a photolithography technique. The loss measurements were performed at 10 Hz and in liquid nitrogen at ~77 K. The measurements were made by placing the specimens in a pickup coil in a susceptibility arrangement placed in a Cu-wire wound magnet. The details of the measurement method were described in Ref. 3. The self-field transport critical-current densities J_{cs} of similarly processed films were also measured using narrow strips (240 μm × 6 mm) at

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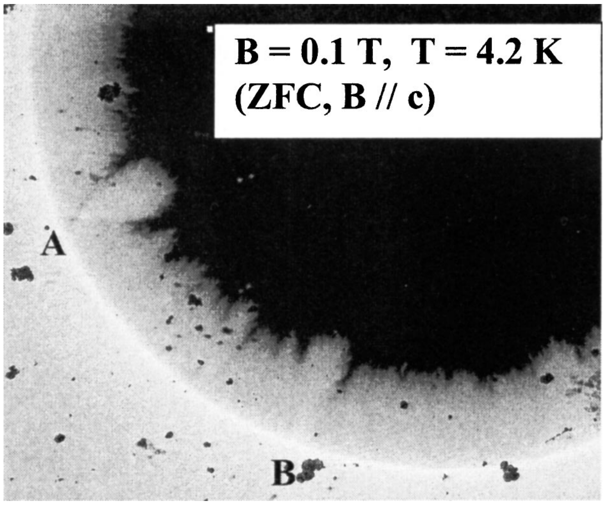

FIG. 1. An example of magnetic field penetration in a 3.0-μm-thick YBCO disk observed by a magneto-optical imaging technique, indicating that this film is magnetically uniform. $T=4.2$ K and $B_a=100$ mT. The film's diameter is 5.2 mm and the bright semicircular trace is the edge of the film. The flux penetration at the locations A and B are due to small defects at the edge due to fabrication of the disk. Also, small black speckles are due to defects in the indicator films.

~75 K. In addition, the dc magnetization of the same specimens used for ac loss measurements was measured in a superconducting quantum interference device magnetometer at 77 K to determine the dc magnetic-field dependence of J_c to compare with that deduced from ac loss measurements. In order to ensure the uniformity of the entire area of the films, observations of the flux penetration around the circumference of the disks were made using a magneto-optical imaging technique in dc magnetic fields and at various temperatures. An example of such images is shown in Fig. 1 for a film of thickness 3.0 μm at 4.2 K during the initial magnetic flux penetration. An image taken at this temperature is shown, since the images are much brighter at low temperatures. Although the flux penetration front in this film was not completely uniform, a macroscopic smoothness of the front of the order of a few tenths of a mm is sufficient for the application of the ac loss theories to the measured losses, as demonstrated previously.[3]

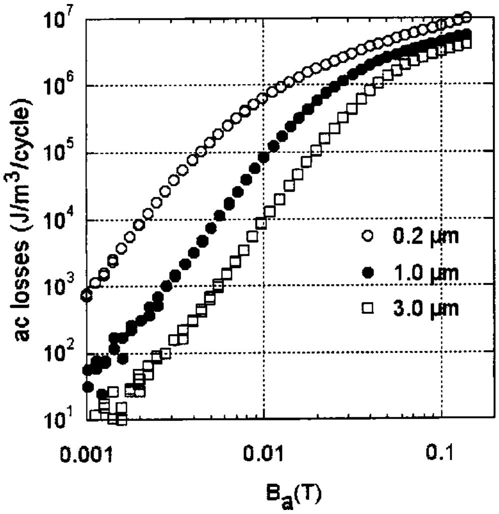

FIG. 2. The ac losses $Q(B_a)$ (in J/m^3/cycle) measured at 10 Hz and 77 K in perpendicular ac magnetic fields as a function of applied ac field amplitude B_a (in T) for YBCO films having thicknesses of 0.2, 1.0, and 3.0 μm.

III. RESULTS, ANALYSIS, AND DISCUSSION

The measured losses $Q(B_a)$ in J/m^3/cycle for these three films are shown in Fig. 2 as a function of the peak amplitude B_a of the applied ac magnetic field. As clearly seen in the figure, the losses at low fields greatly decreased as the film thickness increased. However, the differences in the losses diminished at high fields. In order to understand the strong thickness dependence of the losses, as well as the general behavior of the loss characteristics of these films, we have compared the measured losses with theoretical predictions. Also, a theoretical analysis of the loss data was made in order to compare the properties of the films determined by both ac and dc measurements. To make the comparison transparent, we express the losses in normalized form $Q_N(B_a)$ as

$$Q_N(B_a)=[Q(B_a)/(\pi B_a^2/\mu_0)](3\pi d/8R), \qquad (1)$$

where d and R are the film thickness and radius, respectively. The last factor in Eq. (1) arises from the demagnetization factor for a thin circular disk in a perpendicular magnetic field. In Figs. 3–5, the normalized experimental losses are compared with the theoretically calculated losses using the field-independent Bean model[5] and the field-dependent Kim model.[4] In order to compare the calculated losses using the Bean model with the measured losses, the applied field B_{am} at which the measured normalized losses were at maximum was matched with the field at the maximum of the calculated losses for each specimen. For the comparisons of the losses with the calculated losses using the Kim model, we used the asymptotic expressions for low- and high-field regions[3]

$$Q_N(B_a)\cong(B_a/B_{c\ \mathrm{eff}})^2/\pi, \qquad B_a/B_{c\ \mathrm{eff}}\ll 1, \qquad (2)$$

$$Q_N(B_a)=(B_cB_0/B_a^2)\ln(1+B_a/B_0), \qquad B_a/B_c\gg 1, \qquad (3)$$

where $B_{c\ \mathrm{eff}}=B_c(1-\alpha B_c/B_0)$, α is a constant equal to 0.36 for the Kim model,[4] $B_c=\mu_0 J_c(0)d/2$ is the characteristic field for thin films, and B_0 is the characteristic field in the Kim model, $J_{cK}(B_a)=J_c(0)/(1+B_a/B_0)$. Also, by comparing the losses that were numerically calculated in the previous article[3] and those that were determined using the above asymptotic expressions, we noted that the field ranges that are valid for application of the asymptotic expressions are $B_a/B_{am}<\sim 0.25$ and $>\sim 5$ for low and high fields, respectively. We used these criteria to determine the quality of fitting of the asymptotic expressions to the loss data in extracting the values of B_c and B_0. However, the quality of the data at the fields $B_a/B_{am}<\sim 0.25$ became poor at very low fields because of the limited sensitivity of the loss measurements. Hence, the fitting procedure was used with only the high-field expression, Eq. (3), for the films of thickness 0.2 and 1.0 μm. In the case of the 3.0-μm-thick film, the loss data were not available at sufficiently high fields ($B_a>\sim 5B_{am}$) to apply Eq. (3). Hence, in this case an ac magnetization loop

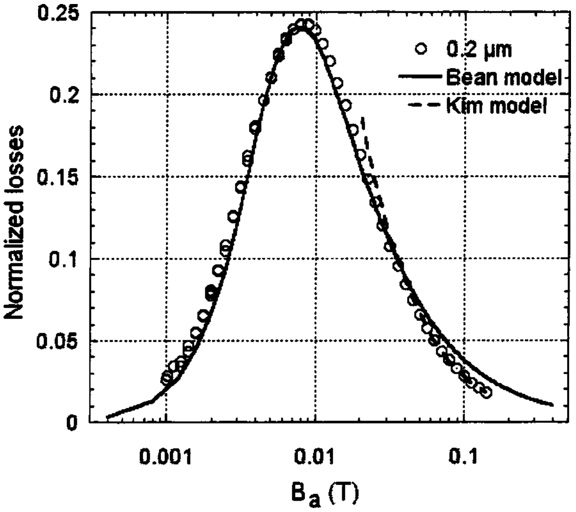

FIG. 3. Measured normalized losses $Q_N(B_a)$ (open symbols) for a 0.2-μm-thick film as a function of applied field B_a compared with numerically calculated losses using the Bean-model critical-current density (solid curve) and the fitted high-field approximation [Eq. (3)] for the Kim-model critical-current density (dashed curve).

was used to determine $J_c(B_a)$. Then, a least-squares method was used to fit the Kim J_c model to the experimental $J_c(B_a)$ in order to deduce the values of B_c and B_0. Using these values in Eqs. (2) and (3), we calculated the losses and compared them with the experimental losses. However, because of background noise, the quality of the ac magnetization loops for the 0.2 and 1.0-μm-thick films was so poor that we could not use these loops for a similar analysis. The values of B_c and B_0 deduced by the above methods from ac measurements were then compared with those from dc magnetization and self-field transport measurements.

As shown in Fig. 3, the ac losses calculated from the Bean model[5] for the thinnest film agreed well over a wide magnetic-field range of the measurements except at the highest fields. In this theory, the applied field amplitude B_{am} at which $Q_N(B_a)$ is at its maximum is related to the characteristic field B_c by $B_c = B_{am}/1.94$. Since $B_{am} = 7.8\,\mathrm{mT}$, $B_c = 4.0\,\mathrm{mT}$. The small deviation between the calculated and the measured losses at very high fields is most likely due to a weak field dependence of J_c in the film. Hence, we used Eq. (3) to calculate the losses at high fields with B_c and B_0 as fitting parameters. The best fit of the calculated losses to the data for $B_a > \sim 5B_c$ was obtained with the values of 4.2 and 90 mT for B_c and B_0, respectively. The B_c determined by this fitting procedure is seen to be in good agreement with the above value obtained using the Beam model. Also, the large value of B_0 indicates a weak field dependence of J_c, as expected from the observed generally good fit between the loss data and the Bean model calculation. The losses calculated using Eq. (3) with these values are also shown in Fig. 3. Using the average value of $B_c = 4.1$ mT, we calculate $J_c(0) \sim 3.3 \times 10^{10}\ \mathrm{A/m^2}$ for the 0.2 μm film. However, this value is substantially smaller than the self-field transport critical-current density $J_{cs}(0)$ $(5.2 \times 10^{10}\ \mathrm{A/m^2})$ measured at 75 K for a similarly processed 0.2 μm film. It is not clear why such a large discrepancy exists between the values of $J_c(0)$ determined by the ac loss and the self-field transport measurements, since magneto-optical imaging indicated that the film was uniform over the entire area. This question will be addressed in the latter part of this article by comparing with similarly derived results for the other two films.

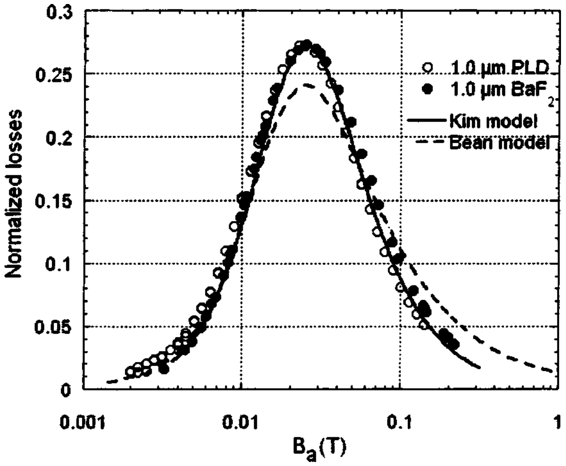

FIG. 4. Normalized losses $Q_N(B_a)$ for 1.0-μm-thick films prepared by PLD and BaF$_2$ processes compared with calculated losses using the Bean (dashed curve) and Kim (solid curve) critical-current models.

In Fig. 4, we compare the losses for the 1-μm-thick films measured in this and our previous study.[3] As seen in the figure, the values and the field dependence of the normalized losses are nearly identical in the two films. The close similarity in the data is quite intriguing considering the fact that these two films were synthesized by two totally different methods, i.e., a PLD and a so-called BaF$_2$ process.[9] The losses calculated using the Bean model deviate substantially from the measured losses for higher fields, indicating that the J_c of this film has a strong field dependence. The numerically calculated losses from our previous work[3] are also shown, indicating a close agreement with the measured losses for both films when the Kim model for the field-dependent J_{cK} is used for the calculation. The values of B_c and B_0 deduced from the numerical calculation were 16 and 56 mT, respectively. Although the calculated and measured losses generally agreed very well, there is a small discrepancy between them at high fields. Hence, we applied Eq. (3) at high fields to determine the characteristic fields for this film. The values of B_c and B_0 so obtained were 14 and 65 mT, respectively, which agrees quite well with those obtained from the numerical calculation. The value of $J_c(0)$ calculated from the average of these two values of B_c is $2.4 \times 10^{10}\ \mathrm{A/m^2}$. Comparing this with the result obtained from a self-field transport measurement, $J_{cs}(0) = 3.2 \times 10^{10}\ \mathrm{A/m^2}$ at 75 K for a 1.1-μm-thick similarly processed film, we see that there still is a significant difference between the values determined from the ac-loss and dc self-field transport measurements.

As shown in Fig. 5 for the 3.0-μm-thick film, the deviation of the losses calculated using the Bean model from the measured losses became more significant, indicating that the field dependence of J_c became stronger as the film thickness increased. The losses calculated with the Kim model using

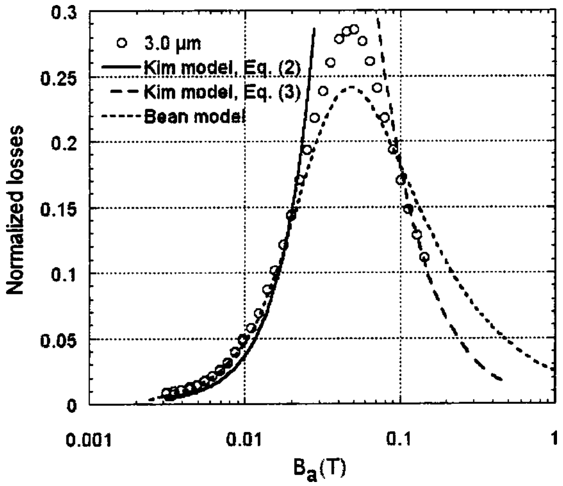

FIG. 5. Normalized losses $Q_N(B_a)$ for a 3.0-μm-thick film (open symbols) as a function of applied ac field amplitude B_a compared with numerically calculated losses using a Bean critical-current density model (short dashed curve) and losses calculated using the asymptotic expressions, Eqs. (2) and (3), for the Kim critical-current model (solid and long dashes).

the asymptotic expressions given in Eqs. (2) and (3) are in good agreement with the measured losses, as also shown in the figure. The parameters B_c and B_0 in the expressions are determined from an ac magnetic hysteresis curve taken as a part of the loss measurements. First, the values of $J_c(B_a)$ from the magnetization were calculated by a standard method from a magnetization loop, $J_c(B_a)=(3/2R)\times\Delta M(B_a)$[10] where $\Delta M(B_a)$ is the width of the hysteresis at B_a. Then, $J_c(B_a)$ was obtained by using the least-squares fit to the Kim model $J_{cK}(B_a)$ for $\sim 0.03\ \mathrm{T} > B_a > 0.1\ \mathrm{T}$, and $J_c(0)$ was determined by extrapolating the Kim model expression to $B_a=0$. This extrapolated $J_c(0)$ was used for calculating B_c, since the direct deduction of $J_c(B_a)$ from $\Delta M(B_a)$ does not provide correct values of $J_c(B_a)$ for $B_a < B_c$.[4] As shown in Fig. 6, the Kim expression provided a good fit to the data over the field region selected with the fitting parameters $B_0=33.4$ mT and $J_c(0)\sim 2.1\times 10^{10}$ A/m^2 ($B_c=39.6$ mT). In contrast to the two thinner films discussed above, this value of $J_c(0)$ is in good agreement with the self-field transport value of 2.0×10^{10} A/m^2 at 75 K for a similarly processed 3.5-μm-thick film.

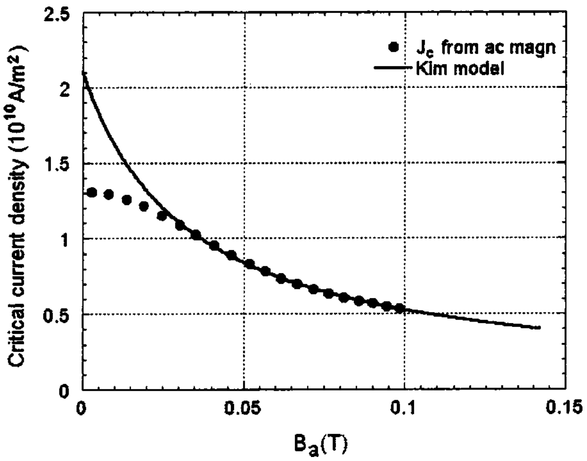

FIG. 6. Critical-current densities of a 3.0-μm-thick YBCO film. The solid circles show $J_c(B_a)$ deduced from the ac magnetic hysteresis and the solid curve is a fitted current density using the Kim model with $J_c(0)=2.1\times 10^{10}$ A/m^2 and $B_0=39.6$ mT.

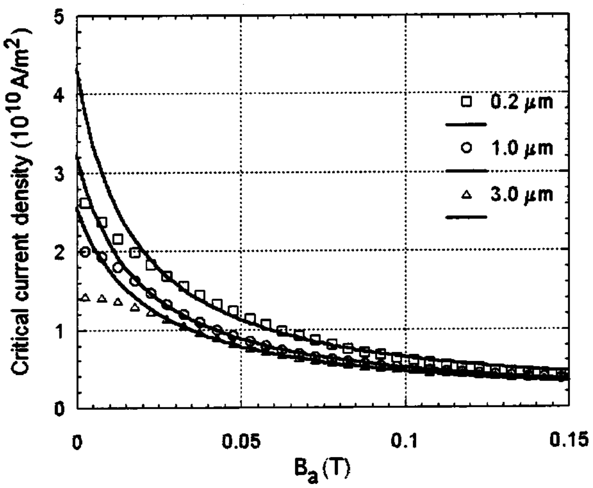

FIG. 7. Critical current densities $J_c(B_a)$ determined from dc magnetization measurements (open symbols) and the calculated $J_c(B_a)$ by fitting the Kim model (solid curves) for three films. The values used to calculate $J_c(B_a)$ by fitting the Kim model are $J_c(0)=6.09\times 10^{10}$ A/m^2 and $B_0=0.030$ T, $J_c(0)=3.2\times 10^{10}$ A/m^2 and $B_0=0.018$ T, and $J_c(0)=2.55\times 10^{10}$ A/m^2 and $B_0=0.023$ T for the 0.2-, 1.0-, and 3.0-μm-thick films, respectively. (J_c is divided by 2 for the thinnest film.)

As described above, in general the theoretical predictions of ac losses in thin superconducting YBCO films in perpendicular fields agreed very well for the entire field range of the measurements if the field dependence of the critical-current density was incorporated into the loss calculation. For the 0.2 μm film, we found that the Bean model-based ac loss calculation also provides a good quantitative fit to the normalized losses. There are two reasons for this. First, we found J_c to have a weaker dependence upon B_a for the 0.2 μm film, i.e., the value of B_0 in the Kim model was larger. Second, because B_{am}, the field at the maximum of the normalized losses, is proportional to the film thickness, the experimental values of B_a required to fully display the loss maximum were lower for the thinnest film, and for these values of B_a, $J_c(B_a)$ was closer to $J_c(0)$. As noted above, there are surprisingly large and puzzling discrepancies in the values of $J_c(0)$ obtained by the ac loss and the dc self-field transport measurements for the films with thicknesses of 0.2 and 1.0 μm. In order to pursue this question further, we calculated the values of B_c and B_0 for these films from the $J_c(B_a)$ determined from dc magnetization loops for these films. The $J_c(B_a)$ determined from dc magnetization curves at 77 K are shown in Fig. 7. In order to determine $J_c(0)$ and B_0, we also used a least-squares method to fit to the $J_c(B_a)$ data with the Kim model for the regions of magnetic $0.02\ \mathrm{T} \leqslant B_a \leqslant 0.1\ \mathrm{T}$ for all of the thick films. The $J_c(B_a)$ curves obtained from this fitting procedure are also shown in Fig. 7. As shown in the figure, the quality of the fit for the 0.2 μm film was poorer than those for the 1.0 and 3.0 μm films. A fitting quality factor for the 0.2 μm film was $R=0.9935$ while those for the 1.0- and 3.0-μm-thick films

TABLE I. Characteristic parameters of YBCO films.

Thickness (μm)	$J_c(0)$ (10^{10} A/m^2)			B_c(mT)			B_0(mT)	
	ac[a]	dc[b]	dc[c]	ac	dc[b]	dc[c]	ac	dc[b]
0.2	3.3	4.3	5.2	4.0[d]/4.2[e]	5.4	6.5	90[e]	17
1.0	2.44	3.2	3.2	14[e]	20	20	65[e]	18
1.0 (BaF_2)	2.55	⋯	⋯	16[f,g]	⋯	⋯	56[f]/80[g]	⋯
3.0	2.1	2.55	2.0	39.6[g]	48	37.6	33.4[g]	23

[a] Calculated from the values of $B_c = \mu_0 J_c(0) d/2$ determined by ac loss analysis or ac magnetization.

[b] Calculated from a dc magnetization measurement.

[c] From dc transport measurements at 75 K and $B_a = 0$ T on similarly processed films.

[d] From fitting the losses calculated using the Bean model (see Ref. 5) to the loss data.

[e] From fitting the normalized losses at high fields using Eq. (3).

[f] From the previous article by a numerical fitting procedure (see Ref. 3).

[g] From an ac magnetization loop.

were $R = 0.999\,58$ and $0.999\,26$, respectively. These extrapolated values of $J_c(0)$ from the fitted $J_c(B_a)$ were taken, and these were used to calculate B_c. These values of $J_c(0)$, B_c, and B_0 from dc magnetization measurements are listed in Table I to compare with those obtained by the two other methods, ac loss and magnetization measurements and dc transport measurements. It should be noted here that the extrapolated values of $J_c(0)$ have some ambiguities when the particular model, in this case the Kim model, which was used in the fitting procedure, for the field dependent $J_c(B_a)$ does not precisely fit the experiment data in the field regions of interest since the extrapolation to the $B_a = 0$ is significant as shown in Fig. 7.

In general, the values of $J_c(0)$ or B_c determined by dc transport and dc magnetization measurements agreed quite well with each other, while those obtained from ac measurements differed significantly from the dc-derived values for the thinner films, 0.2 and 1.0 μm, but agreed well for the 3.0-μm-thick film. This discrepancy is related to the degree of the dependence of J_c on the applied magnetic field B_a. This is clearly illustrated by the values of the characteristic field B_0 in the Kim model. The value of B_0 determined by dc magnetization changed only from ~17 mT for the 0.2 μm film to ~23 mT for the 3.0 μm films, while the value of B_0 determined by ac loss measurements changed from 90 to 33 mT for the same films. One possibility for this difference is the presence of flux creep, which could be significant in YBCO at elevated temperatures. However, this is not a likely source of this unusual observation, since the dc values of J_c are greater than the ac values, contrary to what one expects for flux creep. We do not understand this puzzling phenomenon at this time, but the implication of this surprising result is that we cannot calculate ac losses for very thin superconducting films from knowledge of its dc critical-current density $J_c(B_a)$ nor its dc magnetic hysteresis loop.

Another interesting aspect of the magnetic field dependence of $J_c(B_a)$ of the films determined from dc magnetization measurements, shown in Fig. 7, is the difference in the shape of $J_c(B_a)$ at low fields. For the 1.0 and 3.0-μm-thick films, the magnetization-derived $J_c(B_a)$ deviated from the Kim-model fits at low applied fields, while this was not observed for the 0.2-μm-thick film. This variation can be understood in terms of Fig. 3 of Ref. 4, where the assumed $J_c(B_a)$ for the Kim model and an exponential $J_c(B_a)$ model were compared with the $J_c(B_a)$ calculated using the expression, $J_c(B_a) = (3/2R) \times \Delta M$. Here ΔM was calculated from the magnetization curves derived from the above assumed $J_c(B_a)$. The figure shows that the assumed $J_c(B_a)$ and the $J_c(B_a)$ derived from ΔM deviated for applied fields below B_c in the same manner as shown in Fig. 7 for the 1.0 and 3.0 μm films, where $J_c(B_a)$ from the Kim model deviated from the experimental $J_c(B_a)$ from dc magnetization. For these films, the values of B_a where the deviation becomes noticeable are approximately these films' B_c values, in agreement with the calculations of Ref. 4. For the 0.2 μm film, B_c is very small at ~4–6 mT, as shown in Table I, and it becomes experimentally difficult to observe the rounding of $J_c(B_a)$ by dc magnetization near $B_a = 0$.

Let us return to Fig. 1 and discuss the source of the large differences in the low-field losses among the films with different thicknesses. Since the normalized losses at low fields are given by $Q_N(B_a) \sim (B_a/B_c)^2/\pi$ for the Bean model and by $Q_N(B_a) \sim (B_a/B_{c\,\mathrm{eff}})^2/\pi$ for the Kim model, the losses $Q(B_a)$ [see Eq. (1)] are proportional to $B_a^4/[J_c^2(0) d^3]$. Hence, the losses at low fields have a very strong dependence on the thickness, and the losses for the 3.0 μm film are over two orders of magnitude lower than those for the 0.2-μm-thick film, even though its $J_c(0)$ is larger than that for 3.0-μm-thick film. If we use the values of $J_c(0)$ in Table I, we find that the ratio of the calculated losses in the 0.2 and 3.0 μm films is approximately 4×10^2 at $B_a = 3$ mT, and this is in good agreement with the difference in the losses between these films shown in Fig. 1. At high fields, since the fields penetrate the entire specimen, the above difference due to the film thickness diminishes, and the losses ultimately become independent of the film thickness and proportional to RJ_cB_a and $RJ_c(0)B_0 \ln(B_a/B_0)$ in the Bean and the Kim model, respectively, and this is what is observed in Fig. 1. Thus, this clearly illustrates that the thickness of a film is a dominant factor in determining the losses in low fields when applied fields are perpendicular to the film.

IV. SUMMARY

The ac losses in circular YBCO films having thicknesses of 0.2, 1.0, and 3.0 μm were measured in perpendicular magnetic fields. The general behavior of the ac losses in these films was well described by the theory developed by Shantsev, Galperin, and Johansen[4] which included the field-dependent J_c in calculating the losses. As predicted by this theory, as well as the theory using the Bean model,[5] the importance of the film thickness was clearly demonstrated in determining the losses at low fields. However, as shown previously, it is essential to include a field-dependent critical-current density in the theory to describe the high-field behavior of the losses. Also, a surprising discrepancy was found for thinner films in the values of B_c and B_0 determined by ac and dc measurements. At this point, the causes for this discrepancy are unclear.

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[10] Note that this expression was erroneously given as $J_c=(3d/2R)\times\Delta M$ in Ref. 3.