Temperature dependence of the lower critical field of high-$T_c$ superconducting crystals near $T_c$

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We have measured the nonlinear susceptibility of YBa$_2$Cu$_3$O$_7$, Bi$_2$Sr$_2$CaCu$_2$O$_8$, and untwinned YBa$_2$Cu$_3$O$_7$ crystals near the superconducting critical temperature $T_c$ in order to determine the lower critical field $H_{c1}(T)$. The ac field amplitude dependence of the susceptibility for homogeneous YBa$_2$Cu$_3$O$_7$ and Bi$_2$Sr$_2$CaCu$_2$O$_8$ crystals is in agreement with the geometrical barrier model allowing us to determine the penetration field $H_{1}(T) \approx H_{c1}(T)$. We clearly show that in these crystals the previously reported breakdown of $H_{c1}$ near $T_c$ coincides with the low-temperature ac field amplitude independent onset of the superconducting transition. We show that this anomalous behavior of $H_{c1}(T)$ is due to the influence of inhomogeneities and it is not an intrinsic property. We have also investigated the influence of the earth field on the nonlinear susceptibility, and we demonstrate the importance of its shielding for careful measurements of $H_{c1}$ near $T_c$.

I. INTRODUCTION

Previous investigations of the lower critical field $H_{c1}(T)$ of high-$T_c$ superconductors (HTS’s) showed an anomalous temperature dependence and, in some cases, a sudden suppression near the mean field superconducting critical temperature $T_c$.\(^1\)\(^-\)\(^3\) For example, superconducting quantum interference device measurements of the zero-field-cooled flux expulsion and remanent moment measurements\(^5\) as well as magnetic flux relaxation measurements\(^6\) on several YBa$_2$Cu$_3$O$_7$ (Y123) crystals reported a collapse of $H_{c1}(T)$ at temperatures 1 to 2 K below $T_c$. A similar collapse of $H_{c1}(T)$, but at ~3 K below $T_c$ has been measured in Bi$_2$Sr$_2$CaCu$_2$O$_8$ (Bi2212) crystals using a micro-Hall probe.\(^3\) Strikingly, micro-Hall probe measurements\(^5\) did not find similar effects in Y123 crystals, in contradiction with the results reported in Refs. 2, 6.

Several theoretical works and interpretations tried to clarify this breakdown of the Meissner state. It was speculated that the collapse of $H_{c1}(T<T_c)$ is due to the loss of phase coherence and decoupling of the stacks of superconducting CuO$_2$ planes.\(^7\) Also, it has been suggested that the spontaneous production of thermally activated vortex-antivortex pairs at a Kosterlitz-Thouless-type transition\(^8\) may cause $H_{c1}$ to vanish below $T_c$. On the other hand, it has been argued that the spontaneous creation of vortex-antivortex pairs cannot occur in a quasi-two-dimensional system such as Bi2212.\(^9\) Instead, fluctuations of the order parameter within the vortices would produce a downward renormalization of $H_{c1}$ a few degrees below $T_c$.\(^9\) This theory\(^9\) predicts that the renormalization of $H_{c1}(T)$ depends strongly on the anisotropy of the crystal. The renormalization of $H_{c1}(T)$ due to fluctuations\(^9\) predicts neither its collapse nor a negative curvature for Y123-based HTS, in apparent contradiction with the results of Refs. 2, 6.

Apparently neither the experimental evidence nor the theoretical work has resulted in consent in this field, and more and clear experimental results are needed. Therefore, in this work we use the approach based on the measurement of the global susceptibility, as an attempt to measure the penetration field in HTS crystals with different anisotropies. Our results indicate an anomalous temperature dependence of $H_{c1}(T)$ near $T_c$ for the Y124 and Bi2212 crystals, and its collapse at the low-temperature onset of the superconducting transition indicating that sample inhomogeneities cause this anomaly. The results of a Bi2212 crystal before and after annealing support this conclusion.

II. EXPERIMENTAL DETAILS

A. Sample characterization

The susceptibility signal of a weak pinning superconducting platelet at low applied fields (in our case $H \leq 10$ Oe) in perpendicular geometry depends mostly on vortex penetration through a barrier of geometrical origin.\(^10\)\(^\text{11}\) Therefore, we were careful to choose appropriate crystals for our studies, based on the behavior of the nonlinear susceptibility. Three crystals, reported in this paper, are thin platelets with nearly rectangular shapes and smooth surfaces. Samples with rough surfaces, of irregular shapes or rounded rims proved to be inadequate for these investigations. Nevertheless and in order to get a better characterization of the influence of in-
homogeneities in the measured properties, we have measured also an inhomogeneous Bi2212 crystal (Bi2212).

Table I shows the critical temperature and the dimensions of the studied crystals. Magneto-optical measurements of the magnetic flux distribution in the Bi2212 crystal at 10 K and at 10 Oe applied dc field, show a symmetrical pattern, as published for other HTS’s, without indication of an anomalous penetration of flux due to shape or superconducting inhomogeneities. We note, however, that because these results are obtained at low temperatures cannot necessarily be extrapolated to Tc. This crystal was annealed 10 min at 900 °C in air and then rapidly cooled (Bi2212a). For the Bi2212b crystal a nonsymmetric, inhomogeneous flux distribution pattern was observed.

Figures 1 and 2 show the superconducting transition of three crystals measured by the real component of the ac susceptibility. The Y124 crystal was characterized in previously published studies. The Y123 crystal showed no twinning planes under polarization microscope and, as the Y124 crystal, has no further annealing.

The critical temperature Tc is defined at the onset of the diamagnetic signal χ(T), see Figs. 1 and 2 and below. This signal was measured with an ac field applied perpendicular to the main area, i.e., parallel to the c axis of the crystals, with the earth field compensated. The other component of the earth field parallel to the CuO2 planes was not compensated. Most of the measurements of the ac susceptibility have been performed with an ac field frequency of 166 Hz, using sine-wave integration with respect to the fundamental frequency.

In Figs. 1 and 2 we see clearly that the width of the transition measured by the susceptibility depends on the amplitude of the applied ac field H0. In general, a large ac field amplitude broadens the transition and shifts the onset of diamagnetism to lower temperatures. This broadening is related to the critical current density of the sample and the distribution of the shielding currents generated by the applied ac field. This broadening is not related necessarily to inhomogeneities.

A curious behavior of the transition and its ac field amplitude dependence is observed for the Bi2212a crystal, see Fig. 1. Its transition becomes narrower decreasing H0, down to μ0H0 ~ 200 μT where it reaches a width of ~0.2 K. At

<table>
<thead>
<tr>
<th>Crystal</th>
<th>Size (l×w×d) [μm]</th>
<th>Tc [K]</th>
<th>2W/d</th>
<th>Hc1/Hp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bi2212a</td>
<td>390×300×18</td>
<td>90.2</td>
<td>17</td>
<td>4.5</td>
</tr>
<tr>
<td>Bi2212a#</td>
<td>390×300×18</td>
<td>90.6</td>
<td>17</td>
<td>4.5</td>
</tr>
<tr>
<td>Bi2212b</td>
<td>1100×900×30</td>
<td>90.0</td>
<td>30</td>
<td>6</td>
</tr>
<tr>
<td>Y124</td>
<td>750×410×20</td>
<td>78.9</td>
<td>20</td>
<td>5</td>
</tr>
<tr>
<td>Y123</td>
<td>~2000×600×150</td>
<td>89.0</td>
<td>4</td>
<td>2.7</td>
</tr>
</tbody>
</table>

FIG. 1. Temperature dependence of the real component of the ac susceptibility measured at low ac field amplitudes H0 and with the earth field compensated for the crystals Bi2212a and Bi2212a#. The arrows indicate the defined superconducting transition temperature Tc. The continuous and dotted lines are guides to the eye.

FIG. 2. Temperature dependence of the real component of the ac susceptibility measured at low ac field amplitudes H0 and with the earth field compensated for the crystals Y124 and Y123. The arrows indicate the defined superconducting transition temperature Tc. The continuous and dotted lines are guides to the eye.
lower ac field amplitudes, however, the width of the transition increases and becomes independent of $H_0$ at $\mu_0 H_0 \approx 20 \mu T$, within the resolution of our measurements. At this low ac field amplitudes the transition width reaches a maximum value of $\sim 2$ K. As will become clear below, the observed behavior is due to the existence of a geometrical barrier and the influence of inhomogeneities on it. This barrier vanishes at $T=88$ K.

After annealing the Bi2212a crystal the ac response changed drastically. The transition width at similar ac field amplitudes is smaller. The apparent decrease of the transition width increasing the ac field amplitude as observed in the crystal before annealing, is not measured, see Fig. 1.

For the inhomogeneous crystal Bi2212b, we observed that for ac field amplitudes $\mu_0 H_0 \approx 200 \mu T$, the transition shows a shift in temperature, with a gradual decrease of its width in contrast to the behavior observed for the Bi2212a crystal shown in Fig. 2. Also, the susceptibility does not show perfect shielding at the low-temperature onset of the transition, but only at low enough temperatures. This behavior is also observed for a smaller crystal obtained by cutting the original Bi2212b crystal.

**B. Experimental determination of the penetration field $H_p(T)$**

The electromagnetic behavior of thin superconductors of various shapes has been subject of several experimental and theoretical studies, especially when the magnetic field is applied perpendicular to the main area of the platelet.10–30 Theoretically13–17,21 and experimentally29 it has been shown that in transverse geometry the nonlinear response of a superconductor with relatively large pinning is not accounted for correctly by the Bean critical state model.31 In our case, nonlinear response means the ac field dependence of the susceptibility at constant temperature and dc field.

The simple assumptions of the Bean model have to be modified in the transverse geometry due to demagnetization factors, that enhance the external field at the edges of the sample. We have recently showed that the ac field dependence of the ac susceptibility of structured Y123 thin films in transverse magnetic fields29 can be well understood assuming bulk pinning and a generalized Bean model.15,17,13,22

For platelet samples with relatively low pinning, in sufficiently small dc fields and in transverse geometry, the nonlinear ac susceptibility near $T_c$ can be well explained by the existence of a geometrical barrier, which originates from its flat shape.10,11,23–25 This barrier prevents the penetration of flux into the sample at applied fields that are smaller than the characteristic penetration field $H_p$. If pinning can be neglected and the thickness is sufficiently constant over the whole area, a penetrating vortex undergoes only the influence of the Lorentz force caused by the Meissner currents flowing in the crystal and driving the vortex towards the center of the sample.23,24 The corresponding vortex potential has a minimum in the center and a positive maximum at the edges. Flux lines can penetrate only from the rims into the sample, if they overcome this potential barrier, i.e., if the applied external field exceeds $H_p$. This penetration field has been derived23,26 for a thin, narrow superconducting strip of rectangular shape of width $2W$ and thickness $d$, given by

$$H_p = \frac{2H_{c1}}{\pi} \arctanh \left\{ \sqrt{1 - \left[ \frac{1}{2} (d/W) \right]^2} \right\}. \quad (1)$$

For $d < 2W$ one can simplify Eq. (1) as $H_p = (2H_{c1}/\pi) \sqrt{d/W}$, revealing that the demagnetization factor (in the present case $\sim \sqrt{d/W}$) is reduced as compared to that obtained for an elliptical shape $\sim d/W$.23,19 For fields $H < H_p$ flux lines penetrate only into the narrow region near the rims of a width of the order $d/2$. Recent numerical results for the thin-strip limit ($d < 2W$) give a slightly different relation for the penetration field32

$$H_p = 0.56H_{c1} \left( \frac{d}{2W} \right)^{1/2}. \quad (2)$$

We note that according to the geometrical barrier model the temperature dependence of $H_p(T)$ and $H_{c1}(T)$ are the same. Detailed calculations of the local flux density across the sample and of the static hysteresis,10,23–25 as well as of the nonlinear susceptibilities $\chi'$ and $\chi''$, were confirmed by dc and ac susceptibility measurements,10,11,22,33 and also by scanning ESR probe measurements.34 The geometrical barrier model predicts a discontinuity of the nonlinear ac susceptibility at the field amplitude $H_0 = H_p$, which can be explained as follows: (a) If the amplitude of the external field $H_0 < H_p$, the flux lines penetrate only in a narrow zone at the edges of the sample with a maximum width $\sim d/2$. Therefore, the periodical variation of the external field gives an ac susceptibility that reflects the Meissner state, i.e., $\chi' \approx \chi_{\text{Meissner}}$ and $\chi'' = 0$, independent of $H_0$. (b) If $H_0 > H_p$, the penetration of flux lines into the center of the sample leads to a hysteretic behavior with hysteresis losses (a finite $\chi''$) and causes a breakdown of the (negative) $\chi'$ component. These predictions of the geometrical barrier model have been already demonstrated on suitable crystals11 near $T_c(H \sim 0)$. Therefore, measuring the penetration field and the geometry of the sample one can determine $H_{c1}$ near $T_c$ using Eq. (1) or (2).

**C. Influence of the earth field**

Since our aim is to measure the lower critical field near $T_c$, we should be able to detect penetration fields of the order of 10 $\mu$T or less. Therefore, the shielding of the earth magnetic field is necessary, at least in the direction perpendicular to the main surface of the crystals (parallel to the c axis).

With a small solenoid surrounding the primary and secondary coils used for the susceptibility measurements, we can apply a variable dc field $H_{dc}$ normal to the sample surface. To measure and to shield the earth or any other dc field $H_e$ at the sample position, we measure the second harmonic signal of the crystal as a function of the applied field $H_{dc}$ at a constant temperature $T < T_c$. If the total dc field on the sample $H_t = H_{dc} + H_e > 0$ and the applied ac field amplitude $H_0 > H_p$, the second harmonic signal will be finite due to the asymmetry in the magnetization loop. By applying a dc field $H_{dc} = H_{\text{comp}}$ we can compensate $H_e$ so that the total dc field at the sample becomes zero and the second harmonic signal vanishes. Therefore, we can determine $H_e = -H_{\text{comp}}$ at the sample. Using this procedure we have measured $H_e$ at the
position of the Bi2212 crystal, see Fig. 3(a). From the measurements depicted in Fig. 3(a) we determine a field $\mu_0 H_e = 37.7 \mu T$, in good agreement with the field measured using a Hall probe outside the cryostat. In the inset of Fig. 3(a) we show the second harmonic signal as a function of temperature with and without compensation, indicating that the extracted value of $H_e$ does not depend on $T$, at least in the temperature range of our measurements.

Figure 3(b) shows the susceptibility of the Bi2212a crystal as a function of temperature, with and without earth field compensation. It is interesting to note that the compensation of the earth field shifts the transition to higher temperatures by $\approx 0.3$ K. In the next section we will discuss the influence of the earth field on the ac field dependence of the susceptibility.

FIG. 3. (a) Second harmonic signal as a function of dc field. The signal vanishes at a dc field which compensates exactly the external (earth and surroundings) field on the sample. The measurements were done on the Bi2212a crystal at a temperature $\approx 3$ K below $T_c$. The inset shows the second harmonic signal as a function of temperature with and without compensation of the earth field. (b) Real part of the susceptibility of the same Bi2212 sample as a function of temperature with and without compensation of the earth field. The ac field amplitude used for this measurement was $\mu_0 H_0 = 25 \mu T$ at a frequency of 166 Hz.

III. RESULTS

A. YBa$_2$Cu$_4$O$_8$

Figure 4 shows the two components of the nonlinear ac susceptibility of the Y124 crystal at different temperatures (earth field compensated). The amplitude of the ac field $H_0$ is normalized by the penetration field $H_p$ determined by the kink in the imaginary or real component of the susceptibility.

![Graph](image-url)

**FIG. 4.** The two components of the nonlinear ac susceptibility of the Y124 crystal at different temperatures (earth field compensated). The amplitude of the ac field $H_0$ is normalized by the penetration field $H_p$ determined by the kink in the imaginary or real component of the susceptibility.

At a temperature $T = 78.5$ K the penetration field $\mu_0 H_p \approx 38 \mu T$ is of the order of the measured vertical component of the earth field $H_e$. Therefore the geometrical barrier can be overcome by the earth field. The typical behavior of the nonlinear susceptibility observed at lower temperatures is lost when the earth field is not shielded, as demonstrated in Fig. 5. This measurement explains partially the loss of the geometrical barrier character of the curves measured in Ref. 11 near $T_c$. All the measurements of the ac field dependence of the susceptibility that are shown below have been done with the earth field vertical component compensated.

![Graph](image-url)

**FIG. 5.** Temperature dependence of the penetration field $H_p(T)$; note that for this sample the lower critical field $H_{c1}(T) \approx 5 H_p(T)$ using Eq. (1). It is clearly seen that $H_p$ shows a negative curvature. The extrapolation indicates that it tends to vanish at $T_{c0} = T_c - 0.2$ K (see inset in...
Fig. 6, within the ac amplitude independent transition width. We note that this negative curvature of $H_p(T)$ or $H_{c1}(T)$ is recognized already at temperatures clearly lower than those where a broadening of the shielding signal is observed, see Fig. 6. Note also that the ac field dependence of the susceptibility due to the geometrical barrier is measured in the whole temperature range, including that inside the width of the transition as measured by the real part of the susceptibility at $\mu_0 H_0 = 19$ $\mu$T, see Fig. 6.

Strictly speaking, the breakdown of $H_{c1}$ as observed in Bi2212 in Ref. 5 and in Y123,2,6 is not observed in Y124 in the measured temperature range, but a temperature dependence with a negative curvature. At temperatures $T > 78.6$ K, the ac fields necessary to determine $H_p$ were so small ($< 25$ $\mu$T) that no reliable signal could be detected due to the smallness of the crystal.

### B. Bi$_2$Sr$_2$CaCu$_2$O$_8$

The nonlinear susceptibility curves with and without normalization for the Bi2212a crystal before and after annealing are shown in Figs. 7 and 8, respectively. At low enough temperatures, the susceptibility of the Bi2212a crystal shows the characteristic dependence due to the geometrical barrier, as in the Y124 crystal. However, and in contrast to the Y124 crystal, at a temperature $T_{co} \approx 0.97 T_c$ or higher, the nonlinear susceptibility deviates clearly from the predicted behavior of the geometrical barrier model. There is a broadening of the ac field dependence, that tends to the curve obtained from the nonlinear Bean model,29,17,18,13 see Fig. 7. Therefore, the normalization of the ac field amplitude in Fig. 7 is done by the field at the dissipation maximum $H_m$ and not $H_p$.

Note that the annealed crystal Bi2212a# shows a decrease of the diamagnetic signal as well as of the dissipation maximum at the highest measured temperatures (see Fig. 8) which lie within the superconducting transition width. If we normalize the susceptibility curves according to $H_0 \rightarrow H_0/H_p$ and $\chi'(H_0 \rightarrow 0) \rightarrow -1$ they follow a single curve (see Figs. 7 and 4). However, in contrast to the results for the
same crystal before annealing (Fig. 7) no broadening of the ac field dependence is observed. The geometrical barrier behavior is measured up to the highest temperature \( T = 89.58 \) K.

We note that the vanishing of the geometrical barrier at \( T_{co} \) for the Bi2212a crystal occurs at temperatures when the Meissner signal starts to break down, see also Fig. 9. This loss of the geometrical barrier has been observed in another Bi2212 crystal\(^{11}\) and is not related to an uncompensated earth field.

From the measurements of the nonlinear susceptibility of the Bi2212 crystals we obtained the penetration field \( H_p \) or the lower critical field \( H_{c1} \) as for the Y124 crystal. The temperature dependence of \( H_p(T) \) for the Bi2212a crystal shows a negative curvature as for the Y124 crystal, see Fig. 6, and vanishes at temperatures just below \( T_{co} \) denoted by the arrow in Fig. 9. We stress that this breakdown is not an artifact of the measurements. The abrupt decrease of \( H_p \) starts at a temperature \( T \approx 85.5 \) K, below the temperature \( T_{co} \) where the real component of the susceptibility deviates from the perfect shielding state. At temperatures \( T > T_{co} \) no \( H_p \) can be determined from our measurements. In other words \( H_p(T > T_{co}) = 0 \). The fields plotted in Fig. 9 above \( T_{co} \) are the fields of maximum dissipation \( H_m \). Note that \( H_m \) remains finite and tends to vanish approaching \( T_c \), see Fig. 9.

Regarding the influence of inhomogeneities on \( H_p(T) \), it is interesting to compare the data of the crystal Bi2212a before and after annealing. The annealed Bi2212a# crystal shows a linear temperature dependence for \( H_p(T) \), see Fig. 10, in the whole temperature range. The extrapolation of this dependence to \( \mu_0 H_p = 0 \) \( \mu T \) coincides with the defined critical temperature (see Fig. 1) within experimental error.

The nonlinear susceptibility of the inhomogeneous crystal Bi2212b shows a clear double peak structure as a function of the ac field amplitude at a temperature \( T = 85.7 \) K where the geometrical barrier behavior is lost. Interestingly, the typical geometrical barrier signature due to the existence of \( H_p \) is recovered at higher temperatures. At even higher temperatures \( T > 88 \) K this behavior is lost and a Bean-like dependence is observed as for the Bi2212a crystal. In order to study the influence of the sample size to the ac response observed for the inhomogeneous crystal Bi2212b and to see whether the observed behavior is due to some inhomogeneous parts of the crystal rim, we have broken it in the middle and measured one of the remaining pieces. The obtained results are similar to those of the large, original
temperature dependence. It is interesting to note that the observed dependence of \( H_m \) on the temperature for the Y123 crystal follows the predicted behavior given by the Bean model. The nonlinear susceptibility, see Fig. 4, 7, and 8, shows some evidence for thermally activated relaxation at low fields of our measurements. For fields below 10 Oe and by changing the frequency of the ac field from 30 Hz to 1 kHz, the signals of the nonannealed crystal Bi2212a show a shift in the position of the maximum of \( \chi''(H_0) \) of less than 0.5 K, indicating an activation energy larger than 3 eV. This result cannot be understood within the geometrical barrier model since this leads to a very small probability for thermally activated hopping of vortices. We note, however, that this weak frequency dependence is completely absent in the annealed crystal. It is therefore clear that inhomogeneities influence the frequency dependence of the ac response near \( T_c \).

Taking into account all this evidence and the typical behavior of the nonlinear susceptibility, see Figs. 4, 7, and 8, we argue that the geometrical barrier is the main mechanism for the irreversible behavior in Y124 and Bi2212 crystals at the temperatures and fields of our measurements. A detailed theory of \( H_{c1}(T) \) near \( T_c \), taking into account the influence of self fluctuations of the order parameter, is given by Blatter et al.\textsuperscript{9} As discussed in Ref. 9, thermal fluctuations shift the transition temperature \( T_c \) to lower temperatures. Depending on the anisotropy of the superconductor, this shift can be of the order of 3 K for Bi2212 HTS. Moreover, thermal fluctuations change the curvature of \( H_{c1}(T) \) from zero to negative.\textsuperscript{9} For the less anisotropic crystals such as Y123 a parallel shift of the \( H_{c1}(T) \) without a downward bending is expected from this theory. Taking into account only the results of the Bi2212a and Y124 crystals these theoretical predictions\textsuperscript{8} appear to be in good agreement with our observations: the larger the anisotropy, the larger the expected shift to lower temperatures of the lower critical field. The previously published results in the literature indicate also an anomalous temperature dependence for \( H_{c1}(T) \) in highly anisotropic high-\( T_c \) superconductors. However, we show clearly that the temperature dependence of \( H_{c1} \) [the breakdown of \( H_{c1}(T) \) near \( T_c \) as well as its negative curvature], extracted from \( H_p(T) \), is sensitive to the homogeneity of the crystal and it cannot be taken as an intrinsic property.

IV. DISCUSSION

A clear distinction between the nonlinear response obtained from the geometrical barrier and that from the Bean-Livingston surface barrier is difficult by measuring global or even local nonlinear susceptibility or magnetization. A possible way to study and differentiate the contributions of these two different barrier mechanisms is by changing the shape of the crystals, see Ref. 33. In that work it is shown that in platelet samples with weak bulk pinning and in transverse geometry, the geometrical barrier appears to be the dominant at high temperatures.

One may still ask if the measured response in our crystals shows some evidence for thermally activated relaxation at the low fields of our measurements. For fields below 10 Oe and by changing the frequency of the ac field from 30 Hz to 1 kHz, the signals of the nonannealed crystal Bi2212a show a shift in the position of the maximum of \( \chi''(H_0) \) of less than 0.5 K, indicating an activation energy larger than 3 eV. This result cannot be understood within the geometrical barrier model since this leads to a very small probability for thermally activated hopping of vortices. We note, however, that this weak frequency dependence is completely absent in the annealed crystal. It is therefore clear that inhomogeneities influence the frequency dependence of the ac response near \( T_c \).

Taking into account all this evidence and the typical behavior of the nonlinear susceptibility, see Figs. 4, 7, and 8, we argue that the geometrical barrier is the main mechanism for the irreversible behavior in Y124 and Bi2212 crystals at the temperatures and fields of our measurements. A detailed theory of \( H_{c1}(T) \) near \( T_c \), taking into account the influence of self fluctuations of the order parameter, is given by Blatter et al.\textsuperscript{9} As discussed in Ref. 9, thermal fluctuations shift the transition temperature \( T_c \) to lower temperatures. Depending on the anisotropy of the superconductor, this shift can be of the order of 3 K for Bi2212 HTS. Moreover, thermal fluctuations change the curvature of \( H_{c1}(T) \) from zero to negative.\textsuperscript{9} For the less anisotropic crystals such as Y123 a parallel shift of the \( H_{c1}(T) \) without a downward bending is expected from this theory. Taking into account only the results of the Bi2212a and Y124 crystals these theoretical predictions\textsuperscript{8} appear to be in good agreement with our observations: the larger the anisotropy, the larger the expected shift to lower temperatures of the lower critical field. The previously published results in the literature indicate also an anomalous temperature dependence for \( H_{c1}(T) \) in highly anisotropic high-\( T_c \) superconductors. However, we show clearly that the temperature dependence of \( H_{c1} \) [the breakdown of \( H_{c1}(T) \) near \( T_c \) as well as its negative curvature], extracted from \( H_p(T) \), is sensitive to the homogeneity of the crystal and it cannot be taken as an intrinsic property.

V. CONCLUSION

In conclusion, we have measured the ac field amplitude dependence of the global susceptibility of different HTS crystals near \( T_c \). For the weak pinning HTS crystals, the ac field amplitude dependence follows the predicted behavior due to the geometrical barrier mechanism. Measuring the
penetration field $H_p$, we have shown that the lower critical field for nonannealed Bi2212 and Y124 crystals shows an anomalous dependence near $T_c$, vanishing at $T_{c0} \sim T_c -2 \text{ K}$ and $\sim T_c -0.3 \text{ K}$, respectively. This “collapse” of $H_p$ occurs just at the low-temperature onset of the zero-field superconducting transition and indicates that these effects are not an intrinsic property of the HTS crystals. The measurements on three Bi-based crystals show that the temperature dependence of $H_{c1}(T)$ depends on the sample quality. In particular, the breakdown of $H_{c1}(T)$ as well as the negative curvature is absent for the annealed Bi2212a crystal. For our untwinned Y123 crystal, even very near $T_c$, bulk pinning overwhelms the geometrical barrier effect.

Our measurements with and without compensation of the earth field show clearly the importance of its shielding for the investigation of the superconducting properties near $T_c$.

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