3-D Properties in (RE)BCO Tapes Measured in Fields up to 35T

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(Invited Paper)

***Abstract*—We have measured the temperature and angular dependence of the upper critical field (B_{C2}) for three state of the art (RE)BCO HTS tapes using variable-temperature ac susceptibility measurements in applied fields up to 35 T. The three tapes measured were a Fujikura tape without artificial pinning centers and Superpower tapes with and without artificial pinning centers. We have obtained fits to our $B_{C2}(T,\theta)$ data using both the anisotropic Ginzburg–Landau (G–L) and Klemm's models for layered superconductors. Our calculations suggest that these tapes are three-dimensional (3-D) at all temperatures in zero field but become 2-D in magnetic fields above a crossover field of $457/\gamma$ T, where $\gamma = \sqrt{m_c}/m_{ab}$ is the G–L anisotropy parameter. The values of γ were measured and show that the 3-D–2-D crossover fields in these tapes are at least 130 T.**

***Index Terms*—2G HTS Conductors, cuprates, superconducting materials measurements, magnetic anisotropy, magnetic field measurement, magnetic susceptibility, critical temperature and critical fields.**

I. Introduction

High temperature superconductors (HTS) exhibit highly anisotropic superconducting properties [1]–[6]. The standard description of HTS materials states that the superelectrons condense in parallel 2D CuO planes that are separated by normal regions but coupled via interlayer Josephson coupling [7]. This layered structure means that one can expect a dimensionality crossover from 3D properties close to the critical temperature (T_C) to 2D properties at low temperatures. Lawrence and Doniach [8] developed a model for layered superconductors and showed that in the extreme 2D case there is a divergence in the upper critical field B_{C2} for magnetic fields applied parallel to the superconducting layers at a crossover temperature T^* given by $\xi_c(T^*) = s/\sqrt{2}$, where ξ_c is the coherence length along the c-axis of the material and s is the interlayer spacing. This LD condition can be interpreted as the temperature at which the diameter of the fluxon cores is sufficiently small to fit between the superconducting layers [9]. Dimensional crossovers have been reported in (RE)BCO films [10], $Bi_2Sr_2CaCu_2O_8$ crystals [11] and $Tl_2Ba_2Ca_2Cu_3O_{10}$ films [12]. In this paper we measure the upper critical field of three state-of-the-art (RE)BCO tapes with high critical current densities (J_C) in magnetic fields up to 35 T using variable-temperature susceptibility measurements at different angles θ between the normal to the tape surface and the applied field. For highly ordered single crystals of (RE)BCO, B_{C2} values are very high and accurately described for $T \approx T_C$ by the G-L model with an anisotropy factor $\gamma \approx 5$ where $\gamma = \xi_{ab}/\xi_c = \sqrt{m_c/m_{ab}}$ is the anisotropy parameter and ξ_c and ξ_{ab} (or m_c and m_{ab}) are the effective coherence lengths (or masses) along the inter- and intra-planar directions, respectively [6]. Disorder due to high pinning in these tapes reduces the in-plane scattering times, increases m_{ab} and drives the effective anisotropy factor down to $\gamma \approx 1.5 - 3$ [3], [5]. Low B_{C2} and low γ will tend to decrease the crossover temperature in high J_C tapes. In this paper, we fit our $B_{C2}(T,\theta)$ data using Klemm's layered model and calculate the conditions for dimensional crossover.

The upper critical field of 3D anisotropic superconductors is characterized using the well-known anisotropic Ginzburg-Landau (G-L) theory [13], [14]. In this theory, the material is described as a bulk superconductor with an anisotropic effective mass of the superelectrons. G-L theory assumes that the coherence length in all directions is much larger than the unit cell size. For (RE)BCO single crystals [6], the zero temperature coherence length $\xi_c(0) \approx 2 - 4$ Å [15]–[18], the interlayer spacing $s \approx 12$ Å [19] and the transition temperature $T_C = 92$ K. Hence $\xi_c(0)$ is smaller than the interlayer spacing, and a layered theoretical model is required. The crossover temperature predicted for (RE)BCO using the standard LD model and a temperature dependent coherence length $\xi_c(T) = \xi_c(0)/\sqrt{1 - T/T_C}$ is $T^* \approx 82$ K for $\xi_c(0) = 0.378$ nm [20] but we usually find that the G-L model remains a fairly good approximation at temperatures below even 75 K [2], [6], [14]. Using the G-L relations and the LD condition leads to an approximate value for

Manuscript received October 30, 2018; accepted January 8, 2019. Date of publication January 31, 2019; date of current version March 11, 2019. This work was supported in part by EPSRC under Grant EP/L01663X/1 for the Fusion Doctoral Training Network, was carried out within the framework of the EUROfusion Consortium, and was supported in part by the Euratom research and training programme 2014-2018 under Grant 633053. *(Corresponding author: Andrew P. Smith.)*

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Digital Object Identifier 10.1109/TASC.2019.2895218

the 2D-3D crossover field, when the applied field is parallel to the a-b planes ($B_{\mathrm{C2}} \parallel ab$), given by $B_{\mathrm{C2,ab}}(T^*) \approx \phi_0/\pi\gamma s^2 \approx 457/\gamma\,\mathrm{T}$ for (RE)BCO. Hence in this work, identifying the cross-over temperature reduces to the challenge of extrapolating our B_{C2} data, obtained in fields up to 35 T and angles up to 60 degrees, up to 130 T and 90 degree angles. We have used the Klemm model for these B_{C2} calculations and used the LD condition to find the 2D-3D crossover.

Klemm developed his model [21] to describe the temperature and angular dependence of B_{C2} in the layered transition metal dichalcogenides, in which the interlayer spacing is sufficiently large for 2D behavior to be observed at low fields [22], [23]. The model has also been confirmed to correctly describe artificial multilayer systems [24], [25]. Klemm's work includes a more general microscopic description of the superconductivity than LD and produces more accurate estimates of $B_{\mathrm{C2}}(T,\theta)$, as well as the crossover temperature T^*. Our motivation for measuring and understanding these tapes in very high fields follows recent proposals for fusion energy power plants that require HTS tapes at such high fields and low temperatures [26], [27] that they may operate in the 2D regime.

II. Theory

A. Anisotropic Superconductors

G-L theory gives the angular dependence of the upper critical field of an anisotropic superconductor as

$$B_{\mathrm{C2}}(T,\theta) = \frac{B_{\mathrm{C2}}(T,0)}{\sqrt{\cos^2(\theta) + \gamma^{-2}\sin^2(\theta)}}, \tag{1}$$

where θ is the angle between the applied field and the superconducting materials' *c*-axis [13]. Typically the input parameter for this model is $B_{\mathrm{C2}}(T,0)$ and the angular dependence is provided from Equation (1) with γ as a constant.

B. Layered Superconductors

Lawrence and Doniach discretized the G-L free energy functional to describe infinitesimally thin superconducting planes separated by normal layers [8]. Analogous to G-L theory, the input parameters for the LD model include $B_{\mathrm{C2}}(T,0)$ when the field is along the *c*-axis of the structure (i.e., parallel to the normal to the planes) and the anisotropy parameter γ. In this paper we have assumed a simple empirical law for $B_{\mathrm{C2}}(T,0)$ of the form

$$B_{\mathrm{C2}}(T,0) = B_{\mathrm{C2}}(0,0)\left[1 - \frac{T}{T_C}\right]^n \tag{2}$$

Klemm *et al.* [21] developed the LD model by considering a Hamiltonian for layered superconductors which includes the Chandrasekhar-Clogston paramagnetic limit [28], [29] to eliminate the divergence in $B_{\mathrm{C2}\parallel\mathrm{ab}}$ obtained from the LD model. It also includes strong spin-orbit quenching effects [30], [31], impurity scattering and the pair binding energy, all of which tend to increase B_{C2}. The resultant differential equation for B_{C2} derived by Klemm is

$$\left\{D\left(-\frac{d^2}{dx^2} + \left(\frac{2eBx}{\hbar}\cos\theta\right)^2\right) + J^2\tau\left[1 - \cos\left(\frac{2eBxs}{\hbar}\sin(\theta)\right)\right]\right\}\phi = (2\alpha - 3\tau_{so}(\mu_B B)^2)\phi \tag{3}$$

where D is equivalent to the reciprocal mass for in-plane transport, J is the interlayer coupling strength, τ is the total scattering time for both spin-orbit and impurity scattering ($\tau^{-1} = \tau_{so}^{-1} + \tau_{imp}^{-1}$), α is the coefficient of ψ^2 in the G-L free energy functional. Klemm showed that there is an analogue in layered superconductors to the mass anisotropy ratio where $\gamma^2 = 2D/J^2\tau s^2$ and produced a series expansion solution for B_{C2} from Equation (3) up to 2nd order in $\eta B\sin^2(\theta)/\gamma$ given by

$$O\left[\left(\frac{\eta B_{\mathrm{C2}}\sin^2(\theta)}{\gamma}\right)^3\right] + \left\{\frac{\eta^2}{8}\frac{\sin^4(\theta)}{\gamma^2 a^2(\theta)}\right\}B_{\mathrm{C2}}(T,\theta)^2 - a(\theta)B_{\mathrm{C2}}(T,\theta) + B_{\mathrm{C2}}(T,0) = 0 \tag{4}$$

Where the two free parameters are the anisotropy factor γ and the interlayer spacing $\eta = s\sqrt{e/\hbar}$. The function $a(\theta)$ is the anisotropy function

$$a(\theta) = \left(\cos^2(\theta) + \gamma^{-2}\sin^2(\theta)\right)^{\frac{1}{2}} \tag{5}$$

Equation (4) reduces to G-L theory in the limit of $s, \theta, B_{\mathrm{C2}} \to 0$ as expected. For behavior in high fields and close to $\theta = 90^\circ$ Klemm provided a different expansion of the form

$$B_{\mathrm{C2}}(T,0) = B_{\mathrm{C2}}(T,\theta)\cos(\theta) + \left(\frac{1}{\gamma\eta}\right)^2\left(1 - \exp\left(-\frac{\chi}{2}\right)\right) + O\left[\left(\frac{1}{\gamma\eta}\right)^4\right] \tag{6}$$

Where

$$\chi = \frac{\eta^2 B_{\mathrm{C2}}(T,\theta)\sin^2(\theta)}{\cos(\theta)} \tag{7}$$

The exact regions of validity for these two expansions are not straightforward. Klemm referred to (4) as the 'low field' limit and (6) as the 'high field' limit although in the limit of low angles θ they are equivalent. In the high angle limit (4) reproduces the required bulk 3-D behavior at high temperatures and low fields, and (6) reproduces the required 2-D behavior at low temperatures and high fields. In addition to a more physically justifiable form of $B_{\mathrm{C2}}(T,\ \theta)$, Klemm derived a more accurate equation for the dimensional crossover temperature T^* in terms of digamma functions $\psi(x)$

$$\ln\left(\frac{T^*}{T_C}\right) + \psi\left(\frac{1}{2} + \frac{rT_C}{4\pi T^*}\right) - \psi\left(\frac{1}{2}\right) = 0 \tag{8}$$

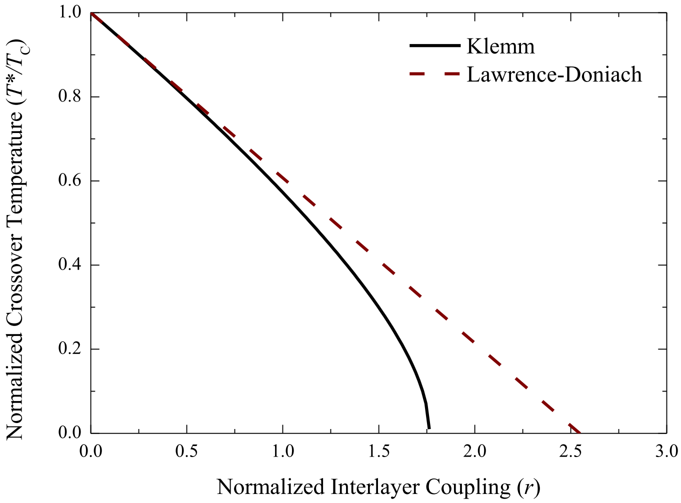

Fig. 1. Normalised crossover temperature $\frac{T^*}{T_C}$ as a function of the interlayer coupling parameter $r = \frac{\hbar^2}{m_c s^2 k_B T_C}$ for the Lawrence-Doniach and Klemm models. The Klemm model predicts a suppression of dimensional crossover below the predictions of the LD model for strongly coupled systems. The difference between the LD and Klemm models is more pronounced in materials with a larger interlayer coupling.

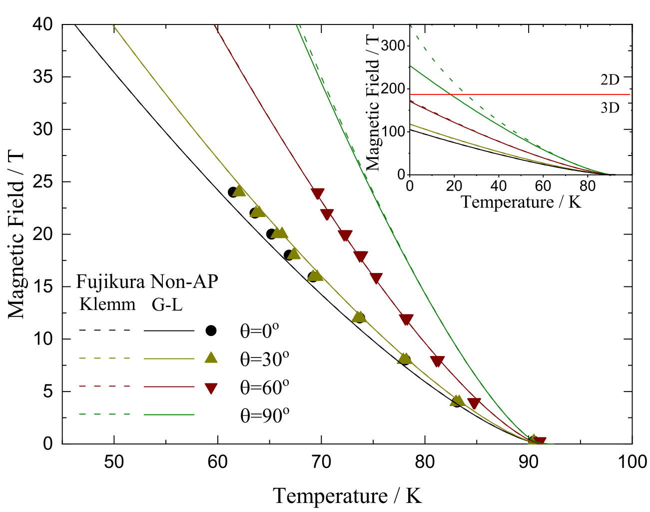

Fig. 2. Angular $B_{C2}(T)$ data for the Fujikura Non-AP tape. The 2 fits are Anisotropic Ginzburg-Landau Theory (solid) and Klemm's Low Field (dashed) Expansions. The inset shows the low temperature extrapolation.

Where $r = \hbar^2/m_c s^2 k_B T_C$ is a dimensionless parameter which gauges the interlayer coupling strength. The predicted crossover temperature as a function of r for both the Klemm and LD models is shown in Fig. 1.

III. Results

AC susceptibility measurements were completed on 3 HTS tapes at LNCMI, Grenoble in fields up to 35 T and up to 24 T in multiple sample orientations at HFLSM, Tohoku University using a bespoke ac. susceptometer [32], [33]. The onset of the diamagnetic transition in the real part of the fundamental susceptibility was used to determine $B_{C2}(T, \theta)$. The measurements were made using a sinusoidal applied field with an rms field strength $B_{rms} \approx 1\,\text{mT}$ and a frequency of 777 Hz. The values of $B_{C2}(T, \theta)$ found experimentally are shown in Figs. 2–4. It should be noted that the onset of the diamagnetic transition shifts as a function of AC excitation field strength and frequency. We have chosen 777 Hz in this work since it is not susceptible to interference from ambient mains voltage sources.

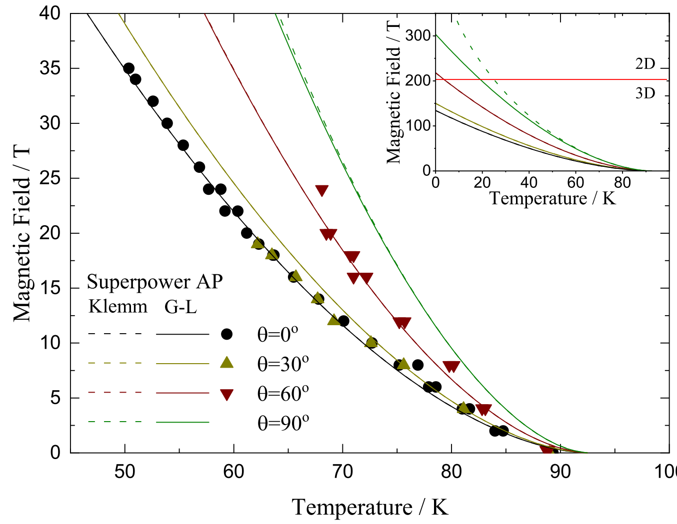

Fig. 3. Angular $B_{C2}(T)$ data for the Superpower AP tape. The 2 fits are Anisotropic Ginzburg-Landau Theory (solid) and Klemm's Low Field (dashed) Expansion. The inset shows the low temperature extrapolation.

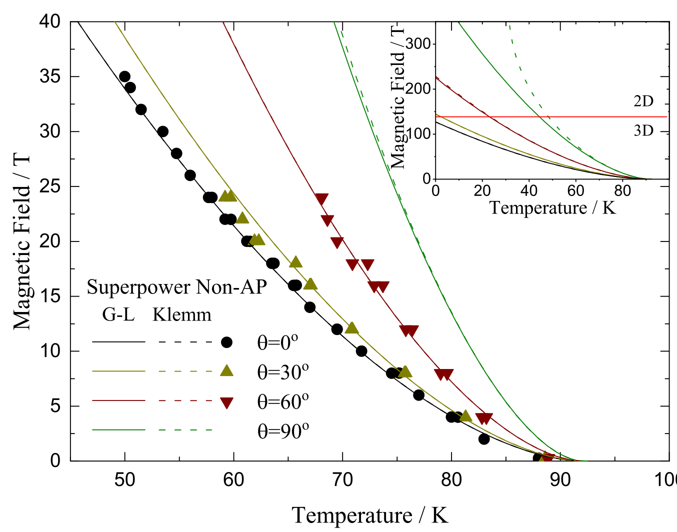

Fig. 4. Angular $B_{C2}(T)$ data for the Superpower Non-AP tape. The 2 fits are Anisotropic Ginzburg-Landau Theory (solid) and Klemm's Low Field (dashed) Expansion. The inset shows the low temperature extrapolation.

A Python script was used to find a global fit for $B_{C2}(T,\ \theta)$ for the G-L model and both Klemm's 'low field' and 'high field' expansions with an interlayer spacing $s = 12\,\text{Å}$. The free parameters γ, $B_{C2}(0, 0)$, T_C and n for Klemm's Low and High Field Fits and anisotropic GL theory are shown in Tables I and II, respectively. T_C was kept as a free parameter because the lowest field measurements we obtained at HFLSM were at

TABLE I
KLEMM HIGH (AND LOW) FIELD FIT

Parameter	Superpower Non-AP	Superpower AP	Fujikura Non-AP
$B_{C2}(0,0)$	127(127) ±6 T	135 (134) ± 9.5 T	105 (105) ± 8 T
T_C	91.9(91.9) ±0.9K	92.6 (92.6) ± 1.5 K	91.1 (91.1) ±1 K
n	1.68 (1.68) ±4%	1.74 (1.73) ± 7%	1.36 (1.36) ±7%
γ	3.42 (3.28) ±8%	2.42 (2.24) ± 7%	2.55 (2.40) ±5%

Table I: Fitted parameters for angular $B_{C2}(\theta, T)$ data up to 35 T using Klemm's High (and Low) Field Expansion. The free parameters for Klemm's low field expansion is given in brackets. Error bars are similar for both expansions.

TABLE II
ANISOTROPIC GINZBURG-LANDAU FIT

Parameter	Superpower Non-AP	Superpower AP	Fujikura Non-AP
$B_{C2}(0,0)$	127 ± 6 T	134 ± 9.5 T	104 ± 8 T
T_C	91.9 ± 0.9 K	92.6 ± 1.5 K	91.1 ± 1 K
n	1.68 ± 4%	1.73 ± 7%	1.37 ± 7%
γ	3.31 ± 9%	2.26 ± 8%	2.42 ± 7%

Table II: Fitted parameters for angular $B_{C2}(T, \theta)$ data up to 35 T using the anisotropic Ginzburg Landau model.

$0.259\,\mathrm{T}$ – the trapped field in the HTS magnet at zero current. Over the range of fields and temperatures of our measurements the free parameter values found using Klemm's two fits were very similar so we have used the 'low field' parameterization in Figs. 2–4, and in their insets, to show the low temperature extrapolation. Furthermore, we have found no evidence for dimensional crossover into the 2-D regime and therefore expect Klemm's 'low field' fit to be accurate at all temperatures.

We have used two approaches to calculating the fields and temperatures that our tapes crossover from 3D behavior close to Tc to 2D behavior: To find crossover temperatures (in zero field), we have used $\partial B_{c2}(T,\pi/2)/\partial T|_{T\approx T_c}$ from the Klemm fits to find $\xi_c(0)$ together with $\xi_c(T) = \xi_c(0)(1-(T/T_c))^{-1/2}$ and the standard G-L relations to find the LD zero field crossover temperature. We have then used the data in Fig. 1 to find a zero-field Klemm crossover temperature. For all three tapes, we find that there are no solutions for the crossover temperature above zero Kelvin. The interpretation of these results is that the Klemm model predicts, in stark contrast to single crystal results, that these tapes are 3D at all temperatures. Our second approach for calculating 2D–3D crossover is to use the G-L relations, including $B_{c2}(T,\pi/2) = \phi_0/2\pi\xi_{ab}\xi_c|_{T\approx T_c}$, to lower temperatures as a useful way of estimating the temperature dependence of the effective coherence length in high fields. The method captures some of the physics of microscopic interactions in the tapes, namely that the diameter of the flux vortices (i.e., the coherence length) can change as a function of field with spin-orbit and paramagnetic effects. As discussed above, the LD condition for (RE)BCO then gives $B_{C2}(T^*) \approx \phi_0/\pi\gamma s^2 = 457/\gamma$ T. This suggests that there exists a dimensional crossover field which is determined by the anisotropy of the material and that materials with a higher γ will exhibit 2-D behavior at lower fields.

IV. DISCUSSION AND CONCLUSION

We have measured the temperature and angular dependence of B_{C2} in three state-of-the-art HTS tapes in high fields up to 35 T using ac susceptibility measurements. We have found that although B_{c2} in these tapes is very high, single crystal (RE)BCO have even higher values of B_{C2} at high temperatures. In particular $\partial B_{c2}/\partial T|_{T\approx T_c}$ and γ are very much higher in (RE)BCO single crystals than tapes [6] which leads to a 3D-2D crossover. We have analyzed our B_{C2} data using anisotropic G-L theory as well as Klemm's theory for layered superconductors and found no qualitative difference for an interlayer spacing $s = 1.2\,\mathrm{nm}$. Since the tapes are fabricated using methods that avoid including high-angle grain boundaries, we have applied these theories which make the implicit assumption that the tapes can be treated as single crystals [34]. The suppression of B_{C2} and γ in the tapes compared to single crystal values is then attributed to the disorder throughout the tape. Surprisingly we have found for all three (RE)BCO tapes that the Klemm model predicts that they remain 3D at all temperatures in zero field. By including additional microscopic interactions, the Klemm model opens the possibility of the core diameter reducing as a function of field and temperature. This leads to a crossover from 3D to 2D behavior in high fields above a crossover field $B^* = 457/\gamma$ T and perhaps a 2D region of phase space in the highest fields at low temperature. However, there are low angle grain boundaries and twin boundaries in the tapes that may be important regions of depressed superconducting parameters. Abrikosov pancake fluxons are then expected [35] and these microstructural features become regions of importance that suppress the superconducting properties that the Klemm model describes. However, although we cannot rule out that there are signals in the noise of our experiments, our onset susceptibility data shows no evidence for inter- and intragranular behavior. This favors the explanation that high J_C brings disorder in (RE)BCO.

From a technological point of view, the important result in this paper is that we have found 3D behavior in these tapes at all measured fields and temperatures up to 35 T. The coherence length for interplanar transport is large, the layers are strongly coupled and G-L and the Klemm models are both good approximation for the angle-dependence of B_{C2}. We expect to be able to distinguish which of these models is better at lower temperatures, higher angles and higher magnetic fields and conclude that concerns about using (RE)BCO tapes in high field applications because of a transition into 2D behavior can be set aside.

ACKNOWLEDGMENT

The authors thank Stephen Lishman and the members of the mechanical workshop in Durham. We acknowledge the support of the LNCMI-CNRS, member of the European Magnetic Field Laboratory (EMFL) and in particular Dr. Chaud and his colleagues as well as Assistant Professor Kohki Takahashi and the researchers and staff at HFLSM, Tohoku University for their help collecting the data.

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