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Thin film superconducting shields

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***Abstract*— To date, magnetic shields utilizing HTS materials mostly comprise bulk materials, usually shaped into a cylinder and then heat treated. We analyze the potential of thin film technology, whereby a layer of superconductor is deposited on a substrate, to fabricate magnetic shields. Films deposited on a curved surface are inevitably granular, leading to reduced critical current density compared to crystalline films. This limits the maximum field that can be screened. Granular films also have an enhanced penetration depth compared to the bulk value, which determines the maximum possible screening at applied fields below the maximum. We demonstrate the utility of a mutual inductance measurement to evaluate small flat test samples of a granular film for their potential as a shielding material in a more complex geometry. This measurement predicts both the maximum magnetic field that can be screened and the residual leakage at fields below the maximum. The tested film was produced by the Electrophoretic deposition of YBCO on a silver substrate. The maximum screening field was comparable to that obtained for a similar film on a cylindrical substrate. We also show comparable results from a crystalline YBCO film.**

***Index Terms*— Granular superconductors, Magnetic shielding, Superconducting materials, Superconducting thin films, YBCO**

I. INTRODUCTION

AN IDEAL superconducting shield can provide a high degree of shielding of external magnetic fields; for example, Symko et. al. [1] found that inside a YBCO cylinder an axial field fell off a factor ~exp(-3z/r) where z is distance from the end and r is the shield radius. This degree of shielding is only possible if the screening currents induced in the superconductor are less than or equal to the critical current and if the thickness of the superconductor is much greater than the penetration depth To date, high temperature superconductor (HTS) films with large critical current can only be produced on flat substrates. This follows from the requirement that the substrate have a well-ordered crystalline orientation. Even if the substrate is a flexible metallic tape the shapes one can generate are limited, and would not include a cylinder as a basic shielding structure. However, methods to produce HTS coatings on arbitrarily shaped substrates with random crystalline orientation are being investigated [2]. Generally this entails a coating with a precursor material which is subsequently heat-treated to produce a polycrystalline HTS coating. Since the grain boundaries are misoriented, the critical current density J_c of such a coating is expected to be far below that of single crystal films. This will determine the maximum field B_{max} that can be screened by the shield, since for example a cylinder exposed to an axial field B would induce an average shielding current density $J=B/\mu_o d$, where d is the superconductor thickness. It has been found [2] that YBCO coatings made by electrophoretic deposition onto silver substrates can shield fields up to 0.2 mT which could be useful in some applications.

When a superconducting coating is in the thin film limit with a field excitation below B_{max} the shielding will be worse than calculated in the thick superconductor limit. A general expression for the field, B, in a cylinder that is valid for any superconductor thickness d is [3]:

$$B/B_x=(2\lambda/r)/\sinh(d/\lambda) \qquad (1)$$

where B_x is the applied field. This shows that for a thick superconductor (d>>λ) the shielding can be nearly perfect (far from the end of the shield). For d≤λ this becomes

$$B/B_x\approx 2\lambda^2/rd. \qquad (2)$$

A second parameter that could limit the shielding effectiveness is the residual resistivity ρ of the superconductor. This arises from thermally activated motion of trapped flux vortices and is generally immeasurably small except very close to the transition temperature. However, it is related to the critical current density and could be significant in granular coatings. A generalization of (2) including a resistive contribution is [4]

$$B/B_x\approx[1/2\lambda^2+j/\delta^2]^{-1}/rd \qquad (3)$$

where δ is the skin depth associated with the film resistivity: $\delta^2=2\rho/\mu_o\omega$. In high J_c films, the contribution from this term is generally negligible except at very high frequency. Eq. 3 is the limiting value for screening effectiveness even at a great distance from the end of the cylinder and at a low enough B_x that the critical current is not exceeded.

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II. MEASUREMENTS OF PLANAR CRYSTALLINE FILMS

To predict the screening capability of a given film technology it is useful to be able to determine the penetration depth (and resistivity, if relevant) of small planar samples; these would represent an intermediate step towards developing a technology for more complicated shapes. This can be done [4] using a pair of small disc-shaped coils positioned on either side of a film specimen. The setup can be used both to determine the critical current density of the film and the transmission of an applied field at lower B_x where the induced current is smaller than the critical value.

To illustrate the former, we give results for a YBCO film of nominal thickness d=400 nm deposited on a single crystal substrate, at 77 K. Fig. 1 shows the dependence of the voltage at the pickup coil as a function of drive current at 1 kHz. We can observe a rather abrupt onset of voltage at an rms current I_{max}~ 45 mA; this is interpreted as the point where the screening currents in the film approach the critical value. The coil current can be related to the maximum current density in the film [7] and in this case we find $J_c \sim 2.5\times10^6$ A/cm^2. From this we can deduce the maximum field a shield of this material could screen is $B_{max}=\mu_o J_c d=12.5$mT.

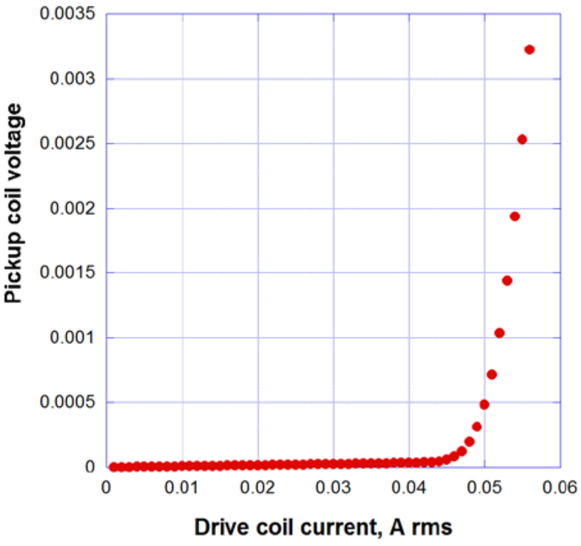

Fig. 1. Dependence of the voltage in a pickup coil as a function of current in a drive coil located next to a crystalline YBCO film. Both coils are much smaller than the dimensions of the flat substrate.

We are also interested in how well this film could screen smaller fields; for this we show the pickup coil voltage on a finer scale (Fig.2). The out of phase component is proportional to drive current up to values close to the critical value. This is a mutual inductance and has two origins: the first is transmission through the film due to a finite penetration depth. An expression for the mutual inductance [5] has a form similar to (3):

$$M=M'\lambda/\sinh(d/\lambda) \qquad (4)$$

where M' can be calculated based on the geometry of the coil setup and the number of turns. A second contribution to the mutual inductance is a stray coupling between the coils due to the finite extent of the sample. The latter can be estimated [4] and is found to be much less than the transmitted part. We can finally deduce a value λ(78K)=305 nm. The maximum screening a cylindrical film of the same material could provide would be $B/B_x=3.5\times10^{-5}$ if the radius is 1 cm using (2).

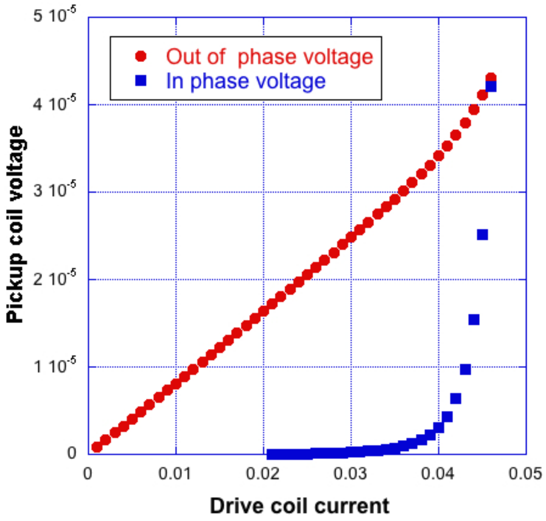

Fig. 2. Same as Fig. 1, but on an expanded scale for lower drive levels.

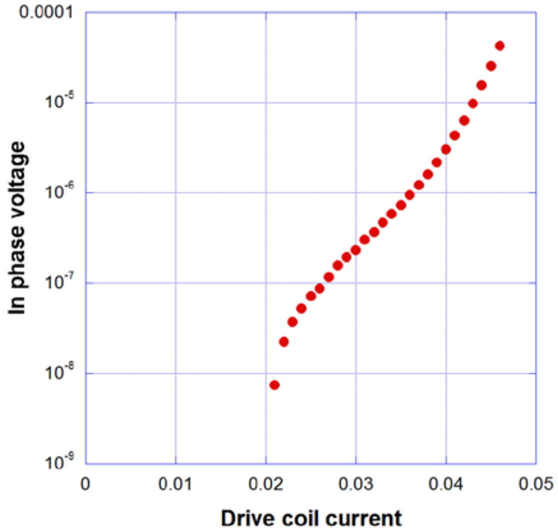

Fig. 3. Showing the in-phase voltage from Fig. 2 on a logarithmic plot.

For the example of Fig. 2 we see that the in phase transmitted voltage component is much smaller than the out of phase component; thus the screening effectiveness is governed by the penetration depth only. Fig. 3 is a log plot of the in phase component of the transmitted voltage. [A component linear in drive current has been removed, on the theory that it arises from a small phase error]. This component represents resistive loss in the superconductor; as expected from a flux creep perspective, it depends more or less exponentially on current over 2 decades. A dimensionless measure of this dependence is $[d(\ln V)/dI]I_{max}$~11.

III. MEASUREMENTS OF CYLINDRICAL GRANULAR FILMS

Of course the crystalline material discussed above could not be deformed into a useful form such as a cylinder, so the screening field is of academic interest only. As a second example we consider the data published for a cylindrical coating of granular YBCO deposited using the Electrophoretic deposition method (EPD) [2]. This has the potential for practical application as a magnetic shield. Here a similar measurement was made using a drive coil outside the cylinder and pickup coil inside. There is an abrupt onset of induced voltage at a specific value of drive field (their Fig. 7) similar to that seen in our Fig. 1. The maximum field for screening the interior was B_{max}~0.22 mT. At lower drive levels the detected field drops more or less exponentially with drive field (their Fig. 8), suggesting that residual resistivity is the controlling factor. The phase of the induced voltage was not given, so this can only be speculated. A dimensionless measure of this dependence is $B_{max}[d(\ln B)/dB_x]$~12. It is remarkable that for such different samples (thin crystalline vs. thick polycrystalline) this value is so similar.

The lowest attenuation they could detect (limited by instrumentation) was 5×10^{-6}. This represents an upper limit on the contribution of the penetration depth to attenuation. Using (2) we infer that $\lambda<8$ µm where we used a thickness d=40 µm. It should be noted that an effective penetration depth of this magnitude is not altogether improbable. In a granular material the effective penetration depth (as well as the critical current density J_c) is governed by the grain boundaries and can be much greater than the intrinsic London penetration depth that applies within a grain. A model that assumes Josephson junctions at each boundary gives the expression [8,9]

$$\lambda_{eff}^2=\phi_o/2\pi g\mu_o J_c \qquad (5)$$

where g is the size of the grains. Using this expression with the measured J_c~400 A/cm^2 and assuming a grain size g=1 µm would yield λ_{eff}~8 µm.

IV. MEASUREMENTS OF PLANAR GRANULAR FILMS.

We now discuss mutual inductance measurements at 77 K of a more recent YBCO film on a flat substrate using EPD. The $YBa_2Cu_3O_{7-x}$ (YBCO) thick film was deposited films on a planar Ag sheet using electrophoretic deposition (EPD) [10]. For this process YBCO powder (SCI Engineering Materials, USA) was milled for 2 hours using a planetary ball mill (PM 400/2, Retsch) with 1.5 mm zirconia grinding balls. A suspension was made with the milled YBCO powder (with 1-2 µm particle size) and 1-butanol. Branched polyethyleneimine (PEI, Sigma-Aldrich) was used as the surfactant. Twelve layers of YBCO were coated on the Ag substrate which were then are subjected to melt processing followed by oxygenation for 12 hours. More details about the sample preparation can be found in ref. 10.

One must operate at low enough frequency that the eddy current screening of the substrate is relatively small, 100 Hz for our measurements. Fig. 4 is similar to Fig. 1 except the drive current is replaced by the calculated maximum parallel field next to the film surface, as outlined in [4]. The pickup coil voltage is likewise converted to a maximum transmitted field. We see that B_{max}~0.22 mT, similar to the results obtained earlier for a cylindrical sample. In Fig. 5 the transmitted field at lower drive levels is shown. We cannot accurately distinguish between the in-phase and out of phase components since the substrate introduces a significant phase shift. The amplitude of the signal drops exponentially, although with a different constant $B_{max}[d(\ln B)/dB_x]$~5 than has been seen in earlier samples. Since the dependence is not linear we deduce that the screening is due to a resistive response as was true for the earlier EPD sample.

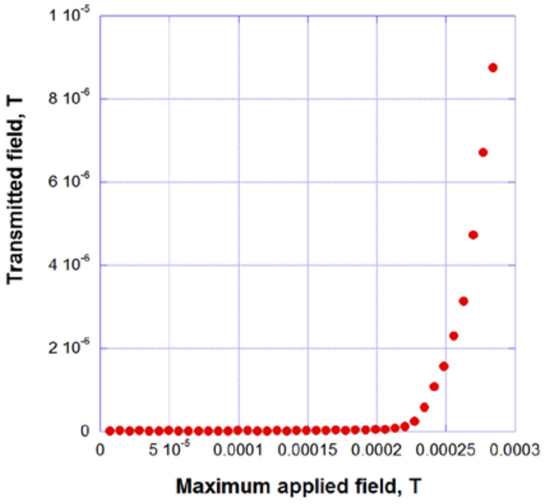

Fig. 4. Data similar to that of Fig. 1 for an EPD sample. The axes have been converted to maximum magnetic field. The frequency is 100 Hz.

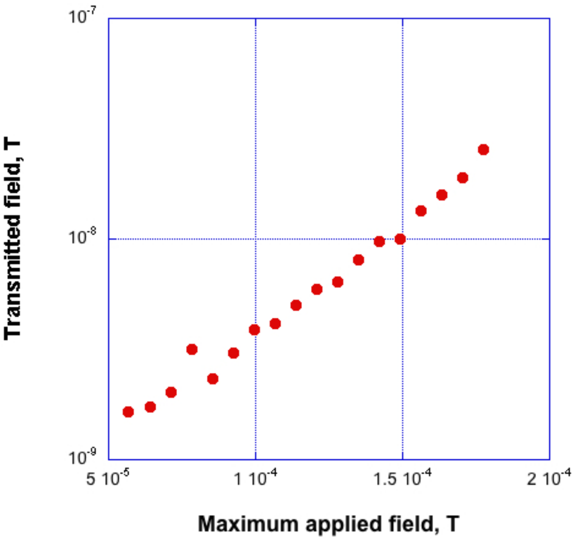

Fig. 5. A logarithmic plot of Fig. 4 at low drive levels.

V. CONCLUSIONS

To evaluate the potential of a technology to deposit HTS films on substrates of arbitrary shape, we propose an initial screening method using small area test samples on flat substrates. It uses a pair of small flat coils mounted on either side of the test sample. Mutual inductance measurements can predict the maximum external field that can be excluded as well as the residual transmitted field at lower external fields.

ACKNOWLEDGMENT

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