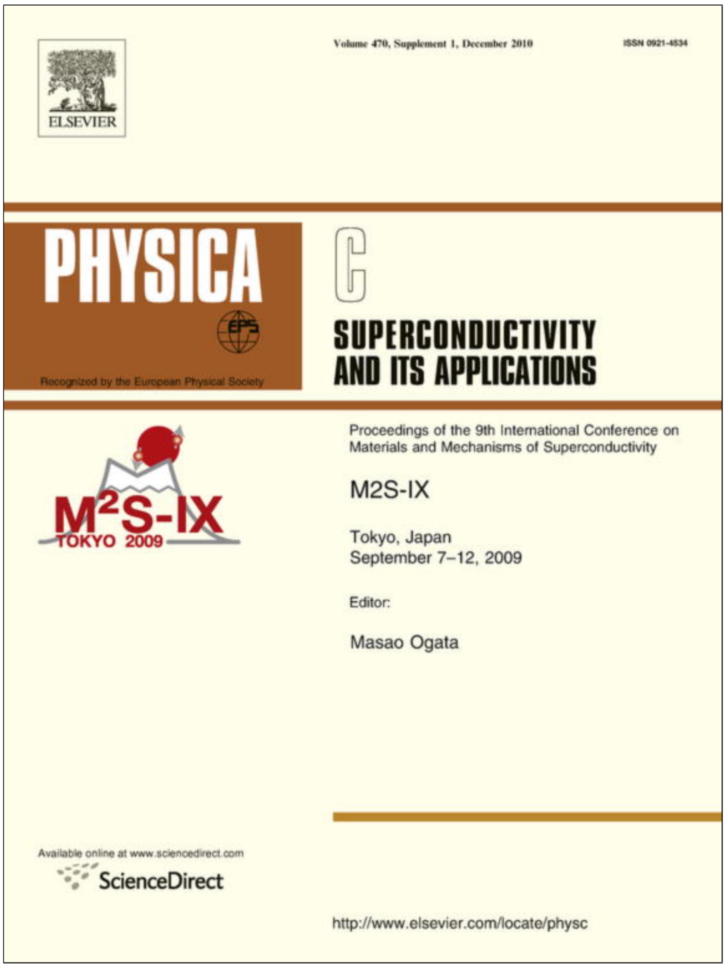

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Numerical extension of the power law $J_c(B)$ to zero field in thin superconducting films

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ABSTRACT

Numerical simulations of the current and field distribution in thin superconducting films are carried out for a given material law $J_c(B)$ and as a function of the applied field H, taking the sample's self-field into account. The dependence of the critical current density on the applied field $J_c(H)$ is computed for comparison with experiment, considering the geometry of transport measurements.

We show that extrapolating the high-field power law $J_c \propto B^{-\alpha}$ to the lowest fields results in a finite critical current at zero applied field $J_c(H=0)$, despite the singularity of $J_c(B)$. Moreover, particular features of the experiment, such as a low field plateau in $J_c(H)$, are reproduced and found to be determined by the self-field.

1. Introduction

When measuring the critical current density J_c in YBCO thin films as a function of the applied field H two distinct regimes are usually observed: starting from zero applied field, $J_c(H)$ first remains approximately constant and then crosses over to a power law $J_c(H) \propto H^{-\alpha}$ dependence. This observation is frequently discussed in terms of a transition from one pinning regime to another.

However, in order to extract information on pinning from, e.g., a transport measurement of J_c, it is essential to determine the critical current density as a function of the magnetic *induction* $J_c(B)$. Consequently, also the contribution of the self-field B_{sf}, which stems from the supercurrents in the sample, to $B = \mu_0 H + B_{sf}$ has to be taken into account. This is particularly important at low applied fields, i.e., when $\mu_0 H$ is comparable to or even smaller than B_{sf}, and it is a priori not clear if a measurement of $J_c(H)$ reveals the intrinsic $J_c(B)$ of the material.

2. Calculation

Numerical calculations similar to [1] allow establishing a relation between an arbitrary material law $J_c(B)$, which controls the current density distribution inside the sample, and the measured quantity $J_c(H)$, i.e., the average current density at a certain applied field. Here, the tape cross-section is divided into discrete elements and initially a current density $J_c(B = \mu_0 H)$ is assigned to each of them. After calculating the self-field distribution inside the sample the elements are updated according to $J_c(B = \mu_0 H + B_{sf})$. The procedure is iterated until a current density and field distribution is found, where all the elements satisfy $J_c(B)$, and the average current density $J_c(H)$ is computed. Varying H results in a $J_c(H)$ curve, which depends on the dimensions of the sample and on the material law, and enables a comparison between $J_c(H)$ and $J_c(B)$ for a sample with a specific cross-section (5 mm × 1 μm in all the simulations).

3. Results

Fig. 1 shows curves generated by $J_c(B) = J_1 B^{-\alpha}$ to analyse the significance of the power law $J_c(H)$ found in transport measurements on YBCO thin films (the parameters are $J_1 = 10^9$ A m^{-2} and $\alpha = 0.5$). At applied fields above 0.01 T, $J_c(H)$ coincides with $J_c(B)$, which demonstrates that in this field range a transport measurement reveals significant information on pinning. If, however, the applied field decreases to below 0.01 T, $J_c(H)$ deviates from $J_c(B)$ and remains approximately constant despite the strong $J_c(B)$ dependence. It follows that a transport measurement of $J_c(H)$ does not disclose the intrinsic $J_c(B)$ of the material in this field range.

Note, that the extrapolation of the high-field power law $J_c(B)$ to the lowest fields reproduces the field independent $J_c(H)$ observed in experiment without any additional assumptions. Further, $J_c(H=0)$ is finite regardless of the (unphysical) divergence of $J_c(B)$ at zero induction.[1] This is a consequence of the self-field: the transport current always maintains a certain magnetic induction

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[1] For stability reasons $J_c(B)$ is cut off during the iteration, but the final configuration satisfies $J_c(B)$ in the entire sample. For symmetry reasons it is necessary that either the number of rows or columns of the discretisation is even.

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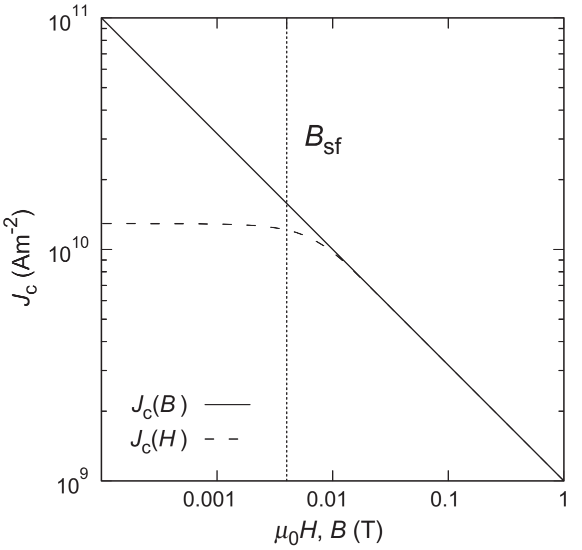

Fig. 1. At high fields (>0.01 T) $J_c(H)$ coincides with the material law $J_c(B)$ because the self-field of the transport current is negligible. If the applied field decreases to the magnitude of the sample's self-field, $J_c(H)$ is approximately constant and differs from $J_c(B)$.

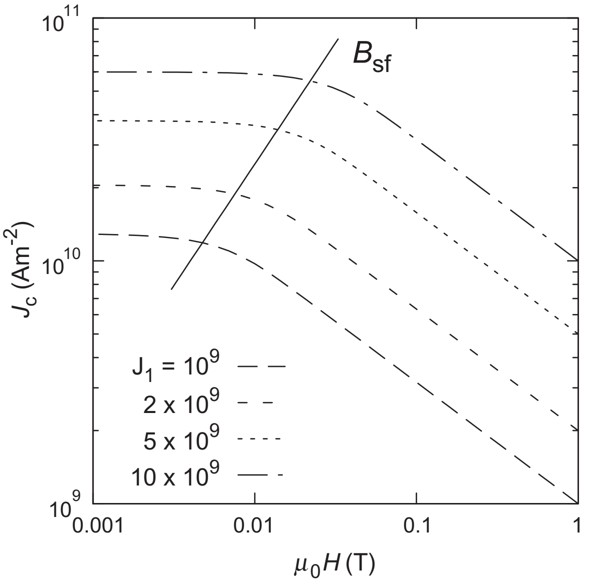

Fig. 2. Simulated $J_c(H)$ curves generated by a power law $J_c(B)$ with increasingly higher current densities. The transition into the self-field regime is correctly described by a simple equation.

inside the sample. As long as μ_0H is negligible compared to B_{sf}, the effect on the mean transport current density is insignificant and $J_c(H)$ is approximately equal to $J_c(H = 0)$. The behaviour changes when μ_0H becomes comparable to B_{sf}. If the applied field is further increased it gradually takes over until it governs the current distribution at high fields and, as a consequence, $J_c(H)$ coincides with $J_c(B)$.

The field, where the transition from self-field to external field controlled current transport occurs, can be quantified using the magnetic field scale introduced in [2] to describe magnetisation and transport currents in thin films

$$B_{sf} \approx \mu_0 c J_c / \pi. \quad (1)$$

Inserting the thickness $c = 1$ μm and the critical current density at zero applied field $J_c(H = 0)$ into (1) results in $B_{sf} \approx 4$ mT, which falls well in between the constant $J_c(H)$ at low fields and the high-field power law dependence (see Fig. 1).

It is clear from the above equation that the transition between the two $J_c(H)$ regimes is shifted to higher fields, when the sample supports higher current densities, an effect frequently observed in temperature dependent $J_c(H)$ measurements. Such an experiment is simulated in Fig. 2, which shows a set of $J_c(H)$ curves computed using increasingly larger values of J_1 to simulate the effect of lower temperatures. The transition into the self-field regime, where $J_c(H)$ becomes constant and differs from $J_c(B)$, is successfully described by (1). The fact that the sample thickness is the only free parameter in this equation provides an easy way to exclude self-field effects before discussing pinning.

4. Conclusion

The relation between the measured $J_c(H)$ dependence assessed in a transport experiment and the intrinsic $J_c(B)$ of the material was analysed by numerical calculations. The computations show that $J_c(H)$ and $J_c(B)$ significantly differ, if the applied field is comparable to or smaller than the field generated by the transport current in the sample. If the applied field is in this range, $J_c(H)$ remains approximately constant and does not reveal information on $J_c(B)$ at the same field. An expression, which depends only on the thickness of the sample, allows to ensure that the observed $J_c(H)$ reflects a material property and is not a self-field effect.

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