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Magnetization Measurements of Hard Superconductors under Dissipative Transport

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Abstract. The hysteretic magnetic flux dynamics of ceramic type-II superconductors under superimposed transport current cycles has been investigated.

Field cooled and zero field cooled experiments were carried-out on polycrystalline $YBa_2Cu_3O_{7-x}$ cylinders by using both temperature and applied field control, to drive the sample into the semi-reversible granular regime. The transport current magnitude was near and above the dissipative threshold. The interplay between shielding and transport due to vortex-pinning interactions, equilibrium magnetization effects, and diamagnetic/paramagnetic relaxation phenomena are shown to play an important role in the range of practical applications.

1. Introduction

Vortex matter interactions in pinned type-II superconductors is a complicated subject, in which a number of physical phenomena take place. Thus, one should consider the force between vortices and pinning sites [1], the crossing interactions between adjacent tilted vortices [2], the equilibrium properties of the flux line lattice, thermal excitations [3], and the influence of granularity in the case of high-T_c superconducting compounds (HTS) [4].

The aforementioned subjects are relevant to provide a quantitative description of realistic situations in which size effects, conduction currents and multicomponent fields within the superconductor are involved.

During the last decades, it has been shown that many observations related to the magnetic response of hard superconductors (including HTS) are well described in the general critical state (CS) framework [2, 5], occasionally modified by Meissner shielding effects (see for instance [6]).

In this work, we present new experimental data on $YBa_2Cu_3O_{7-x}$ cylinders when an externally controlled current, parallel to the applied field, is cycled reaching the dissipative regime.

Complementing previous work on HTS compounds [6, 7], we show that the influence of reversible magnetization must be reconsidered. In particular, our experimental results cannot be explained unless paramagnetic effects (PE) are included [8]. Moreover, a transition from *conventional* diamagnetic flux dynamics to paramagnetic evolution is reported for field cooled experiments.

2. Sample and apparatus

Cylindrical samples of $T_c \approx 91$ K were prepared from YBCO powder, using standard prescriptions for HTS. The specimens were isostatically pressed during 12 h, and sintered under O_2-atmosphere. The electric contacts were painted with Ag paste, and annealed during 10h at 840°C and 10h at 450°C.

As reported [7], a dedicated manual insertion utility probe and sample holder were designed to use in a commercial Quantum Design MPMS-5S (SQUID).

Simultaneous four-wire resistive (longitudinal transport) and inductive (axial magnetic moment) measurements can be performed without introducing distortions. Each sample was glued with varnish in the center of a 112 mm sample holder, fabricated with four twisted copper AWG32 wires (0.203 dia.)

Field cooled (FC) and zero field cooled (ZFC) experiments were carried-out using DC magnetic field in the range 0 - 150 mT ($H_{\max} \sim 10 H_{c1g}$), for $0.75 < T/T_c < 0.95$.

In the experiments with transport cycles, the bias current was applied subsequent to setting up temperature and field.

3. Experimental results

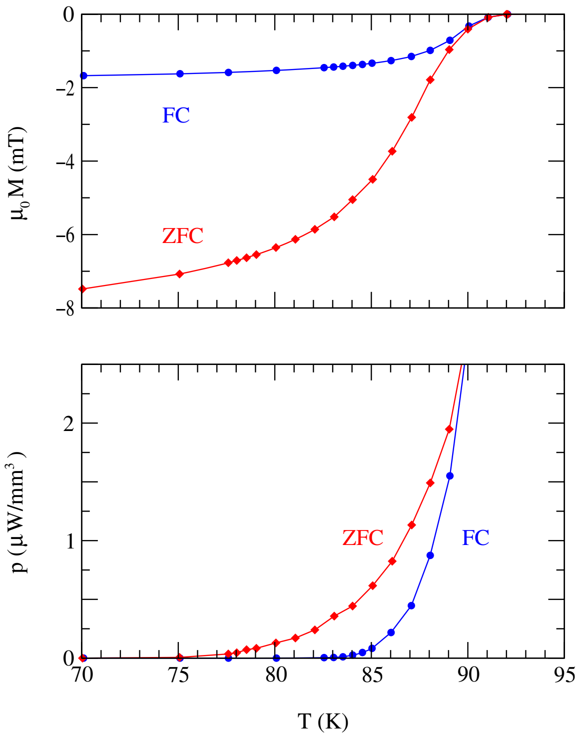

Figure 1. Magnetic moment per unit volume and specific dissipation as a function of temperature for $\mu_0 H = 13$ mT, $I = 100$ mA.

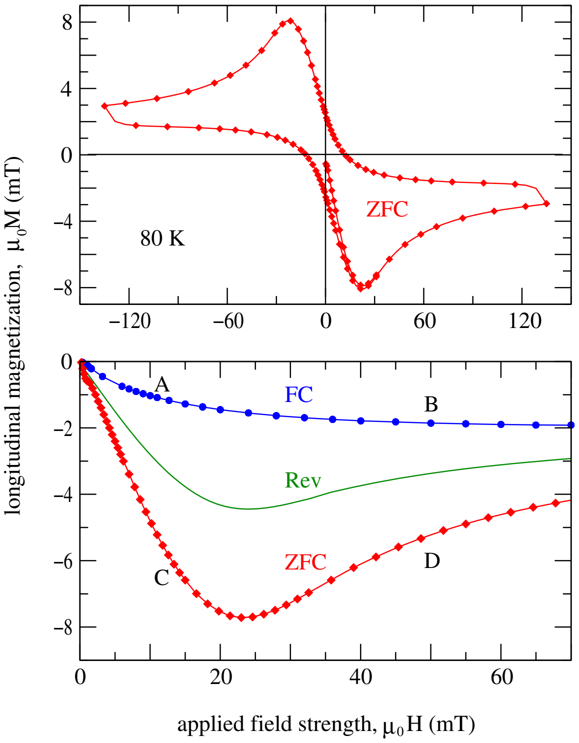

Figure 2. Inductive measurements ($I = 0$) vs. applied magnetic field at $T = 80$ K. Dotted curves indicate direct experimental values, whereas the reversible curve was obtained from the ZFC data.

Fig.1 combines the sample's diamagnetism together with transport losses in FC and ZFC experiments. Note the reduced non-dissipative transport capability in the ZFC situation. This property suggests a model in which transport and shielding current densities are not independently constrained.

As shown in Fig.2, the measured hysteresis loops are noticeably *compressed* into quadrants II and IV, indicating the relevance of equilibrium magnetization effects. In FC experiments the sample was heated above T_c for each field value.

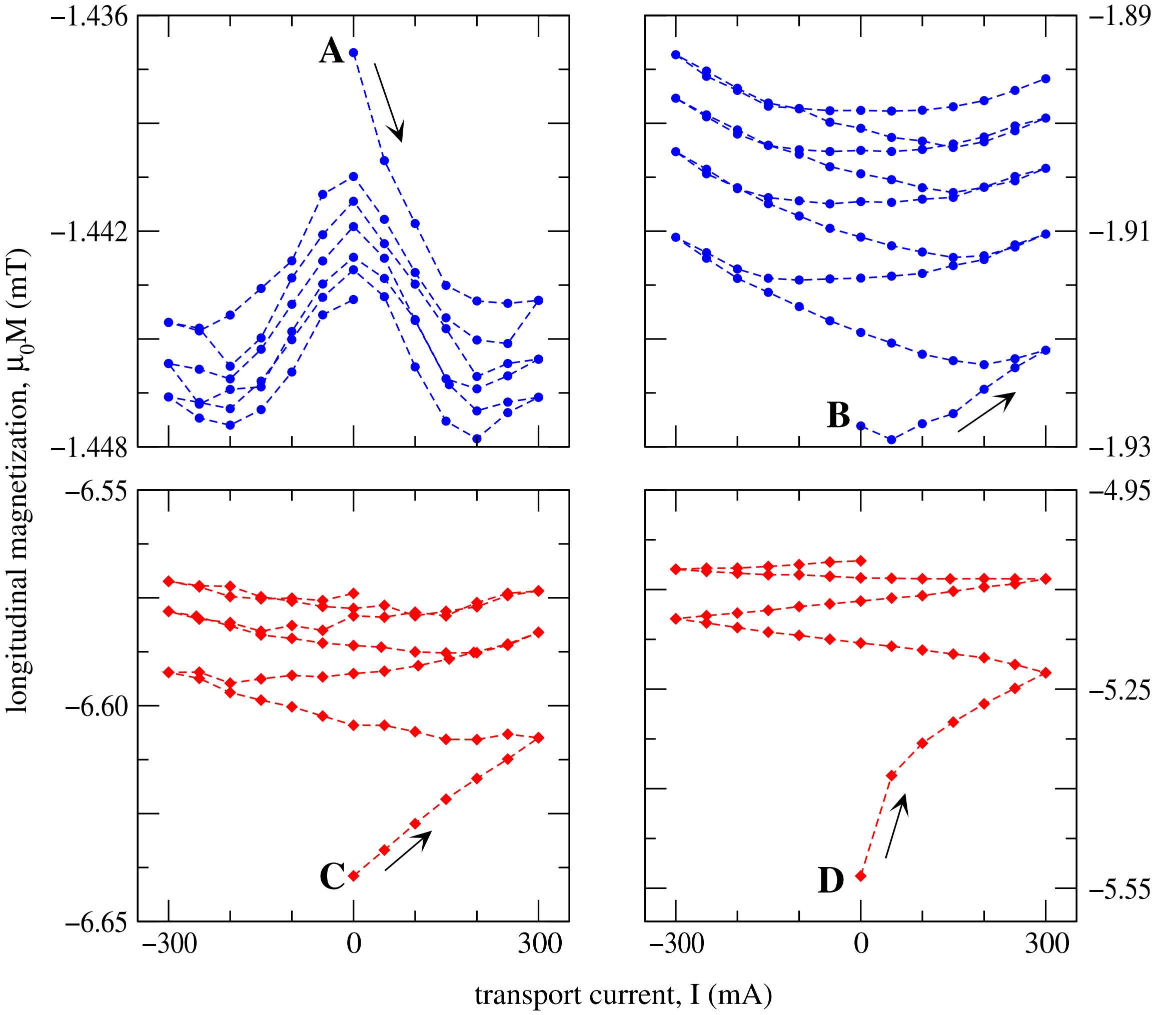

Figure 3. Summary of the magnetization vs. current cycles behavior in FC and ZFC experiments for selected fields, labelled A-D in Fig.2.

In subplots A, C, D of Fig.3, the so-called *magnetization collapse* [5, 7] towards the thermodynamic equilibrium state is observed. In subplot B instead, one can notice a remarkable FC *paramagnetic evolution* which drives the system away from the reversible curve.

4. Theoretical framework

We have used the variational statement of the CS theory [5]

$$\texttt{Min} \quad \frac{\mu_0}{2}\int_{\mathbb{R}^3} \|\vec{H}_{\mathrm{n+1}} - \vec{H}_{\mathrm{n}}\|^2 \quad \texttt{for} \quad \|\vec{J}_{\mathrm{n+1}}\| \leq J_c$$

with $\vec{H}_{\mathrm{n}}$ the magnetic field at the time layer n, and the inclusion of equilibrium magnetization effects by way of appropriate boundary conditions [6]. Fig.4 displays simulated FC and ZFC experiments for applied field $h \equiv H/(J_c R) = 2$ and transport current $i \equiv I/(J_c \pi R^2)$ in the range $-0.8 < i < 0.8$. Recall the flux dynamics towards the equilibrium limit.

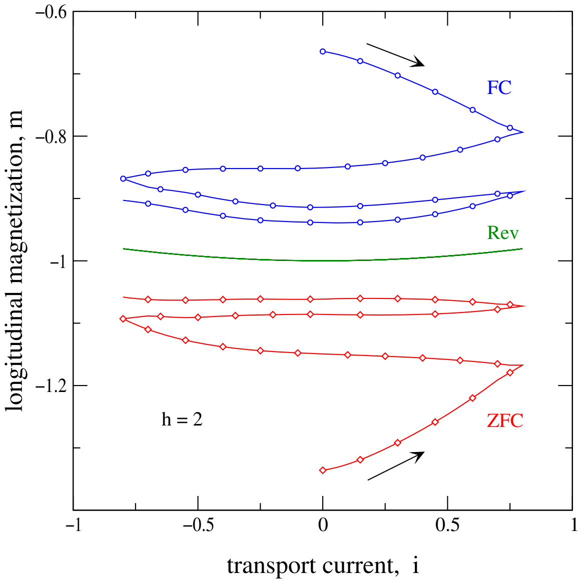

Figure 4. Theoretical magnetization vs. transport current, for FC and ZFC initial conditions. The reversible magnetiztion behavior is also displayed. Dimensionless units are used (see text).

5. Conclusions

Irreversible magnetization collapse towards the equilibrium state is reported in longitudinal configuration for field cooled and zero field cooled experiments. The generalized critical state theory reproduces the dynamics of the collapse.

Anomalous paramagnetic effects within the dissipative regime of transport measurements are reported. The induced flux dynamics drives the sample away from thermodynamic equilibrium. Time relaxation measurements (not shown) indicate that such observations can be explained in the framework of previous (only inductive) investigations [8, 9, 10].

Acknowledgments

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