DECOUPLING RESISTIVE ONSET FROM THE IRREVERSIBILITY FIELD IN HIGH-TEMPERATURE SUPERCONDUCTING COATED CONDUCTORS

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Abstract – The irreversibility field (H_{irr}) marks the boundary below which flux lines are effectively pinned, enabling large, dissipation-free currents in type-II superconductors. In early high-temperature superconductors (HTS), the onset of electrical resistance in transport measurements was empirically observed to coincide with H_{irr}, leading to the widespread practice of using resistive transition as a proxy for the irreversibility line. This equivalence has since become a standard evaluation protocol, even for modern engineered materials. However, we demonstrate that this assumption no longer holds for REBCO-based coated conductors. Using combined magnetization and transport data from commercial tapes, we show a significant decoupling between $\mu_0 H_{irr} \approx 2.7$ T and the resistive onset at ~6.4 T at 77 K—near the magnetically measured upper critical field H_{c2}. Relying solely on low-current transport measurements risks overestimating performance and compromising device reliability. Our findings call for a paradigm shift in the characterization of advanced HTS materials, emphasizing the necessity of complementary magnetic and electrical techniques to accurately assess their applicability limits.

INTRODUCTION

The discovery of high-temperature superconductivity (HTS) in cuprates in 1986 [1] was soon followed by magnetic measurements revealing a critical distinction: while diamagnetism persisted over a wide range of fields and temperatures, magnetic hysteresis—indicative of flux pinning—appeared only below a certain boundary [2], later termed the irreversibility field $H_{irr}(T)$. This observation highlighted a crucial insight: the mere existence of superconductivity does not guarantee its practical utility as without effective pinning, vortex motion causes dissipation, rendering the material unable to carry large, lossless currents. Thus, H_{irr}, not the thermodynamic upper critical field H_{c2}, defines the operational limit for applications.

In the context of early polycrystalline HTS samples transport measurements often showed that the onset of electrical resistance coincided closely with H_{irr} determined magnetically. In some cases, resistive transitions even preceded the onset of irreversibility [3], likely due to percolation current paths limited by weak grain boundaries. These observations reinforced the assumption that the resistive transition could serve as a reliable proxy for the irreversibility line—a convention that became deeply embedded in experimental practice.

Modern second-generation (2G) HTS coated conductors based on REBCO ($REBa_2Cu_3O_{7-\delta}$, RE = rare earth) with nanoscale defect control and kilometer-scale uniformity represent a paradigm shift. Their performance is no longer limited by random grain boundaries, decoupling the mechanisms of magnetic hysteresis phenomena and resistive transition. Here, we show that in commercial 2G-HTS tapes, the resistive onset occurs at ~6.4 T at 77 K, far exceeding the magnetically determined $\mu_0 H_{irr} \approx 2.7$ T.

METHODS

Samples. Measurements were performed on a commercial second-generation high-temperature superconducting coated conductor supplied by S-innovation. The tape architecture consists of a textured metallic substrate (Hastelloy-type alloy, ~40 μm thick), followed by buffer layers (total thickness ~100 nm) providing epitaxial template and diffusion barrier properties. The superconducting layer is composed of YBCO with a nominal thickness of 2.4 μm, deposited via pulsed laser deposition method (PLD). The structure is capped with a 3 μm silver layer for protection and an additional 5 μm copper electroplated layer for thermal and electrical stabilization. The sample was cut into a 5 mm × 1 mm bridge for transport measurements and a D = 3 mm circles for magnetization studies.

Transport Measurements. Electrical resistivity was measured using a standard four-probe DC method in a Quantum Design Physical Property Measurement System (PPMS), equipped with a 13 T superconducting magnet. A constant bias current of I = 20 μA (was applied, and the voltage drop across a 2 mm potential span was recorded as a function of applied magnetic field, swept from 0 to 13 T at a rate of 0.1 T/min, with the field oriented perpendicular to the tape surface ($H \parallel$ c-axis).

Magnetization Measurements. DC magnetization hysteresis loops were acquired using a vibrating sample magnetometer (VSM) option of the PPMS. The sample was mounted on a non-magnetic quartz rod with low-tack adhesive, ensuring minimal mechanical torque. Measurements were conducted at T = 77.4 K, with the magnetic field swept from +10 T to −10 T and back to +10 T. The linear paramagnetic signal at high magnetic fields was subtracted from the data. The irreversibility field H_{irr} was determined as the field at which the forward and reverse branches of the $M(H)$ loop converged within the noise level of ±6e-8 A·m².

RESULTS AND DISCUSSION

The core result of this study is illustrated in Figure 1, which presents a direct comparison between the field-dependent electrical resistance and magnetization of a commercial REBCO-based coated conductor measured at T = 77.4 K with the magnetic field applied perpendicular to the tape surface (H ∥ c-axis). This simultaneous representation reveals a striking discrepancy between two fundamental markers of superconducting behavior: the onset of measurable resistance in transport and the irreversibility field derived from magnetic measurements. The DC magnetization exhibits pronounced hysteresis at low fields, confirming strong flux pinning. The irreversibility field H_{irr} is defined as the field at which the ascending and descending branches of the $M(H)$ loop converge within the measurement noise, indicating the transition to fully reversible flux penetration: $\mu_0 H_{irr} \approx 2.7$ T at 77.4 K.

In stark contrast, Figure 1 also shows that the four-probe voltage remains below the detection threshold up to approximately 6.4 T. Only beyond this field does a finite resistance emerge. This value aligns closely with the upper critical field (H_{c2}), estimated from the suppression of diamagnetism at higher fields, further supporting its identification as the true thermodynamic boundary of superconductivity. Thus, there exists a wide intermediate regime—between 2.7 T and 6.4 T—where the material is both superconducting (zero resistance and diamagnetic) and magnetically reversible (no hysteresis).

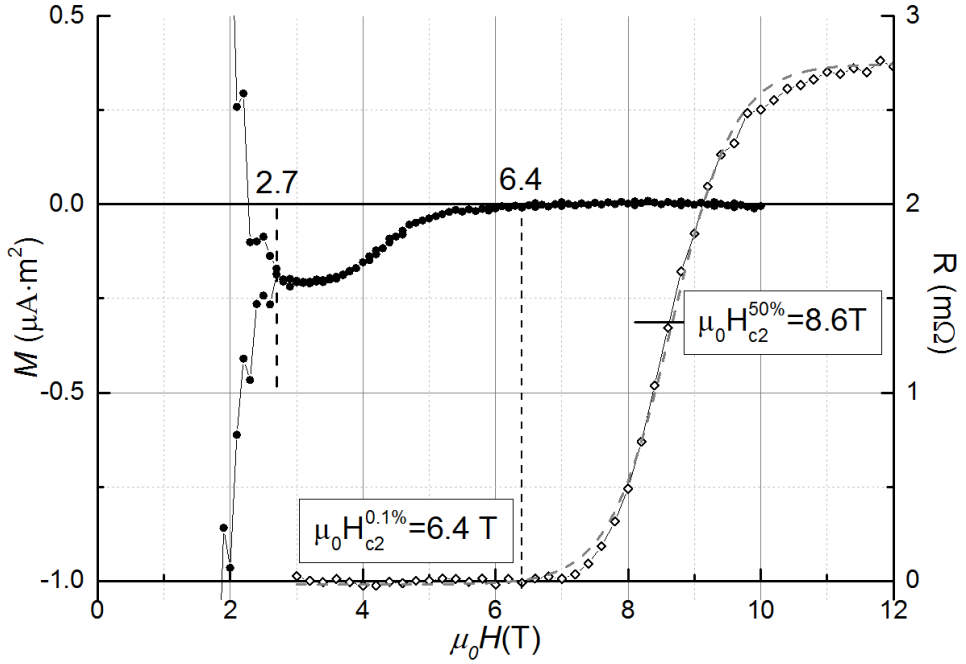

Fig 1. Magnetic hysteresis and resistive transition in a commercial REBCO coated conductor at 77.4 K with the magnetic field perpendicular to the tape surface. The

irreversibility field, $\mu_0 H_{irr} \approx 2.7$ T, is defined by the collapse of magnetization hysteresis (left axis), while resistive onset occurs at ~6.4 T (right axis), near the complete suppression of diamagnetism. The 50% normal-state resistance is reached at 8.4 T.

Thus, the resistive onset in modern coated conductors correlates closely with the suppression of the diamagnetic response, occurring near the upper critical field H_{c2}, while being significantly higher than the irreversibility field H_{irr}. The simultaneous loss of diamagnetism and onset of resistance is unlikely to be coincidental. Such a behavior is not unique to REBCO: similar alignment has been documented in conventional practical superconductors such as Nb-Ti [4, 5]. This consistency across a wide range of materials suggests that H_{irr} phenomenology may be a more universal feature of practical superconductors than is commonly thought.

Yet, many recent studies (see, for example [6, 7]) continue to use the resistance onset as the proxy for H_{irr} estimation in coated conductors, perpetuating an outdated methodology, applicable to granular materials. Our data show that this leads to a systematic overestimation of performance characteristics.

CONCLUSION

The widespread assumption that the onset of electrical resistance coincides with the irreversibility field (H_{irr}) in high-temperature superconductors has long served as a practical benchmark for defining the upper limit of usable superconducting performance. However, present study demonstrates that this equivalence does not hold for modern coated conductors.

In engineered REBCO-based tapes, where nanoscale structural control enables high critical current densities over kilometer-length scales, magnetization measurements reveal an irreversibility field significantly lower than the field at which resistance first appears in transport measurements. Data from commercial S-innovation tapes show $\mu_0 H_{irr} \approx 2.7$ T at 77 K from magnetic hysteresis, whereas resistive onset occurs near 6.4 T, close to the magnetically measured upper critical field H_{c2}. Thus, relying solely on low-current transport measurements to assess the operational limits of coated conductors' risks overestimating their performance envelope, potentially leading to design failures in real-world applications such as high-field magnets or power transmission systems.

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