08

# Asymmetry of critical current angular dependences of coated conductors as a tool for hysteresis loss optimization

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The critical current angular dependences and hysteresis losses of a DyBCO-based coated conductor are studied. It is found that the asymmetry of the critical current angular dependences decreases with increasing magnetic field and/or electric field criterion. The areas of the magnetic moment hysteresis loops differ by 15−20% for equally deviated from the normal angles, indicating a proportional difference in magnetization losses. Thus, even at high fields, where the critical current angular dependences are apparently symmetric, the asymmetry manifests itself through differences in hysteretic losses.

**Keywords:** DyBCO, anisotropy, asymmetry, angular dependence, hysteresis losses.

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## 1. Introduction

The progress of recent decades in the production of second-generation high-temperature superconducting wires (HTSC-2), also known as REBCO-based composite HTSC tapes ($RE\mathrm{Ba_2Cu_3O_{7-\delta}}$, $RE$ — rare earth element) or „coated conductors“, has opened up new perspectives for many practical applications [1]. One of the key features of HTSC-2 tapes, compared with traditional low-temperature technical superconductors (LTSC), is a much more pronounced anisotropy of the current carrying capacity. In many cases, not only the direction of the external field, but also the direction of the Lorentz force acting on the vortex structure plays an essential role for HTSC [2]. This is manifested, for example, in the so-called incomplete diode effect [3], in which the value of the critical current $I_c$ varies depending on the polarity of the transport current [2]. Using this effect simplifies the rectification of alternating current in a superconducting electrical circuit, which reduces the weight and cost of superconducting equipment [4]. Another feature of the anisotropy of composite HTSC tapes is the asymmetry of the angular dependences of the critical current [5]. This phenomenon also has important practical consequences, as it allows optimizing the operating parameters of superconducting devices [6,7]. The microscopic reason for the asymmetry is the inclination of the crystallographic plane $ab$ with respect to the HTSC-2 plane of the tape [2,8]. This inclination is often observed in HTSC tapes in which the texture is obtained using auxiliary ion etching [9]. However, the resulting asymmetry is determined not only by this slope, but also by the complex physics of vortex matter and its motion and pinning mechanisms. As a result, there may be a situation where there is no significant asymmetry, although the deviation of the plane of the $ab$ from the plane of the tape is significant. In this paper, we demonstrate an example of a similar situation and investigate the consequences for hysteresis losses during magnetization reversal.

## 2. Experiment

The samples of the composite HTSC tape were made at NRC „Kurchatov Institute“ [10]. DyBCO ($\mathrm{DyBa_2Cu_3O_{7-\delta}}$) [11] grown by pulsed laser deposition (PLD) on a steel substrate with YSZ (yttria-stabilized zirconia) and $CeO_2$ buffer layers was used as the superconducting layer. The critical current $I_c$ was determined by the conventional criterion $1\,\mu$V/cm based on the volt-ampere characteristic (VAC) recorded by the standard four-contact method in a liquid nitrogen medium ($T = 77\,\mathrm{K}$). The angular dependences $I_c(\theta)$ were extracted from processing a series of waveforms measured at different orientations of the external magnetic field, determined by the angle $\theta$, while maintaining the orthogonality of the magnetic field and the transport current. The angle $\theta$ was measured from the plane of the tape, and varied in the full 360° range with positioning accuracy no worse than 0.5°. The critical current according to alternative electric field criteria ($0.01\,\mu$V/cm and $100\,\mu$V/cm) was calculated from a power-law approximation of the volt-ampere characteristics: $I_c^{0.01} = I_c(0.01)^{1/n}$ and $I_c^{0100} = I_c(100)^{1/n}$, where $n$ is the exponent of the power dependence of the VAC.

Magnetic moment hysteresis loops $M(H)$ were studied on a vibrating magnetometer (LakeShore 7400 Series VSM) in fields up to 1 T at a temperature of 77 K. The samples had a size of $4\times12$ mm and were oriented at different angles to the direction of the magnetic field, similar to Ref. [12].

## 3. Results and discussion

Figure 1 shows the angular dependence of the critical current for various magnitudes of the external magnetic field. A significant dependence of the critical current $I_c$ on the polarity of the transport current is observed for fields of 0.1 T and 0.3 T. With the polarity marked with closed symbols in the figure, the peak near $\theta = 0^\circ$ is higher than the peak near $\theta = 180^\circ$. When the current direction is inverted (open symbols), the peak height ratio reverses: the peak near $\theta = 0^\circ$ is lower than the peak near $\theta = 180^\circ$. It should be noted that the magnitude of the critical current does not change with simultaneous inversion of both the field direction **H** (which corresponds to the rotation of the sample by 180°) and the transport current **j**. And when only one of these two vectors is inverted, the magnitude of the change $I_c$ does not depend on which vector is inverted. This behavior indicates a true dependence not on the polarity of the current, but on the direction of the Lorentz force:

$$\mathbf{F}_L = [\mathbf{j}\times{}_0\mathbf{H}], \quad (1)$$

$\mathbf{F}_L$ is the Lorentz force, **j** is the current density, $\mu_0$ is the magnetic constant, **H** is the external magnetic field.

The magnitude of the anisotropy with respect to the Lorentz force decreases with an increase in the external field, and at 1 T, the angular dependence for the two polarities of the transport current practically coincides.

Another feature that also decreases as the field increases is the asymmetry. This effect is most noticeable in the nonzero derivative of the angular dependence at $\theta = 90^\circ$, when the external field is directed along the normal to the HTSC tape. As a result, the values of the critical current for two directions of the magnetic field deviating from the normal by the same (complementary) angle $\theta'$ do not coincide: $I_c(90^\circ - \theta') \neq I_c(90^\circ + \theta')$.

In the framework of the model proposed earlier in Refs. [2,13,14], the asymmetry of the angular dependence is interpreted as a manifestation of the dualism of the anisotropy of the current-carrying capacity: not only with respect to the direction of the magnetic field, but also with respect to the direction of the Lorentz force. The angular dependence $I_c(\theta)$ is approximated by the formula [15]:

$$I_c(\theta) = I_c^0\sqrt{\frac{[k^L\cos\theta]^2 + [\sin\theta]^2}{[k^U\cos(\theta-\theta_0)]^2 + [\sin(\theta-\theta_0)]^2}}, \quad (2)$$

where $I_c^0, k^L, k^U, \theta_0$ are the fitting parameters. The parameter $\theta_0$ is responsible for the degree of asymmetry, and characterizes the relative rotation of the energy and dimensional bodies of the cooperative potential well [2]. The lines in Figure 1 correspond to an approximation of the experimental data in accordance with formula (2). The selected parameter $\theta_0$ was $-5.7$; $-4.7$; $-4.4$; $-3.2$ for fields 0.1 T; 0.3 T; 0.5 T; 1 T, respectively. Thus, a steady trend towards a decrease in the absolute value of the parameter $\theta_0$ corresponding to a decrease in asymmetry

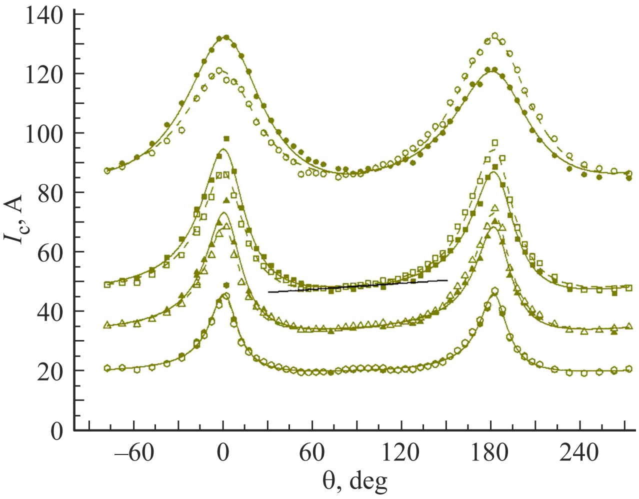


**Figure 1.** The angular dependence of the critical current for fields 0.1 T; 0.3 T; 0.5 T and 1 T (from top to bottom). For 0° and 180°, the field is oriented in the plane of the tape, for 90° and 270°, the field is directed along the normal to the tape. The open and closed symbols correspond to two opposite polarities of the current. Black line — tangent at point $\theta = 90^\circ$ for angular dependence at 0.3 T.

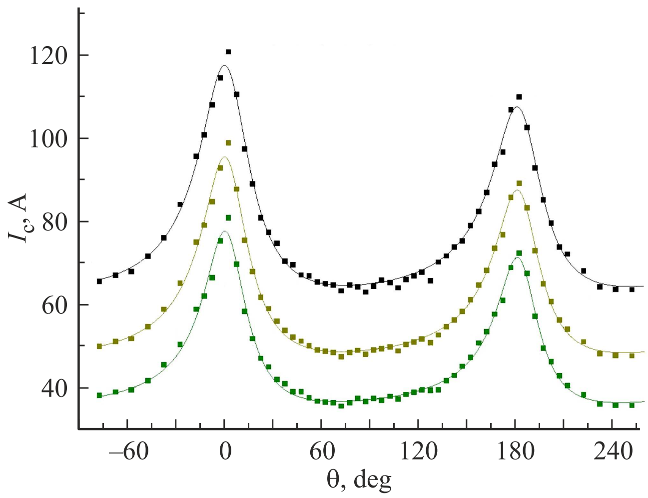


**Figure 2.** The angular dependences of the critical current in the field are 0.3 T for electric field criteria 0.01; 1; 100 $\mu$V/cm (from bottom to top).

is observed with an increase in the magnetic field. This trend is shown in Figure 1 as the tangent at point $\theta = 90^\circ$ approaches the horizontal with increasing field.

Figure 2 shows the angular dependences in the field 0.3 T rearranged for critical currents determined by the criteria 0.01 $\mu$V/cm; 1 $\mu$V/cm; 100 $\mu$V/cm. The parameter $\theta_0$ for these dependencies is $-5.5$; $-4.7$; $-4.1$, respectively. As the electric field criterion increases, the asymmetry decreases.

Thus, the difference in critical currents for complementary (i. e., equally different from normal) angles $I_c(90^\circ - \theta')$ and $I_c(90^\circ + \theta')$ significantly depends on the magnitude of the

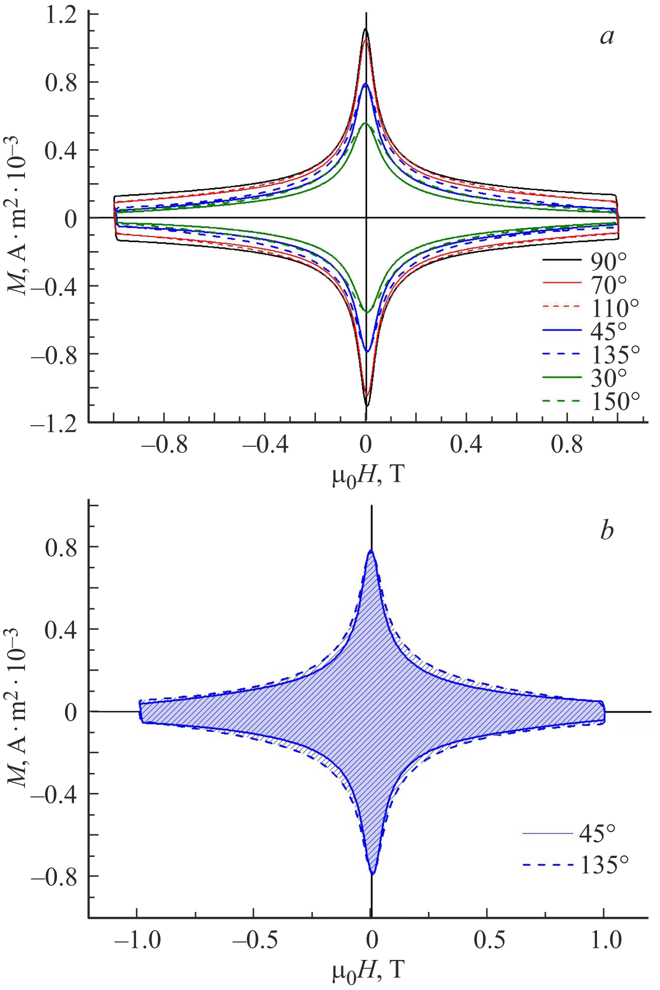


**Figure 3.** *a* — hysteresis of magnetization loops for a series of complementary angles; *b* — comparison of the areas of magnetic moment hysteresis loops for angles 45° and 135°.

magnetic field and the selected electric field criterion. To assess the effect of asymmetry on the magnitude of energy losses during remagnetization, magnetic moment hysteresis loops $M(H)$ were studied (Figure 3).

For complementary angles, the magnitudes of the magnetic moment in the zero external field completely coincide, which confirms the correctness of the calibration and the absence of a systematic error in the positioning of the sample. In the field $\sim 1$ T, the difference in the width of the loops and the magnitude of the magnetic moment is also insignificant, which corresponds to the previously made observation of the almost symmetrical behavior of $I_c(\theta)$ in the external field 1 T. However, differences appear in the range from 0 T to 1 T, and the areas of the hysteresis loops for complementary angles differ by 15–20 %. This behavior is in agreement with the pronounced asymmetry of angular dependencies in the fields of 0.1 T, 0.3 T and 0.5 T.

Thus, in a sufficiently strong magnetic field (in this case, more than 1 T), the value of the critical current remains identical for complementary angles, however, during remagnetization, the hysteresis losses differ by 15 %–20 % in accordance with the area of the hysteresis loops. As a result, even in the absence of an obvious asymmetry at $I_c(\theta|\mu_0 H = 1\,\text{T})$, it still significantly determines operational characteristics. Taking this effect into account when designing superconducting devices makes it possible to significantly reduce energy losses due to the optimal spatial orientation of the tape without modifying its physical parameters.

## 4. Conclusion

The angular dependences of the critical current and magnetic moment hysteresis loops in DyBCO-based composite HTSC tapes have been studied. The anisotropy of the current-carrying capacity is shown not only with respect to the direction of the magnetic field, but also with respect to the direction of the Lorentz force. The degree of asymmetry of the angular dependences decreases both with an increase in the magnetic field and with an increase in the electric field criterion. In sufficiently large magnetic fields, the asymmetry weakens until it completely disappears, which creates the illusion of symmetry. However, the magnetic moment hysteresis loop areas for complementary angles retain differences of 15–20 %, indicating proportional differences in magnetization reversal losses. Thus, the asymmetry manifested in small fields remains important for the design of energy-efficient superconducting devices, even when operating in high magnetic fields.

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### Conflict of interest

The authors declare that they have no conflict of interest.

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