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Magnetization and Flux Capture in a Superconducting Ring Made of High-T_c 2G Tape

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Abstract. This article presents a theoretical examination of magnetization processes and magnetic flux capturing in a superconducting ring. Additionally, experimental investigations of magnetic flux trapping in a ring made of second-generation high-temperature superconducting tape were performed. The obtained experimental results are in excellent agreement with the theoretical model. Furthermore, the critical current in zero magnetic field was measured using a well-established non-contact method based on the capture of magnetic flux within the ring, and these data align with manufacturer-provided values. The method for determining the critical current was further modified by applying a local magnetic field to a small region of the ring. This modification allowed for the study of the critical current dependence on the magnitude and orientation of the magnetic field, providing a straightforward and reliable means of determining the critical current and its anisotropy.

Keywords: superconductivity,high-temperature superconducting tape,superconducting ring,flux capture,critical current,anisotropy.

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Second-generation high-temperature superconducting (2G HTSC) tapes, characterized by high critical current at liquid nitrogen temperature, find applications as cables, transformers, current limiters, and others [1]. One of the key parameters of 2G HTSC tapes is the critical current, denoted as I_c, and its dependence on the value of magnetic field H and field orientation relative to the tape plane (α). To determine the critical current, the resistive method is widely used, providing highly accurate values of I_c(H, α). The use of the resistive method for 2G HTSC tapes with high critical currents requires creating low-resistance current contacts with minimal heat dissipation to the thin superconducting layer (typically 1-2 μm) covered with normal conducting layers. Therefore, non-contact methods for measuring I_c(H) are more favorable. A well-known non-contact method is the measurement of superconductor magnetic field dependence of magnetization M(H) and calculation of critical current from magnetization hysteresis. However, the use of this method relies on the applicability of the critical state model and leads to noticeable errors at low fields [2]. Another non-contact method to determine I_c, which is the focus of this study, uses the capture of magnetic flux in a superconducting ring, allowing the precise determination of the maximum dissipationless current in the tape. This method does not rely on any specific models but requires the creation of a continuous superconducting ring. At a temperature below the critical temperature (T_c) of the superconducting material, a magnetic

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flux is introduced into the ring's cavity, inducing a current within the HTSC tape that generates a magnetic flux opposing the applied flux. By measuring the magnetic field of this current the value of current can be calculated. This non-contact method for measuring critical currents is well-established and has been employed in several studies [3–5].

Rings made of 2G HTSC tapes are used for the design of magnetic systems for various purposes [6–8]. In these studies, significant attention was paid to determining the critical current of the tape and its dependence on the magnetic field. More information about the process of penetration and capture of magnetic flux is contained in the complete hysteresis curve of the magnetic field dependence of the ring magnetization. Previously, the hysteresis dependence of the magnetization of a bulk 2G HTSC ring on the flux of an internal solenoid was discussed in [5].

In the present work we analyze the magnetization curve of a superconducting ring and perform experimental studies of the penetration and capture of magnetic flux within a ring made from 2G HTSC tape produced by SuperOx. This study allowed us to determine the tape critical current dependences on the magnitude and orientation of the magnetic field with respect to the tape plane. In the designed setup an elongate solenoid is placed inside the ring, and at $T < T_c$, a current is introduced into the solenoid to generate magnetic flux within the ring. Subsequently the solenoid turns off, some magnetic flux is captured in the ring and the field of the ring current is recorded by Hall sensor situated in the ring center.

1. Penetration and capture of magnetic flux in a 2G HTSC tape ring

The process of flux penetration and capture in the ring is based on the ability of a superconducting ring to preserve the enclosed magnetic flux until the critical current is reached. This process is schematically illustrated in Figure 1a, where the dependences of the magnetic flux created by the ring's current (Φ_{ring}, blue) and the total magnetic flux $\Phi_\Sigma = \Phi_{ring} + \Phi_{sol}$ (red) on the flux created by the solenoid (Φ_{sol}) are depicted.

As the magnetic flux generated by the solenoid (Φ_{sol}) increases, a current I arises within the superconducting ring, creating a magnetic flux $\Phi_{ring} = I * L_{ring}$, where L_{ring} is the inductance of the ring. In the initial part of the dependence, the total magnetic flux $\Phi_\Sigma = \Phi_{ring} + \Phi_{sol} = 0$, that is complete compensation of the applied magnetic flux. This complete compensation persists until the magnetic flux reaches $\Phi_{sol} = \Phi_c$, where $\Phi_c = I_c * L_{ring}$, and I_c represents the tape critical current at the given temperature. If, at this point, the solenoid current is reduced to zero, the ring's current also decreases to zero, and no flux capture occurs in the ring. However, if the solenoid flux is increased beyond Φ_c, the ring's flux Φ_{ring} remains constant, as the ring current reached its maximum value I_c, and the total flux Φ_Σ starts to increase. The captured flux in the ring (Φ_{sol} switched off) also increases, reaching its maximum at $\Phi_{sol} = 2\Phi_c$. This corresponds to the change in the ring's current from $-I_c$ to $+I_c$. If the solenoid flux decreases from even higher values, the captured flux in the ring remains constant at Φ_c.

A similar reasoning of magnetization and flux capture in the superconducting ring with negative Φ_{sol} values allow to construct the full hysteresis dependence of the ring's magnetization on the magnetic flux generated by the solenoid. The analysis of hysteresis magnetization allows us to obtain the relation between the captured magnetic flux in the ring and the magnitude of the flux initially created by the solenoid and subsequently reduced to zero (Fig. 1b).

2. Experiment

The rings were created from the 12 mm wide 2G HTSC tape (SuperOx). The tape critical current, as specified by the manufacturer, is $I_c = 514$ A at the liquid nitrogen temperature ($T = 77$ K). Using a 0.1 mm thick diamond disc, a longitudinal cut with a length of 10 cm was

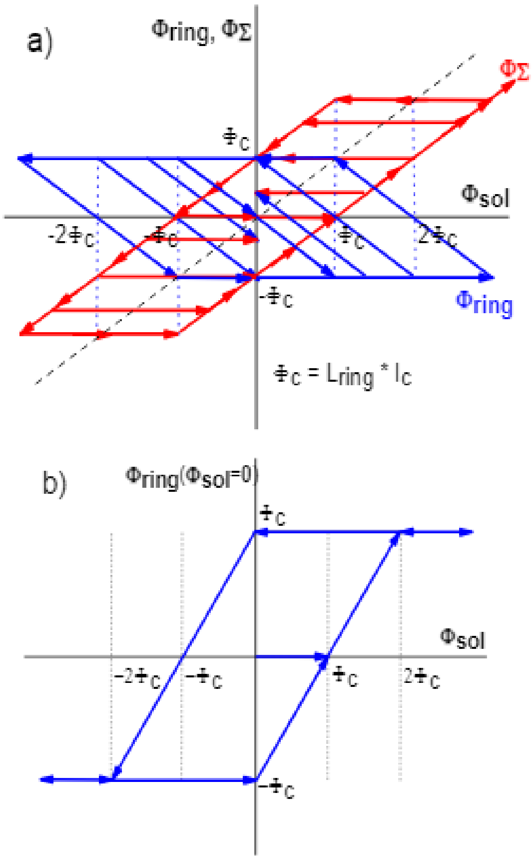

Fig. 1. Process of magnetic flux penetration and capture in the superconducting ring. a) — dependences of the magnetic flux created by the ring's current (Φ_{ring}, blue) and the total magnetic flux Φ_{Σ} (red) on the flux generated by the solenoid (Φ_{sol}); b) — dependence of the captured magnetic flux in the ring $\Phi_{ring}(\Phi_{sol}{=}0)$ on the magnitude of the flux Φ_{sol} initially created by the solenoid and subsequently reduced to zero

made along the middle of the tape width, not reaching the edges. Fig. 2 presents the components of the experimental setup. A solenoid (1) with a 3 cm diameter was inserted into the slit of the tape (2). The Hall sensor was placed at the center of the solenoid. This component of the setup alone allows to measure $I_c(H{=}0)$ by measuring the magnetic field H of ring's current I using the Hall sensor and calculating rings current by the well-known relation: $H = I/2R$, where R is the ring radius.

The setup was additionally equipped with a mechanism (3) to move NdFeB magnets (4) closer and to increase the magnetic field acting on a local region of the tape. Mechanism (5) allows changing the tape orientation (angle α) relative to the local magnetic field with a 5-degree rotation step. By varying the magnitude of the local magnetic field using device (3) and the angle of its orientation using device (5), it is possible to obtain I_c dependences on the magnitude and orientation of the magnetic field.

All measurements were performed at the liquid nitrogen temperature T = 77 K. Initially, the ring is considered to be completely demagnetized, i.e. I = 0. The setup, along with the HTSC tape ring, is cooled down, and a current is applied to the solenoid to generate magnetic flux within the ring. Then, the solenoid switched off and the Hall sensor records the magnetic field of the ring's current in the center of the ring.

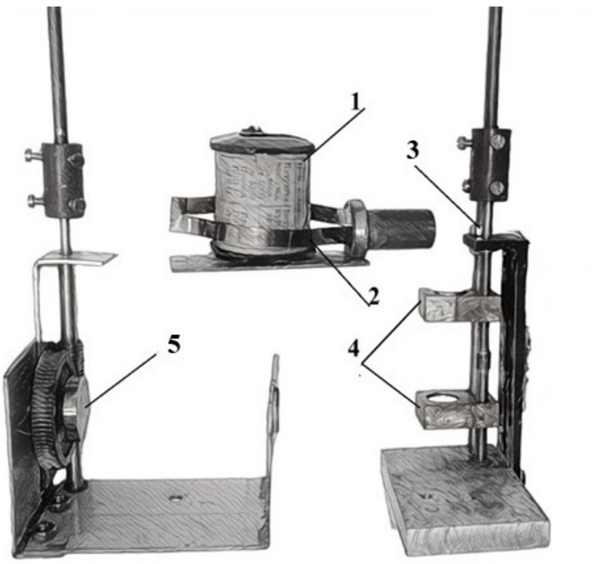

Fig. 2. Setup for non-contact measurements of the I_c(H, α) dependences. Three main setup components are depicted. In the center is the solenoid (1) with the 2G HTSC tape (2) and the Hall sensor at the center of the solenoid. Additional components include: the mechanism for tape orientation changing (3) relative to the field of permanent magnets (4) located on the local field changing mechanism (5)

3. Results

Using the devised setup, a dependence of the magnetic field at the center of the ring H_{center} measured by the Hall sensor and proportional to the ring flux Φ_{ring} = L*I, was obtained as a function of the magnitude of the previously applied (and subsequently reduced to zero) magnetic field of the solenoid H_{sol} (Fig. 3). The field at the center H_{center} is created by the ring current and is therefore proportional to the ring flux Φ_{ring} = L*I, and the field H_{sol} is proportional to the flux Φ_{sol}. Thus, the H_{center}/H_{sol} dependence (Fig. 3) should correspond to the Φ_{ring}/Φ_{sol} dependence (Fig. 1b).

It is evident that there is good agreement between the experiment and the simple model based on the preservation of magnetic flux in the superconducting ring up to its critical current. It is worth noting that the field at which the captured flux starts to rise sharply (250 Oe) is half of the field at which the captured flux saturates (500 Oe), in line with the model analysis. The saturation of the captured flux corresponds to the ring's current reaching its critical value and allows for its estimation using the relation $H_{max} = I_c/2R$. H_{sol} higher than 500 Oe does not lead to an increase in the magnetic flux captured by the ring. Reducing H_{sol} has almost no impact on the value of the captured flux in the ring until the magnetic field changes it's sign, and the flux capture process repeats with the opposite sign.

4. Dependence of the critical current on the magnitude and orientation of the magnetic field

The critical current of the HTSC tape decreases with an increase in the magnetic field, and the application of a magnetic field locally on a small region of the tape results in a reduction in the overall critical current of the ring. Using permanent magnets to create magnetic field acting locally on a small region of the tape, the dependence of the critical current on the external magnetic field was measured. The magnitude of the local magnetic field was varied by changing the distance between the permanent magnets.

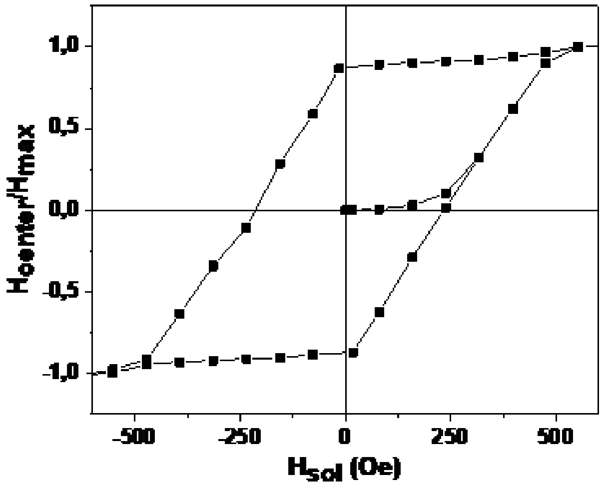

Fig. 3. Dependence of captured flux, created by the currents in the HTSC ring, on H after reducing the magnetic field of the solenoid from H_{sol} to zero

Fig. 4 shows the dependence of the critical current on the external magnetic field oriented perpendicular to the tape plane at T = 77 K. Each point of the dependence was obtained after ring cooling to 77 K in zero magnetic field.

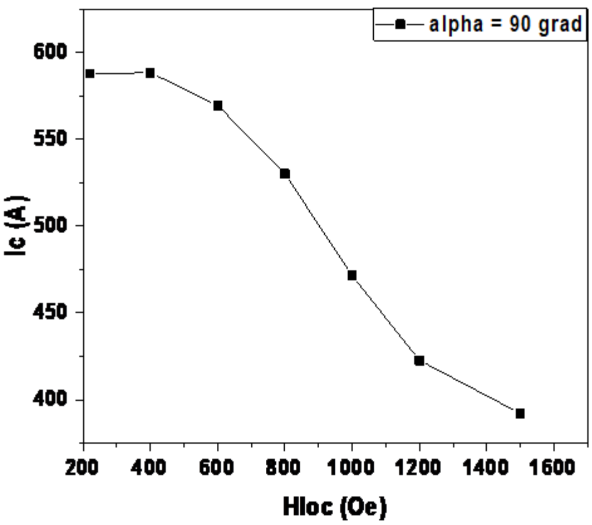

Fig. 4. Dependence of the critical current of the 12mm wide SuperOx tape on the magnitude of the local magnetic field, oriented perpendicular to the tape plane, at T=77K

It's worth noting the high value of the critical current of the tape (580 A) at low magnetic fields (200 Oe), which corresponds to the value provided by the tape manufacturer. When the magnetic field increases to 1.5 kOe, the critical current decreasing is 30%.

By changing the orientation of the tape relative to the local magnetic field orientation, the dependence of the critical current on the angle between the tape plane and the direction of the magnetic field was obtained.

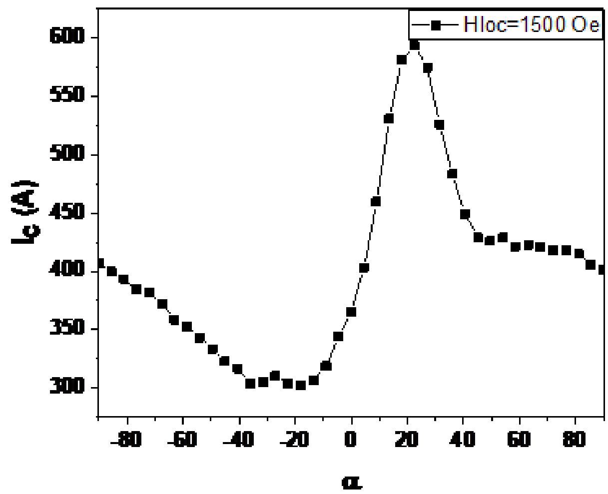

Fig. 5. Dependence of the critical current of the 12mm wide SuperOx tape at T=77K on the angle between the tape plane and magnetic field orientation. Local magnetic field H_{loc} = 1500 Oe

Conclusion

Experimentally obtained complete hysteresis loop of the captured magnetic flux in the ring resembled closely the calculated one. The field at which the captured flux starts to rise sharply (250 Oe) is half of the field at which the captured flux saturates (500 Oe). Measuring the magnetic field at the center of the ring corresponding to the maximum trapped flux reliably allows us to determine the critical current of the tape.

For the 12 mm wide SuperOx HTSC tape the value of the critical current (580 A) at low magnetic fields (200 Oe) corresponds to the value provided by the manufacturer. When the magnetic field increases to 1.5 kOe, the critical current decreasing is 30%. The HTSC tape exhibits a significant and asymmetric dependence of the critical current on the orientation of the applied magnetic field.

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Намагниченность и захват потока в кольце из высокотемпературной сверхпроводящей ленты второго поколения

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Аннотация. В данной статье проведено теоретическое рассмотрение процессов намагниченности и захвата магнитного потока в сверхпроводящем кольце, а также проведено экспериментальное исследование захвата магнитного потока в кольце, изготовленном из высокотемпературной сверхпроводящей ленты второго поколения. Полученные экспериментальные результаты хорошо согласуются с моделью. Дополнительно в работе был измерен критический ток в нулевом поле, используя широко известный бесконтактный метод измерения критического тока на основе захваченного в кольце магнитного потока. Эти данные согласуются с значениями, предоставленными производителем. Данный метод был модифицирован путем применения локального магнитного поля к участку кольца. Это позволило исследовать зависимость критического тока от величины и ориентации магнитного поля, представляя собой простой и надежный способ определения критического тока и его анизотропии.

Ключевые слова: сверхпроводимость, высокотемпературная сверхпроводящая лента, сверхпроводящее кольцо, захват магнитного потока, критический ток, анизотропия.