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Comparison study of critical current angular dependence in YBCO tapes

Abstract. *The article presents a comparative analysis of the angular dependence of the critical current in the second-generation high-temperature superconducting (HTS) YBCO tapes. The study was conducted on three SuperPower tapes: SCS4050, SCS4050-AP, and SCS4050-AP-i, which differed in their pinning parameters influencing the angular dependence of the critical current. The comparative measurements were performed using a custom-designed test setup based on a cylindrical Halbach array, which generated a uniform magnetic field on the tape surface. This setup provides an alternative to electromagnet-based systems, allowing precise evaluation of the angular critical current characteristics in the tested superconducting tapes.*

Streszczenie. *W artykule przedstawiono wyniki analizy porównawczej zależności kątowej prądu krytycznego w wysokotemperaturowych taśmach nadprzewodnikowych HTS drugiej generacji na bazie YBCO. Badania przeprowadzono na trzech taśmach firmy SuperPower: SCS4050, SCS4050-AP oraz SCS4050-AP-i, które różniły się zastosowanymi centrami pinningu, co wpływało na kątową charakterystykę prądu krytycznego. Do przeprowadzenia eksperymentów wykorzystano autorskie stanowisko testowe oparte na cylindrycznym układzie Halbacha, generującym jednorodne pole magnetyczne na powierzchni taśmy. Układ Halbacha stanowi alternatywę dla tradycyjnych systemów testowych opartych na elektromagnesach. (**Badanie porównawcze zależności kątowej prądu krytycznego w taśmach YBCO**)*

Keywords: angular dependence of critical current, high-temperature superconductors, YBCO tapes, Halbach array
Słowa kluczowe: kątowa zależność prądu krytycznego, nadprzewodniki wysokotemperaturowe, taśmy YBCO, układ Halbacha

Introduction

In the process of designing modern superconducting devices, one of the key elements is choosing the right superconducting tape for the application. Commercially available second-generation (2G) tapes, depending on the manufacturer, differ in both the manufacturing method: Rolling-Assisted Biaxially-Textured Substrate (RABiTS), Double Beam Ion Beam Assisted Deposition (IBAD), Inclined substrate deposition (ISD) and the coating technique Pulsed Laser Deposition (PLD), metalorganic chemical vapour deposition (MOCVD), which directly affects the performance and properties of the tapes [1].

In engineering practice, the critical current I_C value, which conventionally represents the boundary between the superconducting state and the normal state, is used as one of the main electrical criteria. It is assumed that in the case of an HTS tape operating in its own field, the value of the critical current is a constant quantity, independent of the orientation of the tape. However, when an external magnetic field is applied to a current-carrying tape, there is a dependence of the value of the critical current on the orientation of the tape with respect to the direction of the magnetic field force lines. Depending on the orientation of the tape with respect to the magnetic field, the critical current reduction factor at a certain tape alignment can reach up to 70-80%, which is an unfavorable characteristic and needs to be taken into account by designers of superconducting devices [2].

The main factor causing the aforementioned orientation-dependent reduction in critical current values is the anisotropy of the superconducting materials themselves. Work in this area, both experimental and theoretical, has been conducted by Durrell [3], Pardo [4], and Gillli [5], among others. While in the case of first-generation (1G) tapes such as BISCO, the angular dependence of the critical current in HTS tapes can be described by one of the well-known models (e.g., Kim, the percolation model [6]), the matter is more complicated in the case of multilayer superconductors. Due to the use of pinning techniques, the angular characteristics of the critical current significantly deviate from the elliptical model or its variations.

Performing characterization of HTS tape samples under certain external conditions (ambient temperature and external induction) is a common practice. Over the years, many solutions have been developed to measure the angular dependence of superconducting tapes. The most common method was the direct current method, which used an electromagnet responsible for generating a uniform magnetic field of varying value on the surface of the tape [7, 8]. This solution has many advantages, nevertheless, due to the size of the electromagnet and the power and control systems, it is characterized as a complicated expensive solution.

The comparison of the angular dependence of the HTS 2G tapes presented in this work is based on the use of the author's test rig, on which the angular dependence of the critical current of the tapes was measured. This represents an attempt at a minimalist approach that allows the research to be realized under space and financial constraints. The bench developed using the additive 3D printing method enables modifications through rapid prototyping and validation of ideas.

The work is divided into several main parts relating respectively to: description of the applied design solution, description of the used approach of semi-automatic measurements using OCR (Optical Character Recognition) method, which is an alternative to data acquisition systems. The essential part of the paper is the results of the angular dependence of critical currents in HTS tapes, performed for different values of induction at a specific temperature of 77K. The paper presents results for tapes from a single manufacturer differing in both the value of the critical current and the method used to reduce the effect of the anisotropy of the HTS material.

The results of the work are comparative characteristics for the selected angular settings that constitute design characteristics used in further design and testing of the limitations of high-temperature materials

Measurement system based on Halbach configuration

In the proposed approach, a homogeneous magnetic field is generated by permanent magnets arranged in a Halbach array configuration [9]. This solution is characterized by simplicity of design, but it does not allow smooth adjustment of the induction value on the tape surface. Changes in the induction value are realized through interchangeable disks, which allows adjustment in the range of 75 mT to 350 mT.

Angular change of the magnetic induction vector in the resulting magnetic dipole is carried out by means of a worm gear, which provides precise angle change over the full angular range. This solution is a modification of an earlier system using a pinion gear [10].

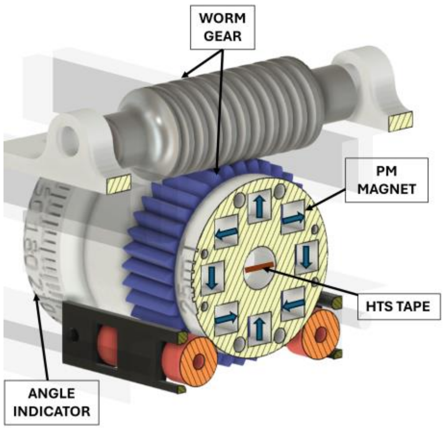

Fig. 1. 3D model of the measurement system for studying the angular dependence of critical current in HTS tapes, with identification of individual components..

The introduction of the worm gear and the modification of the bearing system allow smoother operation of the device while eliminating the risk of bearings freezing.

These improvements contribute to the reliability and precision of the measurement system, which is crucial for the accuracy of the HTS tape characteristics measurements carried out. Fig. 1 presents a 3D model of the system with an extracted cross-section of the disc, contour scale, and worm gear. Most of the mechanical components were made by incremental technology using PLA (Polylactic Acid) material. In the system presented, the value of induction in the area of the HTS tape location can be determined from the following formula:

$$B = B_r \ln\left(\frac{d_o}{d_i}\right)\left(\frac{\sin\left(\frac{\pi}{n_M}\right)}{\left(\frac{\pi}{n_M}\right)}\right) \quad (1)$$

Where: B_r - remanence induction, d_o - outer diameter, d_i - inner diameter, n_M - number of magnets per wavelength

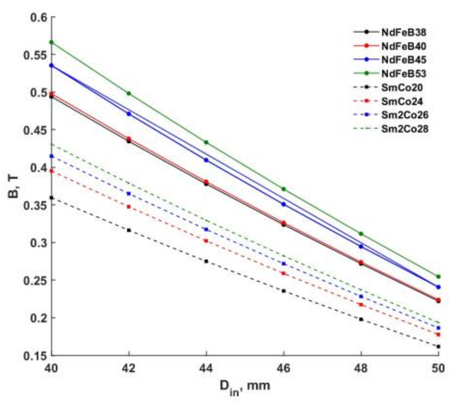

Fig. 2. Graph showing changes in the value of magnetic induction in the test area as a function of Halbach spacing, for SmCo and NdFeB magnets.

The test stand allows the use of magnets of different parameters, both SmCo and NdFeB types. The comparative characteristics of the magnetic induction depending on the spacing of the magnets in the Halbach system, using different types of magnets, are shown in Fig. 2.

Based on the analysis of the characteristics, N38 neodymium magnets were selected, characterized by a higher value of magnetic induction in the test area. The range of magnetic induction generated by the Halbach systems makes it possible to carry out measurements in the so-called self-fields, which reflects the conditions found in typical power equipment such as transformers, cables, and superconducting current limiters.

The presented solution allows to perform angular characterization of HTS tapes, using a novel design approach.

Critical current measurement system

The proposed solution used a semi-automatic data acquisition system based on OCR software. Both the value of the forcing current and the voltage drop across the tested tape section were recorded with a camera and processed accordingly to plot the current-voltage characteristics, from which the value of the critical current was determined according to the electric field strength criterion (2), which is a standard procedure in HTS tape testing.

The operation of the system involves several steps, such as image conversion to grayscale, image blurring, binary thresholding, contour analysis, digit extraction, and normalization. The processed image is then saved to a spreadsheet. A view from the camera before image processing is shown in Figure 3.

Fig. 3. View of camera with OCR system for detection of measured values: 1) voltage drop on the HTS belt, 2) transport current.

$$U = U_c\left(\frac{I(B)}{I_c}\right)^{n(B)} \quad (2)$$

where: U – voltage on the superconductor, U_C – critical voltage above which the superconductor passes into the normal state, I(B) – transport current in the presence of a magnetic field I_C – critical current, n(B) power exponent describing the nonlinearity of the characteristics,

The use of the OCR system provides an alternative to previously conducted studies using LabView-based DAQ systems [11]. It enables acceleration of the processes involved in HTS tape characterization and increases automation and efficiency of measurements, minimizing errors due to manual reading and processing of data.

Preparation of HTS tape samples

Three samples of tapes manufactured by Super Power were prepared for comparative analysis of the tapes. These tapes differed in the values of critical currents, which are summarized in Table 1, and in the production technology aimed at reducing the anisotropy phenomenon. Tapes with stabilizer in the form of copper (Cu) layers with the following designations were tested: SCS4050, SCS4050-AP, and SCS4050-APi_ii, each 4 mm wide and 135 mm long, on which the voltage drop was measured..

Table 1: Parameters of the tested HTS tapes

HTS Tape type	Ic [A]	Info
SCS4050	124	Standard
SCS4050- AP	99	Artificial Pinning
SCS450 APi	120	Improve Artificial Pinning

Special HTS tape terminations, developed using copper plates embedded in tin, were used to improve contact quality. Measuring points, used for four-terminal measurements, were also made tin-plated to improve their conductivity and reliability during testing

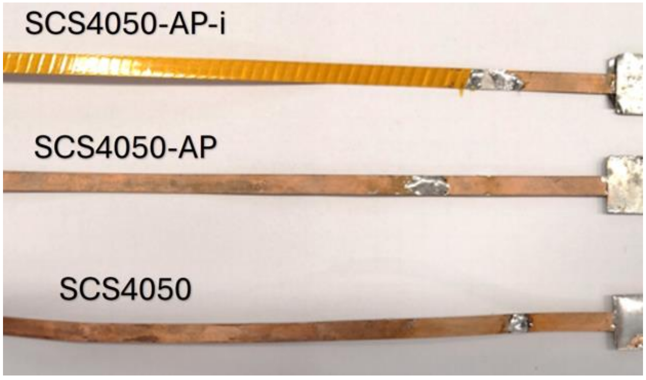

Fig. 4. The figure shows the tested HTS tape samples, arranged sequentially from the bottom: SCS4050, SCS4050-AP, and SCS4050-APi.

Results of critical current measurements of HTS tapes

In order to benchmark the HTS tapes, the critical currents of the mentioned samples were measured using a measurement system based on the Halbach matrix. The tests were carried out for five different values of the external magnetic field, covering the full angular range. The results of the critical currents were normalized against the values corresponding to the critical currents measured in the intrinsic field for a given angle. The determination of the critical current was based on equation (5).

$$\lambda = \frac{I_C}{I_{C(0T)}} \quad (3)$$

Where: I_C – measured critical current, I_{C0} – critical current in own field

Fig. 5 shows the results of measurements of the angular dependence of the critical current for the HTS SCS4050 tape. The angle of 0° corresponds to the arrangement of the tape perpendicular to the magnetic field lines. It can be seen that there is a significant discrepancy in the range of critical currents for individual angles, reaching 20-25%. For an angle of 180°, there is a local maximum of the critical current, increasing with an increase in the applied magnetic field.

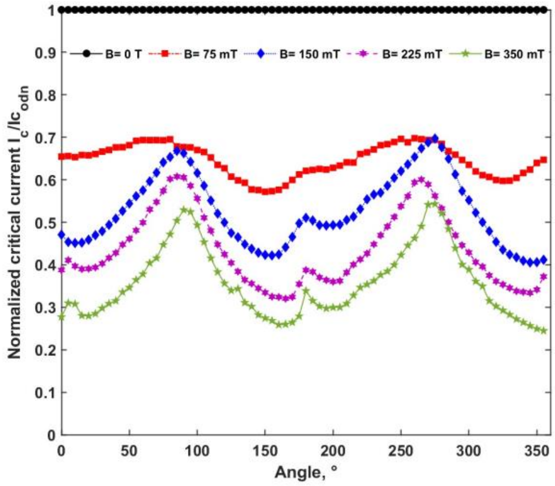

Fig. 5. Normalized values of critical currents for SCS4050 tape. The colors indicate the values of the magnetic field.

The next results, shown in Figure 6, show the effect of modifications to the superconductor structure, referred to as Artificial Pinning. The modifications introduced reduce the differences between the maximum and minimum values of the critical currents for each angle, leading to a more homogeneous distribution of angular dependencies.

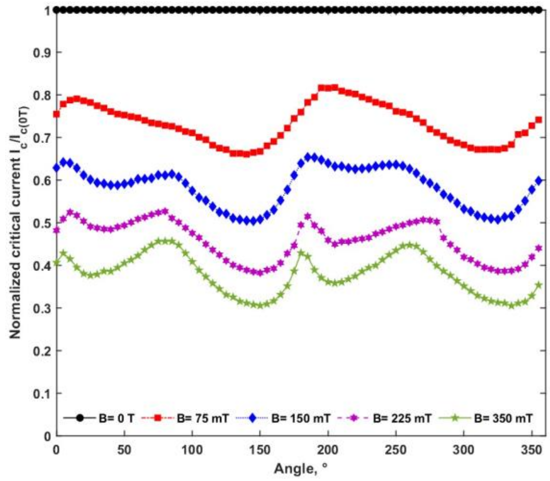

Fig. 6. Normalized values of critical currents for SCS4050-AP tape. The colors indicate the values of the magnetic field..

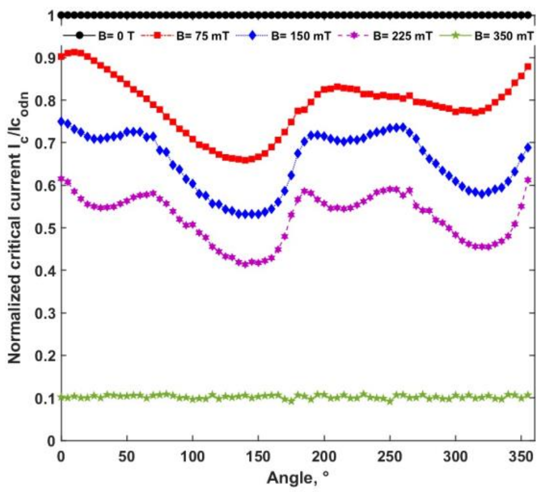

Fig. 7. Normalized values of critical currents for SCS4050-APi tape. The colors indicate the values of the magnetic field.

The application of a magnetic field of 75 mT results in a 20-30% reduction in critical currents, a significant figure considering the tape used. As the magnetic field increases, the level of reduction can reach up to 60% at a field of 250 mT. In the case of SCS4050-APi_ii tape, a significant reduction of 90% in the value of critical currents was observed, regardless of the orientation of the tape with respect to the magnetic field lines.

The presented measurement results will be subjected to a detailed comparative analysis later in the paper.

Comparative analysis of HTS tapes

Three values of external magnetic field were selected for comparative analysis of HTS tapes: 75 mT, 150 mT, and 225 mT. Values normalized against critical currents measured in the self-field were used to collate the results. In the first stage of the analysis, a polar representation was used, which allows visualizing the shapes of the characteristics of the critical currents depending on the orientation angle of the tapes with respect to the magnetic field lines.

This type of graphical representation is particularly useful for observing changes in the symmetry and anisotropy of the current characteristics of the tapes. In the literature, for HTS tapes, models based on elliptical characteristics are often used, which reproduce well the angular dependence of critical currents.

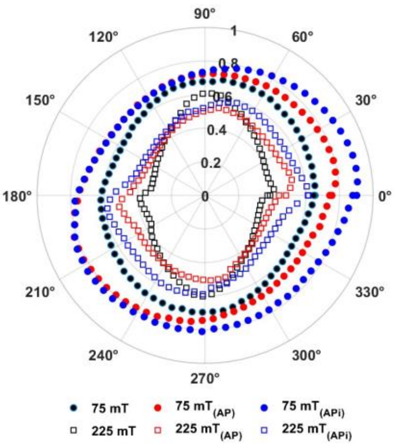

Fig. 8. Comparative polar characteristics of SCS4050, SCS4050-AP, and SCS4050-APi_ii tapes for B = 75 mT and 225 mT.

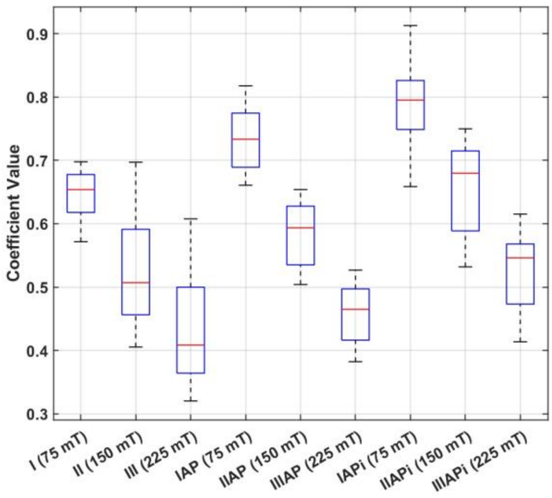

Fig. 9. Comparison of the critical current reduction factor for HTS SCS4050, SCS4050-AP, and SCS4050-APi_ii tapes depending on the value of the magnetic field.

The graph shows that with an increase in the value of the magnetic field, there is a clear change in the shape of the angular characteristics. SCS4050 and SCS4050-AP tapes show a significant difference in the distribution of critical currents, suggesting the effect of modifications to the superconductor structure on reducing anisotropy and more homogeneous behaviour as a function of angle. These characteristics indicate distinct differences in resistance to the influence of an external magnetic field, which may be crucial for their applications in different magnetic orientations.

The next step of the analysis is a summary of the critical current reduction factors for the analyzed tapes and magnetic fields, presented in Fig. 8. The SCS4050 tape shows a high variation and low degree of uniformity of the critical current in the magnetic field, indicating anisotropy.

The SCS4050-AP tape, thanks to Artificial Pinning technology, has better uniformity, although there are still variations at higher field values. The SCS4050-APi_ii tape is the most homogeneous and stable, showing the smallest scatter in results, making it the least sensitive to magnetic field changes.

In superconducting devices, the tapes are rarely arranged in such a way that their orientation with respect to the field lines allows them to fully exploit their characteristics.

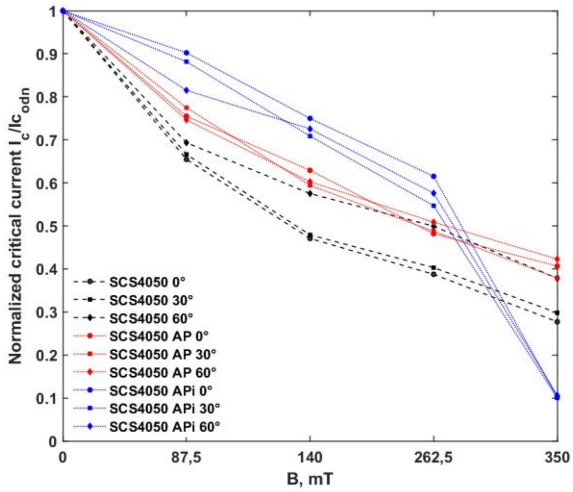

Fig. 10. Comparison of critical current reduction as a function of the applied magnetic field for different orientations of the HTS tapes

Typically, critical current reduction factors are determined for selected tape orientation angles. Figure 10 shows the dependence of critical current reduction on the applied magnetic field for selected angles: 0°, 30°, and 60°. It can be seen that the critical current decreases as the magnetic field increases, and the effect of tape orientation is clear. Tapes with an orientation of 0° have the smallest reduction in critical current, while an orientation at 60° results in the largest reduction in critical current. These data indicate the importance of tape orientation with respect to the magnetic field in terms of maintaining superconducting parameters..

Summary

The article presents a detailed analysis of the angular dependence of the critical current in second-generation superconducting tapes (HTS) based on YBCO, taking into account the influence of the orientation of the tapes with respect to the external magnetic field. The study included three types of SuperPower tapes: SCS4050, SCS4050-AP, and SCS4050-APi_ii, which differed in the pinning techniques used, which affected their critical current angular characteristics.

The tests used a proprietary measuring station built on the basis of the Halbach system, which generates a homogeneous magnetic field on the surface of the tape. The Halbach system is an innovative alternative to traditional electromagnet-based systems, offering both a simplified design and the ability to perform angular measurements over a wide range of magnetic field values.

The use of the Halbach system allowed this to study the angular dependence of critical currents for different values of the magnetic field. The implementation of a semi-automatic data acquisition system using OCR technology significantly reduced the time required to perform measurements compared to manual methods.

Analysis of the angular dependence of the critical current for different tapes showed significant differences in their anisotropy, indicating the influence of pinning technology on the current behavior of the tapes in the magnetic field. The results confirmed that the orientation of the tapes with respect to the magnetic field has a significant impact on their performance, which is crucial in the context of superconducting device design.

In summary, the research conducted has provided the data necessary for further simulation and design analyses of superconductors. It was shown that the orientation of HTS tapes in a magnetic field and the use of appropriate pinning techniques can significantly improve the operational performance of superconducting systems. In addition, the measurement approach based on Halbach's circuit and OCR technology is an effective alternative to traditional measurement methods, offering increased automation and accuracy in analyzing the angular dependence of critical currents.

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