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INTERNATIONAL STANDARD

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colour inside

Superconductivity –
Part 17: Electronic characteristic measurements – Local critical current density and its distribution in large-area superconducting films

Supraconductivité –
Partie 17: Mesurages de caractéristiques électroniques – Densité de courant critique local et sa distribution dans les films supraconducteurs de grande surface

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This second edition cancels and replaces the first edition published in 2013. This edition constitutes a technical revision.

This edition includes the following a significant technical change with respect to the previous edition:

a) A simple method to calculate theoretical coil coefficient k is described in 6.2.1.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
90/462/FDIS	90/464/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

The language used for the development of this International Standard is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

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INTRODUCTION

Over thirty years after their discovery in 1986, high-temperature superconductors are now finding their way into products and technologies that will revolutionize information transmission, transportation, and energy. Among them, high-temperature superconducting (HTS) microwave filters, which exploit the extremely low surface resistance of superconductors, have already been commercialized. They have two major advantages over conventional non-superconducting filters, namely: low insertion loss (low noise characteristics) and high frequency selectivity (sharp cut) [1][1]. These advantages enable a reduced number of base stations, improved speech quality, more efficient use of frequency bandwidths, and reduced unnecessary radio wave noise.

Large-area superconducting thin films have been developed for use in microwave devices [2]. They are also considered for use in emerging superconducting power devices, such as resistive-type superconducting fault-current limiters (SFCLs) [3] [4] [5], superconducting fault detectors used for superconductor-triggered fault current limiters [6] [7] and persistent-current switches used for persistent-current HTS magnets [8] [9]. The critical current density J_c is one of the key parameters that describe the quality of large-area HTS films. Nondestructive, AC inductive methods are widely used to measure J_c and its distribution for large-area HTS films [10] [11] [12] [13], among which the method utilizing third-harmonic voltages $U_3\cos(3\omega t + \theta)$ is the most popular [10] [11], where ω, t and θ denote the angular frequency, time, and initial phase, respectively. However, these conventional methods are not accurate because they have not considered the electric-field E criterion of the J_c measurement [14] [15] and sometimes use an inappropriate criterion to determine the threshold current I_th from which J_c is calculated [16]. A conventional method can obtain J_c values that differ from the accurate values by 10 % to 20 % [15]. It is thus important to establish standard test methods to precisely measure the local critical current density and its distribution, to which all involved in the HTS filter industry can refer for quality control of the HTS films. Background knowledge on the inductive J_c measurements of HTS thin films is summarized in Annex A.

In these inductive methods, AC magnetic fields are generated with AC currents $I_0\cos\omega t$ in a small coil mounted just above the film, and J_c is calculated from the threshold coil current I_th, at which full penetration of the magnetic field to the film is achieved [17]. For the inductive method using third-harmonic voltages U_3, U_3 is measured as a function of I_0, and the I_th is determined as the coil current I_0 at which U_3 starts to emerge. The induced electric fields E in the superconducting film at $I_0 = I_\mathrm{th}$, which are proportional to the frequency f of the AC current, can be estimated by a simple Bean model [14]. A standard method has been proposed to precisely measure J_c with an electric-field criterion by detecting U_3 and obtaining the n-value (index of the power-law E-J characteristics) by measuring I_th precisely at various frequencies [14] [15] [18] [19]. This method not only obtains precise J_c values, but also facilitates the detection of degraded parts in inhomogeneous specimens, because the decline of n-value is more noticeable than the decrease of J_c in such parts [15]. It is noted that this standard method is excellent for assessing homogeneity in large-area HTS films, although the relevant parameter for designing microwave devices is not J_c, but the surface resistance. For application of large-area superconducting thin films to SFCLs, knowledge on J_c distribution is vital, because J_c distribution significantly affects quench distribution in SFCLs during faults.

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SUPERCONDUCTIVITY –

Part 17: Electronic characteristic measurements – Local critical current density and its distribution in large-area superconducting films

1 Scope

This part of IEC 61788 specifies the measurements of the local critical current density (J_c) and its distribution in large-area high-temperature superconducting (HTS) films by an inductive method using third-harmonic voltages. The most important consideration for precise measurements is to determine J_c at liquid nitrogen temperatures by an electric-field criterion and obtain current-voltage characteristics from its frequency dependence. Although it is possible to measure J_c in applied DC magnetic fields [20] [21], the scope of this document is limited to the measurement without DC magnetic fields.

This technique intrinsically measures the critical sheet current that is the product of J_c and the film thickness d. The range and measurement resolution for $J_c d$ of HTS films are as follows.

- $J_c d$: from 200 A/m to 32 kA/m (based on results, not limitation).
- Measurement resolution: 100 A/m (based on results, not limitation).

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-815, *International Electrotechnical Vocabulary – Part 815: Superconductivity* (available at <http://www.electropedia.org>)

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-815 apply, some of which are repeated here for convenience.

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3.1
critical current

I_c

maximum direct current that can be regarded as flowing without resistance practically

Note 1 to entry: I_c is a function of magnetic field strength, temperature and strain.

[SOURCE: IEC 60050-815:2015, 815-12-01]

3.2
critical current criterion

I_c criterion

criterion to determine the critical current, I_c, based on the electric field strength, E, or the resistivity, ρ

Note 1 to entry: E = 10 µV/m or E = 100 µV/m is often used as electric field criterion, and $\rho = 10^{-14}$ Ω · m or $\rho = 10^{-13}$ Ω · m is often used as resistivity criterion.

[SOURCE: IEC 60050-815:2015, 815-12-02]

3.3
critical current density

J_c

electric current density at the critical current using either the cross-section of the whole conductor (overall) or of the non-stabilizer part of the conductor if there is a stabilizer

Note 1 to entry: The overall current density is called engineering current density (symbol: J_e).

[SOURCE: IEC 60050-815:2015, 815-12-03]

3.4
transport critical current density

J_{ct}

critical current density obtained by a resistivity or a voltage measurement

[SOURCE: IEC 60050-815:2015, 815-12-04]

3.5
n-value

<superconductor> exponent obtained in a specific range of electric field strength or resistivity when the voltage/current $U(I)$ curve is approximated by the equation $U \propto I^n$

[SOURCE: IEC 60050-815:2015, 815-12-10]

4 Requirements

The critical current density J_c is one of the most fundamental parameters that describe the quality of large-area HTS films. In this document, J_c and its distribution are measured non-destructively via an inductive method by detecting third-harmonic voltages $U_3\cos(3\omega t + \theta)$. A small coil, which is used both to generate AC magnetic fields and detect third-harmonic voltages, is mounted just above the HTS film and used to scan the measuring area. To measure J_c precisely with an electric-field criterion, the threshold coil currents I_{th}, at which U_3 starts to emerge, are measured repeatedly at different frequencies and the E-J characteristics are determined from their frequency dependencies.

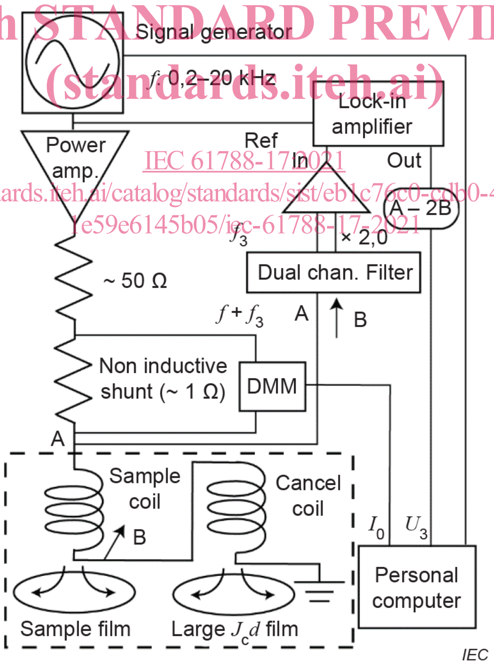
The target relative combined standard uncertainty in the method used to determine the absolute value of J_c is less than 10 %. However, the target uncertainty is less than 5 % for the purpose of evaluating the homogeneity of J_c distribution in large-area superconducting thin films.

5 Apparatus

5.1 Measurement equipment

Figure 1 shows a schematic diagram of a typical electric circuit used for the third-harmonic voltage measurements. This circuit is comprised of a signal generator, power amplifier, digital multimeter (DMM) to measure the coil current, band-ejection filter to reduce the fundamental wave signals and lock-in amplifier to measure the third-harmonic signals. It involves the single-coil approach in which the coil is used to generate an AC magnetic field and detect the inductive voltage. This method can also be applied to double-sided superconducting thin films with no obstacles. In the methods proposed here, however, there is an additional system to reduce harmonic noise voltages generated from the signal generator and the power amplifier [14]. In an example of Figure 1, a cancel coil of specification being the same as the sample coil is used for cancelling. The sample coil is mounted just above the superconducting film, and a superconducting film with a $J_c d$ sufficiently larger than that of the sample film is placed below the cancel coil to adjust its inductance to that of the sample coil. Note that the inductance of the sample coil decreases by 20 % to 30 % due to the superconducting shielding current when it is mounted on a superconducting film. Both coils and superconducting films are immersed in liquid nitrogen (a broken line in Figure 1). Other optional measurement systems are described in Annex B.

NOTE In this circuit, coil currents of about 0,1 A (RMS) and power source voltages of > 6 V (RMS) are needed to measure the superconducting film of $J_c d \approx 10$ kA/m while using coil 1 or 2 of Table 2. A precision power amplifier with sufficiently high power is used to supply such large currents and voltages.



NOTE The broken line surrounds elements immersed in liquid nitrogen.

Figure 1 – Diagram for an electric circuit used for inductive J_c measurement of HTS films

5.2 Components for inductive measurements

5.2.1 Coils

Currently available large-area HTS films are deposited on areas as large as about 25 cm in diameter, while films about 5 cm in diameter are commercially used to prepare microwave filters [22]. Larger $YBa_2Cu_3O_7$ (YBCO) films, about 10 cm in diameter and 2,7 cm × 20 cm, were used to fabricate fault current limiter modules [3] [4] [5]. For the J_c measurements of such films, the appropriate outer diameter of the sample coils ranges from 2 mm to 5 mm. The requirement for the sample coil is to generate as high a magnetic field as possible at the upper surface of the superconducting film, for which flat coil geometry is suitable. Typical specifications are as follows.

a) Inner winding diameter D_1: 0,9 mm, outer diameter D_2: 4,2 mm, height h: 1,0 mm, 400 turns of a 50 µm diameter copper wire.

b) D_1: 0,8 mm, D_2: 2,2 mm, h: 1,0 mm, 200 turns of a 50 µm diameter copper wire.

5.2.2 Spacer film

Typically, a polyimide film with a thickness of 50 µm to 125 µm is used to protect the HTS films. The coil has generally some protection layer below the coil winding, which also insulates the thin film from Joule heat in the coil. The typical thickness is 100 µm to 150 µm, and the coil-to-film distance Z_1 is kept to be 200 µm.

5.2.3 Mechanism for the set-up of the coil

To maintain a prescribed value for the spacing Z_1 between the bottom of the coil winding and the film surface, the sample coil should be pressed to the film with sufficient pressure, typically exceeding about 0,2 MPa [18]. Techniques to achieve this are to use a weight or spring, as shown in Figure 2. The system schematically shown in the figure left is used to scan a wide area of the film. Before the U_3 measurement the coil is initially raised up to some distance, moved laterally to the target position, and then lowered down and pressed to the film. An appropriate pressure should be determined so that too high pressure does not damage the bobbin, coil, HTS thin film or the substrate. It is reported that the YBCO deposited on biaxially-textured pure Ni substrate was degraded by transverse compressive stress of about 20 MPa [23].

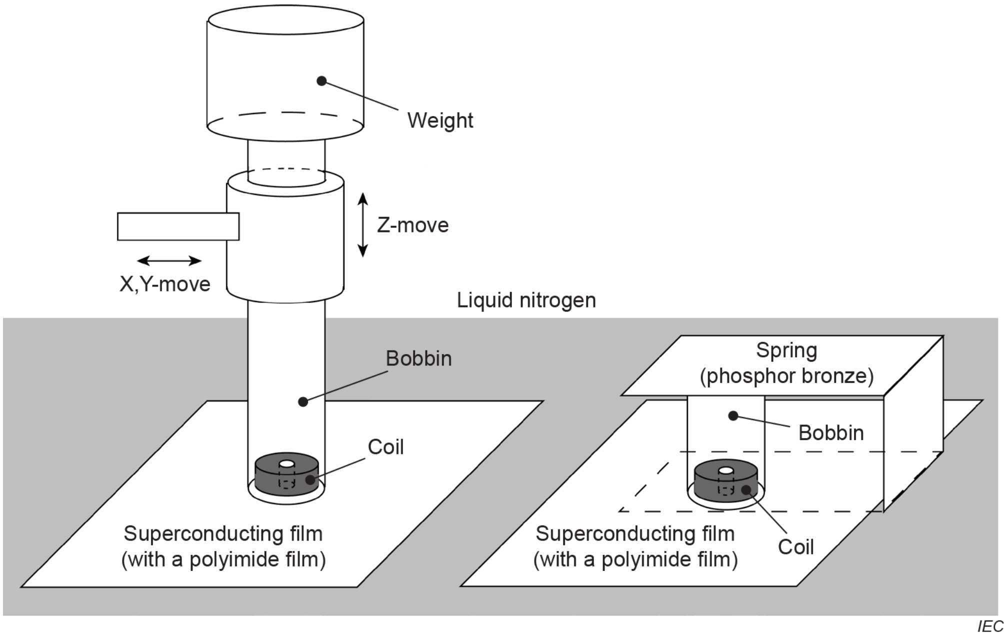


Figure 2 – Illustration showing techniques to press the sample coil to HTS films

5.2.4 Calibration wafer

A calibration wafer is used to determine the experimental coil coefficient k' described in Clause 6. It is made by using a homogeneous large-area (typically about 5 cm diameter) YBCO thin film. It consists of bridges for transport measurement and an inductive measurement area (Figure 3). Typical dimensions of the transport bridges are 20 µm to 70 µm wide and 1 mm to 2 mm long, which were prepared either by UV photolithography technique or by laser etching [24]. In the transport bridge area shown in Figure 3, a transport current can be passed from current terminal 1 to another current terminal 3 through the bridge "a". In this case, terminals 2 and 12 are used as voltage terminals. Similarly, a transport current can be passed from current terminal 1 to another current terminal (5, 7, 9 or 11) through the bridge "b", "c", "d" or "e". In this case, terminals 4, 6, 8 or 10, and 12 are used as voltage terminals.

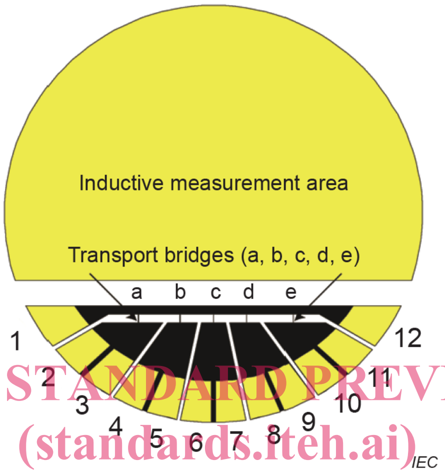


Figure 3 – Example of a calibration wafer used to determine the coil coefficient

6 Measurement procedure

6.1 General

The procedures used to determine the experimental coil coefficient k' and measure the J_c of the films under test are described as follows, with the meaning of k' expressed in Clause A.5.

6.2 Determination of the experimental coil coefficient

6.2.1 Calculation of the theoretical coil coefficient k

Calculate the theoretical coil coefficient $k = J_c d / I_{th}$ from

$$k = F_m, \tag{1}$$

where F_m is the maximum of $F(r)$ that is a function of r, the distance from the central axis of the coil whose inner diameter is D_1, outer diameter is D_2 and height is h (Figure 4). The coil-factor function $F(r) = -2H_r(r, t)/I_0 \cos\omega t = 2H_0/I_0$ is obtained by

$$F(r) = \frac{N}{2\pi S}\int_{R_1}^{R_2} \mathrm{d}r' \int_0^{2\pi} \mathrm{d}\theta \int_{Z_1}^{Z_2} \mathrm{d}z \frac{r' z \cos\theta}{(z^2 + r^2 + r'^2 - 2rr'\cos\theta)^{3/2}}, \tag{2}$$

where $H_r(r, t)$ is the radial component of the magnetic field generated by the sample coil at a upper surface of the superconducting film, N is the number of turns in the sample coil, $R_1 = D_1/2$ is the inner radius, $R_2 = D_2/2$ is the outer radius of the coil, $S = (R_2 - R_1)h$ is the cross-sectional area, Z_1 is the coil-to-film distance, and $Z_2 = Z_1 + h$ [17]. The explanation of Equations (1) and (2) is given in Clause A.3.

A simple method to obtain k is as follows.

a) Calculate the magnetic-field amplitude $H_0(r) = H_r(r, t = 0)$ as a function of r at a position below the coil with a distance Z_1 when a current of I_0 = 1 mA is passed in the sample coil (Figure 5).

b) Obtain the (local) maximum value of $H_0(r)$ when r is changed near $r \approx (R_1 + R_2)/2$.

c) The maximum value of $H_0(r)$ should have a unit of A/m, then the doubled value divided by I_0 (= 1 mA) becomes k (unit: 1/mm). Note that the magnetic field arising from the image coil (i.e. from the shielding current flowing in the superconducting film) cancels out the perpendicular component H_z, and the parallel component H_r doubles. The image coil and its magnetic field generation are shown by the broken lines in Figure 5.

d) For the calculation of coil magnetic fields, a free web site may be used; for example, http://www.sc.kyushu-u.ac.jp/~kajikawa/javascript/field_and_potential-e.html
(the calculation of this site is based on a paper entitled "Calculation of Magnetic Field Distribution of Solenoid Coil by Computer" [25].[2]

Some examples of the theoretical coil coefficient k for typical sample coils are shown in Table 1 with the specifications.

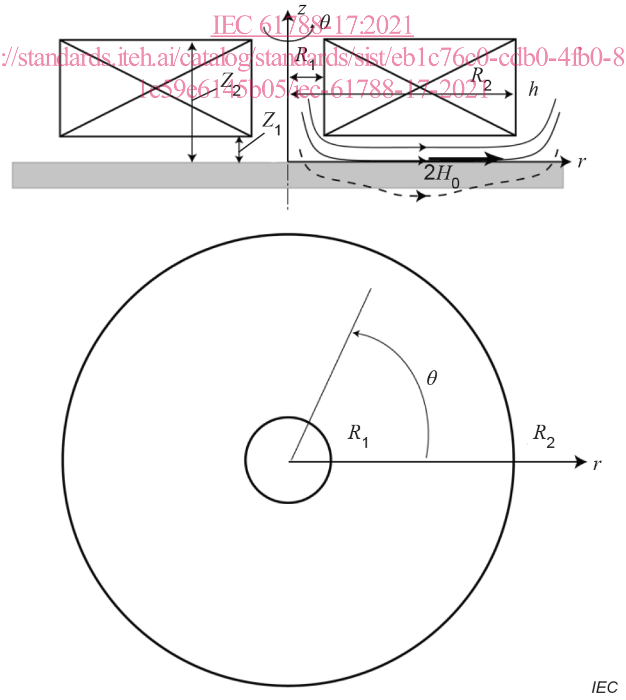


Figure 4 – Illustration of the sample coil and the magnetic field during measurement

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