IEC 61788-17

Edition 1.0 2013-01

INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour inside

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

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

IEC 61788-17:2013

IEC Central Office
3, rue de Varembé
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

About the IEC

The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigenda or an amendment might have been published.

Useful links:

IEC publications search - www.iec.ch/searchpub

The advanced search enables you to find IEC publications by a variety of criteria (reference number, text, technical committee,…).
It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished

Stay up to date on all new IEC publications. Just Published details all new publications released. Available on-line and also once a month by email.

Electropedia - www.electropedia.org

The world's leading online dictionary of electronic and electrical terms containing more than 30 000 terms and definitions in English and French, with equivalent terms in additional languages. Also known as the International Electrotechnical Vocabulary (IEV) on-line.

Customer Service Centre - webstore.iec.ch/csc

If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: csc@iec.ch.

A propos de la CEI

La Commission Electrotechnique Internationale (CEI) est la première organisation mondiale qui élabore et publie des Normes internationales pour tout ce qui a trait à l'électricité, à l'électronique et aux technologies apparentées.

A propos des publications CEI

Le contenu technique des publications de la CEI est constamment revu. Veuillez vous assurer que vous possédez l'édition la plus récente, un corrigendum ou amendement peut avoir été publié.

Liens utiles:

Recherche de publications CEI - www.iec.ch/searchpub

La recherche avancée vous permet de trouver des publications CEI en utilisant différents critères (numéro de référence, texte, comité d'études,…).
Elle donne aussi des informations sur les projets et les publications remplacées ou retirées.

Just Published CEI - webstore.iec.ch/justpublished

Restez informé sur les nouvelles publications de la CEI. Just Published détaille les nouvelles publications parues. Disponible en ligne et aussi une fois par mois par email.

Electropedia - www.electropedia.org

Le premier dictionnaire en ligne au monde de termes électroniques et électriques. Il contient plus de 30 000 termes et définitions en anglais et en français, ainsi que les termes équivalents dans les langues additionnelles. Egalement appelé Vocabulaire Electrotechnique International (VEI) en ligne.

Service Clients - webstore.iec.ch/csc

Si vous désirez nous donner des commentaires sur cette publication ou si vous avez des questions contactez-nous: csc@iec.ch.

IEC®

IEC 61788-17

Edition 1.0 2013-01

INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour inside

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

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

INTERNATIONAL ELECTROTECHNICAL COMMISSION

COMMISSION ELECTROTECHNIQUE INTERNATIONALE

PRICE CODE
CODE PRIX **X**

ICS 17.220.20; 29.050

ISBN 978-2-83220-583-9

Warning! Make sure that you obtained this publication from an authorized distributor.
Attention! Veuillez vous assurer que vous avez obtenu cette publication via un distributeur agréé.

CONTENTS

INTERNATIONAL ELECTROTECHNICAL COMMISSION

SUPERCONDUCTIVITY –

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

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.

International Standard IEC 61788-17 has been prepared by IEC technical committee 90: Superconductivity.

The text of this standard is based on the following documents:

FDIS	Report on voting
90/310/FDIS	90/319/RVD

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all the parts of the IEC 61788 series, published under the general title *Superconductivity*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the stability date indicated on the IEC web site under "http://webstore.iec.ch" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

Over twenty 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 used for emerging superconducting power devices, such as, resistive-type superconducting fault-current limiters (SFCLs) [3–5], 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 [10–13], 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 necessary 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 $I_0 = I_{th}$, 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 remarkable 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.

The International Electrotechnical Commission (IEC) draws attention to the fact that it is claimed that compliance with this document may involve the use of a patent concerning the determination of the E-J characteristics by inductive J_c measurements as a function of frequency, given in the Introduction, Clause 1, Clause 4 and 5.1.

IEC takes no position concerning the evidence, validity and scope of this patent right.

The holder of this patent right has assured the IEC that he is willing to negotiate licenses free of charge with applicants throughout the world. In this respect, the statement of the holder of this patent right is registered with the IEC. Information may be obtained from:

[1] Numbers in square brackets refer to the Bibliography.

Name of holder of patent right:
National Institute of Advanced Industrial Science and Technology

Address:
Intellectual Property Planning Office, Intellectual Property Department
1-1-1, Umezono, Tsukuba, Ibaraki Prefecture, Japan

Attention is drawn to the possibility that some of the elements of this document may be subject to patent rights other than those identified above. IEC shall not be held responsible for identifying any or all such patent rights.

ISO (www.iso.org/patents) and IEC (http://patents.iec.ch) maintain on-line data bases of patents relevant to their standards. Users are encouraged to consult the data bases for the most up to date information concerning patents.

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 describes 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][2], the scope of this standard 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 reference

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050 (all parts), *International Electrotechnical Vocabulary* (available at <http://www.electropedia.org>)

3 Terms and definitions

For the purposes of this document, the definitions given in IEC 60050-815:2000, some of which are repeated here for convenience, apply.

3.1
critical current
I_c
maximum direct current that can be regarded as flowing without resistance

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

[SOURCE: IEC 60050-815:2000, 815-03-01]

2 Numbers in square brackets refer to the Bibliography.

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 $\rho = 10^{-13}\ \Omega \cdot m$ or $\rho = 10^{-14}\ \Omega \cdot m$ is often used as resistivity criterion. ("E = 10 V/m or E = 100 V/m" in the current edition is mistaken and is scheduled to be corrected in the second edition).

[SOURCE: IEC 60050-815:2000, 815-03-02]

3.3
critical current density
***J*$_c$**
the 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 in English, engineering current density (symbol: J_e).

[SOURCE: IEC 60050-815:2000, 815-03-03]

3.4
transport critical current density
***J*$_{ct}$**
critical current density obtained by a resistivity or a voltage measurement

[SOURCE: IEC 60050-815:2000, 815-03-04]

3.5
***n*-value (of a 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 60050-815:2000, 815-03-10]

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 standard, 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.

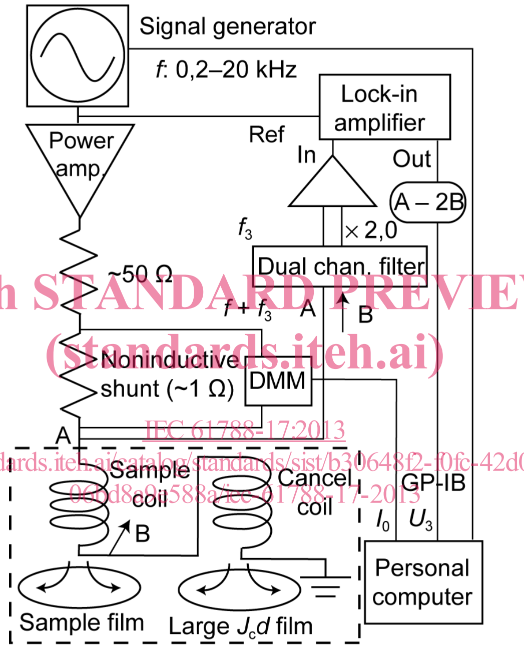
The target relative combined standard uncertainty of the method used to determine the absolute value of J_c is less than 10 %. However, the target uncertainty is less than 5 % for the purpose of evaluating the homogeneity of J_c distribution in large-area superconducting thin films.

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 without hindrance. 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 canceling. 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. 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 1 (6.5). A power amplifier, such as NF: HSA4011, is necessary to supply such large currents and voltages.



IEC 013/13

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 about 5 cm diameter films are commercially used to prepare microwave filters [22]. Larger $YBa_2Cu_3O_7$ (YBCO) films, about 10 cm diameter films and 2,7 cm × 20 cm films, were used to fabricate fault current limiter modules [3–5]. 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 left figure is used to scan wide area of the film. Before the U_3 measurement the coil is initially moved up to some distance, moved laterally to the target position, and then moved 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].

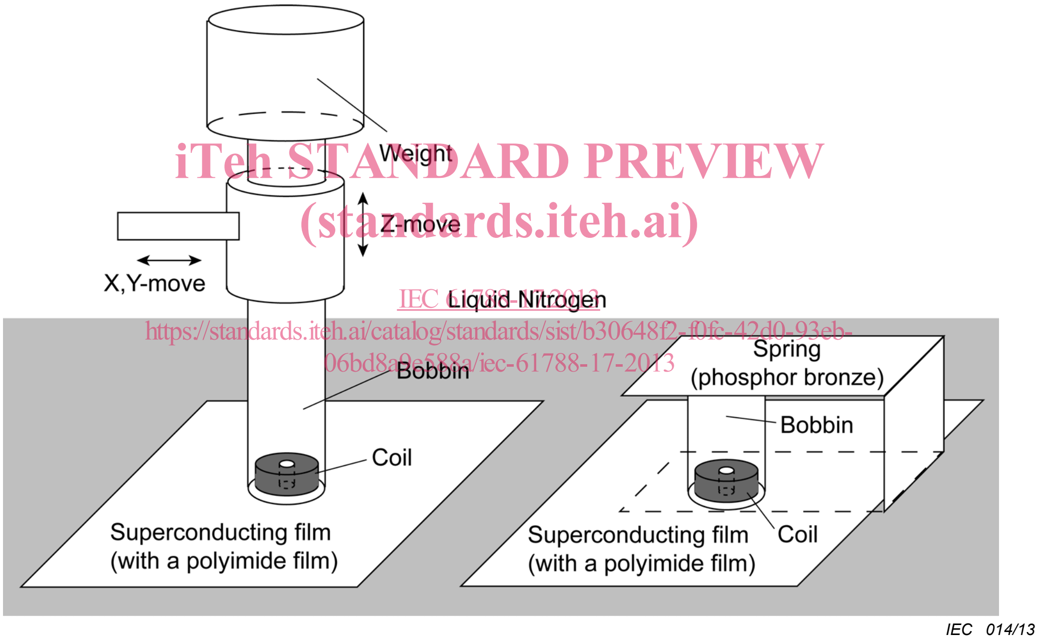


Figure 2 – Illustration showing techniques to press the sample coil to HTS films

5.2.4 Calibration wafer

A calibration wafer is used to determine the experimental coil coefficient *k*’ described in the next section. 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].

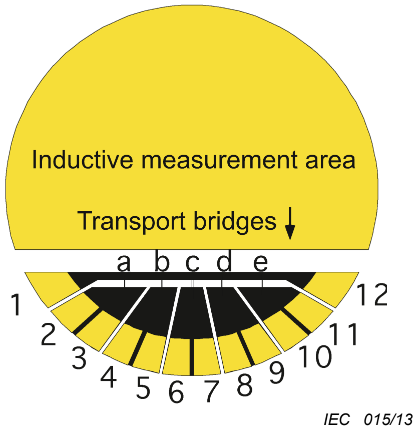


Figure 3 – Example of a calibration wafer used to determine the coil coefficient

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 A.5.

6.2 Determination of the experimental coil coefficient

6.2.1 Calculation of the theoretical coil coefficient *k*

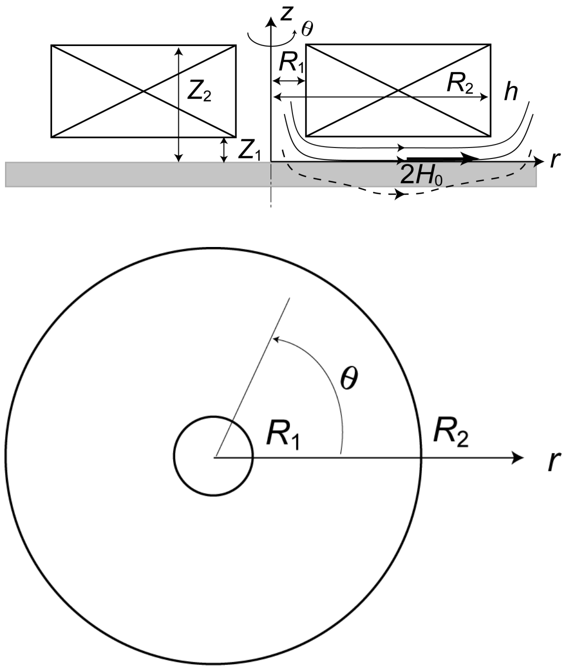
Calculate the theoretical coil coefficient $k = J_c d / I_{th}$ from

$$k = F_m, \qquad (1)$$

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

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

where N is the number of windings, $S = (R_2 - R_1)h$ is the cross-sectional area, $R_1 = D_1/2$ is the inner radius, $R_2 = D_2/2$ is the outer radius of the coil, Z_1 is the coil-to-film distance, and $Z_2 = Z_1 + h$ [17]. The derivation of the Equation (2) is described in A.3.



IEC 016/13

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

6.2.2 Transport measurements of bridges in the calibration wafer

a) Measure the *E-J* characteristics of the transport bridges of the calibration wafer by a four-probe method, and obtain the power-law *E-J* characteristics,

$$E_t = A_{0t} \times J^n. \tag{3}$$

b) Repeat the measurement for at least three different bridges. Three sets of data (n = 20,5 to 23,8) measured for three bridges are shown in the upper (high-*E*) part of Figure 5.

6.2.3 U_3 measurements of the calibration wafer

a) Measure U_3 in the inductive measurement area of the calibration wafer as a function of the coil current with three or four frequencies, and obtain the experimental I_{th} using a constant-inductance criterion; namely, $U_3/fI_0 = 2\pi L_c$. The criterion L_c should be as small as possible within the range with sufficiently large S/N ratios, in order to use the simple Equation (4) for the electric-field calculation (7.1 c) and D.2). An example of the measurement is shown in Figure 6 with $2\pi L_c$ = 2 μΩ•sec.

b) Repeat the measurement for at least three different points of the film.

6.2.4 Calculation of the *E-J* characteristics from frequency-dependent I_{th} data

a) Calculate J_{c0} (= kI_{th}/d) and the average E induced in the superconducting film at the full penetration threshold by

$$E_{avg} \approx 2{,}04\mu_0 f d^2 J_c = 2{,}04\mu_0 k f d I_{th}, \tag{4}$$

from the obtained I_{th} at each frequency using the theoretical coefficient k calculated in 6.2.1. The derivation of Equation (4) is described in A.4.

b) Obtain the *E-J* characteristics

$$E_i = A_{0i} \times J^n \tag{5}$$

from the relation between E_{avg} and J_{c0}, and plot them in the same figure where the transport *E-J* characteristics data were plotted. Broken lines in Figure 5 show three sets of