IEC 61788-15

Edition 2.0 2026-03

INTERNATIONAL STANDARD

REDLINE VERSION

Superconductivity -
Part 15: Electronic characteristic measurements - Intrinsic surface impedance of superconductor films at microwave frequencies

ICS 17.220.20; 29.050

ISBN 978-2-8327-1167-5

IEC 61788-15:2026-03 RLV(en)

THIS PUBLICATION IS COPYRIGHT PROTECTED
Copyright © 2026 IEC, Geneva, Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester. If you have any questions about IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

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

Tel.: +41 22 919 02 11
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 corrigendum or an amendment might have been published.

IEC publications search - webstore.iec.ch/advsearchform
The advanced search enables 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 It also gives information on projects, replaced and withdrawn publications.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 online and once a month by email.

IEC 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: sales@iec.ch.

IEC Products & Services Portal - products.iec.ch
Discover our powerful search engine and read freely all the publications previews, graphical symbols and the glossary. With a subscription you will always have access to up to date content tailored to your needs.

Electropedia - www.electropedia.org
The world's leading online dictionary on electrotechnology, containing more than 22 500 terminological entries in English and French, with equivalent terms in 25 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

Warning! Make sure that you obtained this publication from an authorized distributor.

CONTENTS

FOREWORD 5
INTRODUCTION 1
1 Scope 8
2 Normative references 8
3 Terms and definitions ~~and general concepts~~ 8
4 Requirements 9
5 Apparatus 10
5.1 Measurement equipment 10
5.2 Measurement apparatus 10
5.3 Dielectric rods 12
5.4 Superconductor films and copper cavity 17
6 Measurement procedure 17
6.1 Set-up 17
6.2 Measurement of the reference level 17
6.3 Measurement of the R_S of oxygen-free high ~~purity~~ conductivity copper 18
6.4 Determination of the ~~effective R_S~~ R_{Se} of superconductor films and tan δ of standard dielectric rods 21
6.5 Determination of the penetration depth 23
6.6 Determination of the intrinsic surface impedance 24
7 Uncertainty of the test method 26
7.1 Measurement of unloaded quality factor 26
7.2 Measurement of loss tangent 26
7.3 Temperature 27
7.4 Specimen and holder support structure 27
7.5 Uncertainty in the intrinsic surface impedance 27
8 Test Report 28
8.1 Identification of test specimen 28
8.2 Report of the ~~intrinsic~~ Z_S values 28
8.3 Report of the test conditions 28
Annex A (informative) ~~Additional~~Detailed information relating to Clauses 1 to 8 29
A.1 ~~Concerning the Scope~~General 29
A.2 Requirements 31
A.3 Theory and the measurement procedure for the intrinsic surface impedance 32
A.3.1 Theoretical relation between the ~~intrinsic~~ Z_S and the ~~effective Z_S [1]~~[1] Z_{Se} [14] 32
A.3.2 Calculation of the geometrical factors [22] 37
A.3.3 Procedures for determining the ~~intrinsic~~ Z_S [14] [22] [23] 39
A.4 Dimensions of the standard sapphire rod 40
A.5 Dimensions of the closed type resonators 43
A.6 Test results for type A and type B sapphire resonator 43
A.6.1 Test results for type A resonator 43
A.6.2 Test results for type B sapphire resonator 46

~~[1] In this Annex A, numerals in square brackets refer to Clause A.8, Reference documents.~~

A.7 Uncertainty of the test results 50
~~A.8 Reference documents of Annex A~~ .....
~~Annex B (informative) Uncertainty considerations~~ .....
~~B.1 Overview~~ .....
~~B.2 Definitions~~ .....
~~B.3 Consideration of the uncertainty concept~~ .....
~~B.4 Uncertainty evaluation example for TC 90 standards~~ .....
~~B.5 Reference documents of Annex B~~ .....
Annex B (informative) Additional information relating to determination of the penetration depth and the intrinsic surface impedance of superconductor films at microwave frequencies 59
B.1 General 59
B.2 Experimental requirements for utilizing Formula (A.43) 59
B.2.1 Requirements with regard to the temperature 59
B.2.2 Requirements with regard to the electromagnetic radiation effects 59
B.2.3 Requirements for suppressing mechanical vibrations of the cryocooler 61
B.3 Procedures for determining the penetration depth and the intrinsic surface impedance of YBCO films 61
Annex C (informative) Standard uncertainty evaluation in the test method for the intrinsic surface impedance of superconductor films at microwave frequencies 63
C.1 General 63
C.2 Assessment of combined uncertainty in the Z_S from uncertainties in the R_{Se} and λ 63
C.3 Assessment of combined uncertainty in the Z_S from the measured complex conductivity 64
C.4 Results from the round robin test 65
C.4.1 Uncertainties in the R_{Se} and f_0 65
C.4.2 Uncertainty in the λ 68
C.4.3 Uncertainties in the Z_S of the YBCO films from the round robin test 69
C.4.4 Effects of uncertainty in temperature on $u_r(R_{Se})$ from the round robin test 70
Bibliography 72

Figure 1 – Schematic diagram for the measurement equipment for the intrinsic Z_S of HTS films at cryogenic temperatures 11
Figure 2 – Schematic diagram of a dielectric resonator with a switch for thermal connection 13
Figure 3 – Typical dielectric resonator with a movable top plate 14
Figure 4 – Switch block for thermal connection 15
Figure 5 – Dielectric resonator assembled with a switch block for thermal connection 16
Figure 6 – A typical resonance peak 19
Figure 7 – Reflection scattering parameters S_{11} and S_{22} 20
Figure 8 – Definitions for terms in Table 5 27
Figure A.1 – Schematic diagram for the measurement system 30
Figure A.2 – A motion stage using step motors 31
Figure A.3 – Cross-sectional view of a dielectric resonator 32
Figure A.4 – A diagram for simplified cross-sectional view of a dielectric resonator 37

Figure A.5 – Mode chart for type A sapphire resonator with a cavity diameter of 12 mm 42
Figure A.6 – Frequency response of ~~the~~ type A sapphire resonator 43
Figure A.7 – Q_U versus temperature for the TE_{021} and the TE_{012} modes of ~~the~~ type A sapphire resonator with 360 nm-thick YBCO films 44
Figure A.8 – The resonant frequency f_0 versus temperature for the TE_{021} and TE_{012} modes of ~~the~~ type A sapphire resonator with 360 nm-thick YBCO films 44
Figure A.9 – The temperature dependence of the R_{Se} of YBCO films with the thicknesses of 70 nm to 360 nm measured at ~ 40 GHz 45
Figure A.10 – The temperature dependence of $\Delta\lambda_e$ for the YBCO films with the thicknesses of 70 nm and 360 nm measured at ~ 40 GHz 45
Figure A.11 – The temperature dependence of the penetration depth λ of the 360 nm-thick YBCO film measured at 10 kHz using the mutual inductance method and at ~ 40 GHz using type A sapphire resonator 46
Figure A.12 – The temperature dependence of the ~~intrinsic surface resistance~~ R_S of YBCO films with the thicknesses of 70 nm to 360 nm measured at ~ 40 GHz 46
Figure A.13 – Mode chart used for type B sapphire resonator with a cavity diameter of 15,78 mm 47
Figure A.14 – Frequency response of type B sapphire resonator 48
Figure A.15 – The temperature dependence of the R_{se} for the 300 nm-thick YBCO films measured at ~ 38 GHz 48
Figure A.16 – The temperature dependence of $\Delta\lambda_e$ for the 300 nm-thick YBCO film measured at ~ 38 GHz 49
Figure A.17 – The temperature dependence of σ_2 for the 300 nm-thick YBCO films measured at ~ 38 GHz 49
Figure A.18 – The temperature dependence of the R_S for the 300 nm-thick YBCO films measured at ~ 38 GHz 50
~~Figure A.13 – Comparison of the temperature-dependent value of each term in Equation (A.35) for the TE_{021} mode of the standard sapphire resonator .....~~
~~Figure A.14 – Comparison of the temperature-dependent value of each term in Equation (A.35) for the TE_{012} mode of the standard sapphire resonator .....~~
~~Figure A.15 – Temperature dependence of uncertainty in the measured intrinsic R_S of YBCO films .....~~
Figure B.1 – A comparison between variations in the temperature of the top plate and the rest of the sapphire resonator over time 60
Figure B.2 – The temperature dependence of the ratio of Δf_0 to f_0 for type A sapphire resonator having YBCO endplates for the gap distances of 0 µm (filled) and 10 µm (open) 60
Figure B.3 – The temperature dependence of TE_{021}-mode Q_U of type A sapphire resonator for the gap distances of 0 µm (filled) and 10 µm (open) 61
Figure C.1 – The temperature dependence of the measured TE_{021}-mode Q_U vs. temperature data from the round robin test 66
Figure C.2 – The temperature dependence of the measured resonant frequencies of the TE_{021} mode for the sapphire resonator under the round robin test 66
Figure C.3 – The temperature dependence of the relative uncertainty in the TE_{021} mode Q_U and the TE_{012} mode Q_U from the round robin test 67

Figure C.4 – The temperature dependence of the relative uncertainty in the TE_{021} mode f_0 vs. temperature data from the round robin test 67

Figure C.5 – Comparison of the temperature dependence of the measured R_{Se} at ~ 38 GHz for the YBCO films under the round robin test 68

Figure C.6 – The temperature dependence of the relative uncertainties in the R_{Se} (open circle) and R_S (filled circle) at ~ 38 GHz for the YBCO films under the round robin test 69

Figure C.7 – The temperature dependence of the relative uncertainties in the TE_{021}-mode Q_U from the RRT (open circle) and that due to the presumed uncertainty of 0,5 K in the temperature (cross) at ~ 38 GHz for type B sapphire resonator 71

Table 1 – Typical dimensions of a sapphire rod 17

Table 2 – Typical dimensions of OFHC cavities and HTS films 17

Table 3 – Geometrical factors and filling factors calculated for the standard sapphire resonators 21

Table 4 – Specifications of Vector Network Analyser 26

Table 5 – Type B uncertainty for the specifications on the sapphire rod 27

~~Table A.1 – Geometrical factors and filling factors calculated for the standard sapphire resonator .....~~

~~Table B.1 – Output signals from two nominally identical extensometers .....~~

~~Table B.2 – Mean values of two output signals .....~~

~~Table B.3 – Experimental standard deviations of two output signals .....~~

~~Table B.4 – Standard uncertainties of two output signals .....~~

~~Table B.5 – Coefficient of variations of two output signals .....~~

Table C.1 – Values of ε_{r4}, l, t, β_4, β_{z4}, β_h, λ and $\coth(t/\lambda)$ at 30 K 64

Table C.2 – The average values for the R_{Se} and the R_S of the YBCO films from the round robin test and the relative uncertainties in the R_{Se} and the R_S 70

INTERNATIONAL ELECTROTECHNICAL COMMISSION

_____

Superconductivity - Part 15: Electronic characteristic measurements - Intrinsic surface impedance of superconductor films at microwave frequencies

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.
9) IEC draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). IEC takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, IEC had not received notice of (a) patent(s), which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at https://patents.iec.ch. IEC shall not be held responsible for identifying any or all such patent rights.

This redline version of the official IEC Standard allows the user to identify the changes made to the previous edition IEC 61788-15:2011. A vertical bar appears in the margin wherever a change has been made. Additions are in green text, deletions are in strikethrough red text.

IEC 61788-15 has been prepared by IEC technical committee 90: Superconductivity. It is an International Standard.

This second edition cancels and replaces the first edition published in 2011. This edition constitutes a technical revision.

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

a) informative Annex B, combined relative standard uncertainty in the intrinsic surface impedance is added;
b) the terms, ‘precision and accuracy’, are replaced with uncertainty;
c) results from a round robin test are added.

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

Draft	Report on voting
90/550/FDIS	90/556/RVD

Full information on the voting for its approval 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/publications.

A list of all parts in 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 document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

– reconfirmed,
– withdrawn, or
– revised.

INTRODUCTION

Since the discovery of high T_C superconductors (HTS), extensive researches have been performed worldwide on electronic applications and large-scale applications with HTS filter subsystems based on $YBa_2Cu_3O_{7-\delta}$ (YBCO) having already been commercialized [1][2].

Merits of using HTS films for microwave devices such as resonators, filters, antennas, delay lines, etc., include i) microwave losses from HTS films could be extremely low and ii) no signal dispersion on transmission lines made of HTS films due to extremely low ~~microwave~~ intrinsic surface resistance (R_S) [2] and frequency-independent penetration depth (λ) of HTS films, respectively.

In this regard, when it comes to designing of HTS-based microwave devices, it is important to measure the intrinsic surface impedance (Z_S) of HTS films with $Z_S = R_S + jX_S$ and $X_S = \omega\mu_0\lambda$ (here ω and μ_0 denote the angular frequency and the permeability of vacuum, respectively, X_S, the intrinsic surface reactance, and $X_S = \omega\mu_0\lambda$ is valid at temperatures not too close to the critical temperature T_C of HTS films).

Various reports have been made on measuring the R_S of HTS films at microwave frequencies with the typical R_S of HTS films as low as 1/100 to 1/50 of that of oxygen-free high ~~purity~~ conductivity copper (OFHC) at 77 K and 10 GHz. The R_S of conventional superconductors such as niobium (Nb) could be easily measured by using Nb cavities by converting the resonator quality factor (Q) to the R_S of Nb. However, such conventional measurement method could no longer be applied to HTS films grown on dielectric substrates, with which it is basically impossible to make all-HTS cavities. Instead, for measuring the R_S of HTS films, several other methods have been useful, which include microstrip resonator method [3], coplanar microstrip resonator method [4], parallel plate resonator method [5] and dielectric resonator method ([6] to [11]). Among the stated methods, the dielectric resonator method has been very useful due to the fact that the method enables to measure the ~~R_S~~ microwave surface resistance in a non-invasive way and with accuracy. In 2002, the International Electrotechnical Commission (IEC) published the dielectric resonator method as a measurement standard [12].

The test method given in this document enables to measure not only the ~~intrinsic surface resistance~~ R_S but also the ~~intrinsic surface reactance~~ X_S of HTS films regardless of the film's thickness by using single sapphire resonator, which differs from the existing IEC standard (IEC 61788-7~~:2006~~) that is limited to measure the surface resistance of superconductor films having the thicknesses of more than 3λ at the measured temperature by using two sapphire resonators. In fact, the measured surface resistances of HTS films with different thicknesses of less than 3λ mean effective values instead of intrinsic values, which cannot be used for directly comparing the microwave properties of HTS films among one another [13], [14]. Use of a single sapphire resonator as suggested in this document also enables to reduce uncertainty in the measured surface resistance that ~~might~~ can result from using two sapphire resonators with sapphire rods of ~~even slightly~~ different quality.

The test method given in this document can also be applied to HTS coated conductors, HTS bulks and other superconductors having established models for the penetration depth.

This document is intended to provide an appropriate and agreeable technical base for the time being to engineers working in the fields of electronics and superconductivity technology.

The test method covered in this document has been discussed at the VAMAS (Versailles Project on Advanced Materials and Standards) TWA-16 meeting.

---

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

1 Scope

This part of IEC 61788 describes measurements of the intrinsic surface impedance (Z_S) of HTS films at microwave frequencies by a modified two-resonance mode dielectric resonator method [14], [15]. The object of measurement is to obtain the temperature dependence of the intrinsic surface impedance, Z_S, at the resonant frequency f_0.

The frequency and thickness range and the measurement resolution for the ~~intrinsic~~ Z_S of HTS films are as follows:

– frequency: up to 40 GHz;
– film thickness: greater than 50 nm;
– measurement resolution: 0,01 mΩ at 10 GHz.

It is crucial that the ~~intrinsic~~ Z_S data at the measured frequency, and that scaled to 10 GHz be reported for comparison, assuming the f^2 rule for the intrinsic surface resistance, R_S (f < 40 GHz), and the f rule for the intrinsic surface reactance, X_S ~~for comparison, shall be reported~~.

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:~~2000~~2024, *International Electrotechnical Vocabulary - Part 815: Superconductivity*

~~IEC 61788-7:2006, *Superconductivity – Part 7: Electronic characteristic measurements – Surface resistance of superconductors at microwave frequencies*~~

3 Terms and definitions ~~and general concepts~~

~~3.1 Terms and definitions~~

For the purposes of this document, the terms and definitions given in IEC 60050-815~~, one of which is repeated here for convenience,~~ and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

– IEC Electropedia: available at https://www.electropedia.org/
– ISO Online browsing platform: available at https://www.iso.org/obp

3.1
surface impedance
~~impedance of a material for highfrequency electromagnetic wave which is constrained to the surface of the material in case of metals and superconductors~~

impedance of a metallic material or a superconductor when a high-frequency electromagnetic wave is constrained to the surface

Note 1 to entry: The surface impedance governs the thermal losses of superconducting RF cavities.

Note 2 to entry: This entry was numbered 815-13-60 in IEC 60050-815:2015.

[SOURCE: IEC 60050-815:20242000, 815-04-62 815-22-33]

~~3.2 General concepts~~

3.2
intrinsic surface impedance

~~In general, the surface impedance Z_S of conductors, including superconductors, is defined as the ratio of the tangential component of the electric field (E_t) and that of the magnetic field (H_t) at a conductor surface:~~

~~$$Z_S = \frac{E_t}{H_t} = R_S + jX_S \quad (1)$$~~

~~Here R_S denotes the surface resistance and X_S, the surface reactance. If the thickness of the conductor (or the superconductor) under test is sufficiently greater than the penetration depth of electromagnetic fields, Z_S is expressed by~~

~~$$Z_S = \left(\frac{\mu}{\varepsilon}\right)^{\frac{1}{2}} = \left(\frac{j\mu_0\omega}{\sigma}\right)^{\frac{1}{2}} \quad (2)$$~~

~~with ε and μ denoting the permittivity and the permeability of the conductor (or the superconductor) under test, respectively, μ_0, the permeability of vacuum, σ, the conductivity of the conductor (or the superconductor), and ω, the measured angular frequency, and is called the intrinsic surface impedance. σ is real for the conductor and complex for the superconductor.~~

impedance of conductors (or superconductors) having the thicknesses sufficiently greater than the skin depth (or the penetration depth), with the intrinsic surface impedance Z_S defined as the ratio of the tangential component of the electric field (E_t) and that of the magnetic field (H_t) at a conductor or a superconductor surface:

$$Z_S = E_t / H_t = R_S + jX_S \quad (1)$$

3.3
effective surface impedance

~~If the thickness of the conductor (or the superconductor) under test is not sufficiently greater than the penetration depth of electromagnetic fields, Z_S as defined by Equation (1) in 3.2.1 becomes significantly different from that defined by Equation (2) in 3.2.1. In this case, Z_S as defined by Equation (1) is called the effective surface impedance Z_{Se} with~~

~~$$Z_{Se} = \frac{E_t}{H_t} = R_{Se} + jX_{Se} \quad (3)$$~~

~~Here R_{Se} denotes the effective surface resistance and X_{Se}, the effective surface reactance.~~

impedance of conductors (or superconductors) having the thicknesses not sufficiently greater than the skin depth (or the penetration depth) as defined by

$$Z_{Se} = E_t / H_t = R_{Se} + jX_{Se} \quad (2)$$

with Z_{Se} being significantly different from Z_S in Formula (1).