IEC 61788-7

Edition 2.0 2006-10

INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour inside

Superconductivity –
Part 7: Electronic characteristic measurements – Surface resistance of superconductors at microwave frequencies

Supraconductivité –
Partie 7: Mesures des caractéristiques électroniques – Résistance de surface des supraconducteurs à des hyperfréquences

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FOREWORD

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International Standard IEC 61788-7 has been prepared by IEC technical committee 90: Superconductivity.

This bilingual version (2020-07) corresponds to the monolingual English version, published in 2006-10.

This second edition cancels and replaces the first edition, published in 2002, of which it constitutes a technical revision. Examples of technical changes made are: 1) closed type resonators are recommended from the viewpoint of the stable measurements, 2) uniaxial-anisotropic characteristics of sapphire rods are taken into consideration for designing the size of the sapphire rods, and 3) recommended measurement frequency of 18 GHz and 22 GHz are added to 12 GHz described in the first edition.

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

FDIS	Report on voting
90/193/FDIS	90/198/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.

The French version of this standard has not been voted upon.

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

IEC 61788 consists of the following parts, under the general title *Superconductivity*:

Part 1: Critical current measurement – DC critical current of Cu/Nb-Ti composite superconductors
Part 2: Critical current measurement – DC critical current of Nb_3Sn composite superconductors
Part 3: Critical current measurement – DC critical current of Ag- and/or Ag alloy-sheathed Bi-2212 and Bi-2223 oxide superconductors
Part 4: Residual resistance ratio measurement – Residual resistance ratio of Nb-Ti composite superconductors
Part 5: Matrix to superconductor volume ratio measurement – Copper to superconductor volume ratio of Cu/Nb-Ti composite superconductors
Part 6: Mechanical properties measurement – Room temperature tensile test of Cu/Nb-Ti composite superconductors
Part 7: Electronic characteristic measurements – Surface resistance of superconductors at microwave frequencies
Part 8: AC loss measurements – Total AC loss measurement of Cu/Nb-Ti composite superconducting wires exposed to a transverse alternating magnetic field by a pickup coil method
Part 9: Measurements for bulk high temperature superconductors – Trapped flux density of large grain oxide superconductors
Part 10: Critical temperature measurement – Critical temperature of Nb-Ti, Nb_3Sn, and Bi-system oxide composite superconductors by a resistance method
Part 11: Residual resistance ratio measurement – Residual resistance ratio of Nb_3Sn composite superconductors
Part 12: Matrix to superconductor volume ratio measurement – Copper to non-copper volume ratio of Nb_3Sn composite superconducting wires
Part 13: AC loss measurements – Magnetometer methods for hysteresis loss in Cu/Nb-Ti multifilamentary composites

The committee has decided that the contents of this publication will remain unchanged until the maintenance result 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.

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INTRODUCTION

Since the discovery of some Perovskite-type Cu-containing oxides, extensive research and development (R & D) work on high-temperature oxide superconductors has been, and is being, made worldwide, and its application to high-field magnet machines, low-loss power transmission, electronics and many other technologies is in progress.

In various fields of electronics, especially in telecommunication fields, microwave passive devices such as filters using oxide superconductors are being developed and are undergoing on-site testing [1,2][1].

Superconductor materials for microwave resonators, filters, antenna and delay lines have the advantage of very low loss characteristics. Knowledge of this parameter is of primary importance for the development of new materials on the supplier side and for the design of superconductor microwave components on the customer side. The parameters of superconductor materials needed for the design of microwave low loss components are the surface resistance R_s and the temperature dependence of the surface resistance.

Recent advances in high Tc superconductor (HTS) thin films with R_s several orders of magnitude lower than that of normal metals have increased the need for a reliable characterization technique to measure this property [3,4]. Traditionally, the R_s of Nb or any other low temperature superconducting material was measured by first fabricating an entire three dimensional resonant cavity and then measuring its Q-value. The R_s could be calculated by solving the EM field distribution inside the cavity. Another technique involves placing a small sample inside a larger cavity. This technique has many forms but usually involves the uncertainty introduced by extracting the loss contribution due to the HTS films from the experimentally measured total loss of the cavity.

The best HTS samples are epitaxial films grown on flat crystalline substrates and no high quality films have been grown on any curved surface so far. What is needed is a technique that: can use these small flat samples; requires no sample preparation; does not damage or change the film; is highly repeatable; has great sensitivity (down to 1/1 000th the R_s of copper); has great dynamic range (up to the R_s of copper); can reach high internal powers with only modest input powers; and has broad temperature coverage (4,2 K to 150 K).

The dielectric resonator method is selected among several methods [5,6,7] to determine the surface resistance at microwave frequencies because it is considered to be the most popular and practical at present. Especially, the sapphire resonator is an excellent tool for measuring the R_s of HTS materials [8,9].

The test method given in this standard can be also applied to other superconductor bulk plates including low Tc material.

This standard 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 standard is based on the VAMAS (Versailles Project on Advanced Materials and Standards) pre-standardization work on the thin film properties of superconductors.

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

SUPERCONDUCTIVITY –

Part 7: Electronic characteristic measurements – Surface resistance of superconductors at microwave frequencies

1 Scope

This part of IEC 61788 describes measurement of the surface resistance of superconductors at microwave frequencies by the standard two-resonator method. The object of measurement is the temperature dependence of R_s at the resonant frequency.

The applicable measurement range of surface resistances for this method is as follows:

– Frequency:	8 GHz < f < 30 GHz
– Measurement resolution:	0,01 mΩ at 10 GHz

The surface resistance data at the measured frequency, and that scaled to 10 GHz, assuming the f^2 rule for comparison, are reported.

2 Normative references

The following referenced documents are indispensable for the application 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 (IEV) – Part 815: Superconductivity*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-815 apply.

In general, surface impedance Z_s for conductors, including superconductors, is defined as the ratio of the electric field E_t to the magnetic field H_t, tangential to a conductor surface:

$$Z_s = E_t / H_t = R_s + jX_s$$

where R_s is the surface resistance and X_s is the surface reactance.

4 Requirements

The surface resistance R_s of a superconductor film shall be measured by applying a microwave signal to a dielectric resonator with the superconductor film specimen and then measuring the attenuation of the resonator at each frequency. The frequency shall be swept around the resonant frequency as the centre, and the attenuation–frequency characteristics shall be recorded to obtain Q-value, which corresponds to the loss.

The target precision of this method is a coefficient of variation (standard deviation divided by the average of the surface resistance determinations) that is less than 20 % for the measurement temperature range from 30 K to 80 K.

It is the responsibility of the user of this standard to consult and establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to use.

Hazards exist in this type of measurement. The use of a cryogenic system is essential to cool the superconductors to allow transition into the superconducting state. Direct contact of skin with cold apparatus components can cause immediate freezing, as can direct contact with a spilled cryogen. The use of an r.f.-generator is also essential to measure high-frequency properties of materials. If its power is too high, direct contact to human bodies can cause an immediate burn.

5 Apparatus

5.1 Measurement system

Figure 1 shows a schematic diagram of the system required for the microwave measurement. The system consists of a network analyzer system for transmission measurement, a measurement apparatus, and a thermometer for monitoring the measuring temperature.

An incident power generated from a suitable microwave source such as a synthesized sweeper is applied to the dielectric resonator fixed in the measurement apparatus. The transmission characteristics are shown on the display of the network analyzer.

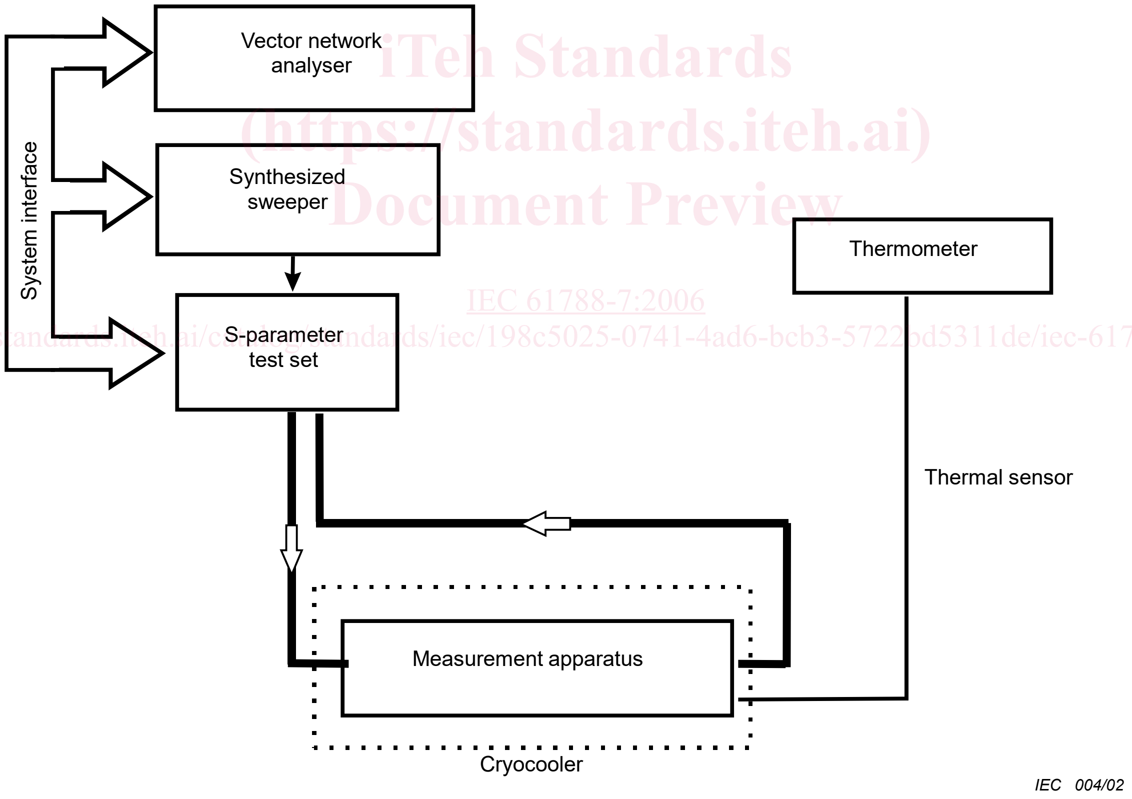

Figure 1 – Schematic diagram of measurement system for temperature dependence of R_S using a cryocooler

The measurement apparatus is fixed in a temperature-controlled cryocooler.

For the measurement of R_S for superconductor films, a vector network analyzer is recommended. A vector network analyzer has better measurement accuracy than a scalar network analyzer due to its wide dynamic range.

5.2 Measurement apparatus for R_s

Figure 2 shows a schematic of a typical measurement apparatus (closed type resonator) for the R_s of superconductor films deposited on a substrate with a flat surface. The upper superconductor film is pressed down by a spring, which is made of phosphor bronze. The plate type spring is recommended to be used for the improvement of measurement accuracy. This type of spring reduces the friction between the spring and the other part of the apparatus, and allows the smooth movement of superconductor films due to the thermal expansion of the dielectric rod. In order to minimize the measurement error, the sapphire rod and the copper ring shall be set in coaxial.

Two semi-rigid cables for measuring transmission characteristics of the resonator shall be attached on both sides of the resonator in an axial symmetrical position ($\phi = 0$ and π, where ϕ is the rotational angle around the central axis of the sapphire rod). Each of the two semi-rigid cables shall have a small loop at the ends. The plane of the loop shall be set parallel to that of the superconductor films in order to suppress the unwanted TM_{mn0} modes. The coupling loops shall be carefully checked for cracks in the spot weld joint that may have developed upon repeated thermal cycling. These cables can move right and left to adjust the insertion attenuation (IA). In this adjustment, coupling of unwanted cavity modes to the interested dielectric resonance mode shall be suppressed. Unwanted, parasitic coupling to the other modes reduces the high Q value of the TE mode resonator. For suppressing the parasitic coupling, special attention shall be paid to designing high Q resonators. Two other types of resonators along with the closed type shown in Figure 2 can be used. They are explained in Clause A.4.

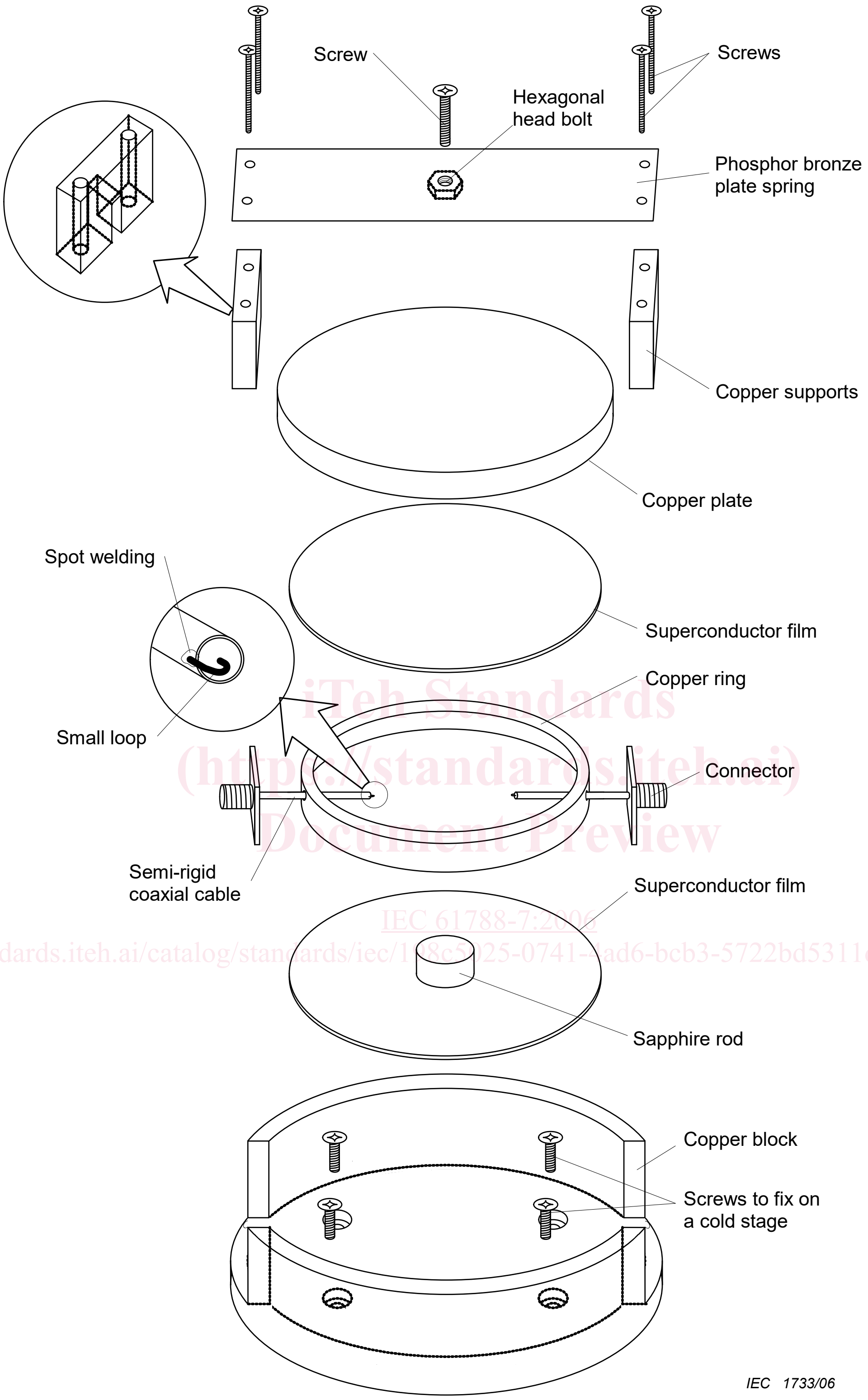

Figure 2 – Typical measurement apparatus for R_s

A reference line made of a semi-rigid cable shall be used to measure the full transmission power level, i.e., the reference level. This cable has a length equal to the sum of the two cables of the measurement apparatus. The semi-rigid cable with the outer diameter of 1,20 mm is recommended.

In order to minimize the measurement error, two superconductor films shall be set to be parallel to each other. To ensure that the two superconductor films remain in tight contact with the ends of the sapphire rod, without any air gap, both of the surfaces of the films and the ends of the rod shall be cleaned carefully.

5.3 Dielectric rods

Two dielectric rods with the same relative permittivity, ε', and loss factor, tan δ, preferably cut from one cylindrical dielectric rod, are required. These two rods, standard dielectric rods, shall have the same diameter but different heights: one has a height three times longer than the other.

It is preferable to use standard dielectric rods with low tan δ to achieve the requisite measurement accuracy on R_S. Recommended dielectric rods are sapphire rods with tan δ less than 10^{-6} at 77 K. Specifications on the sapphire rods are described in 7.1. In order to minimize the measurement error in R_S of the superconductor films, both ends of the sapphire rods shall be polished parallel to each other and perpendicular to the axis. Specifications for the sapphire rods are described in Clause 7.

The diameter and the heights of the standard sapphire rods shall be carefully designed so that the TE_{011} and TE_{013} modes do not couple to other TM, HE and EH modes, since the coupling between TE mode and other modes causes the degradation of unloaded Q. A design guideline for the standard sapphire rods is described in Clause A.5. Table 1 shows typical examples of dimensions of the standard sapphire rods for 12 GHz, 18 GHz, and 22 GHz resonance. At higher frequencies the unloaded Q value will be lower, which makes the measurement easier, and the error will be lower.

Table 1 – Typical dimensions of pairs of standard sapphire rods for 12 GHz, 18 GHz and 22 GHz

Frequency GHz		**Diameter**	**Height**
		d mm	h mm
12	Short rod (TE_{011} resonator)	11,4	5,7
	Long rod (TE_{013} resonator)	11,4	17,1
18	Short rod (TE_{011} resonator)	7,6	3,8
	Long rod (TE_{013} resonator)	7,6	11,4
22	Short rod (TE_{011} resonator)	6,2	3,1
	Long rod (TE_{013} resonator)	6,2	9,3

6 Measurement procedure

6.1 Specimen preparation

From error estimation, the film diameter shall be about three times larger than that of the sapphire rods. In this configuration, the reduction in precision of R_s due to the different radiation losses between TE_{011} and TE_{013} mode can be considered negligible, given the target precision of 20 %. The film thickness shall be about three times larger than the London penetration depth value at each temperature. If the film thickness is much less than three times the London penetration depth, the measured R_s should mean the effective surface resistance.

Table 2 shows dimensions of the superconductor films recommended for the standard sapphire rods of 12 GHz, 18 GHz, and 22 GHz.

Table 2 – Dimensions of superconductor film for 12 GHz, 18 GHz, and 22 GHz

Standard dielectric rod		**Superconductor film**	
Frequency GHz	**Diameter** d mm	**Diameter** d' mm	**Thickness** µm
12	11,4	>35	≅0,5
18	7,6	>25	≅0,5
22	6,2	>20	≅0,5

In case of using closed type resonators, the dimensions of the superconductor films shall also be designed taking into account the dimension of the copper cylinder between the superconductor films. A design guideline for the dimension of the copper cylinder of the closed type resonator is described in Clause A.6.

6.2 Set-up

Set up the measurement equipment as shown in Figure 1. All of the measurement apparatus, standard sapphire rods, and superconductor films shall be kept in a clean and dry state as high humidity may degrade the unloaded Q-value. The specimen and the measurement apparatus shall be fixed in a temperature-controlled cryocooler. The specimen chamber shall be generally evacuated. The temperatures of the superconductor films and standard sapphire rods shall be measured by a diode thermometer, or a thermocouple. The temperatures of the upper and lower superconductor films, and standard sapphire rods must be kept as close as possible. This can be achieved by covering the measurement apparatus with aluminum foil, or filling the specimen chamber with helium gas.

6.3 Measurement of reference level

The level of full transmission power (reference level) shall be measured first. Fix the output power of the synthesized sweeper below 10 mW because the measurement accuracy depends on the measuring signal level. Connect the reference line of semi-rigid cable between the input and output connectors. Then, measure the transmission power level over the entire measurement frequency and temperature range. The reference level can change several decibels when temperature of the apparatus is changed from room temperature to the lowest measurement temperature. Therefore, the temperature dependence of the reference level must be taken into account.