IEC 61788-22-2

Edition 1.0 2021-10

INTERNATIONAL STANDARD

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**Superconductivity –
Part 22-2: Normal state resistance and critical current measurement –
High-T_c Josephson junction**

**Supraconductivité –
Partie 22-2: Mesurage de la résistance à l'état normal et du courant critique –
Jonction Josephson à T_c élevée**

IEC 61788-22-2:2021-10(en-fr)

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INTERNATIONAL
ELECTROTECHNICAL
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ICS 29.050

ISBN 978-2-8322-1039-7

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FDIS	Report on voting
90/484/FDIS	90/486/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/standardsdev/publications.

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

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- withdrawn,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

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INTRODUCTION

IEC 61788-22 (all parts) is a series of International Standards on superconductor electronic devices. Superconductivity offers various possibilities of realizing sensors and detectors for a variety of measurands. Several types of superconductor sensors and detectors have been developed, using such features as superconducting energy gaps, sharp normal-superconducting transition, nonlinear current-voltage characteristics, superconducting coherent states and quantization of magnetic flux. Superconductors are influenced by interaction with electromagnetic fields, photons, ions, etc. The superconductor sensors and detectors have extremely high performance in resolution, time response and sensitivity, which cannot be realized by any other sensors and detectors.

IEC 61788-22-1 lists various types of superconductor sensors and detectors. A key element of some sensors and detectors is Josephson junction. The superconductor material types used for Josephson junctions are divided into two categories: low-T_c superconductor (LTS) and high-T_c superconductor (HTS). This document (IEC 61788-22-2) defines a measurement method of normal state resistance (R_n) and intrinsic critical current (I_{ci}) of HTS Josephson junctions, which are used for magnetic measurement with superconductor quantum interference device (SQUID), detection of millimetre to terahertz band radiation and other applications.

The measurement method covered in this document is intended to give an appropriate and agreeable technical base for those engineers working in the field of superconductor technology. Although the mechanism of high-T_c superconductivity is under investigation, the occurrence of the Josephson effect in such weak link structures as bicrystal, step-edge and ramp edge is reliable, and characteristic parameters for conventional LTS Josephson junctions are valid also for HTS Josephson junctions. The important parameters of HTS Josephson junctions for designing superconductor devices are normal state resistance (R_n) and critical current (I_c), which are combined as I_cR_n product that is obtained experimentally. At this moment, most HTS Josephson junctions exhibit a non-hysteretic characteristic voltage-current (U–I) curve, which is typical for superconductor/normal-conductor/superconductor (SNS) junctions. On U–I curves, two types of distortions are often observed: noise-rounding and self-heating effects. Especially, maximum current values without voltage drop on the U–I curves are often considerably reduced because of the noise-rounding effect, and therefore it is difficult to estimate an intrinsic critical current value. This document provides a method to obtain intrinsic values by selecting a data set range to eliminate the distortions and by fitting a model function even when two effects are present.

The critical current obtained by this standard method is therefore called intrinsic critical current with the variable symbol of I_{ci}, eliminating the noise-rounding effect on U–I curves. On the other hand, the normal state resistance is insensitive to the noise rounding and it is possible to avoid the self-heating effect, so that the variable symbol R_n is used. The $I_{ci}R_n$ product is more essential for designing superconductor devices than the I_cR_n product. I_{ci} values estimated by this document are usually higher than experimental I_c values.

Practical application of this document to HTS Josephson junctions is shown in Annex A. The estimation method in this document is applied to SNS-type LTS Josephson junctions to check universality in Annex B.

SUPERCONDUCTIVITY –

Part 22-2: Normal state resistance and critical current measurement – High-T_c Josephson junction

1 Scope

This part of IEC 61788 is applicable to high-T_c Josephson junctions. It specifies terms, definitions, symbols and the measurement and estimation method for normal state resistance (R_n) and intrinsic critical current (I_{ci}), based on a combination of selecting a data set from measured U–I curves with a geometric mean criterion and fitting a hyperbolic function to that data set.

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 61788-22-1, *Superconductivity – Part 22-1: Superconducting electronic devices – Generic specification for sensors and detectors*

IEC 60617, *Graphical symbols for diagrams*: available at http://std.iec.ch/iec60617

IEC 60050-815:2015, *International Electrotechnical Vocabulary – Part 815: Superconductivity*: (available at http://www.electropedia.org/

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

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

3.1
***U*–*I* characteristic curve**
V–*I* characteristic curve
I–*V* characteristic curve
data set of voltage drop between two superconductors of a Josephson junction and current applied to the junction

3.2
normal state resistance
R_n
normal resistance
resistance between two superconductors forming a Josephson junction in a normal-conducting state

Note 1 to entry: In a Josephson bridge junction, a normal state resistance is also defined as the resistance at a bias current that suppresses superconductivity well above critical current, when the self-heating effect is negligible.

Note 2 to entry: In a Josephson tunnel junction, a normal state resistance is also defined as the tunnelling resistance at a bias voltage well above $2\Delta/e$, where Δ is the energy gap and e is the elementary electric charge, when the self-heating effect is negligible.

3.3
intrinsic critical current
I_{ci}
maximum direct current that can be applied to a Josephson junction without causing a voltage drop across the junction in the absence of noise-rounding on a U–I characteristic curve

Note 1 to entry: Critical current (I_c) is the maximum direct current value that can be applied to a Josephson junction experimentally so that it can be regarded as flowing without resistance (IEC 61788-22-1).

Note 2 to entry: The method described in this document estimates I_{ci}, the value of which is usually higher than I_c.

3.4
geometric mean

square root of the product of dU/dI and U/I obtained from a U–I characteristic curve

3.5
noise-rounding effect

effect of noise on a U–I characteristic curve

Note 1 to entry: The U–I curve shape near I_{ci} is rounded from an ideal shape by the noise-rounding effect. Because of this, an I_c value is lower than the I_{ci} value.

3.6
self-heating effect
effect of power dissipation due to transport current applied to a Josephson junction on a U–I characteristic curve

Note 1 to entry: The current generates heat, and a U–I curve shape in a high current region well above I_{ci} deviates upward above a straight line corresponding to R_n.

4 Symbols

U voltage drop across two superconductors connected by a weak link

NOTE "V" can also be used.

I current flowing through two superconductors connected by a weak link

R_n normal state resistance

I_c experimental critical current

I_{ci} intrinsic critical current estimated by this document

$u_{A,R}$ type A standard uncertainty of R_n

$u_{A,I}$ type A standard uncertainty of I_{ci}

$u_{B,R}$ type B standard uncertainty of R_n

$u_{B,I}$ type B standard uncertainty of I_{ci}

5 Principle of measurement method

On U–I curves, two types of distortions are often observed: noise-rounding and self-heating. When the noise-rounding effect is negligible, the I_{ci} value is the maximum current applied to the junction without resistance. When the self-heating effect and the nonlinear property due to superconductivity are negligible, the R_n value of the junction corresponds to a value of U/I at a current much higher than the critical current of the junction. Since a high probe current may cause damage to the junction, the determination of R_n may need to be based on a range of the U–I characteristic curve obtained for moderate currents. The moderate currents are also effective in avoiding the self-heating effect. Here, a nonlinear least-squares fitting method with the hyperbolic function is practical to determine the values of R_n and I_{ci}. Even when these two types of the distortions exist, the combination of the geometric mean criterion and the hyperbolic function fitting gives proper R_n and I_{ci} values.

The R_n and I_{ci} values of a HTS Josephson junction are determined by selecting a data set from the whole data set of a U–I characteristic curve with the geometric mean criterion, and then by fitting the hyperbolic function model (or resistively-shunted junction (RSJ) model) [1][1] to that selected data set. This is called the combined method. The geometric mean criterion and the hyperbolic function fitting method are described in Clause 7.

6 Apparatus

6.1 General

The apparatus required for this measurement method includes a cryogenic system and an electrical measurement system.

6.2 Cryogenic system

An open cryostat with liquid nitrogen shall be used to cool Josephson junctions. The cryostat shall have an open structure so that the pressure of the bath is equal to atmospheric pressure. The atmospheric pressure on earth is normally between 950 hPa and 1 050 hPa, corresponding to a temperature range from 76,8 K to 77,7 K. Measurement during abnormal weather conditions shall be avoided. An atmospheric pressure value from a weather report source near the measurement site or measured locally shall be reported. The cryostat should be equipped with a magnetic shield with an attenuation factor of over 100 (−40 dB) and a RF shield with 1 000 (−60 dB) at 100 kHz. A specimen probe, which may consist of a junction or junctions, a specimen holder and a support structure, shall be cooled from room temperature to liquid nitrogen temperature over a time period of at least three minutes.

It is well known that I_c depends on flux trapping that occurs during cooling process from a normal-conducting state to a superconducting state. Therefore, the cooling process from a temperature above T_c to a base temperature of the liquid nitrogen bath and the R_n and I_{ci} estimation shall be repeated at least 10 times, and the R_n and I_{ci} values obtained from the U–I data set showing the highest I_{ci} value shall be reported.

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

6.3 Electrical measurement system

A measurement system for $U–I$ characteristic curve data sets should consist of a waveform generator, a data acquisition system, differential amplifiers and other necessary instruments such as filters. A four terminal method shall be applied to measure voltage and current. The digital values of voltage and current shall be stored on the data acquisition system with an analogue-to-digital converter (ADC) having a resolution better than eight bits. The $U–I$ data sets are transferred to a computer for estimating R_n and I_{ci}. Other equivalent measurement systems may also be used.

When a waveform generator is used, a current bias with a constant sweep rate shall be applied to the junction and corresponding voltage drop is measured. The current bias shall be triangularly swept from a minus value to a positive value or vice versa while the voltage is recorded. The time for the ramp from $-I_m$ to $+I_m$ shall be longer than 10 ms, where I_m is the maximum current. A sweep frequency (f_s) lower than 50 Hz ensures quasi-DC measurement, in which the effects of stray capacitance and junction capacitance are negligible. The data sampling number per second shall be between $100 \times f_s$ and $200 \times f_s$ to obtain enough data points. The $U–I$ data in the first quadrant and the absolute value data in the third quadrant shall be used for the R_n and I_{ci} estimation described in Clause 7.

Differential amplifiers should be used to separate the grounds of the cryostat and the data acquisition system. The input resistance of differential amplifiers should be higher than 100 kΩ. The input resistance of the data acquisition system should be set at a high value, for example 1 MΩ. Low pass filters with a cutoff frequency of less than approximately 1 MHz should be used. The data measurement range should be approximately $I_m \approx 5 \times I_{ci}$ to avoid any damage to the junction and to obtain enough data points. The origin offset shall be minimized before the data acquisition.

6.4 Circuitry

An example of the equivalent circuit for the $U–I$ characteristic curve measurement is shown in Figure 1. The Josephson junction indicated by IEC 60617-S01926:2017-10 and the surrounding wiring are in a superconducting state. The normal-superconducting boundaries indicated by IEC 60617-S01925:2017-10 distinguish the superconducting circuit and the normal-conducting one. The waveform generator, shunt resistor and data acquisition system may be placed at room temperature. The waveform generator and the digital oscilloscope may be replaced by equivalent instruments.

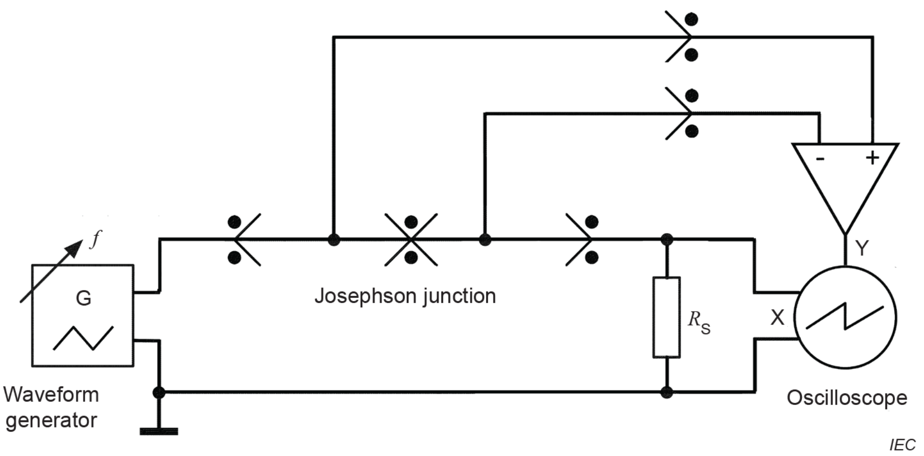

Figure 1 – Typical circuitry for voltage-current ($U–I$) characteristic curve measurement

The data acquisition system records the voltage (U_y) between two electrodes of the Josephson junction and the voltage (U_x) across the shunt resistor of resistance R_s. The current values should be obtained by dividing the U_x values by R_s. The R_s should be more than 1 000 times smaller than the input resistance of the oscilloscope or the differential amplifier. The tolerance of the shunt resistor should be better than ±0,05 %. When the oscilloscope is set at X-Y mode, U–I characteristic curves can be seen on-screen to check the extent of the noise-rounding and self-heating effects, and the origin offset. U–I curve data sets with considerably large effects of noise-rounding and self-heating cannot be used to estimate R_n and I_{ci}. In this case, the measurement apparatus or the junction structure shall be improved.

7 Estimation of normal state resistance (R_n) and intrinsic critical current (I_{ci})

7.1 Calculation method

The R_n and I_{ci} values shall be estimated by optimizing the variables R_n and I_{ci} with the least-squares fitting method so that the hyperbolic function expressed by Formula (1) [1] fits best to a U–I characteristic data set as shown in Figure 2 after selecting a data set range in accordance with the geometric mean criterion mentioned in 7.2.

$$U = R_n\sqrt{I^2 - I_{ci}^2} \ \text{ for} |I| > |I_{ci}|, \quad U = 0 \ \text{ for} |I| < |I_{ci}| \tag{1}$$

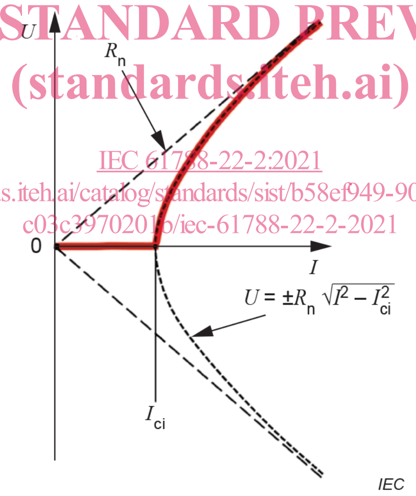

Figure 2 – Ideal U–I characteristic curve (red line) and hyperbolic function (RSJ) model curve (dotted line)

In order to avoid the effects of the noise-rounding and self-heating, a data set range for fitting shall be determined by the geometric mean criterion, taking into account three curves of $\mathrm{d}U/\mathrm{d}I$, U/I and $(\mathrm{d}U/\mathrm{d}I \times U/I)^{0,5}$ plotted against I. The appropriate data set range shall be such that the geometric mean curve $(\mathrm{d}U/\mathrm{d}I \cdot U/I)^{0,5}$ against I has a plateau within 5 % deviation and $\mathrm{d}U/\mathrm{d}I$ decreases monotonously. The geometric mean of R_n is expressed by Formula (2).

$$R_n = \sqrt{(\mathrm{d}U/\mathrm{d}I) \times (U/I)}, \tag{2}$$

where

$$\mathrm{d}U/\mathrm{d}I = IR_\mathrm{n} \Big/ \sqrt{I^2 - I_\mathrm{ci}^2} \tag{3}$$

and

$$U/I = \left(R_\mathrm{n}/I\right) \times \sqrt{I^2 - I_\mathrm{ci}^2}\ , \tag{4}$$

thus

$$\left(\mathrm{d}U/\mathrm{d}I\right) \times \left(U/I\right) = R_\mathrm{n}^2\ . \tag{5}$$

The dU/dI and U/I values can be calculated by using a measured U–I data set. By selecting a data set appropriate for the least-squares fitting from the whole U–I characteristic curve, the effects of noise-rounding and self-heating are minimized.

The hyperbolic function nonlinear fitting method shall be applied to a data set selected by the geometric mean method. The convergence condition of fitting routine should be that the R_n and I_ci parameters are stationary at a digit position that corresponds to the rightmost digit of standard uncertainty values (standard deviation values) with two significant figures (see Table A.1 and Table B.1). For practical calculation, software packages with a function of nonlinear least-squares fitting can be used to estimate R_n and I_ci and corresponding standard deviation of these mean quantities. The software packages make no meaningful difference in estimation results. Actual estimation examples are found in 8.3.2 and Annex A.

7.2 Geometric mean criterion for hyperbolic function fitting

A data set range appropriate for the hyperbolic function fitting method shall be such that the geometric mean curve (dU/dI·U/I)^{0,5} against I has a plateau within 5 % deviation and dU/dI decreases monotonously as I increases.

8 Standard uncertainty

8.1 General

Type A uncertainty, which is the evaluation of a component of measurement uncertainty by a statistical analysis, is estimated by the standard deviations of R_n and I_ci when Formula (1) is fitted to the U–I characteristic data set selected by the geometric mean criterion [2] [3]. The Type A uncertainty of this document is estimated by using the typical U–I curve of JL350 in Annex A. Type B uncertainty, which is the evaluation of uncertainty by means other than the statistical analysis, includes uncertainty arising from variation in temperature and measurement of voltage and current [2] [3].

The total standard uncertainty of this measurement method is the sum of the Type A uncertainty and Type B uncertainty according to the propagation law. Actual application of this document requires the Type A uncertainty estimation from experimental data only. Taking into account the Type B uncertainty values tabulated in Table 2 and Table 3, the Type A uncertainty values shall be kept less than the values in 8.5.

8.2 Type A uncertainty

The mean quantities R_n and I_ci and their standard deviation values of $u_{\mathrm{A},R}$ and $u_{\mathrm{A},I}$ are obtained by minimizing the sum of

$$J=\sum_{j=1}^{m}\left[U_j-\left(R_n\sqrt{I_j^2-I_{ci}^2}\right)\right]^2 , \tag{6}$$

where, I_j and U_j (j = 1, …, m) are the data set selected by the geometrical mean criterion.

For uncertainty estimation, the sensitivity matrix $\mathbf{X}$ is expressed by Formula (7):

$$\mathbf{X}=\begin{bmatrix}\left(\frac{\partial U}{\partial R_n}\right)_{j=1} & \left(\frac{\partial U}{\partial I_{ci}}\right)_{j=1}\\ \vdots & \vdots \\ \left(\frac{\partial U}{\partial R_n}\right)_{j=m} & \left(\frac{\partial U}{\partial I_{ci}}\right)_{j=m}\end{bmatrix} \tag{7}$$

where

$$\frac{\partial U}{\partial R_n}=\sqrt{I_j^2-I_{ci}^2} \tag{8}$$

and

$$\frac{\partial U}{\partial I_{ci}}=\frac{R_n I_{ci}}{\sqrt{I_j^2-I_{ci}^2}} \tag{9}$$

Therefore, the uncertainty matrix of the parameter is expressed by Formula (10):

$$\mathbf{U}=\left(\mathbf{X}^{\mathrm{T}}\mathbf{X}\right)^{-1}\times\hat{\sigma}^2=\begin{bmatrix}u^2(R_n) & u(R_n,I_{ci})\\ u(R_n,I_{ci}) & u^2(I_{ci})\end{bmatrix} \tag{10}$$

where

$$\hat{\sigma}^2=\frac{J}{m-1} \tag{11}$$

For typical Type A uncertainty estimation, the U–I data set with the largest relative standard uncertainty (standard deviation divided by average) values is selected from the HTS junctions in Annex A. The data of the junction TUT in Table 1 are excluded, since the sinusoidal current scan does not meet this document. The largest relative uncertainty values are 0,029 % for R_n and 0,33 % for I_{ci} for the junction JL350, and the corresponding standard deviation values are 0,003 8 Ω and 0,21 µA in Table 1.