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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**



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SUPERCONDUCTIVITY –

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

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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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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 $I_c R_n$ 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 $I_c R_n$ 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

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- 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 k Ω . The input resistance of the data acquisition system should be set at a high value, for example 1 M Ω . 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.

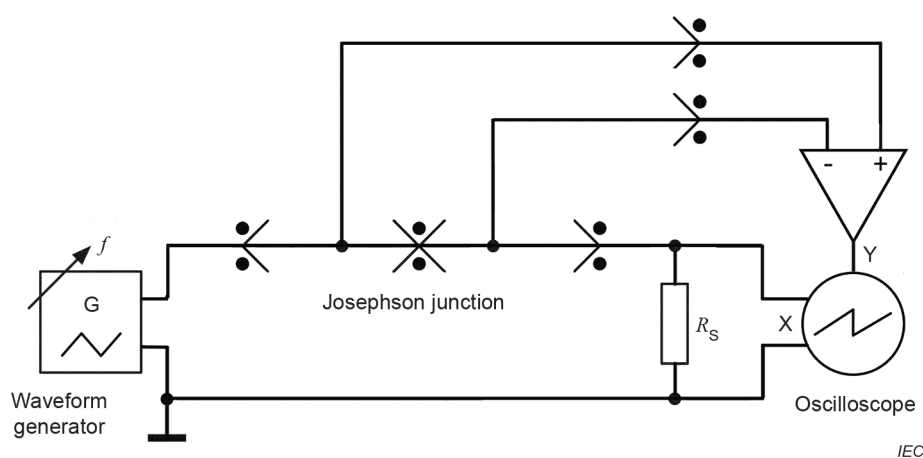


Figure 1 – Typical circuitry for voltage-current (U – I) characteristic curve measurement

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 $\pm 0,05$ %. 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.

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

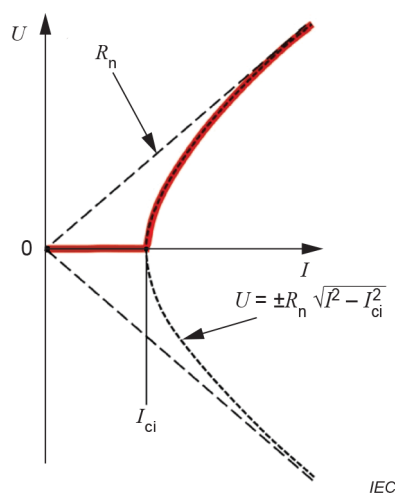


Figure 2 – Ideal $U-I$ characteristic curve (red line) and hyperbolic function (RSJ) model curve (dotted line)

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 dU/dI , U/I and $(dU/dI \times U/I)^{0,5}$ plotted against I . The appropriate data set range shall be such that the geometric mean curve $(dU/dI \times U/I)^{0,5}$ against I has a plateau within 5 % deviation and dU/dI decreases monotonously. The geometric mean of R_n is expressed by Formula (2).

$$R_n = \sqrt{(dU/dI) \times (U/I)}, \quad (2)$$

where

$$dU/dI = IR_n / \sqrt{I^2 - I_{ci}^2} \quad (3)$$

and

$$U/I = (R_n/I) \times \sqrt{I^2 - I_{ci}^2}, \quad (4)$$

thus

$$(dU/dI) \times (U/I) = R_n^2. \quad (5)$$

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 $(dU/dI \cdot U/I)^{0.5}$ 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 $u_{A,R}$ and $u_{A,I}$ are obtained by minimizing the sum of

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

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

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

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

where

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

and

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

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

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

where

$$\hat{\sigma}^2 = \frac{J}{m-1} \quad (11)$$

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.

Table 1 – Typical relative standard Type A uncertainty for high- T_c Josephson junctions

Junction (type)	Estimation by combined method					
	R_n	$u_{A,R}$	Relative standard uncertainty	I_{ci}	$u_{A,I}$	Relative standard uncertainty
	Ω	Ω	%	μA	μA	%
JL350 (YBCO step-edge)	12,934 0	0,003 8	0,029	63,33	0,21	0,33
JL351 (YBCO step-edge)	9,304 2	0,001 8	0,019	32,651	0,045	0,14
TUT (YBCO step-edge)	0,810 0	0,005 0	0,62	358,2	3,5	0,98

8.3 Type B uncertainty

8.3.1 General

The Type B uncertainty of the measurement of R_n and I_{ci} in this document is expressed by Formula (12) and Formula (13):

$$u_{B,R}^2 = \left(\frac{\partial R_n}{\partial T} \right)^2 \times u_T^2 + \left(\frac{\partial R_n}{\partial U} \right)^2 \times u_U^2 + \left(\frac{\partial R_n}{\partial I} \right)^2 \times u_I^2 \quad (12)$$

and

$$u_{B,I}^2 = \left(\frac{\partial I_{ci}}{\partial T} \right)^2 \times u_T^2 + \left(\frac{\partial I_{ci}}{\partial U} \right)^2 \times u_U^2 + \left(\frac{\partial I_{ci}}{\partial I} \right)^2 \times u_I^2 \quad (13)$$

where

$\partial R_n / \partial T$ is a sensitivity of R_n to a variation of temperature T ;

$\partial R_n / \partial U$ is a sensitivity of R_n to a variation of voltage U ;

$\partial R_n / \partial I$ is a sensitivity of R_n to a variation of current I ;

u_T , u_U and u_I are the standard deviation values for the measurement of temperature, voltage and current, respectively.

The notation for I_{ci} is the same as that for R_n .

8.3.2 Temperature

U – I curve measurement shall be carried out in a liquid nitrogen bath. The temperature variation between 76,8 K and 77,7 K is expected from the variation of atmospheric pressure on earth. The $\partial R_n / \partial T$ was approximated by obtaining R_n values at T_1 and T_2 by applying this document to experimental U – I curves, and then calculating $[R_n(T_2) - R_n(T_1)] / [T_2 - T_1]$. The same method was applied to I_{ci} . U – I curves of a bicrystal YBCO junction tagged as "TUT-JJ05" were measured at 75,8 K and 76,3 K. The data set range determined with the geometric mean criterion and the U – I curves with the hyperbolic function fitting results (RSJ model) are shown in Figure 3 and Figure 4 for 75,8 K and 76,3 K, respectively.

For 75,8 K a data set between 35 μA and 107 μA indicated by the arrow was selected for hyperbolic function fitting as shown in Figure 3 (a). The least-squares fitting with Formula (1) gives $R_n = 1,540\ 0\ (0,001\ 8)\ \Omega$ and $I_{ci} = 29,16\ (0,13)\ \mu\text{A}$ at 75,8 K. Figure 3 (b) shows a hyperbolic curve of $U = R_n \times (I^2 - I_{ci}^2)^{0,5}$ with the estimated values in red and an ohmic line (normal state resistance) of $U = R_n \times I$ in blue.

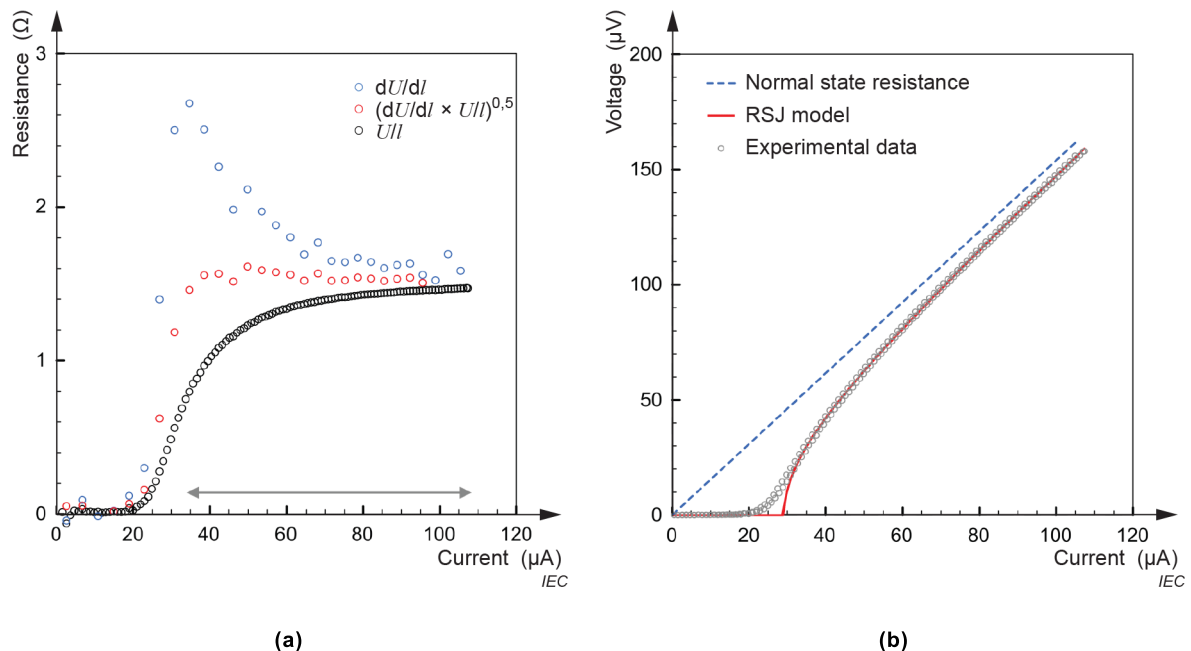


Figure 3 – Geometric mean criterion and RSJ model fitting for TUT-JJ05 at 75,8 K

For 76,3 K a data set between 31 μA and 98 μA indicated by the arrow was selected for hyperbolic function fitting as shown in Figure 4 (a). The least-squares fitting with Formula (1) gives $R_n = 1,539\ 6\ (0,001\ 8)\ \Omega$ and $I_{ci} = 26,32\ (0,11)\ \mu\text{A}$ at 76,3 K. Figure 4 (b) shows a hyperbolic curve of $U = R_n \times (I^2 - I_{ci}^2)^{0,5}$ with the estimated values and an ohmic line of $U = R_n \times I$.

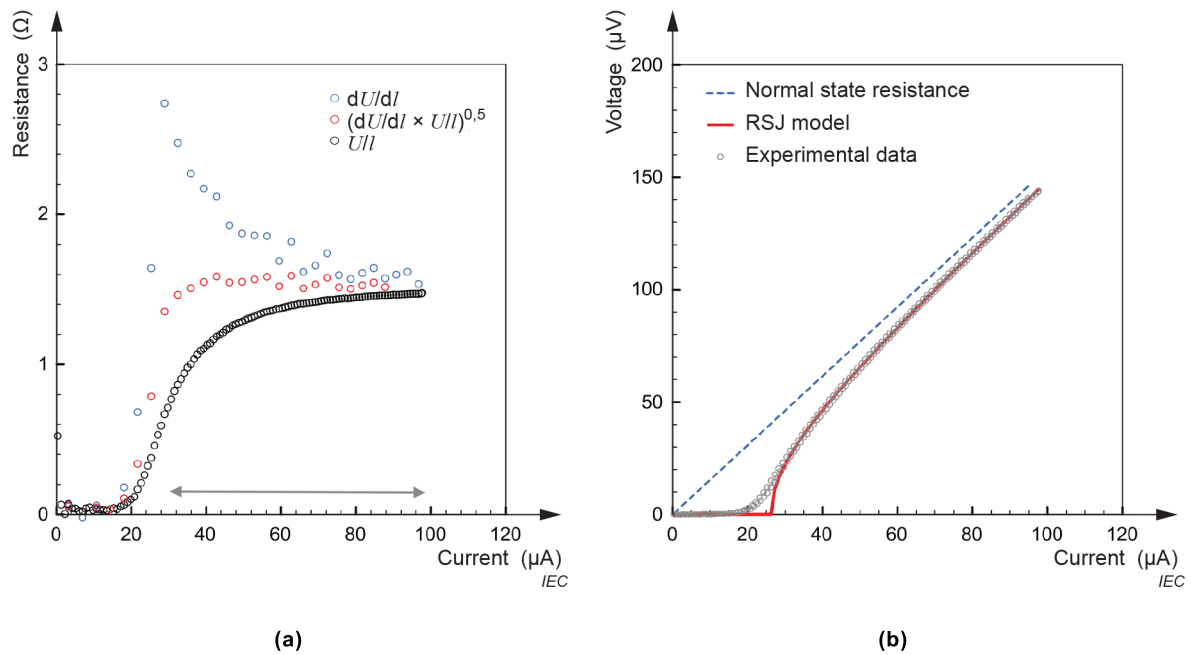


Figure 4 – Geometric mean criterion and RSJ model fitting for TUT-JJ05 at 76,3 K

Consequently, the temperature sensitivity coefficients are estimated at $\Delta R_n/\Delta T = -0,000\ 8\ \Omega/\text{K}$ and $\Delta I_{ci}/\Delta T = -5,68\ \mu\text{A}/\text{K}$. u_T is estimated by a standard deviation of $(77,7\ \text{K} - 76,8\ \text{K}) / 2\sqrt{3} = 0,26\ \text{K}$, providing a uniform probability density function for T .

8.3.3 Voltage measurement

For a voltage measurement using the data acquisition system, the signal should be measured with a relative standard uncertainty of 0,3 % that is typical in data acquisition systems with an amplifier, an ADC with a resolution of eight bits, and other necessary circuits.

The $\partial R_n/\partial U$ and $\partial I_{ci}/\partial U$ are estimated by using the combined method with a 1 μV bias added to the measured $U-I$ curve. Accordingly, the typical sensitivity coefficients of $\Delta R_n/\Delta U$ and $\Delta I_{ci}/\Delta U$ are calculated by using the $U-I$ data set of TUT-JJ05 at 76,3 K.

The original normal state resistance is 1,539 6 Ω, and the 1 μV bias results in 1,549 8 Ω. Therefore, the $\Delta R_n/\Delta U$ sensitivity is 0,010 2 Ω/μV.

The original intrinsic critical current I_{ci} is 26,32 μA, and the 1 μV bias results in 25,85 μA. Therefore, the $\Delta I_{ci}/\Delta U$ sensitivity is -0,47 μA/μV.

u_U is estimated by taking into account a full-scale range of 1 mV for an ADC system, which makes the standard deviation of 3 μV at the maximum.

8.3.4 Current measurement

For the current measurement using the data acquisition system, the voltage across a shunt resistance should be measured by an ADC with a relative standard uncertainty not exceeding 0,3 %.

The $\partial R_n/\partial I$ and $\partial I_{ci}/\partial I$ are estimated by using the combined method with a 1 μA bias added to the measured $U-I$ curve. Accordingly, the typical sensitivity coefficients of $\Delta R_n/\Delta I$ and $\Delta I_{ci}/\Delta I$ are calculated by using the $U-I$ data set of TUT-JJ05 at 76,3 K.

The original normal state resistance is 1,539 6 Ω , and the 1 μA bias results in 1,526 5 Ω . Therefore, the $\Delta R_n/\Delta I$ sensitivity is $-0,013 \Omega/\mu\text{A}$.

The original intrinsic critical current I_{ci} is 26,32 μA , and the 1 μA bias results in 27,50 μA . Therefore, the $\Delta I_{ci}/\Delta I$ sensitivity is 1,18 $\mu\text{A}/\mu\text{A}$.

u_I is estimated by taking into account a full-scale range of 10 mV for an ADC system divided by a shunt resistance R_s . The full-scale range is set at 10 times larger than that for the voltage measurement of Josephson junctions. The standard deviation of an ADC system at the 10 mV full scale is assumed to be 30 μV at the maximum. The R_s value is assumed to be 100 Ω , of which tolerance shall be better than $\pm 0,05 \%$, which makes a standard deviation value of $100 \Omega \times 0,000 5 / \sqrt{3} = 0,029 \Omega$ in a uniform probability density function. The variance of U/R_s is maximum at the full scale of 10 000 μV of the ADC: $(30 \mu\text{V} / 100 \Omega)^2 + (10\,000 \mu\text{V} / 100 \Omega^2 \times 0,029 \Omega)^2 = 0,090 8$ in a unit of $(\mu\text{A})^2$. This maximum standard deviation of 0,30 μA is used in the following estimation.

8.4 Budget table

Typical estimation of standard uncertainty in this document is summarized in Table 2 and Table 3. The total standard uncertainty value of $u_{\text{total},R}$ is calculated by summing the Type A uncertainty $u_{A,R}$ and the Type B uncertainty $u_{B,R}$ according to the propagation law.

Table 2 – Budget table for R_n

Factor	Parameter symbol	Symbol of standard deviation and type	Sensitivity coefficient	Standard deviation of parameter	Contribution to $u_{\text{total},R}$
U – I measurement	–	$u_{A,R}$, A	–	–	0,001 8 Ω
Temperature	T	u_T , B	–0,000 8 Ω /K	0,26 K	0,000 2 Ω
Voltage	U	u_U , B	0,010 Ω /μV	3,0 μV	0,030 Ω
Current	I	u_I , B	–0,013 Ω /μA	0,30 μA	0,003 9 Ω
Combined standard uncertainty		$u_{\text{total},R}$	0,030 Ω		
Relative standard uncertainty		1,9 %			
$R_n \pm$ expanded uncertainty (coverage factor $k = 2$)		1,540 $\Omega \pm$ 0,060 Ω			

The total standard uncertainty value of $u_{\text{total},I}$ is calculated by summing the Type A uncertainty $u_{A,I}$ and the Type B uncertainty $u_{B,I}$ according to the propagation law.

Table 3 – Budget table for I_{ci}

Factor	Parameter symbol	Symbol of standard deviation and type	Sensitivity coefficient	Standard deviation of parameter	Contribution to $u_{\text{total},I}$
$U-I$ measurement	–	$u_{A,I}$, A	–	–	0,14 μA

Temperature	T	u_T , B	–5,7 $\mu\text{A/K}$	0,26 K	1,5 μA
Voltage	U	u_U , B	–0,47 $\mu\text{A}/\mu\text{V}$	3,0 μV	1,4 μA
Current	I	u_I , B	1,2 $\mu\text{A}/\mu\text{A}$	0,30 μA	0,36 μA
Combined standard uncertainty		$u_{\text{total},I}$	2,1 μA		
Relative standard uncertainty		8,0 %			
$I_{\text{ci}} \pm$ expanded uncertainty (coverage factor $k = 2$)		26,3 $\mu\text{A} \pm 4,2 \mu\text{A}$			

8.5 Uncertainty requirement

As shown in the typical uncertainty in Table 2 and Table 3, the voltage measurement uncertainty considerably influences the total uncertainty $u_{\text{total},R}$ and $u_{\text{total},I}$. In addition, the $u_{\text{total},I}$ is dominated by the temperature variation, which is physically reasonable. In order not to significantly exceed the level of the standard uncertainty in Table 2 and Table 3, the values of $u_{A,R}$ and $u_{A,I}$, which are the standard deviation values of the least-squares fitting, shall be less than $2 \times u_{A,R}$ or $2 \times u_{A,I}$. The corresponding relative standard uncertainty of $u_{A,R}/R_n$ and $u_{A,I}/I_{\text{ci}}$ shall be less than 0,2 % and 0,8 %, respectively. When either $u_{A,R}/R_n$ or $u_{A,I}/I_{\text{ci}}$ exceeds these values, the measurement apparatus shall be improved.

9 Test report

9.1 Identification of test device

The test device shall be identified by the following:

- name of the manufacturer;
- device serial number or equivalent identification;
- Type of Josephson junction.

9.2 R_n value

R_n value obtained by this document

9.3 I_{ci} value

I_{ci} value obtained by this document

9.4 Standard uncertainty

Relative standard uncertainty values of $u_{A,R}/R_n$ and $u_{A,I}/I_{\text{ci}}$ in Type A uncertainty

9.5 Atmospheric pressure

Atmospheric pressure value obtained from the nearest meteorological station or local measurement.

9.6 Miscellaneous optional report

The following data may be reported optionally:

- R_n value by geometric mean method;
- R_n value in each measurement run;

- I_{ci} value in each measurement run;
- raw $U-I$ curve;
- temperature converted from an atmospheric pressure value;
- temperature measured by a sensor;
- structure of cryostat, magnetic shield and RF shield;
- configuration of electric measurement system;
- chemical composition of the thin film and the substrate material.

Annex A (informative)

Calculation technique and practical application to high- T_c Josephson junctions

A.1 General

Annex A gives informative reference on calculation of R_n , I_{ci} and Type A standard uncertainty. The combination of the geometric mean method and the hyperbolic function fitting method is applied to artificially-produced U – I curves and experimental U – I curves of HTS Josephson junctions. It is possible to evaluate R_n and I_{ci} properly even when noise-rounding and self-heating effects are non-negligible.

A.2 Hyperbolic function fitting method

U – I characteristics curves of high- T_c Josephson junctions are explained by the hyperbolic function of Formula (1) [1]. Figure A.1 is an ideal U – I characteristic curve of a junction with $R_n = 10\ \Omega$ and $I_{ci} = I_c = 30\ \mu A$, where the data sets of U_j and I_j are artificially produced. The U_j and I_j express j -th data of U and I . The R_n and I_{ci} values and the corresponding uncertainty (standard deviation) values of $u_{A,R}$ and $u_{A,I}$, which are called Type A uncertainty deduced by statistical analysis, are estimated by optimizing the R_n and I_{ci} parameters in such a way that the sum of the squares of difference between the measured data and Formula (1) is minimized, which is nonlinear least-squares fitting. The nonlinear least-squares fitting can be performed using regression analysis function of commercial software packages. In addition, a solver procedure file for estimating R_n , I_{ci} and corresponding standard uncertainty values is available at: <https://www.iec.ch/tc90/supportingdocuments>.

In reality, deviation from the hyperbolic curve is observed in many cases. Two major causes for the deviation are noise-rounding and self-heating. Figure A.2 shows a U – I curve of a junction that suffers a noise-rounding deviation in a current range less than $30\ \mu A$ and a self-heating deviation in a current range larger than $150\ \mu A$, where the data sets of U_j and I_j are artificially produced. Hyperbolic curve fitting using the whole data set gives an unreliable estimation. A practical solution is to select a proper data set in a range that is not affected by the two effects. The geometric mean method in Clause A.3 provides a good criterion for selecting the data set.

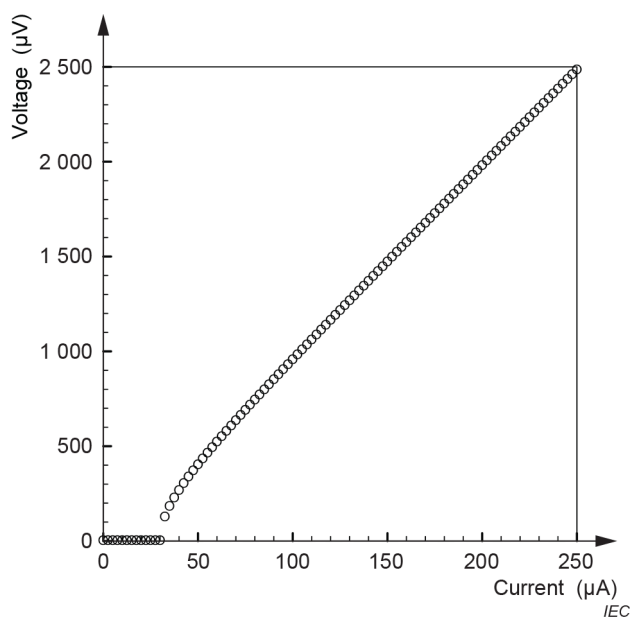


Figure A.1 – U – I curve based on resistively shunted junction (RSJ) model

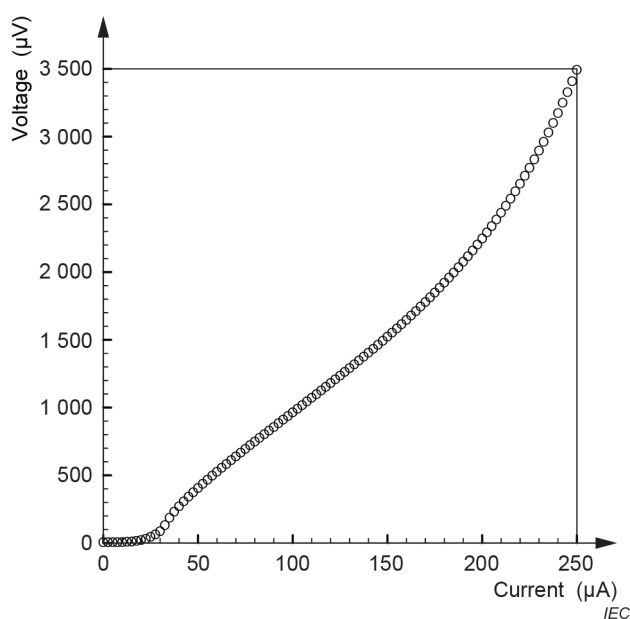


Figure A.2 – U – I curve affected by noise-rounding and self-heating

A.3 Geometric mean method

The geometric mean method is an approach to calculate R_n with the geometric mean of a derivative of voltage with respect to current, dU/dI , and a voltage/current ratio, U/I , from a measured U – I data set by using Formula (2) to Formula (5).

For the calculation of dU/dI and U/I , $(U_{j+1} - U_j) / (I_{j+1} - I_j)$ and U_j/I_j are used incrementally. The value of R_n is calculated by $[(U_{j+1} - U_j) / (I_{j+1} - I_j)]^{0,5} \times (U_j/I_j)^{0,5}$.