IEC 61788-4

Edition 3.0 2011-07

INTERNATIONAL STANDARD

NORME INTERNATIONALE

colour inside

**Superconductivity –
Part 4: Residual resistance ratio measurement – Residual resistance ratio of Nb-Ti composite superconductors**

**Supraconductivité –
Partie 4: Mesure du rapport de résistance résiduelle – Rapport de résistance résiduelle des supraconducteurs composites de Nb-Ti**

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SUPERCONDUCTIVITY –

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FOREWORD

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International Standard IEC 61788-4 has been prepared by IEC technical committee 90: Superconductivity.

This third edition cancels and replaces the second edition published in 2007. It constitutes a technical revision. The main revisions are the addition of two new annexes, "Uncertainty considerations" (Annex B) and "Uncertainty evaluation in test method of RRR for NbTi" (Annex C).

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

FDIS	Report on voting
90/263/FDIS	90/275/RVD

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

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

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

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

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- withdrawn,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

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INTRODUCTION

Copper is used as a matrix material in multifilamentary superconductors and works as an electrical shunt when the superconductivity is interrupted. It also contributes to recovery of the superconductivity by conducting heat generated in the superconductor to the surrounding coolant. The cryogenic-temperature resistivity of copper is an important quantity, which influences the stability of the superconductor. The residual resistance ratio is defined as a ratio of the resistance of the superconductor at room temperature to that just above the superconducting transition.

In this International Standard, the test method of residual resistance ratio of Nb-Ti composite superconductors is described. The curve method is employed for the measurement of the resistance just above the superconducting transition. Other methods are described in Clause A.3.

SUPERCONDUCTIVITY –

Part 4: Residual resistance ratio measurement – Residual resistance ratio of Nb-Ti composite superconductors

1 Scope

This part of IEC 61788 covers a test method for the determination of the residual resistance ratio (*RRR*) of composite superconductors comprised of Nb-Ti filaments and Cu, Cu-Ni or Cu/Cu-Ni matrix. This method is intended for use with superconductors that have a monolithic structure with rectangular or round cross-section, *RRR* less than 350, and cross-sectional area less than 3 mm^2. All measurements are done without an applied magnetic field.

The method described in the body of this standard is the "reference" method and optional acquisition methods are outlined in Clause A.3.

2 Normative references

The following referenced document is 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

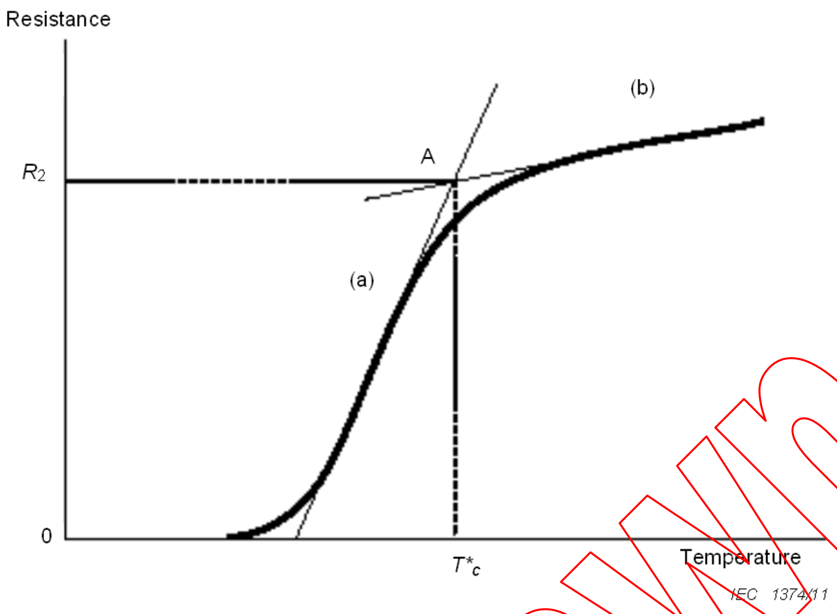
For the purpose of this document, the terms and definitions given in IEC 60050-815 and the following apply.

3.1
residual resistance ratio
RRR
the ratio of resistance at room temperature to the resistance just above the superconducting transition

NOTE In this standard for Nb-Ti composite superconductors, the room temperature is defined as 293 K (20 °C), and the residual resistance ratio is obtained in Equation (1) below, where the resistance (R_1) at 293 K is divided by the resistance (R_2) just above the superconducting transition.

$$RRR = \frac{R_1}{R_2} \qquad (1)$$

Figure 1 shows schematically a resistance versus temperature curve acquired on a specimen while measuring the cryogenic resistance. Draw a line in Figure 1 where the resistance sharply increases (a), and draw also a line in Figure 1 where the temperature increases but the resistance remains almost the same (b). The value of resistance at the intersection of these two lines at $T=T_c{}^*$, A, is defined as resistance (R_2) just above the superconducting transition.



Temperature T_c* is that at the intersection point.

Figure 1 – Relationship between temperature and resistance

4 Requirements

The resistance measurement both at room and cryogenic temperatures shall be performed with the four-terminal technique.

The target relative combined standard uncertainty of this method is defined as an expanded uncertainty (k = 2) not to exceed 5 % based on the coefficient of variation (COV) of 2,5 % in the intercomparison test (see Clause C.2).

The maximum bending strain, induced during mounting the specimen, shall not exceed 2 %.

5 Apparatus

5.1 Material of measuring mandrel or of measuring base plate

Material of the measuring mandrel for a coiled specimen or of the measuring base plate for a straight specimen shall be copper, aluminium, silver, or the like whose thermal conductivity is equal to or better than 100 W/(m·K) at liquid helium temperature (4,2 K). The surface of the material shall be covered with an insulating layer (tape or a layer made of polyethylene terephthalate , polyester, polytetrafluoroethylene , etc.) whose thickness is 0,1 mm or less.

5.2 Diameter of the measuring mandrel and length of the measuring base plate

Diameter of the measuring mandrel shall be large enough to keep bending strain of the specimen less than or equal to 2 %.

The measuring base plate shall be at least 30 mm long in one dimension.

5.3 Cryostat for the resistance, R_2, measurement

The cryostat shall include a specimen support structure and a liquid helium reservoir for the resistance, R_2, measurement. The specimen support structure shall allow the specimen, which is mounted on a measurement mandrel or a measurement base plate, to be lowered and raised into, and out of, a liquid helium bath. In addition, the specimen support structure shall be made so that a current can flow through the specimen and the resulting voltage generated along the specimen can be measured.

6 Specimen preparation

The test specimen shall have no joints or splices, and shall be 30 mm or longer. The distance between two voltage taps (L) shall be 25 mm or longer. A thermometer for measuring cryogenic temperature shall be attached near the specimen.

Some mechanical method shall be used to hold the specimen against the insulated layer of the measurement mandrel or base plate. Special care shall be taken during instrumentation and installation of the specimen on the measurement mandrel or on the measurement base plate so that no excessive force, which may cause undesired bending strain or tensile strain, shall be applied to the specimen.

The specimen shall be instrumented with current contacts near each end of the specimen and a pair of voltage contacts over a central portion of the specimen. The specimen shall be mounted on a measurement mandrel or on a measurement base plate for these measurements. Both resistance measurements, R_1 and R_2, shall be made on the same specimen and the same mounting.

7 Data acquisition and analysis

7.1 Resistance (R_1) at room temperature

The mounted specimen shall be measured at room temperature (T_m (K)), where T_m satisfies the following condition, $273 \leq T_m \leq 308$. A specimen current (I_1 (A)) shall be applied so that the current density is in the range of 0,1 A/mm² to 1 A/mm² based on the total wire cross-sectional area, and the resulting voltage (U_1 (V)), I_1 and T_m shall be recorded. Equation (2) below shall be used to calculate the resistance (R_m) at room temperature. The resistance (R_1) at 293 K (20 °C) shall be calculated using equation (3) for a wire with Cu matrix. The value of R_1 shall be set equal to R_m, without any temperature correction, for wires that do not contain a pure Cu component.

$$R_m = \frac{U_1}{I_1} \tag{2}$$

$$R_1 = \frac{R_m}{[1 + 0{,}00393 \times (T_m - 293)]} \tag{3}$$

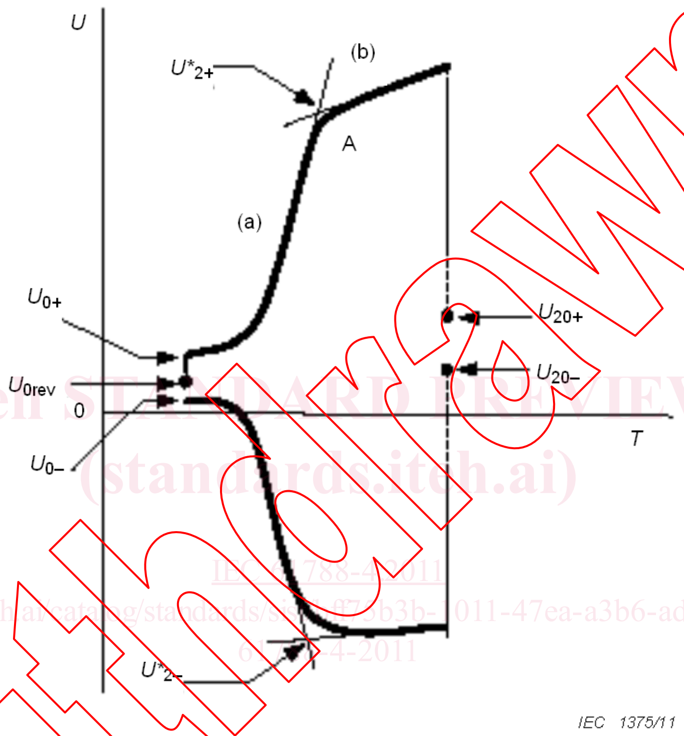
7.2 Resistance (R_2*) just above the superconducting transition

Under a strained condition of the specimen, the measured cryogenic resistance, R_2*, is not a correct value for R_2. The corresponding correction of the strain effect will be described in 7.3.

7.2.1 The specimen, which is still mounted as it was for the room temperature measurement, shall be placed in the cryostat for electrical measurement specified under 5.3. Alternate cryostats that employ a heating element to sweep the specimen temperature are described in Clause A.2.

7.2.2 The specimen shall be slowly lowered into the liquid helium bath and cooled to liquid helium temperature over a time period of at least 5 min.

7.2.3 During the acquisition phases of the low-temperature R_2* measurements, a specimen current (I_2) shall be applied so that the current density is in the range of 0,1 A/mm² to 10 A/mm² based on the total wire cross-sectional area, and the resulting voltage (U(V)), I_2 (A), and specimen temperature (T (K)) shall be recorded. In order to keep the ratio of signal to noise high enough, the measurement shall be carried out under the condition that the absolute value of the resulting voltage above the superconducting transition exceeds 10 µV. An illustration of the data to be acquired and its analysis is shown in Figure 2.



Voltages with subscripts + and – are those obtained in the first and second measurements under positive and negative currents, respectively, and U_{20+} and U_{20-} are those obtained at zero current. For clarity, U_{0rev} is not shown coincident with U_{0-}. Voltages U_{2+}* and U_{2-}* with asterisk are those at the intersection points.

Figure 2 – Voltage (*U*) versus temperature (*T*) curves and definitions of each voltage

7.2.4 When the specimen is in superconducting state and test current (I_2) is applied, two voltages shall be measured nearly simultaneously: U_{0+} (the initial voltage recorded with a positive current polarity) and U_{0rev} (the voltage recorded during a brief change in applied current polarity). A valid R_2* measurement requires that excessive interfering voltages are not present and that the specimen is initially in the superconducting state. Thus, the following condition shall be met for a valid measurement:

$$\frac{\left|U_{0+} - U_{0\,rev}\right|}{\overline{U}_2} < 1\ \% \tag{4}$$

where $\overline{U}_2$ is the average voltage for the specimen in the normal state at cryogenic temperature, which is defined at 7.2.10.

7.2.5 The specimen shall be gradually warmed so that it changes to the normal state completely. When the cryostat for the resistance measurement specified under 5.3 is used, this can be achieved simply by raising the specimen to an appropriate position above the liquid helium level.

7.2.6 The specimen voltage versus temperature curve shall be acquired with the rate of temperature increase maintained between 0,1 K/min and 10 K/min.

7.2.7 The voltage versus temperature curve shall continue to be recorded during the transition into the normal state, up to a temperature somewhat less than 15 K. Then, the specimen current shall be decreased to zero and the corresponding voltage, U_{20+}, shall be recorded at a temperature below 15 K.

7.2.8 The specimen shall then be slowly lowered into the liquid helium bath and cooled to the same temperature, within ±1 K, where the initial voltage signal U_{0+} was recorded. A specimen current, I_2, with the same magnitude but negative polarity (polarity opposite that used for the initial curve) shall be applied and the voltage U_{0-} shall be recorded at this temperature. The procedural steps 7.2.5 to 7.2.7 shall be repeated to record the voltage versus temperature curve with this negative current. In addition, the recording of U_{20-} shall be made at the same temperature, within ±1 K, where U_{20+} was recorded.

7.2.9 Each of the two voltage versus temperature curves shall be analyzed by drawing a line (a) through the data where the absolute value of voltage sharply increases with temperature (see Figure 2) and drawing a second line (b) through the data above the transition where the voltage is nearly constant with temperature. U_{2+}* and U_{2-}* in Figure 2 shall be determined at the intersection of these two lines for the positive and negative polarity curves respectively.

7.2.10 The corrected voltages, U_{2+} and U_{2-}, shall be calculated using the following equations, $U_{2+} = U_{2+}^* - U_{0+}$ and $U_{2-} = U_{2-}^* - U_{0-}$. The average voltage, $\overline{U_2}$, shall be defined as

$$\overline{U_2} = \frac{|U_{2+} - U_{2-}|}{2} \tag{5}$$

7.2.11 A valid R_2* measurement requires that the shift of thermoelectric voltage be within acceptable limits during the measurements of the U_{2+} and U_{2-}. Thus, the following condition shall be met for a valid measurement,

$$\frac{|\Delta_+ - \Delta_-|}{\overline{U_2}} < 3\% \tag{6}$$

where Δ_+ and Δ_- are defined as $\Delta_+ = U_{20+} - U_{0+}$ and $\Delta_- = U_{20-} - U_{0-}$. If the R_2* measurement does not meet the validity requirements in 7.2.4 and this subclause, then improvement steps either in hardware or experimental operation shall be taken to meet these requirements before results are reported.

7.2.12 Equation (7) shall be used to calculate the measured resistance (R_2*) just above the superconducting transition.

$$R_2^* = \frac{\overline{U_2}}{I_2} \tag{7}$$

7.3 Correction on measured R_2* for bending strain

If there is no pure Cu component in the superconductor, then R_2 shall be set equal to R_2*.

For a specimen with a pure Cu component, the bending strain shall be defined by $\varepsilon_b = 100 \times (h/r)$ (%), where h is a half of the specimen thickness and r is the bending radius. If the bending strain is less than 0,3 %, then no correction is necessary, and R_2 shall be set equal to R_2*.

If neither of the above two situations applies, then the resistance R_2 just above the superconducting transition under the strain-free condition shall be estimated by

$$R_2 = R_2^* - \Delta\rho \times \frac{L}{S_{Cu}} \quad (8)$$

where $\Delta\rho$ is defined below and S_{Cu} and L are defined in 8.4. The increase in the resistivity of pure copper at 4,2 K due to tensile strain, ε(%), is expressed by

$$\Delta\rho\ (\Omega m) = 6{,}24 \times 10^{-12}\varepsilon - 5{,}11 \times 10^{-14}\varepsilon^2; \qquad \varepsilon \le 2\ \% \quad (9)$$

The calculation of equation (9) shall be carried out assuming that the equivalent tensile strain ε is (1/2) ε_b and (4/3π) ε_b for rectangular and round wires, respectively. The bending strain dependency of residual resistance ratio for pure copper is described in A.1.

7.4 Residual resistance ratio (*RRR*)

The *RRR* shall be calculated using Equation (1).

8 Uncertainty and stability of the test method

8.1 Temperature

The room temperature shall be determined with a standard uncertainty not to exceed 0,6 K, while holding the specimen, which is mounted on the measuring mandrel or on the measuring base plate, at room temperature.

8.2 Voltage measurement

For the resistance measurement, the voltage signal shall be measured with a relative standard uncertainty not to exceed 0,5 %.

8.3 Current

When the current is directly applied to the specimen with a programmable DC current source, the specimen test current shall be determined with a standard uncertainty not to exceed 0,3 %.When the specimen test current is determined from a voltage-current characteristic of a standard resistor by the four-terminal technique, the standard resistor, with a relative combined standard uncertainty not to exceed 0,3 %, shall be used.”

The fluctuation of d.c. specimen test current, provided by a d.c. power supply, shall be less than 0,5 % during every resistance measurement.

8.4 Dimension

The distance along the specimen between the two voltage taps, (L), shall be determined with a relative combined standard uncertainty not to exceed 5 %.

In the case of the wire with pure Cu matrix, the cross-sectional area of Cu matrix (S_{Cu}) shall be determined using a nominal value of copper to non-copper ratio and nominal dimensions of the specimen.

9 Test report

9.1 *RRR* value

The obtained *RRR* value shall be reported as

$$RRR(1 \pm U_{re}) \ \ (n = \cdot \ \cdot \ \cdot \ ), \tag{10}$$

where $U_{re} = 2u_r$ ($k = 2$) is the expanded relative uncertainty with u_r denoting the uncertainty, k is a coverage factor and n is the sampling number. It is desired that n be larger than 4 so that the normal distribution can be assumed for the estimation of the standard deviation. If n is not sufficiently large, a square distribution shall be assumed. In case of $n = 1$ the analytic method described in Annex C shall be used with $b/R_2 = 1{,}46 \times 10^{-2}$ estimated from the intercomparison test.

9.2 Specimen

The test report for the result of the measurements shall also include the following items, if known.

a) manufacturer

b) classification and/or symbol

c) shape and area of the cross-section

d) dimensions of the cross-sectional area

e) number of filaments

f) diameter of the filaments

g) Cu to Nb-Ti ratio, Cu-Ni to Nb-Ti ratio, or Cu, Cu-Ni to Nb-Ti ratio, or volume ratio among Cu-Ni, Cu, and Nb-Ti.

h) cross-sectional area of the Cu matrix (S_{Cu})

9.3 Test conditions

9.3.1 The following test conditions shall be reported for the measurements of R_1 and R_2.

a) total length of the specimen

b) distance between the voltage measurement taps (L)

c) length of the current contacts

d) transport currents (I_1 and I_2)

e) current densities (I_1 and I_2 divided by the total wire cross-sectional area)

f) voltages (U_1, U_{0+}, U_{0rev}, U_{2+}*, U_{20+}, U_{0-}, U_{2-}*, U_{20-} and $\overline{U_2}$)

g) resistances (R_m, R_1, R_2* and R_2)

h) resistivities ($\rho_1 = (R_1 \times S_{Cu})/L$ and $\rho_2 = (R_2 \times S_{Cu})/L$)

i) material, shape, and dimensions of the mandrel or the base plate

j) installation method of the specimen in the mandrel or the base plate

k) insulating material of the mandrel or the base plate

9.3.2 The following test conditions shall be reported for the measurement of R_1.

a) temperature setting and holding method of the specimen

b) T_m: Temperature for measurement of R_m